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ABSTRACT

This course in instrumentation and controls is one of 16 courses in the Energy Technology Series developed for an Energy Conservation-and-Use Technology curriculum. Intended for use in two-year postsecondary technical institutions to prepare technicians for employment, the courses are also useful in industry for updating employees in company-sponsored training programs. Comprised of eight modules, the course is designed to provide the student with practical knowledge and skills in the specification, use, and calibration of measuring devices and the principles and applications of automatic control process. A detailed examination is made of control systems for electrical power production, heating, air conditioning, and manufacturing. Written by a technical expert and approved by industry representatives, each module contains the following elements: introduction, prerequisites, objectives, subject matter, exercises, laboratory materials, laboratory procedures (experiment section for hands-on portion), data tables (included in most basic courses to help students learn to collect or organize data), references, and glossary. Module titles are Principles of Process Control, Instruments for Fluid Measurements--Pressure and Level, Fluid Flow Measurement, Instruments for Mechanical Measurement, Pneumatic Controls, Automatic Control Systems, and Boiler and Other Special Control Systems. (YLB)

INSTRUMENTATION AND CONTROLS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
601 LAKE AIR DRIVE
WACO, TEXAS 76710

DEC. 1981

PREFACE

ABOUT ENERGY TECHNOLOGY MODULES

The modules were developed by TERC-SW for use in two-year postsecondary technical institutions to prepare technicians for employment and are useful in industry for updating employees in company-sponsored training programs. The principles, techniques, and skills taught in the modules, based on tasks that energy technicians perform, were obtained from a nationwide advisory committee of employers of energy technicians. Each module was written by a technical expert and approved by representatives from industry.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify and define, rather than words with many interpretations, such as know, understand, learn and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Laboratory Materials, which identify the equipment required to complete the laboratory procedure.

Laboratory Procedures, which is the experiment section, or "hands-on" portion of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

References, which are included as suggestions for supplementary reading/viewing for the student.

Glossary, which defines and explains terms or words used within the module that are uncommon, technical, or anticipated as being unfamiliar to the student.

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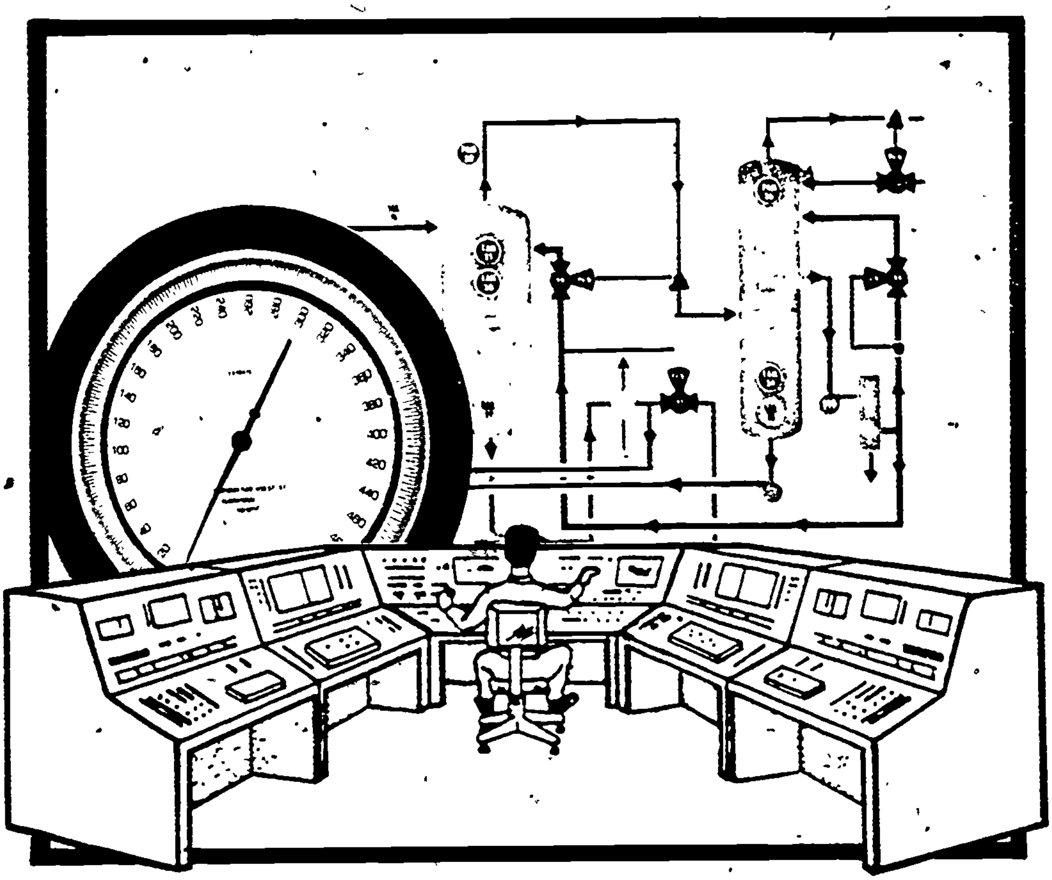

MODULE IC-01

PRINCIPLES OF PROCESS CONTROL

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INTRODUCTION

Automatic control was once envisioned primarily as a means of reducing production cost by increasing production rates with fewer people. The continuous unattended control of large manufacturing facilities is common, and has become a design criterion in the development of new installations. With production cost continually being curtailed by the utilization of instrument applications, the necessity to protect a fragile environment from polluting substances has resulted in the development of measurement and control instrumentation systems that seemed impossible to implement previously. Presently, a new criterion is constantly being considered in every facet of life in our industrial society. That criterion is energy conservation. The concept of energy conservation and management is paramount in every phase in the development and operation of processes. Instrumentation measurement and control has played - and is playing - an important role in the field of energy conservation.

The purpose of this module is to present and discuss the principles of measurement and control. The means by which a process is automatically monitored and controlled will be discussed, as well as the dynamic process conditions that affect process controllability.

PREREQUISITES

The student should have a basic understanding of algebra and physics.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
   a. Process.
   b. Process control.

c. Open-loop control.

d. Closed-loop control.

e. Feedback.

f. Error signal.

g. Closed-loop control components:

Measuring means.

Controlling means.

Final control element.

2. List the advantages and limitations of the following:

a. Open-loop control.

b. Closed-loop control.

3. State the process requirements for closed-loop control.

4. List four types of processes and give their dynamic characteristics.

INSTRUMENTATION AND CONTROL: THE CONCEPT

Goods and services are produced in response to needs and desires. When a need or desire has been recognized, the resulting item or service can be produced only if three factors are present. There must be an idea or concept of what the final product will be and how it will solve the need or desire that generated it. The raw materials, energy, and knowledge that will compose the final product must be available. And, there must be a method that will combine the knowledge, energy, and raw materials into the final product. This method is called a process.

A process may be as simple a filling a tank with water, or it may be as complicated as the production of a synthetic fiber or the launching of a space shuttle. Whatever the process, there must be a means of measuring the degree of success or failure toward the production of the final product. Further, it is not sufficient to measure the degree of success or failure, there must be a way for corrective action to be taken to ensure the best possible final product. By linking measurement with corrective action, control systems are created.

The basic concepts of measurement and control are utilized in a simple process as illustrated in the following example.

> A small community has has great difficulty in maintaining a constant pressure in their water system and has decided to correct this problem. The first step in the solution to their problem is to erect a water tank on a hill at the edge of town. The water tank is constructed with an inlet from the local water supply and an outlet directly into the primary water main. It is known that if the level of the water in the tank is maintained at a constant depth the pressure at the outlet will remain steady.

The process is to maintain the level in the water tank at a specific place; this is called the set point or control point. There are many types of variables that will affect the water level of the tank; each of these variables can be given a special title that will be used from this point on.

- Process variable - the variable that is compared against the set point directly. In the example of the water tank, the process variable is the actual water level that will be compared directly with the desired water level, or set point.
- Manipulated variable - the variable that can be changed at will in such a way as to directly affect the process variable. In the example of the water tank, the manipulated variable is the inlet water flow rate that can be changed by opening or closing a valve.
- Disturbance variable - any variable that adversely affects the process variable and cannot be controlled. In the case of the water tank, the disturbance variable is the rate at which water is drawn from the tank.

In the example of the water tank, measurement enters the picture when we compare the process variable (actual water level) to the set point (desired water level). The process will be controlled when the information provided by the measurements is used to stabilize the process variable at the set point; this can be achieved in two ways - open-loop control or closed-loop control.

OPEN-LOOP CONTROL

Of the two systems of control, the open-loop control system has the fewest number of components and requires the most human involvement. Figure 1 illustrates the water tank using an open-loop control system. Just how this type of control system works can be seen by returning to the example.

> After the water tank was erected the town council became involved in a dispute over how to stabilize the water level at the set point. Most felt that the inlet water flow could be adjusted to the average consumption rate of the previous year, with periodic checks by a maintenance person. By this time it was late autumn and the amount of water being drawn by the residents was at a very low level; thus, there was more water being supplied to the tank than was being drawn from it, and it began to overflow. The maintenance person closed the inlet valve and the level began to drop. The next

day, another maintenance person returned to check the tank and found that the level was at the desired point so the inlet valve was not opened at all. On the third day, the maintenance person found that the actual water level was well below the desired level and opened the inlet valve to let some water in. This process continued on for a month, during which time the tank overflowed twice and went completely dry once. In addition to those three occasions, water pressure still fluctuated from one day to the next.

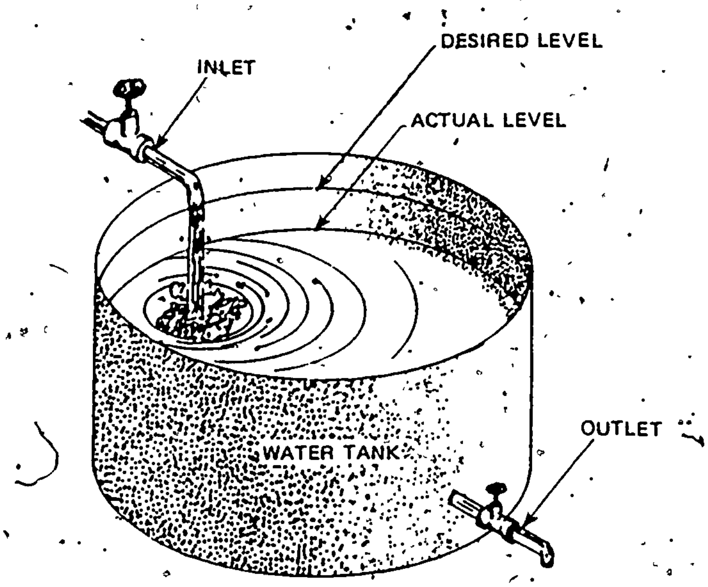

Figure 1. Open-loop control system.

The example of the water tank points out the basic operation and the basic faults of the open-loop control system. Measurements are made on a periodic basis and corrective action is initiated on the basis of those measurements, independent of what is happening with the process at that time. The manipulated variable (inlet water flow rate) was adjusted without regard to what the process variable (actual water level) was doing with respect to the set point (desired water level). When there is a situation where the need for the final product - called the demand - fluctuates frequently, the open-loop control system usually is found to be inadequate. The objective of any control system is to maintain a controlled variable (process variable) at a desired value or condition (set point). In Figure 1, the process variable (actual water level) was maintained at the set point by opening or closing the input valve to manipulate the rate of inlet water flow. If the rate of water flowing into the tank is equal to the water flowing out of the tank, the level will be stable. This is called maintaining a balance between the supply and the demand. Supply is flow in, and demand (or load) is flow out. Thus the objective of any control system is to make supply equal to demand. As demonstrated in the above example, this is not a simple matter because the demand was not constant and the maintenance people were never successful at repositioning the control valve on the inlet for every change that occurred with the load.

While the open-loop control system is simple, the lack of compensation based upon load changes makes its use in most industrial applications undesirable. Operation of the system could be greatly enhanced if the supply to the process were dependent upon the process variable. When this is achieved a closed-loop control system results.

CLOSED-LOOP CONTROL

A closed-loop control system is responsive to changes in process variations. This type of system is most common in the automatic control of processes. Response to changes in the process variations is achieved through the use of what is known as feedback. Feedback is information based upon measurement between the process variable and the set point that causes a change in the manipulated variable to take place in such a way that supply is balanced against demand. Figure 2 demonstrates the components of a closed-loop system in block diagram form.

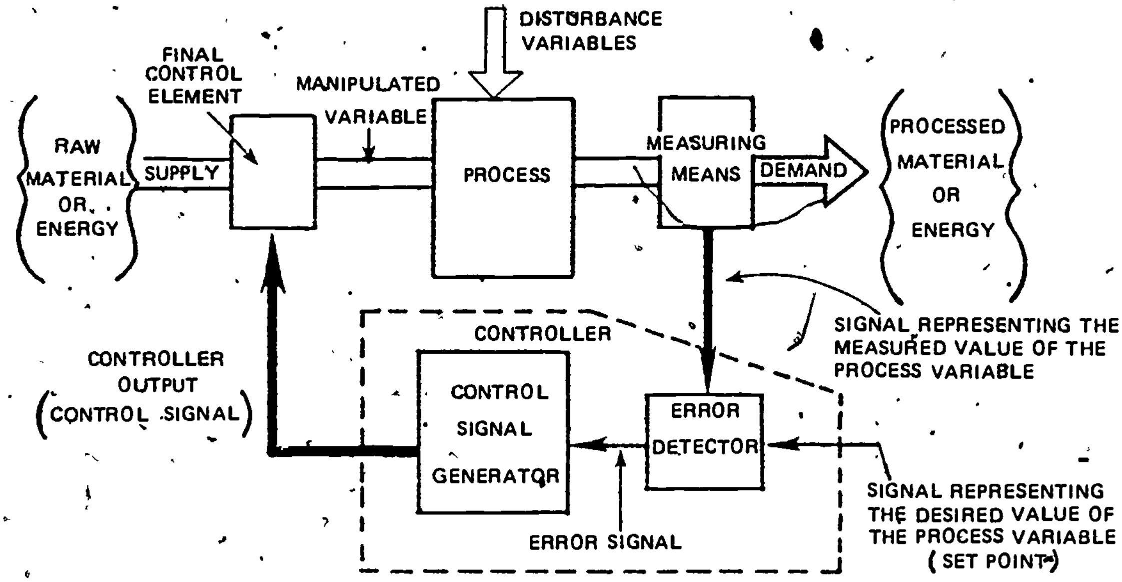

Figure 2. Components of a closed-loop system.

The closed-loop system depicted in Figure 2 performs the following four basic operations.

1. Measures the process variable. The instrument that performs this function is commonly called a transmitter, measuring means, or the primary element.
2. Computes the error signal (difference between set point and process variable), which is the function of the error detector.
3. Uses the error signal to generate a control signal to operate the final control element.
4. Regulates the manipulated variable via the final control element to drive the value of the process variable toward the set-point value.

To further explain the operation of a closed-loop control system, we can return to our example of the water tank and Figure 3.

The town council meets at the close of the month. Through examination of the records concerning water pressure versus time and the large number of complaints, it is obvious that the open-loop control is a failure. After some discussion, it is decided that the town will install a closed-loop control system. A simple float-controlled valve is installed in the tank at the inlet.

Figure 3 is a simplified drawing of the closed-loop control system employed by the town council of the example. The float acts as the measuring means. The lever attached to the float and a pivot on the inlet pipe acts to transmit the "control signal" to the final control element. Our final control element is a spring-loaded valve that is normally open. The controller, containing the error detector and control signal generator, is the float-and-lever assembly. To understand the operation of this and most closed-loop systems, let us inspect operation of this system step-by-step.

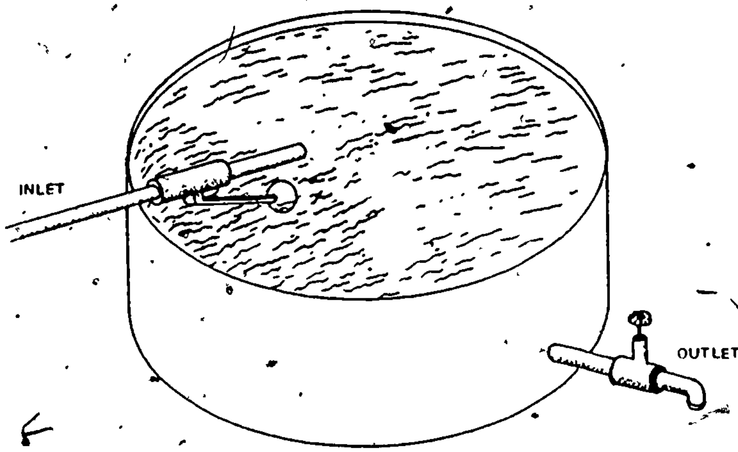

Figure 3. Example closed-loop control system.

We will assume that the system starts out with the process variable stable at the set point. At this beginning point there is a no-load condition; no water is flowing out of the tank.

1. A person or a group of people open their water faucets and create a demand for water from the tank; a disturbance variable is introduced to the system (Figure 4a).
2. The process variable (actual water level) begins to change (drop) carrying the float with it and causing the lever that has kept the valve (final control element) closed to move and begin to open the valve (Figure 4b).
3. Demand increases, causing the valve on the inlet to open more, thus increasing the inlet water flow (manipulated variable).

4. When inlet water flow increases to the point at which the supply equals the demand, the process variable (actual water level) stabilizes below the set point.
5. Demand decreases, allowing the process variable to change toward the set point. The float will rise with the level and act to slow down the rate of flow into the tank by decreasing the amount of opening in the valve (Figure 4c).

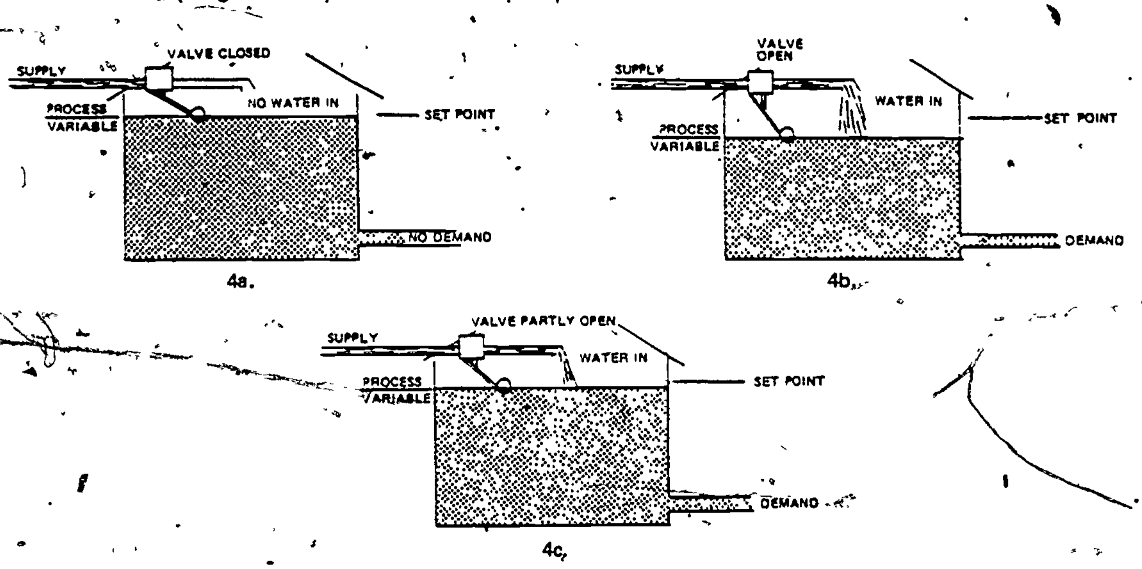

Figure 4. Control-loop operation.

Notice that the manipulated variable acts in a way opposite to the direction of the process variable. When the process variable is going down the manipulated variable goes up, i.e., water level drops and inlet flow rate increases.

Thus, process-control systems can be simply defined as "a group of components that maintain a desired result by regulating input." The desired result may be a specific level, temperature, flow, pressure, voltage, pH, density, viscosity, or one of many other possible parameters. The process-control system can regulate or control the input in the process by a number of means. The most common final control elements are valves, dampers, linkages, and variable electrical components such as resistors, capacitors, and chokes. When measurement is continuous and is linked to control of the final control element, we have closed-loop control - also known as automatic control or automatic feedback control.

Many system operating characteristics must be considered in the design or operation of a control system. Components within the system must be matched with the dynamic characteristics of the process. This procedure must, at all times, ensure the safe and efficient operation of the process. When a control system operates in a manner that is unsafe to people and/or equipment, or when it is operated inefficiently, then we say that the system has failed.

A properly designed control system, open-loop or closed-loop, must make the process fail-safe. In the circumstances resulting from a loss of instrument operation or instrument control signals, fail-safe means that the process will be maintained at - or returned to - a safe condition.

OPERATION OF THE FINAL CONTROL ELEMENT AND FAIL-SAFE CONDITIONS

In the design of all process control systems there must be concern for fail-safe operation from the beginning. In the example, if you were to design the process control for the water tank would you decide to cause the level to fail high or fail low? If a hazardous condition exists when the level is too high, it should fail low. If a hazardous condition arises when the level is too low, the level should fail high.

One example of the operation of the final control element component found in many closed-loop systems is worth examination. The final control element in this example is a diaphragm-operated, spring-opposed, reciprocating control valve. A sealed pneumatic signal, 3 to 15 pounds per square inch gage (psig), causes the valve to move from one extreme position to the other.

In the air-to-open valve, the valve is closed with any air pressure that is less than or equal to 3 psig. As pressure increases the valve opening will increase to its maximum at the upper pressure limit of 15 psig.

When the valve is controlling the flow of material or energy into a system that should fail low, the valve should fail in the closed position and be an air-to-open valve. You should use an air-to-close valve if the system must fail open, thereby causing the system to fail high.

The fail-safe feature of processes may seem to be of little importance when it does not matter whether the process fails high or low. This is of major concern, however, in most temperature and pressure processes where a thermal run-away or over-pressure situation could produce catastrophic results.

CONTROLLER ACTION

Process controllers either generate an increase in output signal when the process variable increases, or cause the output signal to decrease when the process variable increases. By a simple adjustment or switch selection, most process controllers can provide either output selection. When an increase in process measurement causes an increase in the controller output, the controller is direct-acting.

A reverse-acting controller causes the output to decrease when the process variable increases. The valve operation is selected for a feedback control system to provide fail-safe operation. The controller action is selected to provide negative feedback; the manipulated variable acts to oppose the action of the process variable.

VALVE AND CONTROLLER SELECTION

Suppose a need existed for a valve and controller action to control a process in which it was vital for a tank to fail empty. We can use Figure 5 to depict the closed-loop control system for this situation where we must have the level fail low. For the level to fail low, the valve must be closed because of a loss of signal; this requires an air-to-open valve. When the level increases, the valve must close. This requires a decrease in signal from the controller. For a decrease in controller output to yield an increase in the process variable, the controller must be a reverse-acting controller. If, however, the controller action desired is for the tank level to fail full, the valve must fail open and be air-to-close. An increase in level requiring the valve to close requires a direct-acting controller. The selected valve operation and controller action are important and must be considered when designing equipment for control systems.

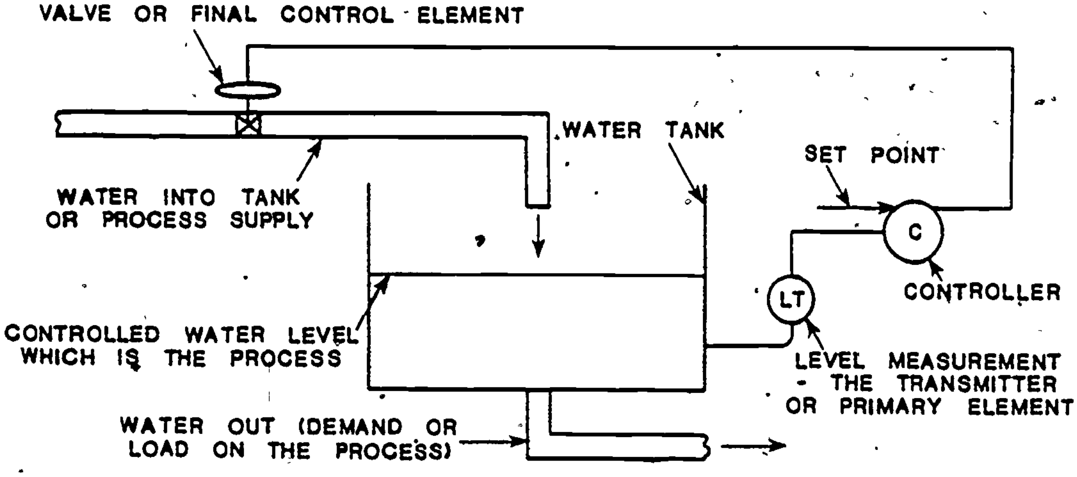

Figure 5. Closed-loop control system.

In selecting process equipment, consider the process in Figure 6. This is another level process that differs from that in Figure 5. In Figure 6, the control valve regulates the flow out of the tank to maintain a level. By using the reasoning established in the previous discussion, valve operation and controller action can be selected.

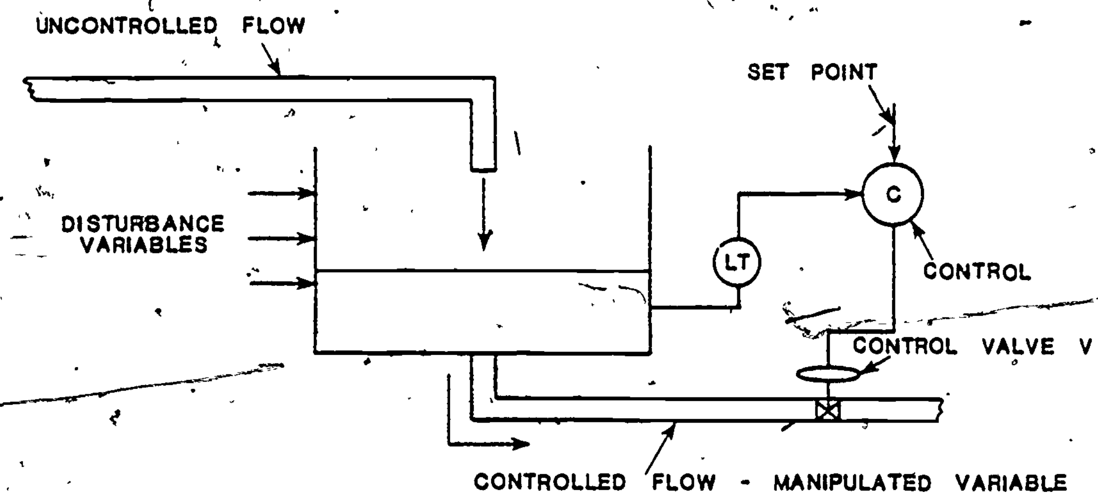

Figure 6. Level process with flow out as the manipulated variable.

For the level to fail low, the valve must be air-to-close and the controller must be reverse-acting. When the level is to fail high, the valve must fail closed (or air-to-open) and the controller must be direct-acting. The selection of valve operation and controller action is summarized in Table 1 for the processes in Figures 5 and 6.

TABLE 1. VALVE OPERATION AND CONTROLLER ACTION
(for the processes in Figures 5 and 6).

	Process in Figure 5		Process in Figure 6	
	Fail Empty	Fail Full	Fail Empty	Fail Full
Valve Operation	Air-to-open	Air-to-close	Air-to-close	Air-to-open
Controller Action	Reverse	Direct	Reverse	Direct

PROCESS DYNAMICS - CAPACITY VERSUS CAPACITANCE

Now that the principle of automatic feedback control has been established, it is important to consider the process and inspect the relationship between process input and output. The process can be represented as a black box in a block diagram (as in Figure 7). The process performs a transfer function between input and output. A transfer function is the mathematical relationship between the input and the output of a control system. The input is a supply of energy and/or material from the control valve positioned by the controller. The output, in this explanation, is considered to be the process measurement on the scaler output signal from the measuring means.

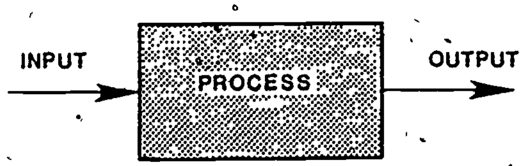

Figure 7. Block diagram of a process.

When the input to a process changes, the controller must add energy and/or material to the process at a rate to which the process can respond. In the example of the water tank, if the valve controlling the input water flow is opened too much or for too long a time, the level will overshoot the set point. If the valve is opened too little or not long enough, the level will not reach the set point. The manner in which the process responds to a load change and supply change determines the rate at which energy and/or material must be added to the process.

Consider the control of a simple process like the speed control of an automobile. On a straight, level section of highway, when the accelerator is held in one position, the speed of the automobile will be maintained. The flow of gasoline into the carburetor (energy being added to the process) is at a constant rate exactly equal to that required to maintain speed. The automobile is neither accelerating nor decelerating. However, when the load on the process is increased by an incline in the highway, the automobile will slow down.

To maintain a constant speed, fuel flowing to the carburetor must increase at a rate to which the automobile can respond. This rate depends upon the transfer function of the process. A big truck with a heavy load responds to a large amount of energy provided by a large engine that has the ability to regulate large amounts of fuel flow. The same fuel flow would cause a high acceleration rate for a compact automobile. Likewise, industrial processes react differently to various load and supply changes.

For processes with different transfer functions or reaction rates, consider the level processes in Figure 8.

In Figure 8, both level tanks have the same capacity or can retain the same amount of material in gallons (or any desired unit of measurement). For the purpose of level measurement, which is usually in linear units - feet, inches, and so forth - the dynamic characteristics of the processes Figure 8a and Figure 8b are completely different. The term "capacitance" is used to describe the dynamic properties of the process. While capacity is a measurement of volume, capacitance is a measure of length and volume. The unit of capacitance measurement in this instance is:

$$\frac{\text{Foot}}{\text{Gallon}}$$

This unit relates level (length) to volume. It can be seen that the process in Figure 8a has greater capacitance than that of Figure 8b.

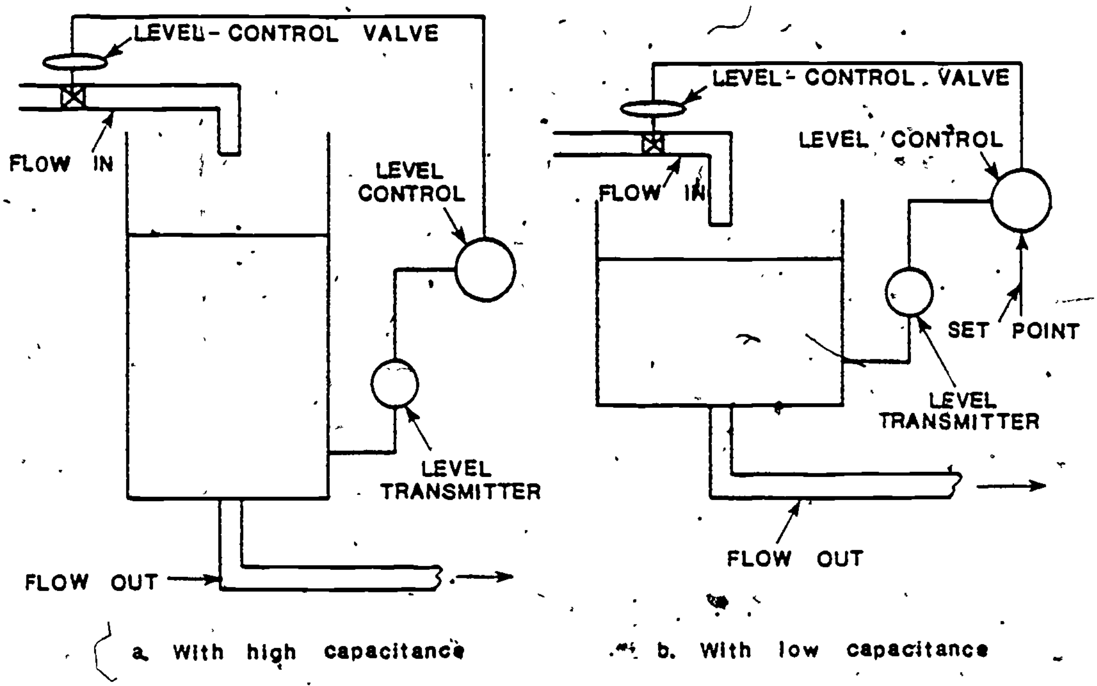

Figure 8. Level processes.

The process response to a load change is important when considering capacitance in control systems. For a given disturbance variable, the high-capacitance process undergoes a greater change than the lower-capacitance process of Figure 8b, though the capacities of Figures 8a and 8b are equal. The relationship between instrument selection, adjustment, and process dynamics will be studied in Module IC-05, "Instruments for Mechanical Measurement."

The most common types of processes controlled by feedback control applications are the following:

- Liquid level.
- Fluid flow.
- Pressure.
- Temperature.

Processes involving liquid level have been discussed prior to this point in the module. The liquid-level process is easy to explain and understand, and the student most likely has ~~some familiarity with it~~. Control of the liquid-level process is normally easier to obtain in comparison to other processes.

The ease with which control of the liquid level is obtained is due to many factors; they are: control at extremely close tolerances is rarely needed, the process is normally very linear, measurements are easily made, and the response time and reaction rates are favorable. These characteristics will be elaborated on in Module IC-02, "Instruments for Fluid Measurement: Pressure and Level."

Control of fluid flow is the most common process. In previous discussion of level control, flow of material into and out of the various tanks was regulated to control level; actual flow quantities were not controlled. The first consideration in controlling a process is measurement of the variable to be controlled. Although flow quantity was not measured, it was the manipulated variable. Flow is the manipulated variable used to control most processes. Even when not controlled to exact quantities as a manipulated variable, the precise control of flow is necessary in many applications. A flow process is shown in Figure 9.

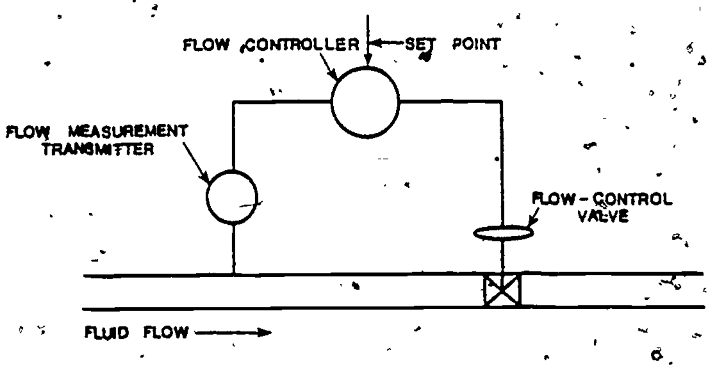

Figure 9. Flow control process.

The flow process in Figure 9 utilizes the same principle as level processes. The process measurement is provided by the measuring transmitter, which generates a signal proportional to flow and transmits a signal to the controller. The controller compares the signal representing the flow quantity to the reference (or set point) valve. Then the controller generates a signal that is a function of the error signal and transmits a signal to the control valve, which regulates the flow quantity to the desired value.

The control of pressure is not as common in most process applications as liquid level and fluid flow, but is important in some applications. The pressure-control process of Figure 10 has the same fundamental control characteristic as other control processes. The student should be able to identify the control components and describe the control principles and operation of this system; it is similar to flow and level processes previously described.

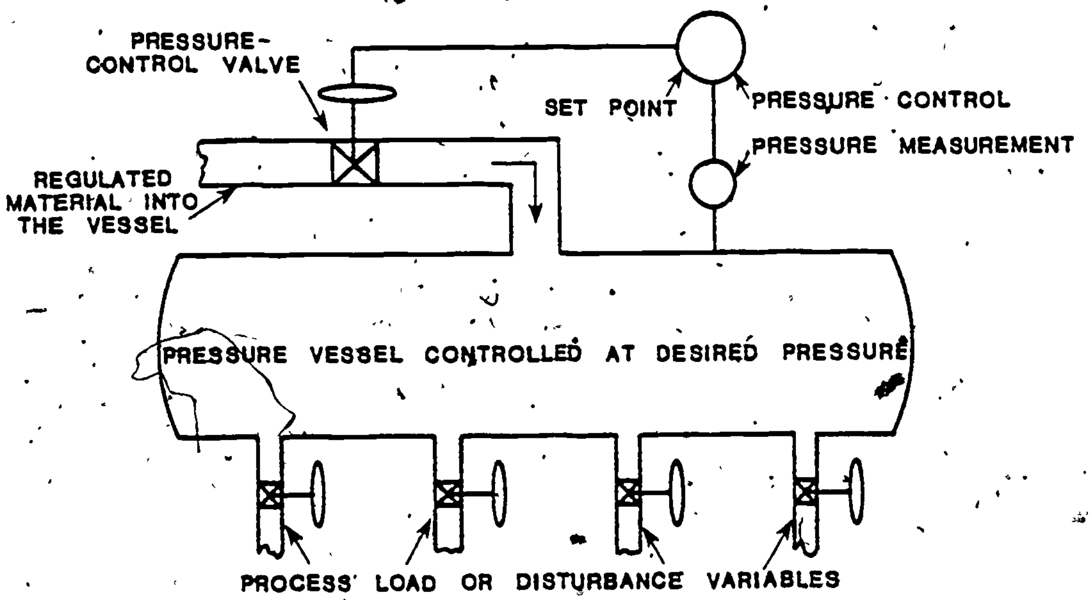

Figure 10. Pressure-control process.

The process in Figure 11 controls temperature by regulating the flow of steam through the heat exchanger. This process, though operating on the

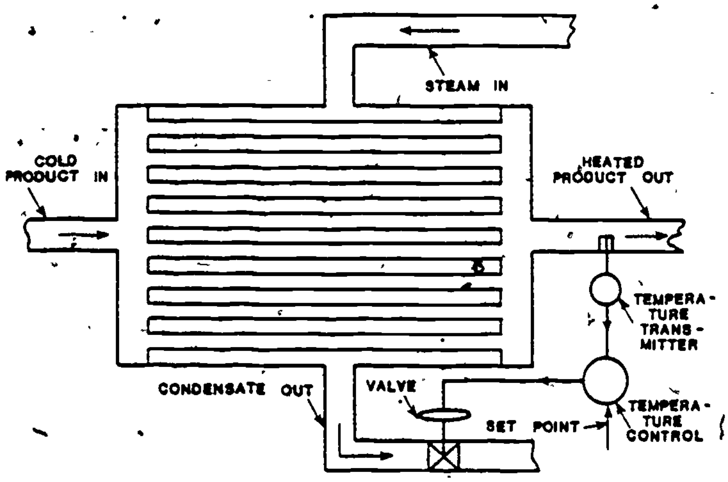

Figure 11. Temperature-control process.

same principle of feedback as those previously described, has a significantly different dynamic characteristic. This characteristic is the ability to store energy. When the control valve changes the steam flow into the heat exchanger, the temperature of the product does not immediately respond to the change in input energy. The steam must first heat the tubes of the exchanger. Then the energy must be transferred to the process material, which then transfers the energy to the temperature transmitter. The time lost between a decrease in temperature at the transmitter (caused by a load increase) and the resulting increase in product temperature (resulting from an increase in steam flow caused by the controlling action of the control system) are considerations that make the temperature process a difficult control situation.

DEAD TIME AND LAG TIME

Temperature processes can absorb and store more energy than other processes. However, they can also exhibit much dead time. To better understand the temperature process of Figure 11, assume that the product flowing out is heated to the desired temperature, while steam flows in at a constant rate. These variables are controlled by the valve regulating the flow of condensate out of the heat exchanger. If the product flows into the exchanger at a constant temperature and flow rate while the above conditions are maintained, the temperature of the emerging heated product is constant. This is not usually the case, however, because processes do undergo load changes from time to time. If the flow of cold product into the exchanger varies (decreases, for example), the temperature of the emerging hot product increases because the product absorbs more energy from the steam.

When the temperature of the heat product varies, the variation is detected by a deviation between set point and process variable, generating an error signal at the controller input. The controller output will change based on the error signal (the difference between set point and process variable), causing the control valve to reposition. This changes the flow of steam into the heat exchanger. In some processes, the change in manipulated variable has a sudden effect on the process. However, in the temperature process, steam must first change the temperature of the exchanger tubes. Then the exchanger tubes change the process temperature. The transducer of the temperature transmitter (that portion of the transmitter in contact with the product) must absorb or release energy (depending upon an increase or decrease in product temperature) before a change in output signal can occur. The time lost in the transfer of energy ~~in the~~ process is dead time - or transfer lag. Transportation lag, also known as lag time, is the time lost to how long it takes the transmitter and error detector to generate an error signal that will cause the controller to respond to the variation in the process variable. The terms "first-" and "second-order lag" have also been used to define dead time and lag time. Temperature processes have greater amounts of dead time and lag time, making their control more difficult.

The process-control systems described in this module - liquid level, fluid flow, pressure, and temperature - are all feedback control systems. The "feedback" is information derived from comparing the value of the process variable to the set point, which is transmitted to the controller. Ideally, the controller output causes a repositioning of the final control element to achieve or maintain a balance between supply to the process and load on the process. Following a load change, the controller output should continue to maintain a balance between supply and demand until the process is returned to the set point.

The information that is fed back to the controller in these control systems can be via manual action on the part of a person and on a periodic basis (open-loop control) or can be through instrumentation that allows immediate and constant response (closed-loop control). There is one drawback to these control systems: a change in process or a deviation from set point must happen before the controller can take corrective action. The material and/or energy that is to be controlled must change before the controller will correct for a load change or other disturbance variable. This sometimes precludes the use of feedback control. However, in most situations, this problem can be overcome by the correct design and application of the feedback control system.

EXERCISES

1. For the temperature process in Figure 11, determine the proper valve operation and controller action to provide both high- and low-temperature fail-safe operation. Complete Table 2.

TABLE 2. VALVE OPERATION AND CONTROLLER ACTION.

	Fail High	Fail Low
Valve Operation		
Controller Action		

2. Draw a temperature process similar to the one in Figure 11 to control temperature by adding cooling to the process instead of heat. This can be done by regulating the flow of cold water through the tube of the heat exchanger. Select the proper valve operation and controller action to provide for both fail-safe high and fail-safe low operation. Complete Table 3.

TABLE 3. VALVE OPERATION AND CONTROLLER ACTION.

	Fail High	Fail Low
Valve Operation		
Controller Action		

LABORATORY MATERIALS

Pump (P_1). An electrically-operated pump that will deliver 10 to 20-gal/min flow against a 20-psig head pressure.

Two control valves, diaphragm-operated by 3 to 15 psig. The valves can be single-seated, air-to-oper or air-to-close, with a 1-inch body and 1/2-inch trim.

Two strip-chart recording controllers with fast (1 inch/minute) and slow (1 inch/hour) chart speeds. The controller should be pneumatic, with conventional 3 to 15 psig input and output.

Two 20-gallon tanks to use as the reservoir and process. The reservoir should be flat, about 10 to 12 inches high. The cylinder used for the process should be about 8 feet high and 10 to 12 inches in diameter.

One level transmitter that has an adjustable range approximately 0-20 to 0-200 inches H_2O, and pneumatic 3 to 15 psig input and output.

One flow transmitter (with integral orifice) approximately 0.250 inches that has an adjustable range approximately 0-20 to 0-200 inches H_2O.

Assorted hoses, pipes, tubing, and wiring that will be used to connect the process and instruments.

LABORATORY PROCEDURES

1. Use a combination flow and level system as shown in Figure 12, and identify all components including the following:
   a. Flow transmitter, T_1.
   b. Flow controller, C_1.
   c. Flow control valve, V_1.
   d. Level transmitter, T_2.
   e. Level controller C_2.
   f. Level valve, V_2.

   Connect the process as shown in Figure 12 and install the instruments.

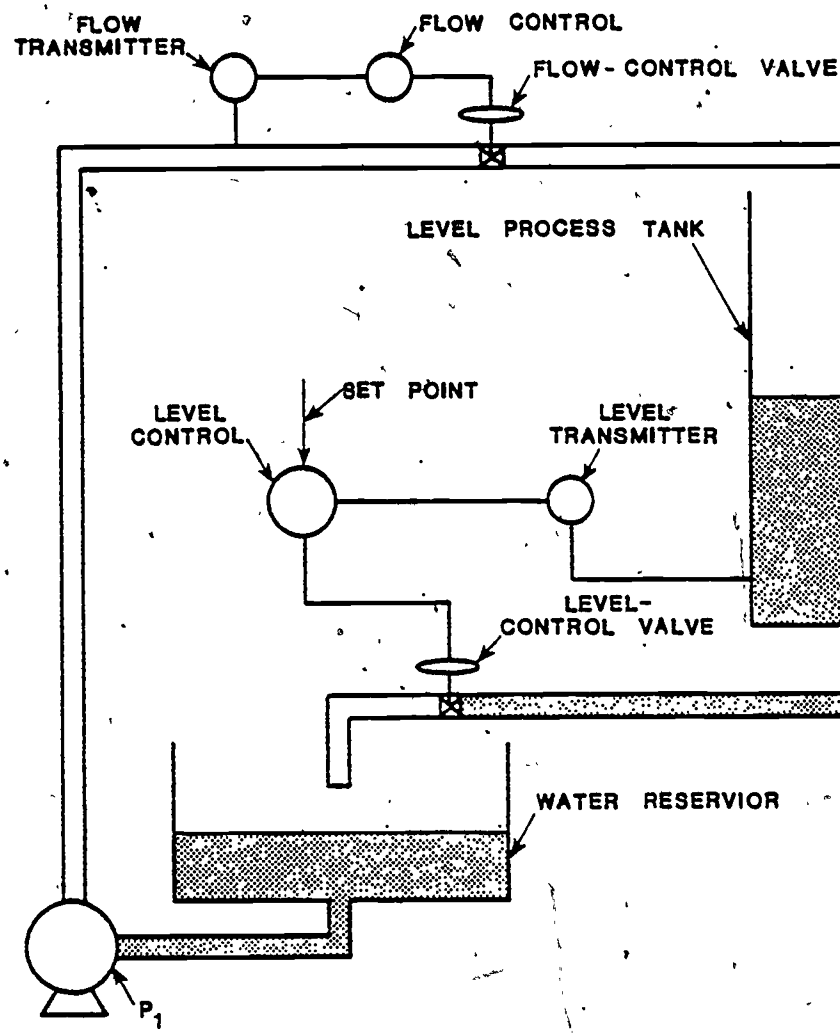

Figure 12. Flow-level process.

2. By referring to equipment instruction manuals, connect the instruments as indicated by the drawing in Figure 12. With the controllers on manual (or hand) control for open-loop control of the process, position the flow and level valves. Note the valve operation as signal-to-open or signal-to-close.
3. Using a water hose or other water source, fill the water reservoir.
4. Close V_2 with the level controller in manual operation.

5. Open V_1 half-way. The half-open valve position can be ascertained by observing the position indicator on the valve.
6. Start P_1 and establish the flow into the tank at a nominal value of 20% to 50% as measured by the flow-measuring instruments.
7. With the flow maintained constant at the value established in Step 6, monitor the level of the tank by observing the level-measurement instrument.
8. When the level reaches approximately 50% of its maximum value, open V_2 with the manual adjustment from the level controller. By repeated adjustments as necessary, determine the proper valve opening to maintain the level at a constant value of 50%.
9. By completion of the procedures to this point, V_2 has been manually controlled to maintain a balance between supply (the water entering the tank) and demand (the water leaving the tank) on the level process.
10. Increase the flow into the tank by about 10% of the maximum amount, and adjust V_2 to maintain the level at its original value.
11. Decrease the flow into the tank by 20% of the maximum value, and adjust V_2 from the level controller to maintain the level at the original value.
12. By completing Steps 10 and 11, manual or open-loop control of a process to compensate for load changes has been achieved.
13. The procedures for this exercise have been completed. Secure all equipment by stopping P_1, closing V_r, and opening V_2. This will return the water to the reservoir.

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Hunter, Ronald P. Automated Process Control Systems. Englewood Cliffs, NJ: Prentice-Hall, 1978.

GLOSSARY

Automatic control system: A control system having one or more automatic controllers connected in closed loops with one or more processes.

Control system: A system in which one or more outputs are forced to change in a desired manner as time progresses.

Controller: The decision-making component of the closed-loop control system. It compares the actual value of the process variable against the desired value for the process variable, and transmits a control signal that will act on the manipulated variable in such a way as to minimize the difference.

Disturbance variable: Undesired command signal in a control system.

Error signal: The difference between the desired value of the process variable and the actual value of the process variable.

Fail-safe condition: A condition to which a process will return or be maintained upon the failure of any one or all control devices. The condition must be the least hazardous of all possible conditions.

Feedback: Information in a closed transmission path about the status of the process variable; generated by the measuring means; transmitted to a controller that regulates an input variable to maintain the process variable at the desired condition.

Final control element: The component of a control system that regulates the manipulated variable.

Measuring means: The instrument or instrument system that monitors the process and supplies information to the controlling means. The information is used to ascertain the actual process condition.

Manipulated variable: The input variable to a process that directly affects the process variable in a way to maintain or achieve a desired condition.

Open-loop control system: A control system in which the only regulation of input variables is accomplished by manual control with little regard for the actual condition of the process.

Process: A series of continuous or regularly-occurring actions taking place in a predetermined or planned manner for the purpose of obtaining a desired final product.

Process control: Manipulation of the conditions of a process that bring about a desired change in the output characteristics of the process.

Process capacity: The characteristic of a process that enables it to retain or store material and/or energy.

Set point: The desired value of a process variable that we wish to reach or maintain during the operation of the process.

TEST

INSTRUMENTATION AND CONTROLS

Module IC-01

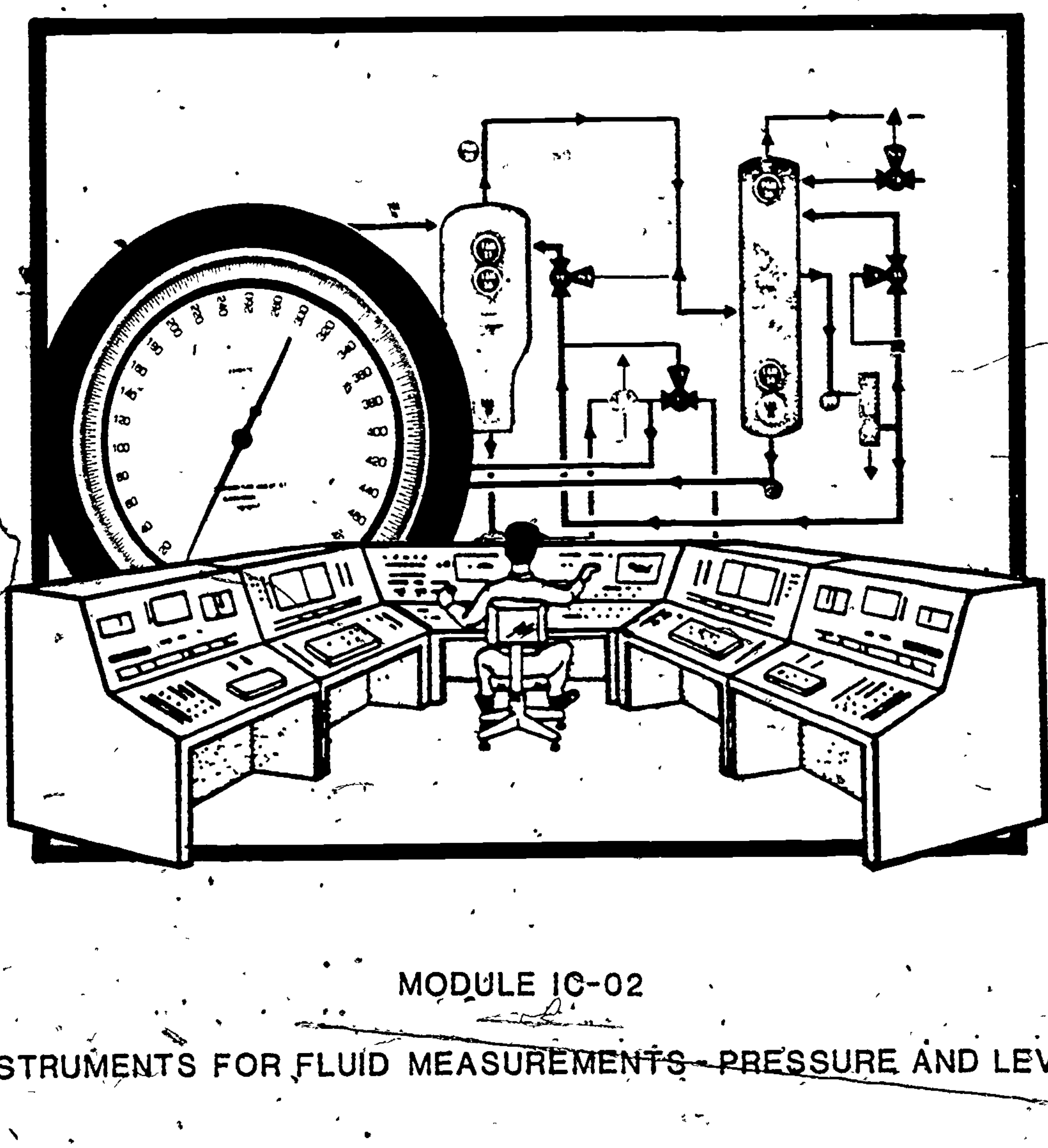
"Principles of Process Control"

1. Define the following terms:
    a. Process.
    b. Process control.
    c. Open-loop control.
    d. Closed-loop control.
    e. Negative feedback.
2. List the components of a closed-loop control system, and explain the operation of each.
3. Explain the purpose of a closed-loop control system, and explain the operation by which this is achieved.
4. Explain process dynamics.
5. List four processes normally controlled by automatic feedback control.

ENERGY TECHNOLOGY

CONSERVATION AND USE

INSTRUMENTATION AND CONTROLS



MODULE IC-02

INSTRUMENTS FOR FLUID MEASUREMENTS—PRESSURE AND LEVEL

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Most control systems in present use utilize the concepts of automatic feedback control. The foremost prerequisite for feedback control is measurement of the variable to be controlled. Essentially, any medium that can be measured can be controlled, and that which cannot be measured cannot be controlled. Regardless of the sophistication of the control system, the control quality can be no better than the measuring means.

Of the four basic process types - pressure, liquid level, fluid flow, and temperature - pressure measurement is the most fundamental because many of the variable measurements depend on inferred values from pressure measurements. This module deals with the fundamentals of pressure-measuring instruments and explains the methods of using these instruments to measure liquid level. Level-measurement instruments that are not based on the principles of pressure measurements are also covered in this module. Discussions are included that stress the means by which instrument output indications are scaled to represent known quantities of measurement values.

PREREQUISITES

The student should have a basic understanding of algebra and physics and should have completed Module IC-01, "Principles of Process Control," of Instrumentation and Controls.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain the objective and purpose of process measurement.
2. List the standard unit of measurement for the following processes:
   a. Pressure.
   b. Liquid level.

3. State a theory measurement for each of the processes listed in Objective 2.
4. List the operating principle of an instrument that performs the measurement of the processes listed in Objective 2.
5. Explain the concepts of instrument spanning and calibration.
6. Define inferred measurement.
7. Perform a calculation that relates pressure to level measurement.
8. Describe the calibration procedure for instruments used in measuring the processes listed in Objective 2.

CONTROL QUALITY OF THE SYSTEM

All of the components in a closed-loop control system are of equal importance in that the absence or malfunction of any one component will cause the system to cease operation. However, the degree of success that a system obtains in control of a process is influenced most strongly by two components; the measuring means and the controller. Without measurement of the actual condition of the process, automatic feedback control cannot be achieved. This feedback signal established by the transmitter (measuring means) generates the error signal through comparison with the set point and provides the basis of corrective action to be taken by the controller.

Because the feedback controller action is initiated and actuated by the feedback signal from the measuring transmitter, the overall control quality of the control system can never surpass that of the measuring means. Control quality depends not only on the static accuracy of the measuring instrument, but on the dynamic accuracy (performance) as well. The transmitter will respond to process changes as fast as process variations occur in order to prevent the corresponding controller actions from being delayed. While pressure-, level-, and flow-measuring devices are generally quick to respond to changes in process conditions, lag time in the control systems caused by the longer response time of temperature measurement can present serious problems in control quality.

The control quality of any control system is an expression of how well the system is able to maintain the process variable at the set point. To be able to make this determination it is necessary to have a means of making measurements. Measurement is the comparison of one quantity to another special quantity that is accepted as the reference or standard quantity. No comparison can ever be exact, there will always be a difference between the standard and the other quantity, this difference is called an error. The smaller the error, the greater the accuracy, and a higher accuracy means a better control quality.

For our industrial processes to be efficient and reliable it is vital that measurements have integrity - a dimension that is measured and found to be one inch at one site should be found to be one inch at all other sites. To ensure this, the standards for all measurements in the United States are listed with the National Bureau of Standards (NBS) in Washington, DC. The standards maintained by NBS are called primary standards; other organization and companies have their own copies of the primary standards - called secondary standards. The secondary standards are compared periodically against the primary standards and are used as comparison for tertiary standards which are copies of the secondary standards. This chain of copies, supported by periodic comparison, provides a means of traceability that ensures a conformity of measure throughout industry; thus an automobile part manufactured in Michigan will have the same dimensions as a replacement part manufactured in California.

A major concept that must be considered when measurement and the integrity of measurements are discussed is accuracy. Accuracy is defined as "the closeness by which a measured value conforms to the actual value." Test instruments are used to determine the values of the process variables, and each has its own accuracy. The accuracy of an instrument or of test equipment is expressed by the percentage of uncertainty of any reading taken.

Care must be exercised when a measurement is made with a test instrument that uses a readout that has its uncertainty expressed as "plus or minus a percentage of the full scale reading." The dangers that can be hidden behind this statment are shown in Example A below.

EXAMPLE A: METER SELECTION BASED ON ACCURACY REQUIREMENTS.	
Given:	A process variable is measured by a voltage level and must be maintained within 3% of its set point of 50 volts. There are two voltmeters available to perform the measurement. Both meters have the same range values: 0 - 1 volt, 0 - 10 volts, and 0 - 100 volts. Meter A has a stated accuracy of ± 2% full-scale reading. Meter B has a stated accuracy of ± 1% full-scale reading.
Find:	Which meter will ensure that our measurements of the set point will be within 3%.

Solution: It is obvious that, regardless of which meter is used, the highest range (0 - 100 volts) must be used. Calculate the uncertainty of a 50-volt reading for each meter.

Meter A

Reading = 50 volts ± 2% full scale (100 volts)
= 50 volts ± 2 volts

Thus, meter A could read anything from 48 volts to 52 volts for an actual input voltage of 50 volts.

Meter B

Reading = 50 volts ± 1% full scale (100 volts)
= 50 volts ± 1 volt

Thus, meter B could read anything from 49 volts to 51 volts for an actual input voltage of 50 volts.

Notice that we must have an uncertainty less than 3% of 50 volts, or 50 volts ± 1.5 volts. Meter A has an uncertainty of 2 volts, which is 4% of 50 volts, even though it had a stated accuracy of 2%. Meter B is the only meter that will ensure that our measurements will be within 3% (1.5 volts) of the set point.

It is evident that more information is needed about measurement devices than just to say they are 1% or 2% accurate. A person should know what the percentage is in reference to - percentage of actual reading, or what. The most accurate readings will be those that are taken in the upper third of the range when the percentage is of full scale.

Now that you have been presented information regarding what can affect the quality of measurements, it is important that you be exposed to what measurements will be made and the factors related to those measurements.

PRESSURE MEASUREMENT

Pressure may be described as a force acting over an area. Mathematically the most common equation for pressure is:

$$P = F/A \quad \text{Equation 1}$$

where: F = force.
A = area.
P = pressure.

The standard units of measure used for pressure are determined by the system of measure with which a person is working. According to the International System of Units, which is based upon the old MKS (meter-kilogram-second) system, pressure is measured in units called Pascal (Pa) where 1 Pa = 1 Newton/square meter. This module will deal primarily with the English (or foot-pound-second) system of measurement where pressure is measured in units of psi (pounds per square inch).

Everyone is subjected to pressure but is unaware of it. Man has evolved in an environment that is under constant pressure - the weight of the air lying over everything. At sea level this weight of air results in a pressure of 14.7 psi. We are not aware of this atmospheric pressure because the force of the air pushing in is balanced by other forces in our bodies pushing out. A building is unaffected by the pressure because the force of the atmosphere pushing in on the outside walls is balanced by the force of the atmosphere inside the building pushing out. Awareness of pressure occurs only when there is an imbalance of pressures and we observe the effects.

Measurement came about only after men became aware of the existence of the quantity and realized the importance of measuring it. Pressure was recognized as a quantity that could be measured only after the effects of unbalanced pressures were observed. For example: a balloon can be inflated because we inject air with a pressure that is greater than the atmospheric pressure; the balloon ceases to expand when the atmospheric pressure is balanced by the pressure of the air inside the balloon. A building that is closed up will explode when a tornado passes over it because the pressure inside the building is greater than the pressure outside the building.

The same thing that gives us our awareness of a quantity that can be measured also gives the means by which to do the measurement. We measure pressure by comparing an unknown pressure against a different, known pressure; we observe the effects of the unbalance on substances or an object. The known pressure is the reference pressure; it is the standard against which we measure. The ideal standard would be zero pressure; however, achieving a zero pressure (a perfect vacuum) is theoretically impossible, as this would require that there be no single atom of anything present in defined volume of space. Even the space between the planets is estimated to have at least one atom of hydrogen per cubic meter of volume. Due to modern technology, it is possible to approach a vacuum near that found between the planets; because of this it is known that atmospheric pressure at sea level is approximately 14.7 psi.

Due to the difficulty in obtaining a good vacuum, the most common reference used to measure pressure is that of the atmospheric pressure in the immediate vicinity of the measurement instrument - this is called the ambient pressure. So that we can distinguish what the reference of a measurement is, a convention of notation has been adopted. When a measurement is made with respect to ambient pressure as the reference, the value is called gage pressure, and the units of measure are written as psig (pounds per square inch gage). When a measurement is made with zero pressure as the reference, the value is called absolute pressure, and the units of measure are written as psia (pounds per square inch absolute). Absolute and gage pressure measurements are related by the equation:

$$P_{absolute} = P_{gage} + P_{atmosphere} \qquad \text{Equation 2}$$

where: $P_{absolute}$ = pressure in units of psia.
P_{gage} = pressure in units of psig
$P_{atmosphere}$ = pressure in units of psia.

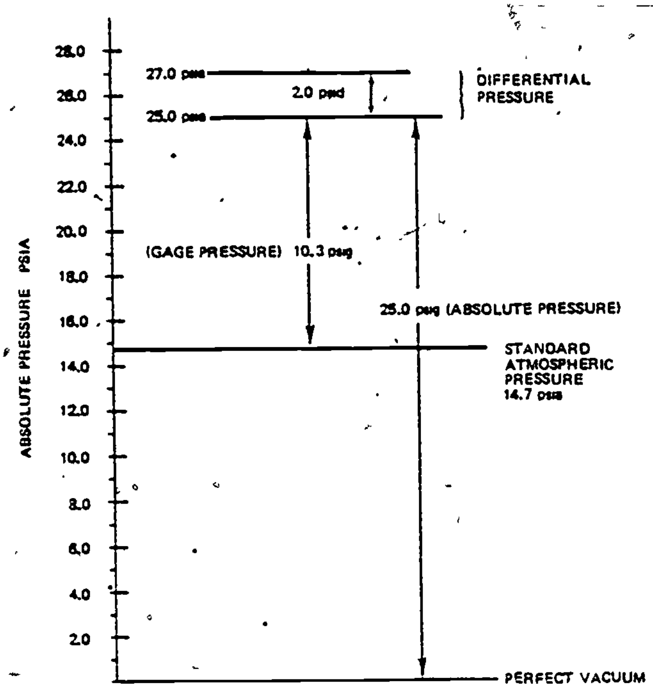


Figure 1. Kinds of pressure (examples).

Ambient pressure is determined by the latitude, altitude, and gravitational acceleration of the location. Most instances do not require a knowledge of the absolute pressure, therefore it does not matter; it is the difference in pressure that matters to the pressure gages. Figure 1 illustrates how the different pressures are related.

LIQUID MANOMETERS

The term "manometer" is a name given to pressure gages capable of responding to small pressure changes. It is derived from Greek origin - the term "mano" meaning thin, or rate, and the term "meter" meaning to measure. Therefore, manometer probably once signified a gas or vapor gage; but, today, it is generally accepted that a manometer signifies a liquid-type gage used to measure low differential pressure. Though sometimes used as a process-measuring instrument, manometers are most commonly used as accurate, secondary standard calibrating instruments in laboratories. The two general types of manometers are U-tube and bell. Both have similar operating principles, but the U-tube is discussed in the following paragraphs.

The U-tube manometer shown in Figure 2 is constructed by bending a glass tube into the shape of a U, filling the tube about half-full with a liquid of known specific gravity (density of liquid/density of water), and

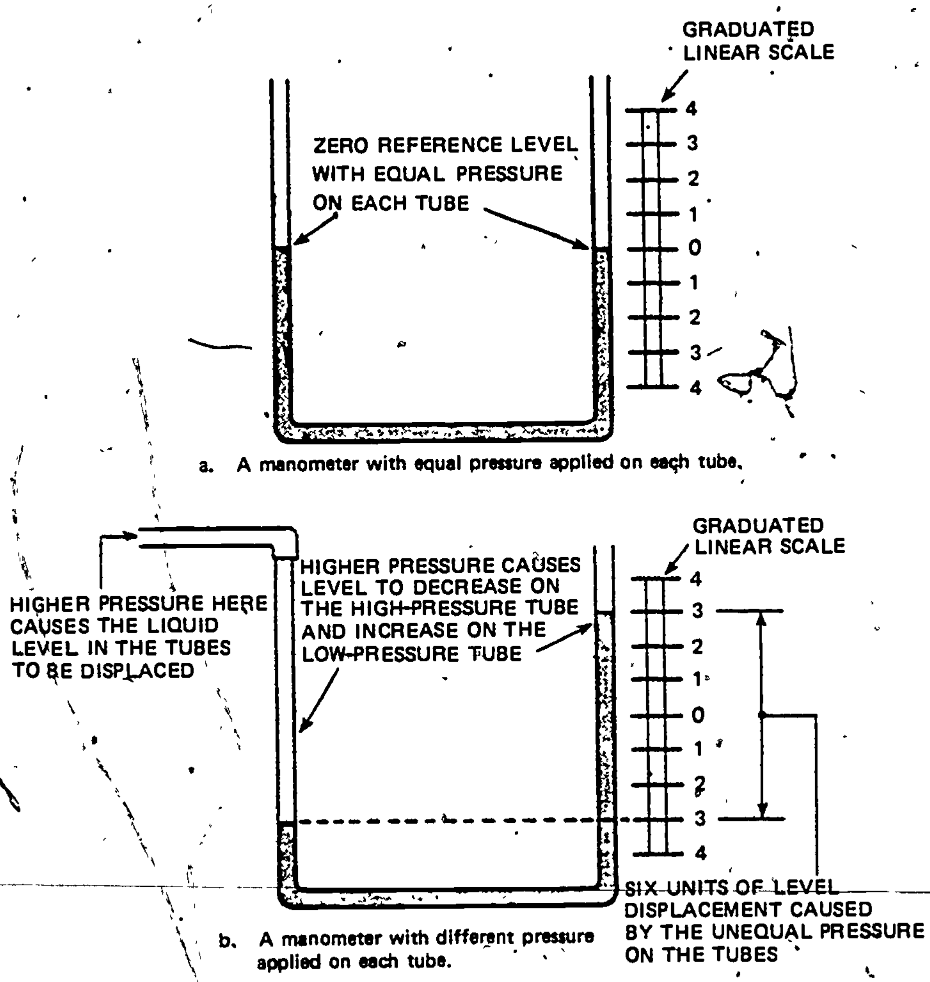


Figure 2. U-tube manometers.

marking a scale to measure the displacement of the liquid level in the two legs of the tube. With equal pressure applied to each tube, the liquid in each tube will be at the same level. When there is a difference in pressure on the two tubes, the liquid level in the tubes will be displaced, and the amount of the displacement (distance between levels) will be proportional to the difference in pressure. The relationship between the amount of displacement and the pressure difference on the two tubes can be explained by referring to Figure 3.

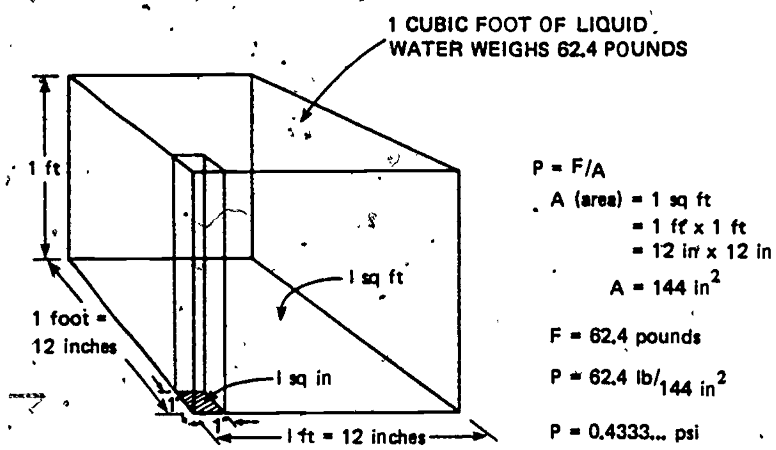


Figure 3. Relationship between pressure and a column of liquid.

From Figure 3, it can be seen that a one-foot column of water exerts a pressure of 0.433 psi. By dividing 0.433 by 12, the pressure exerted by a column of water one inch high is 0.036 psi. These values - 0.433 psi/ft water and 0.036 psi/in - provide the basis for using the displacement of a column of liquid to measure pressure. This is termed "head-type pressure measurement" because a column of liquid is commonly called a liquid level.

In manometers, water is used as the liquid to measure small pressure difference; but for large pressure measurement, the water columns would be too high. For example, atmospheric pressure (14.7 psi) would cause a column of water to be displaced 33.9 ft as seen by the calculation:

$$\frac{14.7 \text{ psi}}{0.433 \text{ psi/ft}} = 33.9 \text{ ft}$$

To measure higher values of pressure, heavier liquids are used in manometers. Oils heavier than water sometimes are used for this purpose; however, mercury is most commonly used. The specific gravity of mercury is 13.55, and a pressure will displace a column of mercury 1/13.55 the distance that a column of water would be displaced. Or, this may be stated as follows: For equal values of displacement, pressures 13.55 times greater can be measured by using mercury as the manometer liquid. The following formula can be used to express the relationship between liquid head displacement, pressure, and liquid specific gravity:

$$h = \frac{P}{0.433(G)} \qquad \text{Equation 3}$$

where: h = Liquid displacement, in feet.
P = Pressure, in lb/sq in.
G = Manometer liquid specific gravity with respect to water.
0.433 = A constant that is the pressure (psi) of a one-foot column of water.

Example B shows a calculation of pressure using Equation 3.

EXAMPLE B: CALCULATION OF PRESSURE.	
Given:	A liquid with a specific gravity of 2.48. The column of liquid is 43 ft.
Find:	The pressure, in psi, caused by the liquid column.
Solution:	Using Equation 3 and solving for P,
	P = h (0.433)(G)
	= 43 ft (0.433 in/ft)(2.48)
	P = 46.17 psi.

PRESSURE TRANSDUCERS

Transducers are devices that transform one form of energy into another form of energy that is more usable. A basic, broad class of transducers are the Bourdon tubes. These are pressure elements that transform pressure into mechanical movement or motion.

Bourdon Tubes and Pressure Elements

There are several types of Bourdon tubes used as pressure transducers. The most commonly used in process pressure measurement are the following:

- C-tube.
- Spiral.
- Helical.

Pressure elements that are commonly used as transducers are the following:

- Diaphragm.
- Bellows.
- Capsule.

Bourdon tubes are constructed of a thin, springy type of metal that expands when pressure is applied and returns to its original shape when the pressure is removed. Usually, one end of the Bourdon tube is fixed, and one end is free to move. Movement (tip travel) results at the free end (tip) when pressure is applied to the open, fixed end. The movement produced by the Bourdon tubes shown in Figure 4 may vary from one-fourth of an inch to a

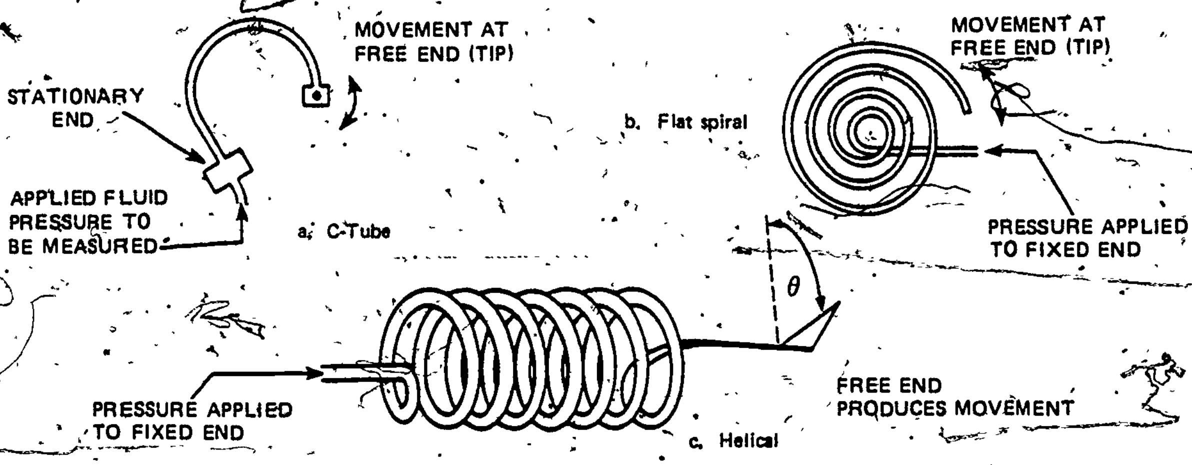


Figure 4. Bourdon tubes.

few-thousandths of an inch. This movement conforms to Hook's law, which states the following: Within elastic limits, the free end will experience a movement that is proportional to the fluid pressure applied to the fixed end.

The C-tube is perhaps the most common of all Bourdon tube types. It is generally easier to manufacture to uniform standards and in large quantities; thus it is less expensive. C-tube Bourdon tubes can be made to occupy small, shallow spaces, with enough depth to allow legible dials for pressure gages and other indicating instruments. Less tip travel is common for the C-tube when compared to the tip travel common to the helical and spiral types of Bourdon tubes. The tip travel for a C-tube is normally restricted to 345°. This tip travel can be amplified by an arrangement of link and lever devices or sector-pinion gears, and can be used to position an indicator hand, or pointer, on a pressure gage. Amplification of the free-end tip travel is not normally used in pressure controllers or transmitters. The unamplified motion is sufficient to position a flapper with respect to a nozzle for pneumatic devices or to move an iron "slug" in a linear variable differential transformer (LVDT) for electronic or electrical devices. The operating pressure range of C-tube Bourdon tubes is from a few pounds to several thousand pounds per square inch. Tube construction - usually the thickness and type of material - determine the pressure range.

Spiral and helical Bourdon tubes provide more tip travel and are generally more sensitive to small pressure differences than the C-tube types. The operating range of a spiral or helical Bourdon tube can be from a few fractions of a pound per square inch of pressure to around 500 pounds per square inch of pressure.

Pressure Elements

Pressure elements are mechanical devices used as pressure transducers in applications where lower pressure ranges are prevalent and greater accuracy is required. While Bourdon tubes are used in gages and pressure sensors or transmitters for higher pressure applications, pressure elements are used in transmitters for lower-range service (usually less than 100 psig) and for receiver instruments (such as controllers, recorders, and indicators).

Bellows are made of springy material formed in the shape of a thin-wall tube. The tube is then worked to form deep convolutions, which allow the tube to expand much like an accordion. Bellows have a sealed end and an open end, to which the pressure to be measured is applied. The increase of pressure inside the bellows forces the bellows to stretch, producing a movement at the free end. Two bellows can be situated so that the movement of one is in opposition to the difference of the two pressures. This arrangement is used in the measurement of differential pressure. Figure 5 shows two bellows that are used for pressure and differential-pressure measurements.

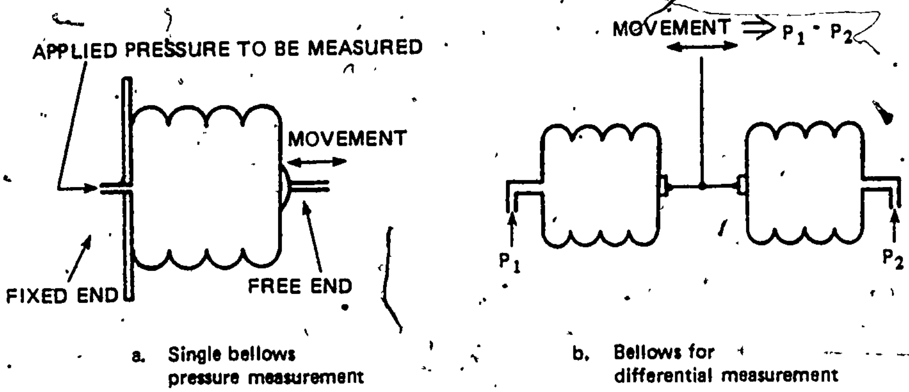


Figure 5. Bellows used for pressure and differential measurement.

Diaphragm

Pressure diaphragms are made of either a pliable fabric material or a thin and pliable metal. These transducers normally are larger in surface area than any of the other type discussed and, therefore, will respond to much lower pressure ranges. They are commonly used in differential-pressure-measuring instruments. In such applications, the edges are sealed to the case and fixed in that position. A difference in pressure on the side causes a movement at the center that is converted to measurement. See Figure 6.

Capsules consist of two diaphragms that are welded or otherwise fastened together at the edges. Usually a fluid such as silical gel is sealed between the two diaphragms to transmit the force from one chamber to the other.

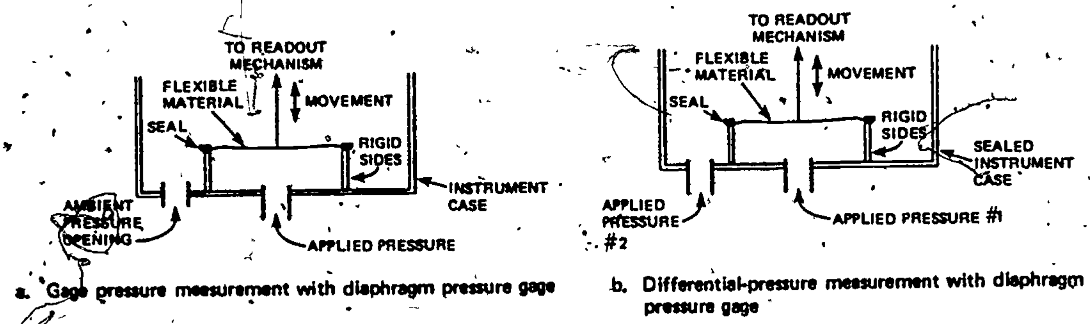


Figure 6. Diaphragm-type pressure gages.

Strain Gages

A popular transducer for pressure measurement is the strain gage. Strain gages are made of thin wires that have a uniform resistance to length ratio. These are bonded to a flexible or pliable support such as paper or plastic. A change in pressure on the strain gage causes a variation of force that tends to distort, stretch, or compress the resistive element. The distortion causes a change in the physical characteristics (length and diameter) of the wire; this, in turn, causes the resistance to change. The resistance change, which normally is small, is measured by a d.c. Wheatstone resistance bridge. Figure 7 shows an arrangement used to measure with a strain gage. The bridge is initially balanced by adjusting R_3. A change in the pressure applied to the strain gage causes the bridge to be unbalanced,

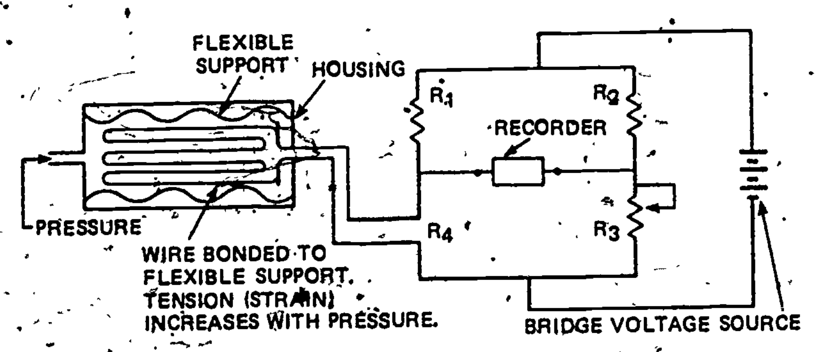


Figure 7. Strain gage and bridge measuring circuit.

thereby causing a change in the recorder response. This application provides a very accurate means of measurement with a wide range of sensitivities. The sensitivity can be altered by changing the value of R_1 and R_2, the recorder sensitivity, or the value of the bridge voltage.

Pressure measurement, as covered in this module, is used in the actual control of pressure processes (as shown in Figure 8) and as indirect measurements of liquid level and fluid flow. (Note: Any of the various pressure transducers discussed in this module can be used as a transducer in the pressure transmitter in Figure 8 to cause a signal proportional to pressure to be generated.)

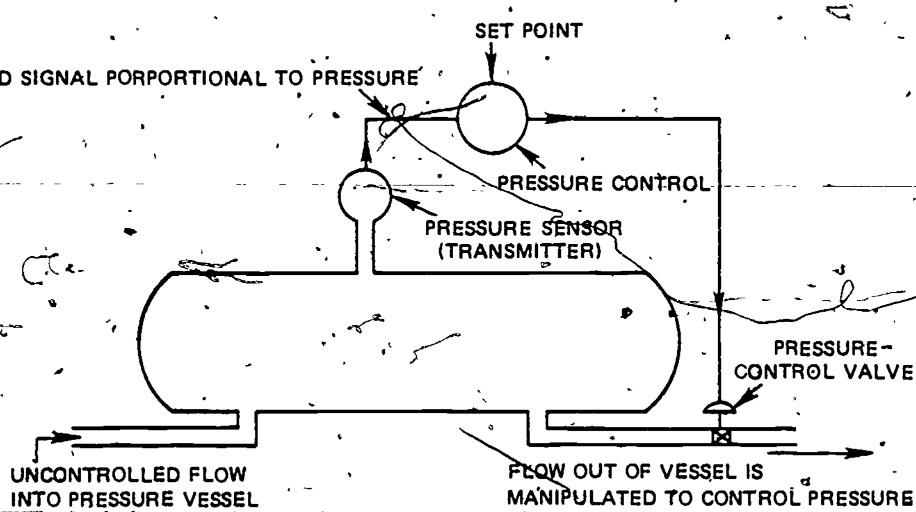


Figure 8. Pressure-control process.

CALIBRATION OF PRESSURE TRANSMITTERS AND GAGES

All measuring devices used in the process industries must be checked from time to time for accuracy and correct operation. This is usually done by an instrument technician who accomplishes these procedures by using standard and established bench or laboratory methods. The calibration of any device consists of simulating the actual process conditions and making the instrument response correspond to the measured, simulated input. If the instrument to be checked or calibrated is a local indicator - as a pressure gage, for example - the pointer movement should correspond to the measured input. For example, if a pressure gage is to measure pressure in the pressure range of 0 to 100 psig, the pointer should travel 100% as the pressure changes 100%, or from 0 to 100 psig. To calibrate a pressure-measuring device, the test setup shown in Figure 9 can be used. The general calibration procedure is to apply a pressure to the calibration pressure header, to read and note the indication of each pointer and, by calibration adjustments (zero, span, and angularity), to make the readings of the meter under test correspond to the test instrument (secondary standard). Step-by-step procedures to do this will be given in the Laboratory Procedures portion of this module.

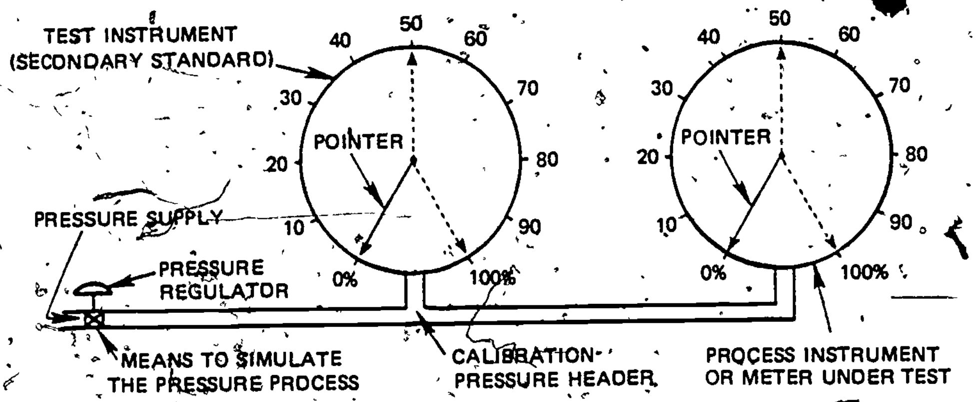


Figure 9. Test apparatus used to calibrate a pressure gage.

LIQUID-LEVEL MEASUREMENTS

The measure of liquid level usually is accomplished by the utilization of the following types of sensors:

- Float-operated devices.
- Head-type (or pressure) devices.
- Capacitance devices.
- Conductance electrodes.
- Ultrasonic detectors.
- Radiation detectors.
- Displacers.

All of the devices listed above generate a motion, force, or some other response to a movement of the surface of a liquid.

FLOAT-OPERATED DEVICES

Floats are the simplest or most common of the level devices used; but their application is usually limited to two positions: ON-OFF control or local indication. Normally, they are not used in transmitters to generate a scaled signal for transmission. Figure 10 shows applications where floats are used to measure liquid level.

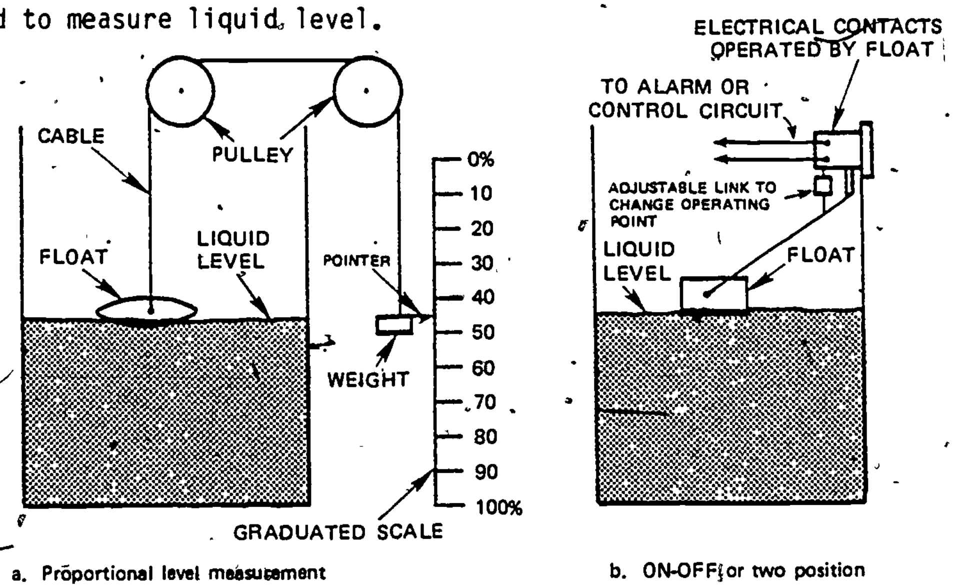


Figure 10. Float-operated level devices.

HEAD-TYPE (OR PRESSURE) DEVICES

By referring to Equation 3 of this module and reviewing the principles of manometers, it can be seen that the relationship between pressure and liquid head is such that one of these two variables can be inferred from the measurement of the other one. A manometer is used to determine an unknown pressure quantity by measuring a displacement of a column of liquid - called a hydrostatic head, or, simply, a head. The application can be reversed to measure a value of liquid level.

The level-measurement technique depicted in Figure 11 is a head-type level-measurement application. The pressure applied to the pressure transmitter at the bottom of the tank is proportional to the height of the liquid level in the tank and the density of the fluid. If the tank is open, or at atmospheric pressure, a simple pressure transmitter can be used for the measurement (Figure 11b). If it is a closed vessel under pressure, a differential pressure-measuring device is needed, as shown in Figure 11a. The static pressure on the tank in Figure 11a is applied to both sides of the differential pressure transmitter and will not affect the response of the instrument. If the pressure changes, it will change on both sides of the differential pressure (d/P) transmitter, and the transmitter will respond only to changes in level.

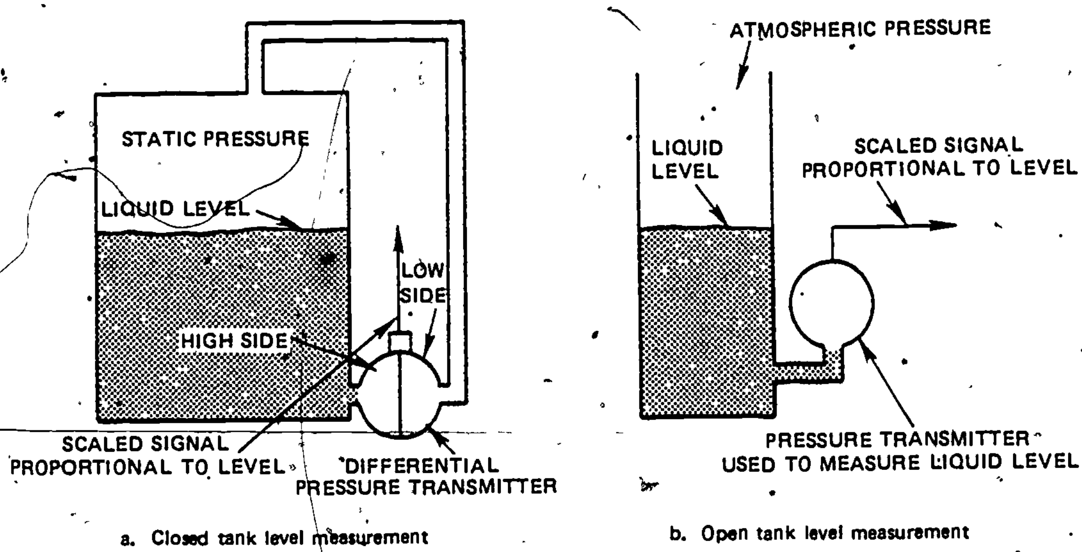


Figure 11. Liquid-level measurement by a hydrostatic head.

The fact that one tank is larger in diameter than the other (in Figure 11) bears no significance. The surface area of the tank has no effect on the pressure applied to the transmitter caused by the liquid head, because the pressure is force per unit area or pounds per square inch. The total force will be greater on the bottom of the larger tank, but not the pressure.

EXAMPLE C: CALCULATION OF RANGE OF PRESSURE TRANSMITTER.	
Given:	The liquid level is to be measured from 2 ft to 100 ft in the tank in Figure 11a. The liquid in the tank has a specific gravity of 0.68. Two feet is the zero reference level because the transmitter is located 2 ft above the tank bottom.
Find:	The range of pressure transmitter needed to measure the level.
Solution:	From Equation 1, $h = \frac{P}{0.433(G)}$, and solving for P, $P = h(0.433)(G)$, and substituting, $= (100 - 2)(0.433)(0.68)$ $P = 28.85$ psig

From Example C, it is evident that the pressure transmitter will operate in the range from 0 psig to 28.85 psig. Zero psig corresponds to 2 feet of liquid level, and 28.85 psig corresponds to 100 feet of liquid level for a fluid with a specific gravity of 0.68. To demonstrate how a liquid level between the two extremes (0 - 28.85 psig) would appear on the pressure transmitter, Figure 12 and Example D are offered.

To clarify how a head-type measurement can be used to indicate a level we will examine the following examples and Figure 12.

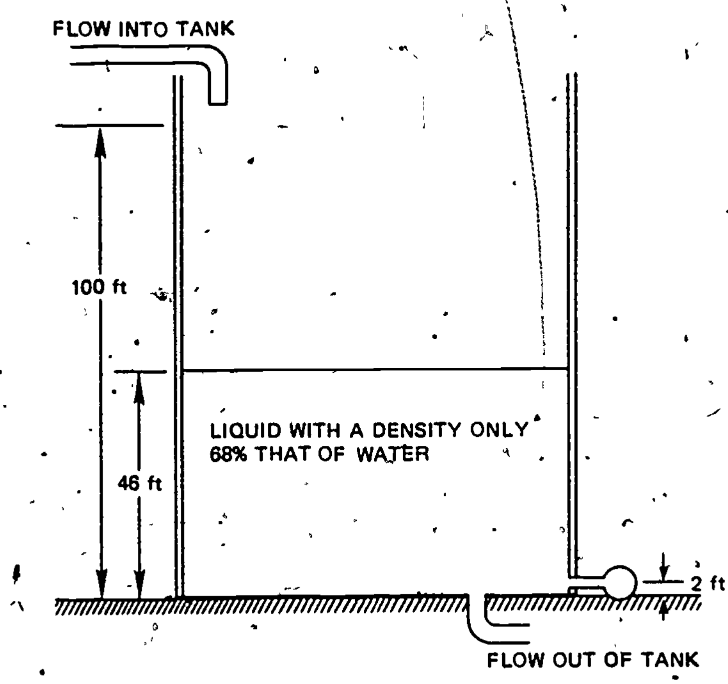


Figure 12. Pressure measurement as level indicator.

EXAMPLE D: SCALING.	
Given:	The liquid level is 46 ft high, as measured from the tank bottom; whereas the level-measuring transmitter is 2 ft from the bottom.
Find:	The percent of full-scale indication of the level-measuring transmitter.
Solution:	In this and all scaling problems, it should be observed that the percent of span measured on the input of the level transmitter will equal the percent of output. The percent of measurement input is:

$$\frac{(46 - 2)}{(100 - 2)} (100) = \frac{44}{98} (100) = 44.89\% \text{ of the full measured value.}$$

The output response of the level transmitter will be 0-28.85 psig. The actual pressure response caused by the level is:

(28.85)(44.89%) = 28.85 (0.4489) = 12.85 psig

The purpose of the pressure transmitter, that being an indicator of level, can be fulfilled in many ways. The pressure transmitter readout device (meter) could be calibrated to read out in units of percent of total volume (2% - 100%), or feet of head (2 ft - 100 ft), or in pressure (0 psig - 28.85 psig) with a conversion chart or factor by which the height could be calculated.

A means by which a pressure measurement can be converted into a height measurement is shown in Example E.

EXAMPLE E: DETERMINATION OF LEVEL.	
Given:	The pressure gage (transmitter) of Figure 12 now reads 9.45 psig.
Find:	What is the level of liquid in the tank - the level from the tank bottom, and not from the level of the transmitter.
Solution:	By Equation 3: $h = P/0.433\ (G)$ $h = 9.45/(0.433)(0.68) = 32.09$ ft $\therefore$ level = 32.09 ft + 2 ft = 34.09 ft By conversion factor: $\frac{\text{maximum height (from transmitter)}}{\text{maximum gage pressure}} = \text{ft/psig}$ 98 ft/28.85 psig = 3.396 ft/psig level = (9.45 ft)(3.396 ft/psig) + 2 ft = 34.09 ft

CAPACITANCE DEVICES

By immersing two electrodes into a tank (as shown in Figure 13), the liquid level can be measured by measuring the change in capacitance between the two electrodes. As the level changes, the liquid between the electrodes changes. The liquid is the dielectric of the capacitor. When the liquid changes, the capacitance will change accordingly.

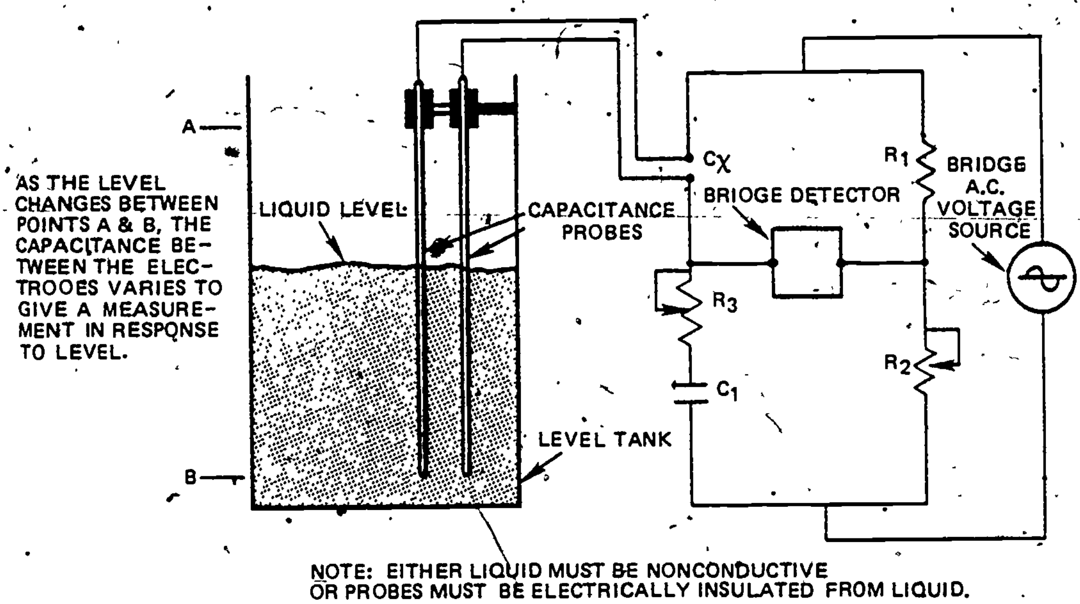


Figure 13. Capacitance-type liquid-level measurement.

The dielectric constant of air and most other gases is one (1), whereas most other substances have higher values. If this capacitance between the electrodes is assumed to be C (a constant) when the tank is empty, and the tank is filled with a liquid having a dielectric constant of four (4), the capacitance for the full tank will be 4C. This will cause the value of C_X in Figure 13 to unbalance the bridge, and the unbalance will be proportional to level.

The capacitance bridge, which is similar to the d.c. Wheatstone bridge, is excited by an a.c. voltage. When an audible frequency is used, the bridge detector can be a speaker or other audio device. For industrial applications, the detector is usually a recorder that receives a scaled signal from the bridge.

In Figure 13, R_2 and R_3 are precision variable resistors adjusted to balance the bridge at the zero reference level. R_2 is a fixed-value precision resistor, C_1 is a fixed-value capacitor, and C_x represents the variable capacitance between the plates. The value of C_x is expressed mathematically by Equation 4. R_1 and R_3, called ratio resistors, can be selected to help determine the overall bridge sensitivity.

$$C_x = \frac{R_1}{R_3}(C_1) \qquad \text{Equation 4}$$

Capacitance level-measurement devices are use in applications where other level-measuring techniques could not be used successfully. They are normally more expensive and difficult to maintain. If the dielectric constant of the liquid material is known, values of C_x corresponding to different values of level can be connected to the bridge circuit. Calibration adjustments are then made to the bridge detector to calibrate the overall bridge circuit. However, empirical calibration techniques are more commonly employed, whereby the calibration adjustments are made to correspond to actual level values. In such cases, it is necessary to be able to determine the actual level values by alternate means.

CONDUCTANCE ELECTRODES

Conductance electrodes can be used where the conductivity between the electrodes is a function of the amount of liquid between them, much like the variable capacitance in the previous discussion. The electrodes are then connected to a d.c. bridge measuring circuit where unbalance detector response is a function of liquid level. Level measurement by conductivity is seldom used in the process and manufacturing industries.

ULTRASONIC DETECTORS

Level measurement by ultrasonic-type detectors finds little or no use in the process industries; but these detectors are used when all other means of level measurement are totally inadequate.

The principle of level measurement by ultrasonic detectors involves an ultrasonic generator and detector. Sound waves are generated at the bottom of a tank or vessel and received or measured at the same location. The sound waves leaving the source, or generator, travel through the liquid medium and are reflected at the surface. If the speed of sound in the liquid medium is known, level measurement then becomes a matter of measuring the time it takes the sound waves to make the round trip from the source to the detector. These measurements can be made with such precision and accuracy that 0.1% accuracy in level measurement can be achieved. Ultrasonic level-measurement techniques are used in depth finders for sea and ocean craft, as well as for oil well depth measurement.

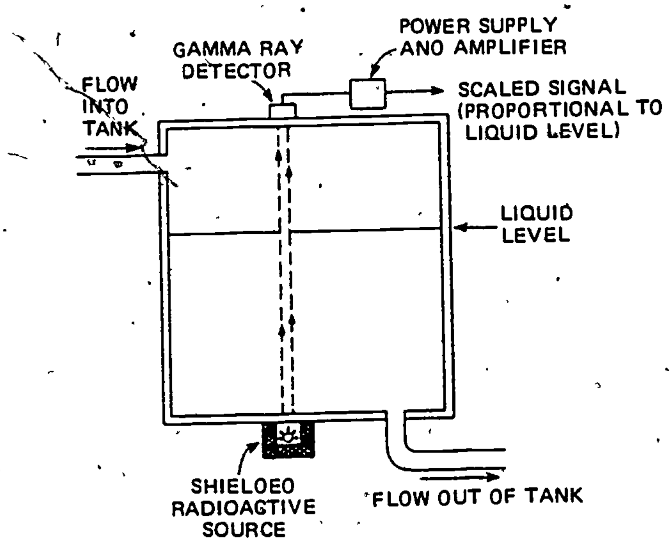


Figure 14. Radiation-type liquid-level measurement.

Another means of conducting a level measurement indirectly and with no physical contact between the fluid being measured and the measuring device is illustrated in Figure 14. Radioactive radium (Ra^{226}) decays to become radon (a radioactive gas). In the process of decay, alpha particles and gamma rays are emitted. The alpha particles have little ability to penetrate and thus have no value to the operation; gamma rays, however, have high penetrability and offer a very accurate and efficient means of level measurement.

Gamma rays lose energy in proportion to the amount of material through which they travel; for a given distance traveled, the greater the density of the substance, the greater the energy loss. The amount of energy lost in penetrating the metal bottom and top of the tank in Figure 14 is a constant, thus only the amount of fluid in the tank (level) can cause a change in energy loss of the gamma rays. By knowing the amount of energy loss per foot of the liquid and being able to measure the energy received at the detector, it is a simple matter to calculate the depth of liquid in the tank, because the average gamma energy at the source is known.

Level measurement by gamma ray detection is accurate, but it is expensive when compared to head-type and other level-measuring devices. Like the ultrasonic type, it should be used only as a last resort.

DISPLACERS

An important level application is the measure of interface level. A liquid interface is the point at which two liquids that have different specific gravity values meet, or come together. Common applications involving the measurement of interface level are in the chemical, petroleum, and petro-chemical industries where water and a petroleum product form an interface (Figure 15). Liquid-level interface measurement is based on a small

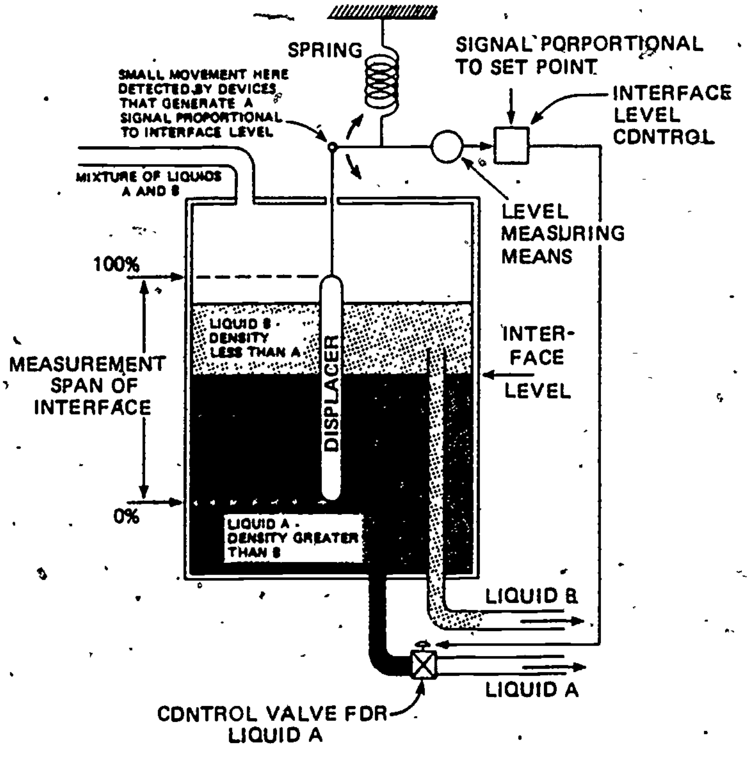


Figure 15. Interface level measurement and control system.

amount of movement of the displacer caused by the different amount of buoyance caused by the liquids of different densities. When the tank is completely filled with the lighter liquid B_i, the displacer will exert a greater force on the spring - which is caused by the lower buoyant force of the liquid. When the tank is completely filled with the heavier material A, the displacer will exert less force on the spring - which is caused by the increased buoyant force of the heavier liquid. The different forces exerted on the spring cause the displacer to have a small vertical movement that is transmitted to the level transducer by the link-and-lever arrangement shown. This is the input to the level transmitter that is the feedback link in the control system. The displacer movement is a function of the interface level.

EXERCISES

1. Convert 45 inches of water column to:
   a. Inches of mercury column.
   b. psig.
   c. psia. (Assume atmospheric pressure at sea level.)
2. Express atmospheric pressure as:
   a. psig.
   b. psia.
   c. Inches of mercury column.
   d. Feet of water column.
3. What would be the pressure range of a level transmitter used to measure liquid level from 0 to 88 ft if the liquid has a specific gravity of 1.2?
4. What is the pressure applied to the transmitter in Exercise 3 above when the level measurement is 32 feet?
5. List three different means of level measurement, with at least one advantage and one disadvantage of each.
6. List the maximum pressure that can be measured in psig with a mercury manometer that is 30-in high.

LABORATORY MATERIALS

100-lb air supply source
A fixed 20-psig pressure regulator

A 30-in laboratory quality mercury bell manometer with a psig scale and an inches-of-water scale

A variable regulator capable of 0.1% regulation up to maximum regulated pressure of 20 psig

0-5 psig pressure gage with 0.1-psig resolution

0-30 psig pressure gage with 0.5-psig resolution

2 globe valves (one-fourth-inch MPT with one-fourth-inch NPT)

Approximately 10 ft of one-fourth-inch polyethylene tubing

Approximately 4 ft of one-fourth-inch pipe

Assorted pipe and tubing fittings

LABORATORY PROCEDURES

LABORATORY 1. GAGE CALIBRATION FOR A 0-30 psig GAGE

1. Connect the equipment as shown in Figure 16 using the 0-30 psig gage as the meter under test.
2. Adjust the variable regulator to its lowest setting or by turning the adjusting knob to the full counterclockwise position.
3. With block valve 2 open, slowly open block valve 1. The purpose of block valve 2 is to vent the pressure on the header to atmosphere should block valve 1 leak in the closed position. This helps to prevent the possible loss of mercury in the manometer if, by accident, a component malfunctions and the pressure on the manometer becomes excessive.
4. While opening block valve 2, observe the indication on the manometer and pressure gage. The readings should stay at zero.
5. With zero pressure on the header, adjust the manometer for an indication of zero. Micrometer adjustments are usually provided to do this.

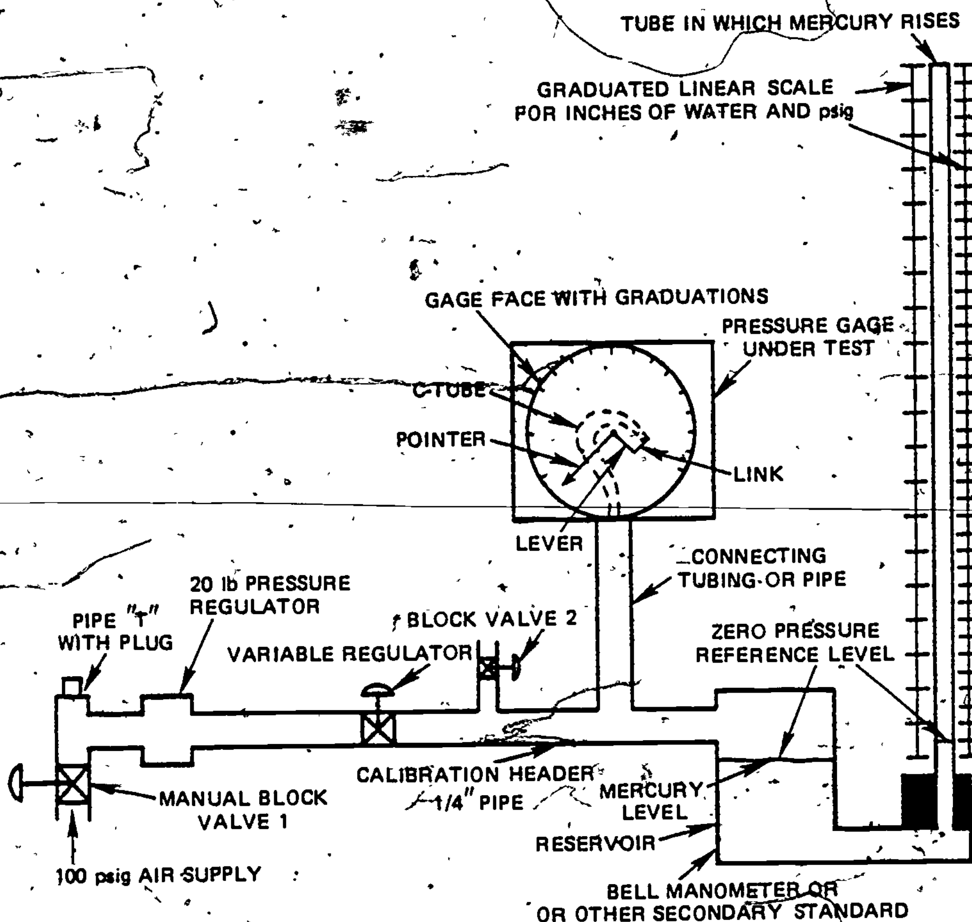


Figure 16. Apparatus for pressure-gage calibration, using a bell manometer as a secondary standard.

6. Zero the pressure gage by making certain that the pointer is at the zero position. This can be done by using a micrometer adjusting screw on the point or by removing the pointer and replacing it to point to the zero reading. The glass must be removed for this procedure.
7. Close block valve 2 while observing the pressure readings on the gage and manometer. Any increase in the response of either instrument - the manometer or gage - indicates a leak in the regulator. Positive shut-off of regulators is not necessary, but the leak should not be great enough to cause the manometer to deflect more than a couple of inches of water.

8. Slowly increase the pressure by increments equal to 10% of the full-scale value of the meter under test. This would be increments of 30 psig, called the measured value. For each increment, observe and record the corresponding value as read on the manometer. This is the actual value. Record the values in the Data Table. Turn the regulator to the extreme left position to put zero pressure on the header.
9. Plot a calibrtation curve, using the values in the Data Table, as illustrated in Figure 17.

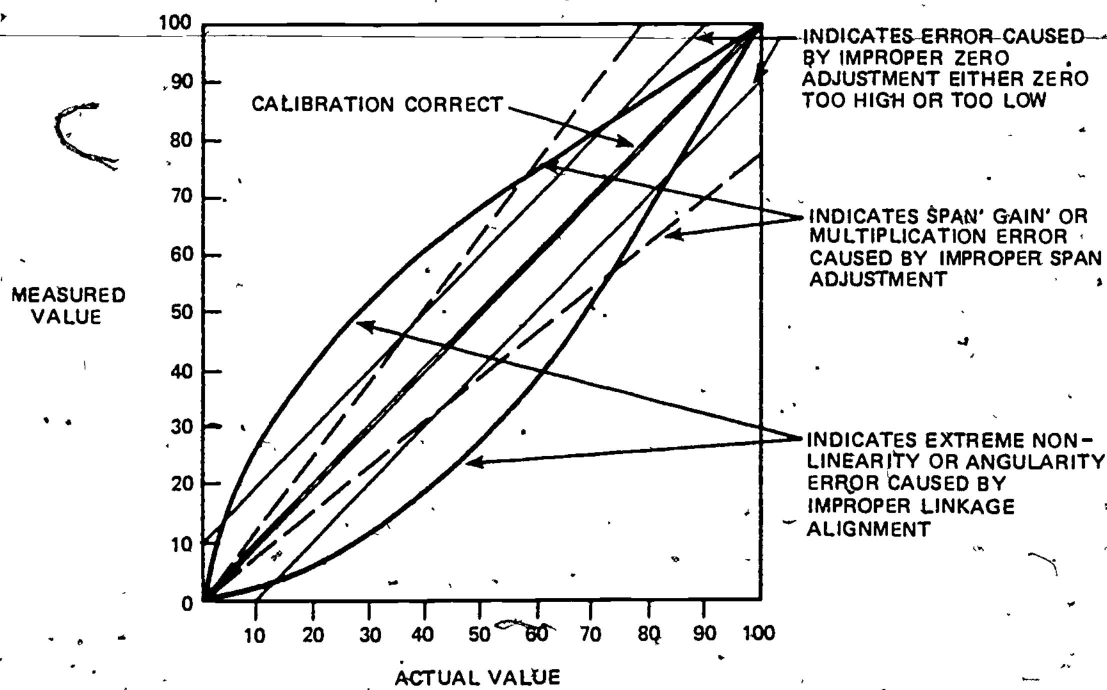


Figure 17. A calibration curve.

10. If the calibration curve shows accurate calibration, the procedure is complete. If the calibration is not accurate, continue the procedure.
11. If zero error exists, as shown on the calibration curve, open block valve 2 and repeat Steps 5 through 9.

12. If span error exists, remove the glass and face plate and make a span adjustment by changing the length of the lever. Lengthen the lever to increase span, and shorten the lever to decrease it.
13. Repeat Steps 5 through 9 and 12 until the calibration is complete. Most pressure gages do not have adjustments for angularity error. Angularity error is caused by damaged components and excessive wear. Angularity is corrected by adjusting the link (Figure 15) when such adjustments are provided.
14. Dismantle the test apparatus. The procedure is now complete.

LABORATORY 2. GAGE CALIBRATION FOR A 0-5 psig GAGE

Using a 0-5 psig gage, repeat all fourteen steps of Laboratory 1.

DATA TABLE

DATA TABLE.				
Percent of Full-Scale Value	Measured Value		Actual Value	
	Procedure 1	Procedure 2	Procedure 1	Procedure 2
0				
10				
20				
30				
40				
50				
60				
70				
80				
90				
100				

REFERENCES

Hunter, Ronald P. Automated Process Control Systems Concept and Hardware. 10th ed. Englewood Cliffs, NJ: Prentice-Hall, 1978.

Woodruff, John. Basic Instrumentation. 2nd ed. Austin, TX: Petroleum Extension Service, University of Texas, 1964.

GLOSSARY

Accuracy: The closeness to which a measured value agrees with an actual value.

Control quality: A measure of the ability of a control system to achieve a desired process condition. Usually this is a measurement with respect to process recovery from an upset or a load change.

Dynamic accuracy: Accuracy relating to instruments or systems in a state of change.

Hydrostatic head: The pressure exerted by a vertical column of liquid, usually water, or one with a known specific gravity.

Interface: The intersection of two nondispersible liquids of different specific gravities.

Manometer: A device used for pressure measurement, usually a secondary standard. It consists of a glass tube and reservoir filled with liquid. Pressure applied to the reservoir causes the liquid to rise in the tube. The height to which the liquid rises is measured in linear units and converted to pressure. The scale is normally calibrated in pressure units.

Pressure element: A device that produces a uniform amount of movement or motion caused by physical distortion. The physical distortion is caused by the applied pressure that is to be measured.

Secondary standard: A device used as a standard in shop and laboratory calibrations. Its accuracy is usually traceable to a primary standard.

Static accuracy: Accuracy relating to stable static conditions or operations.

TEST

INSTRUMENTATION AND CONTROLS

Module IC-02

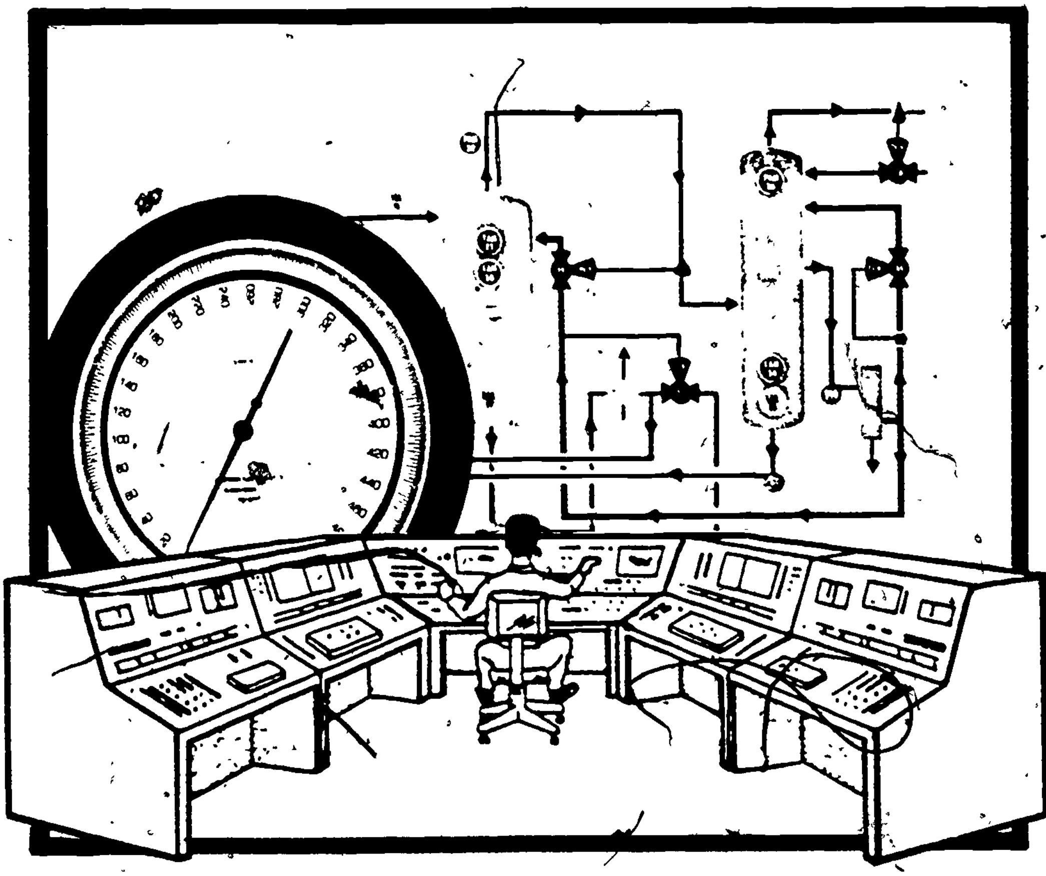
"Instruments for Fluid Measurements - Pressure and Level"

1. Make the following pressure conversions:
   a. ________ inches of mercury = 45 inches of water.
   b. ________ psig = 10 inches of mercury.
   c. ________ inches of water = 7 inches of mercury.
2. Atmospheric pressure, at sea level, is equal to:
   a. ________ psig.
   b. ________ psia.
   c. ________ inches of mercury.
   d. ________ feet of water.
3. The pressure range of a level transmitter used to measure 0 to 100 feet of liquid with a specific gravity of 1.2 is ________ psig.
4. When the liquid level is 32 feet, the hydrostatic-head pressure applied to the level measuring instrument in Question 3 above is ______ psig.
5. List four pressure elements.
6. List three means or methods of level measurement.
7. List two types of measurement standards.
8. List the standard unit of liquid level measurement in the MKS system and the FPS system.
9. The maximum level at standard ambient conditions that can be measured with a 0-5 psig gage is ________.
10. The minimum amount of water level that can be measured with the 0-5 psig gage used in Laboratory Procedure 2 is ____________.
11. Level measurement by hydrostatic head is called an ____________.
12. List two units of measurement for liquid level.
13. List three units of measurement for pressure.
14. Because of ease, simplicity, and expense, the most common means of level measurement in industrial applications is ____________.
15. A laboratory standard for pressure measurement less than 15 psig is ____________
16. List four pressure elements used as tranducers.
17. Two devices used to convert the movement of a pressure element to a transmitted signal are ________ and ____________.
18. The closeness to which a measured value conforms to the actual value is called ______________________.

ENERGY TECHNOLOGY

CONSERVATION AND USE

INSTRUMENTATION AND CONTROLS



MODULE IC-03

FLUID FLOW MEASUREMENT

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Many industrial processes require an accurate measurement of fluid flow through pipes. The importance of this measurement lies in the fact that fluid flow is generally the manipulated variable in most process control loops. The increased emphasis on efficient material and energy cosumption has placed even more significance on the control of fluid low in production economics. For example, when energy was inexpensive, the measurement of steam or gas flow was of little consequence. Now, however, with soaring fuel and material costs, it is very cost effective to measure accurately fuel and produce flow rates, regardless of the initial cost of the measurement equipment. The costs of installing measuring instruments in process control is normally recovered in a very short time.

The purpose of this module is to present the various types of flow measuring devices used in process flow monitoring and to discuss their principles of operation. Mounting procedures - wherever critical - are discussed, as well as calibration and check-out procedures. The selection of flow measuring instruments for specific applications - advantages and disadvantages - are also covered.

PREREQUISITES

The student should have a basic understanding of algebra and physics and should have completed Modules IC-01 and IC-02 of Instrumentation and Controls.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms, using assigned units, where applicable:
   a. Discharge coefficient.
   b. Diameter ratio.

c. Reynolds number.

d. Taps.

2. List and explain operating principles (include descriptions, characteristics, and applications) of various differential pressure sensing flowmeters.
3. Discuss flow-measurement secondary elements (transducers).
4. Sketch a typical differential-pressure flow-sensing device and transmission channel.
5. Install an orifice plate and a venturi tube in pipes; measure pressure drops as functions of flow; calculate flows, based on nominal discharge coefficients, for each device.
6. Calibrate an orifice plate and a venturi tube by making a differential-pressure versus flow curve; calculate discharge coefficient.

In many industrial processes the flow of fluids is used to regulate other variables - temperature, pressure, or level. When one of these other variables is the manipulated variable of a process, the measurement of the flow is less important. However, when flow is itself the manipulated variable of a process then accurate measurements of flow and the changes of flow rate are required.

The fluids that are to have their flow measured may be of two types: compressible (gases) or incompressible (liquids or gases moving at low speed). The measure of the flow of these fluids may be in terms of quantity or quantity rate. The quantity measure will be predominantly in units of weight or volume, and primarily in the FPS (foot-pound-second) or English system of measure. Quantity rate will be the flow measure of interest in this module and will also use units from the English system of units, such as pounds per second (lb/s) or cubic feet per second (ft^3/s).

BASIC PRINCIPLES OF FLOW MEASUREMENTS

To understand fluids in a specific system, it is necessary to be familiar with some of the elementary characteristics of fluids while they are in motion or static (not moving).

FLUID FLOW

Significant flow characteristics include:

- Volume and mass flow.
- Steady and unsteady flow.
- Mass force and energy changes that occur in flow.

The latter characteristic involves the "law of conservation of mass, energy and momentum." The conservation of mass is easily understood; e.g., the amount of fluid entering a pipe (assuming no leaks) must be the same as the fluid exiting from the pipe.

FLUID STATICS

Pressure is transmitted through fluids to all parts of contact. This phenomenon, based on Pascal's law for static fluids, states that the pressure on a particle or element of a static nonflowing fluid is the same in all directions, neglecting pressure due to the weight of the fluid itself.

A typical example of this law would be an inflated tire. Air pressure is the same everywhere in the tube. A useful application of this law is the hydraulic piston used to lift a car at a service station. A heavy car can be lifted with a reasonably low-pressure system (Figure 1).

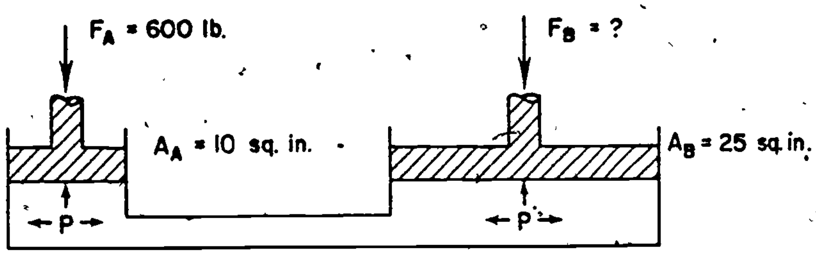


Figure 1. Hydraulic system.

Assume two pistons of different size are connected as shown. By Pascal's law, pressure P is equal throughout the system. If the downward force on piston A is 600 lbf, the calculated pressure exerted on the fluid by piston A is:

$$P_A = \frac{F_A}{A_A} = \frac{600\ \text{lbf}}{10\ \text{in}^2} = 60\ \frac{\text{lbf}}{\text{in}^2} = 60\ \text{psi}$$

Because P is constant,

$$P_B = \frac{F_B}{A_B}$$

therefore

$$F_B = P_B A_B$$
$$= P_A A_B$$
$$= 60 \frac{\text{lbf}}{\text{in}^2} \times 25 \text{ in}^2 = 1500 \text{ lbf}$$

Under normal industrial conditions, the fluid in a power system is most often under pressure and completely fills the pipes, tanks and assemblies of the systems. Its pressure is due in part to the force of gravity or weight of the fluid (statics), in part to forces applied externally by pumps or compressors, and in part to the result of adding energy to the fluid (e.g., water to steam).

VELOCITY AND MASS FLOW RATE

The mass of fluid that passes a given point in a fluid system in a unit of time is referred to as mass flow rate - the rate (or speed) at which fluid moves past a particular point in the system. Mass and velocity of flow are often considered together. With other conditions unaltered - that is, with volume of input unchanged - the velocity of flow increases as cross-sectional area (size) of a pipe decreases; inversely, the velocity of flow decreases as cross-sectional area increases. In an open river or stream, flow velocity generally is slow through wide sections and rapid through narrow sections, even though the volume of water passing each part of the stream is the same. The equation for this continuity of mass is expressed as follows:

$$V_A A_A \rho_A = V_B A_B \rho_B \qquad \text{Equation 1}$$

where: V = average velocity of fluid.
A = cross section of pipe.
ρ = density of fluid.

COMPRESSIBILITY AND TEMPERATURE EFFECTS

If fluid density is constant (i.e., if there are no temperature or compression effects, such as expansion or contraction), then the mass equation of continuity is equivalent to the volumetric equation of continuity:

$$A_A V_A = A_B V_B \qquad \text{Equation 2}$$

Liquids are essentially noncompressible (however, they are affected by temperature). Liquids can be only slightly compressed, even under extreme pressures. For example, if 100 psi is applied to a body of water, the original volume will only decrease 0.03 percent.

The effects of temperature are not as negligible, for example, the density of water in an operating reactor's coolant system is about half its density at room temperature. Since heat-transfer capabilities and energy carrying capacities of coolants in power plants are related to fluid mass rather than volume, it is important to be able to measure mass flow or to be capable of correcting volumetric flow.

BERNOULLI'S ENERGY EQUATION

With the previous discussion in mind, the first practical consideration of fluid-flow measurement requires the stating of an energy balance. Bernoulli developed an energy equation for an incompressible fluid with a constant density. In a frictionless flow of fluid through a pipe (Figure 2), three significant components are measured in terms of "heads" (equivalent weights of columns of fluid in units of feet or meters). These columns are defined as velocity head (kinetic head), pressure head and elevation head (potential energy of the fluid). For instructional purposes, they are combined to illustrate Bernoulli's energy equation for the flow of incompressible fluids:

$$\frac{V^2}{2g} + \frac{P}{\rho g} + Z = H \qquad \text{Equation 3}$$

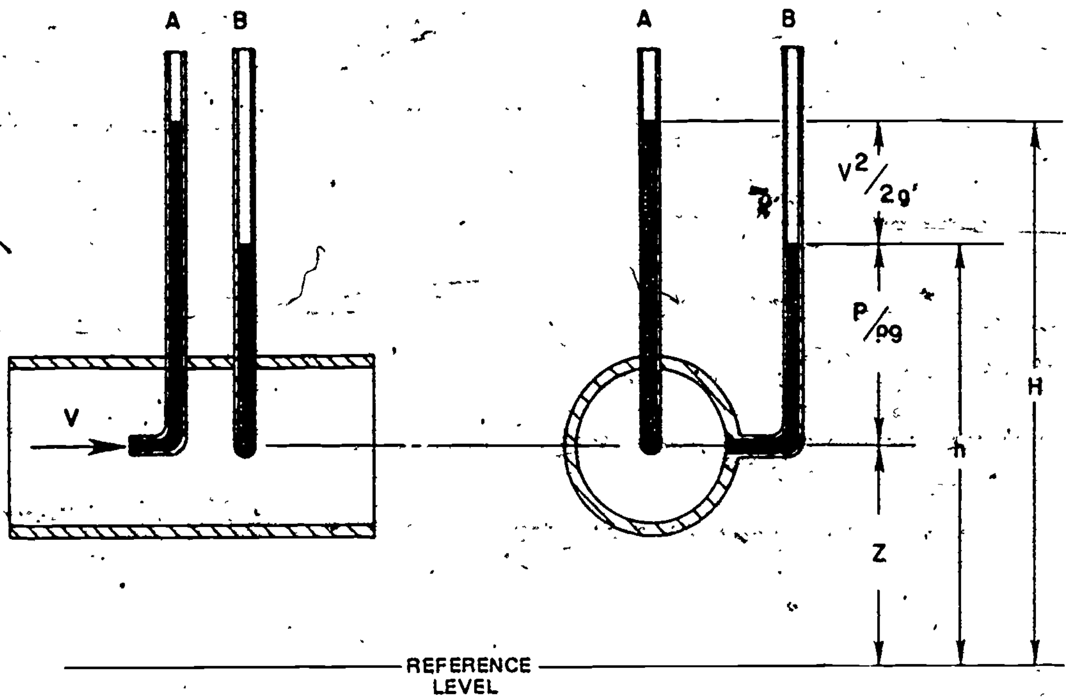


Figure 2. Total and static heads for fluid flow.

where: H = constant (called total head or total pressure), usually measured in feet of fluid.

$\frac{V^2}{2g}$ = velocity head, with units of $(\frac{ft}{sec})^2$ $(\frac{sec^2}{ft})$ or feet.

$\frac{P}{\rho g}$ = pressure head, in feet.

Z = elevation head (height of fluid above a reference level) in feet.

The term ρg is the gravity force (weight per unit volume), i.e., specific weight. Thus, $\frac{P}{\rho g}$ may be written as $\frac{P}{W}$, in units of feet; $\frac{P}{W}$ represents energy per lb of fluid needed to raise its pressure by P (where W = weight).

It is sometimes convenient to refer to the sum of the terms $(\frac{P}{W} + Z)$ as the <u>static</u> (piezometric) <u>head</u>. In the energy equation, internal energy of the fluid is assumed to be constant. One form of internal energy is heat energy.

Tubes inserted in a pipe (Figure 2) are identified as A and B. Tube A is bent so that its open end faces directly upstream (perpendicular). The fluid stream striking this open end is brought to rest (stagnant). This tube is called a pitot tube, measures both the velocity head and the pressure head (i.e., the total flow head).

Tube B, inserted in the pipe wall so that its open end is flush with the inner wall, causes no disturbances to flow. Fluid flows past the open end of this static tube without deceleration, which allows it to record static (piezometer) head.

The level in Tube A (total head of fluid above the reference level) exceeds the level in Tube B (representing static head of the fluid) by an amount equal to the velocity head. Note: All heads are convertible to pressures: i.e., velocity head represents velocity pressure; the static head represents static pressure:

$$\text{Pressure } (P) = \rho g \text{ (head)}$$

where: ρ = mass density, mass/unit volume.
g = gravitational acceleration constant, distance/(unit time)^2.
head = displacement of column in manometer, distance.

Thus, using standard FPS units of measure:

$$\begin{aligned}(V^2/2g)(\rho g) &= [(ft/s)^2 \div ft/s^2][(lbm/ft^3)(ft/s^2)] \\ &= (lbm/ft\text{-}s^2)\end{aligned}$$

Remember: according to physics, F(force) = m(mass) x a(acceleration)
Thus m = F/a and lbm = lbf (pound force)/(ft/s^2)

$$\begin{aligned}(lbm/ft\text{-}s^2) &= (lbf\text{-}s^2/ft)/(ft\text{-}s^2) \\ &= lbf/ft^2 = P\end{aligned}$$

Friction, which is always present, must be considered. In practical cases, loss of head or pressure by friction is caused by the fluid flow. This loss is subtracted from the velocity head and added to the static head.

If one end of the pipe were higher than the other, the elevation head, Z, would be the difference, in feet, between any two points of measurement.

MEASUREMENTS AND CHARACTERISTICS

A wide variety of instruments and techniques are used in industry to measure quantity and rate of fluid flow, and its pressure (or levels). Flow rates are expressed in both volumetric (gallons, cubic feet, etc.), and weight (lbf) units per unit time. Gases are generally measured by cubic feet per minute (or hour), steam in pounds per hour and liquids in gallons per minute (or hour). The most accurate method of measuring liquid flow would be by weighing the quantity of flow; remember, specific weight, density and specific volume all change with temperature change in the fluid. Conversion between volumetric flow and weight (mass) flow may be expressed simply:

$$Qm = \rho Q_V \qquad \text{Equation 4}$$

where: ρ = density of fluid.
Qm = mass flow rate.
Q_V = volumetric flow rate.

The closed cycle systems found in many industrial processes make the above method impractical. Thus, flows must either be measured by (1) application of the principle of "conversion of mechanical energy" through the conversion of a fluid's velocity to the various types of pressure heads discussed previously, or (2) by mechanical displacements induced by flow, with such devices as paddles, floats or turbines. Categorically, all the above devices are called flowmeters.

CLASSIFICATION OF DEVICES

Typically, various types of flowmeters may be grouped as follows:

- Volumetric.
- Area.

- Differential.
- Momentum.
- Electromagnetic.
- Ultrasonic.

From the above, there is usually one device that is more appropriate for a particular process instrumentation need. Selection of a specific meter depends on required accuracy, operating environment, expense, and durability.

A basic consideration of flow sensing is that all flowmeters consist of two parts: (1) primary element; i.e., the element in contact with the flowing fluid, and (2) secondary element, which translates the interaction into numbers and indicates (or otherwise displays or records) the desired information.

Flow sensors for industrial processes can be placed in one of two classes; differential pressure or inferential flowmeters, or linear flowmeters. This module will deal with rate measurements primarily; these are inferred from the effects of the fluid rate on pressure, force, heat transfer, flow area, and so on.

FLOWMETER FUNDAMENTALS

If a constriction is placed in a pipe in which a fluid is flowing, there will be an increase in the fluid velocity, and an increase in kinetic energy at the constriction point. This statement, based on the "conservation of mass" relationship (Figure 3), can be calculated as follows:

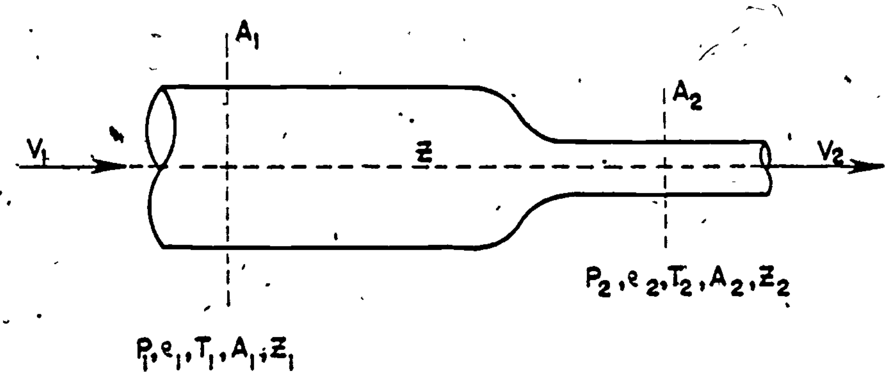


Figure 3. One-dimensional flow system.

$$Q = A_1 V_1 \rho_1 = A_2 V_2 \rho_2 \qquad \text{Equation 5}$$

where: Q = volumetric flow (a constant).
A = area of pipe (cross sectional).
ρ = density of fluid.
V = velocity of fluid.
T = temperature of fluid.

Velocities are considered to be average velocities; in reality, however, velocity varies across the pipe diameter, beginning as zero at the wall to a maximum in the center. In an ideal case, the Bernoulli equation can be combined with Equation 5:

$$Q = CA\sqrt{2gh} = A_2 V_2 \qquad \text{Equation 6}$$

where: C = coefficient of discharge for constriction.
A = cross-sectional area of constriction.
g = gravitational constant = 32.2 ft/sec^2.
h = differential pressure (static) or head, $(P_1 - P_2)$.

This relationship is called the "square-root" law and, basically, applies to any type of restriction. It is confined, however, to incompressible ideal fluids in this module.

The coefficient of discharge is an empirical constant, based on type of constriction (diameter ratio), and is equivalent to:

$$C = \frac{Q_{actual}}{Q_{ideal}} \qquad \text{Equation 7}$$

This constant also depends on the magnitude of the Reynolds number (N_{Re}), a function of turbulence, density, viscosity and velocity of the fluid. Thus, the constant, C, actually includes a separate constant called the "approach factor."

$$\frac{1}{\sqrt{1 - (d/D)^4}}$$ Equation 8

where: d = area, A_2, of constriction (such as an orifice).
D = diameter or area, A, of pipe.

(Note: In the actual development of working equations for commercial applications of head or differential-pressure flowmeters, Equations 6 and 8 require additional correction factors for specific fluids, temperature, and other variables. These factors are normally found on the specification sheets for such devices.)

In short, C is introduced to account for deviations from the ideal Bernoulli equation. Its value is generally near unity, although precise determination must be achieved by empirical calibration.

Pressure-sensing connections, or taps, are small holes located accurately (in accordance with recognized standards) so that published discharge coefficients for a specific flowmeter are applicable. (The differential pressure that measures static pressure varies with choice of taps.)

For many industrial situations, pitot tubes occupy a place of only minor importance as primary elements for head flowmeters. They are, however, effective tools for spot checks and scans of flow streams. The latter is important in determining velocity distributions or profiles across pipes or ducts.

DIFFERENTIAL-PRESSURE DEVICES AND CHARACTERISTICS

Orifices, nozzles and venturis are by far the most common types of flowmeters used in industrial process closed circuits. Figure 4 shows these three differential pressure devices and a pressure vs. position graph for each.

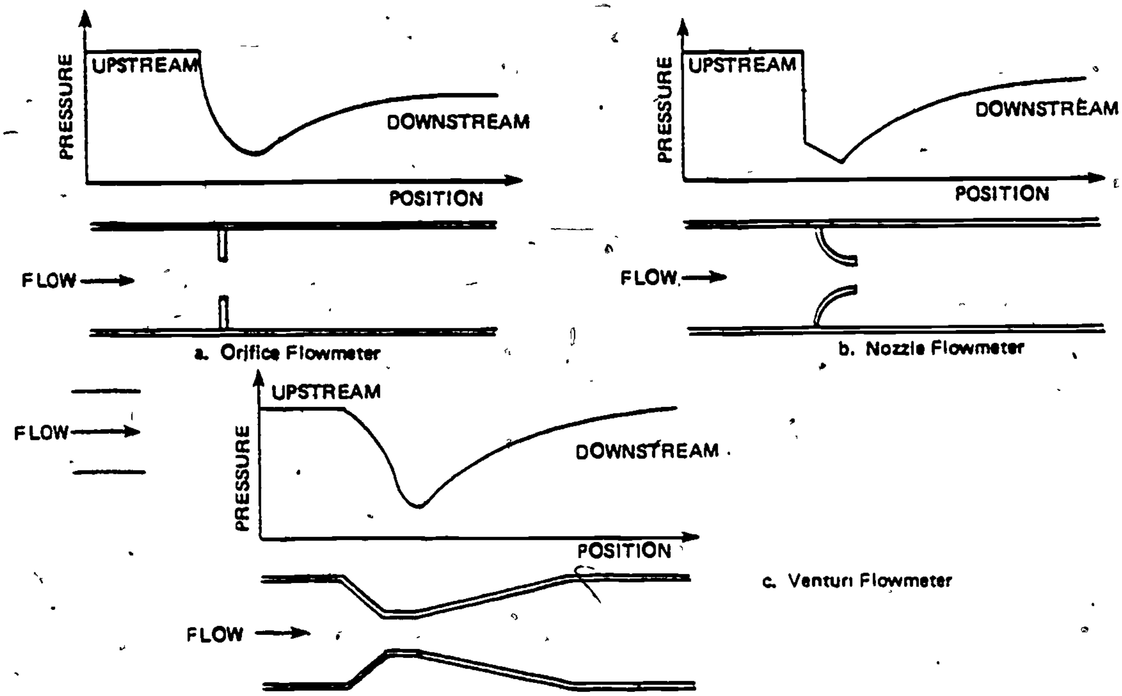


Figure 4. Differential-pressure devices and pressure characteristics.

ORIFICE PLATES

The orifice plate is probably the earliest and most common primary device in commercial use. Characteristics favoring its choice include:

- Ease of manufacture.
- Reproducibility.
- Ease of inspection.
- Ease of installation.
- Economy.

The orifice plate is simply a thin disk clamped between gaskets in a flanged joint. Usually, a concentric circular hole in the plate is smaller than the internal pipe diameter.

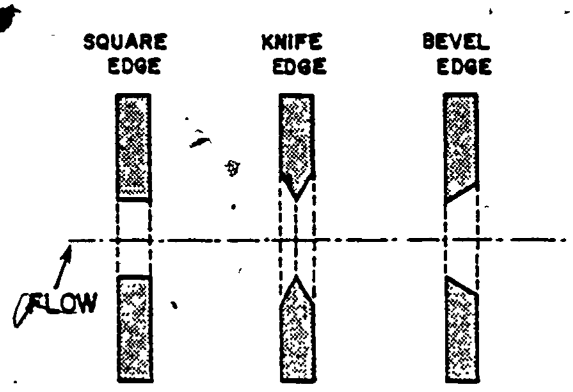


Figure 5. Orifice plates.

Pressure connections for attaching a differential gage (or separate static gages) are made at side holes in the pipe wall on both sides of the plate. The plate hole may be square, knife edged or beveled edged (Figure 5). ASME-designed (American Society for Manufacturing Engineers) orifice plates can be used without individual calibration with great assurance of accuracy.

In a typical orifice meter (Figure 6), tap locations must be located very accurately according to one of three arrangements recognized by the ASME Code.

Flow through a sharp-edged or square concentric orifice plate is characterized by a change in velocity, which reaches a maximum at a point slightly downstream from the orifice. Beyond that point, velocity reduces to its original value. Note: Pressure is minimum where velocity is maximum, in addition it has been noticed that the cross-sectional area at this point is minimum and is actually smaller than the opening; this position is called the vena contracta.

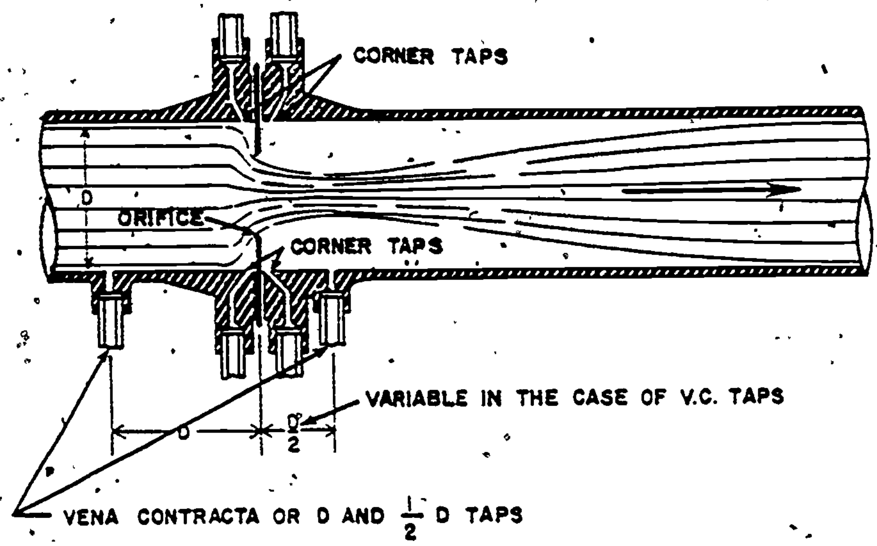


Figure 6. Typical orifice meter.

The basic working equation for an orifice plate (based on Equation 6) may be stated as follows:

$$Q = C_o A \sqrt{\frac{2g\ (P_1 - P_2)}{\rho\ [1 - (\frac{D_o}{D_1})^4]}} \qquad \text{Equation 9}$$

where: Q = volume flow rate.

A = cross-sectional area of orifice.

D_o = diameter of orifice, ft.

D_1 = inside diameter of pipe, ft.

C_o = orifice discharge coefficient, which varies with type of orifice, position of tap and Reynolds number (N_{Re}).

P_1 = upstream pressure.

P_2 = downstream pressure.

ρ = weight density of fluid, lbf/ft^3.

$\frac{D_o}{D_1}$ = β, diameter ratio.

The above variable may be related to the orifice coefficient, C (Figure 7).

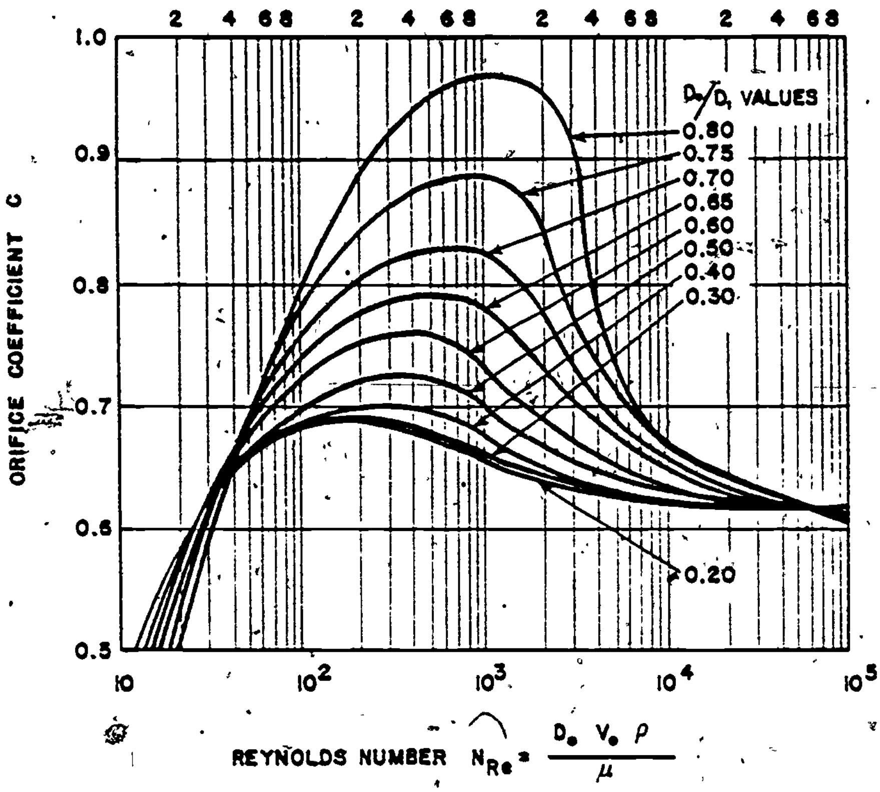


Figure 7. Orifice coefficient C for circular square-edged orifice with corner taps.

Given a known volumetric flow rate, orifice and pipe dimensions, fluid density and expected N_{Re}, a discharge coefficient can be determined. In turn, expected differential pressure also may be calculated. In actual cases, the calibrated values of an orifice are known and, in turn, an unknown flow differential pressure can be measured. This pressure is plotted versus flow (Figure 8).

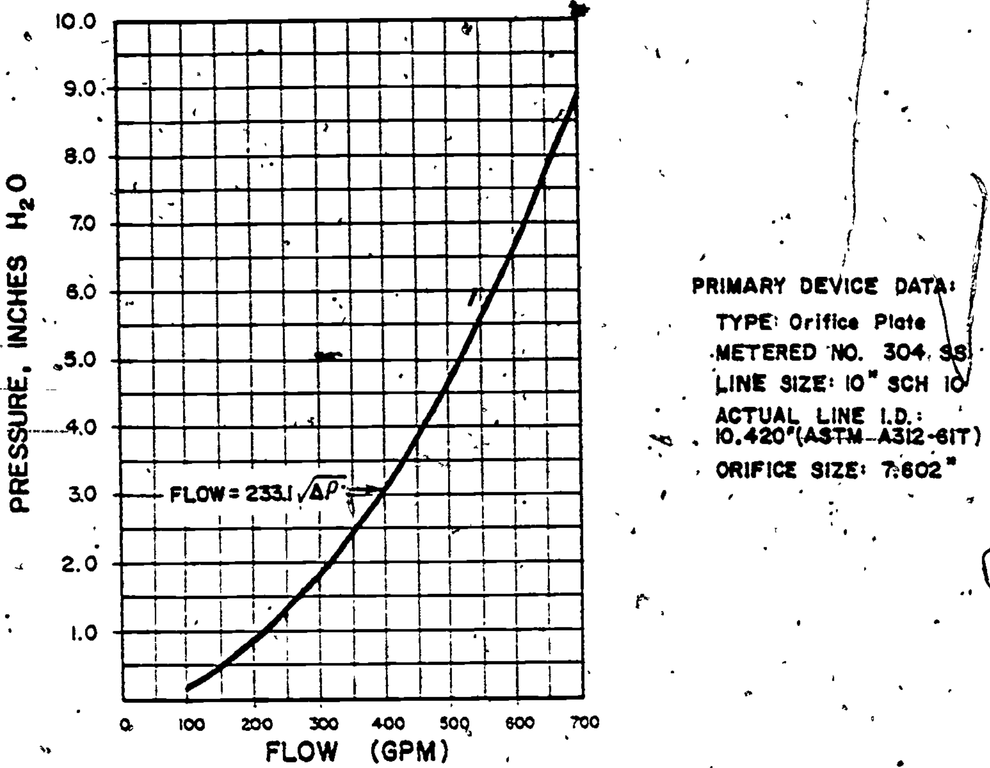


Figure 8. Manometer differential pressure across orifice versus flow.

EXAMPLE A: FLOW VS. DIFFERENTIAL PRESSURE.	
Given:	Pipe I.D. = 4 in = D_1. Orifice I.D. = 2 in = D_0 (square-edged with corner taps). Reynolds number = 4000. Fluid = water.
Find:	Orifice coefficient and flow as a function of differential pressure.
Solution:	For a Reynolds number of 4000 and D_0/D_1 of 0.5, orifice coefficient (C_0) is given as 0.66 from Figure 7; therefore; $C_0 = 0.66$

By using Equation 9:

$$Q = C_oA \sqrt{\frac{2g(P_1 - P_2)}{\rho\left[1 - \left(\frac{D_o}{D_1}\right)^4\right]}}$$

$$= (0.66)\left(\frac{\pi \, 1^2}{12^2} \, ft^2\right) \times \sqrt{\frac{2 \times 32.2 \text{ ft/sec}^2 \times (P_1 - P_2)}{62.4 \frac{\text{lbf}}{\text{ft}^3} \left(1 - \left[\frac{2/12}{4/12}\right]^4\right)}}$$

$$= (0.66)(0.2318) \quad \times \quad \sqrt{\frac{64.4 \text{ ft/sec}^2 \times (P_1 - P_2)}{62.4 \text{ lbf/ft}^3 \times (0.9375)}}$$

$$= 0.0144 \text{ ft}^2 \sqrt{1.101 \frac{\text{ft}^4}{\text{sec}^2 \times \text{lbf}} (P_1 - P_2)}$$

$$= 0.015 \sqrt{P_1 - P_2}, \ \frac{\text{ft}^3}{\text{sec}}$$

where P_1 and P_2 are pressure in psf.
If P_1 and P_2 are given in psi,

$Q = 0.181 \quad P_1 - P_2$, ft^3/sec.

FLOW NOZZLES

Smaller holes in an orifice plate cause flow to be pressed together farther downstream from the orifice; thus the discharge coefficient departs measureably from unity. In contrast, a flow nozzle gives a smooth, convergent section, which discharges the flow more parallel to the axis of flow and with less convergence and pressure loss (Figure 9).

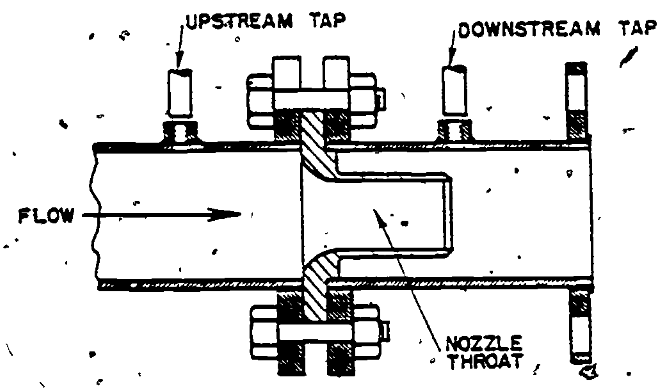


Figure 9. Flow nozzle with pipeline taps.

Briefly, the nozzle is described as a short cylinder, one end of which is flared to form a flange that can be clamped between pipe flanges. The purpose of the smooth, curved entrance to the nozzle is to lead the fluid smoothly (with minimum turbulence) into the measuring section (throat area).

The flow nozzle passes approximately 60 percent more flow than an orifice with the same differential pressure and the same ratio of throat-diameter to internal-pipe-diameter.

A flow nozzle can be installed in a welded pipe, but it cannot be used to meter flow in either direction. It is successfully used in installations where limited lengths of straight pipe limit orifice usefulness. Turbine engineers use flow nozzles extensively in turbine performance testing.

VENTURI TUBES

The venturi tube is essentially a smooth extension of the flow nozzle with a subsequent gradual, divergent, conical section that expands until the original pipe diameter is again attained (Figure 10). This tube, used mostly in large pipes, is more accurate than an orifice plate or flow nozzle, but considerably more expensive and more difficult to install.

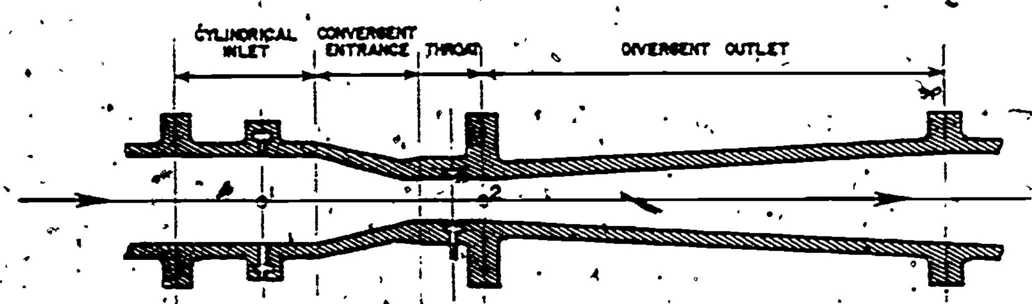


Figure 10. Typical venturi tube.

The basic working equation for a venturi tube is similar to that used for orifice calculations:

$$Q = C_V A_2 \sqrt{\frac{2g\ (P_1 - P_2)}{\rho\ [1 - (\frac{A_2}{A_1})^2]}} \qquad \text{Equation 10}$$

where: Q = average velocity at point 2, ft/sec.

$P_1 - P_2$ = differential pressure, lbf/ft^2.

A_2 = cross-sectional area at point 2, ft^2.

ρ = weight density of fluid, lbf/ft^3.

C_v = venturi discharge coefficient, which varies with geometry, flow rate and fluid.

Venturi tube design favors their use in continuous-flow slurries and suspended matter that normally might clog or alter the characteristics of an orifice plate or its taps.

PITOT TUBES

In general, a pitot tube for determining flow by differential pressure, consists of two members, one for indicating the sum of the static and velocity pressures at a point in a body of fluid in motion, and the other for indicating static pressure only. The first is known as an "impact tube" and the pressure registered by it as the "total head" or "stagnation pressure" (Figure 11).

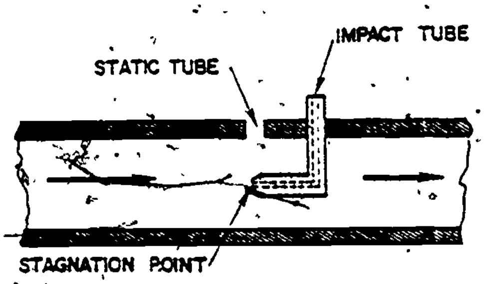


Figure 11. Pitot tube, independent static-tap.

Beginning again with the Bernoulli equation, it can be shown that flow past the pitot tube is characterized by the same general type equations previously discussed for orifice plates and venturi tubes: (See Figure 11.)

$$V_1 = C_p \sqrt{\frac{2g(P_1 - P_2)}{\rho}} \qquad \text{Equation 11}$$

where: V_1 = velocity of fluid in line with pitot head.
C_p = impact coefficient.
P_1 = impact pressure (absolute) (if $V_2 = 0$).
P_2 = static pressure in flowing fluid, absolute.
ρ = weight density, lbf/ft^3.

It is important to note that velocity is measured at only one point in a cross section of fluid flow (contrasted with other flow elements, which consider the average or effective velocity of an entire stream).

ELBOW DEVICES

There are many instances in which it is only necessary to know that a loss or a relative drop in flow has occurred. For example, in a PWR, the primary coolant flow rate in each loop is established by a constant-speed pump. To detect a loss or reduction in flow, an elbow differential-pressure device (Figure 12) is used. $P_1 - P_2$ is an established value for the desired flow. As the primary coolant flow drops off, the differential pressure is reduced. This signal annunciates and, in some cases, trips the reactor.

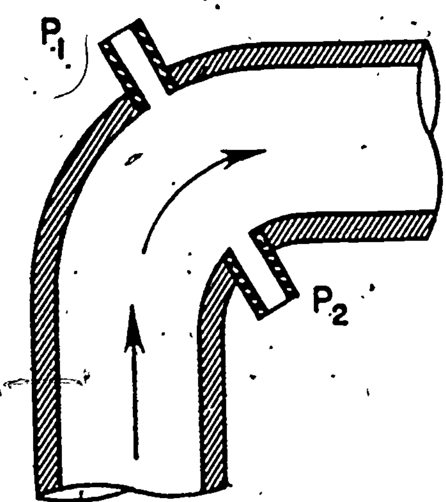


Figure 12. Elbow differential-pressure flow sensor.

INSTALLATION/OPERATION

Regardless of the primary element selected, certain important installation factors should be considered to ensure accurate measurements:

- Location in piping, in relation to (a) bends (elbows); (b) changes in pipe cross section.
- Possible need for approach-straightening vanes (streamliners).
- Location and type of pressure taps.
- Dimensions and conditions of pipe surface before and after element.
- Position of element relative to direction of fluid flow.
- Type and arrangement of piping from primary element to differential-pressure measuring instrument.

Abnormal velocity and distribution at pressure measurement points influences readings from any of the head flowmeters previously didscussed. For this reason, it is important to install elements with adequate lengths of straight, smooth approach pipe.

When the piping layout, especially adjacent elbows and partially closed valves, do not allow sufficient streamlining of the flow to eliminate pressure disturbances, straightening vanes are used. These vanes eliminate swirls, cross-currents and eddies set up by fittings, valves and elbows upstream (Figure 13). These units are welded into pipe nipples and mounted between companion flanges to form line sections.

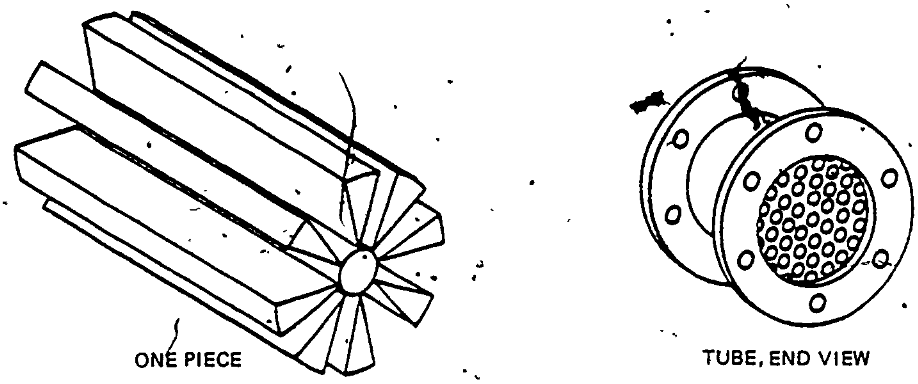


Figure 13. Straightening vanes.

TRANSDUCERS AND TRANSMITTERS

In remote transmission systems, a secondary element (transducer) is considered to include both the transmitter containing the measuring mechanism and the receiver. In effect, the direct mechanical connection of a self-contained secondary element is replaced by a pneumatic or electric position-transmitting mechanism.

The two general classes of measuring mechanisms of differential-pressure transmitters are the motion-balance type and the widely used force-balance type.

In a force-balance system, output is supplied to a pneumatic bellows or electromagnet that opposes the force exerted by the measuring mechanism. In a typical device, sometimes referred to as a D.P. (differential-pressure) cell or a delta-P cell (Figure 14), a change in differential pressure changes the air gap at a nozzle tip, thereby changing nozzle pressure. This change, in turn, is amplified to provide an output signal.

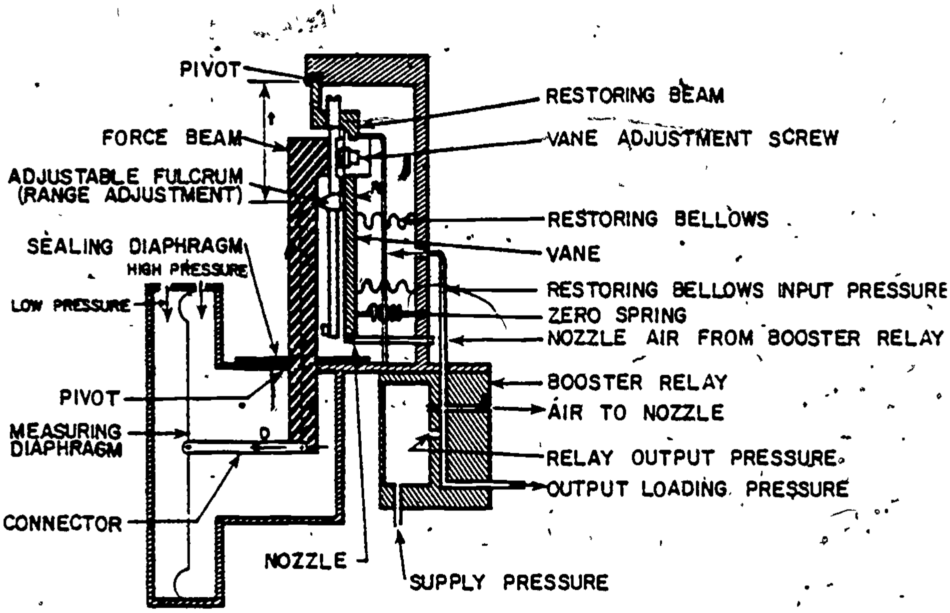


Figure 14. D.P. cell.

CALIBRATION

Commercial differential-pressure flowmeters, generally, are designed according to ASME standards. Vendors calibrate their orifices, nozzles and venturi tubes within their own very sophisticated facilities. On the basis of these calibrations, head-type flowmeters are sold with accompanying specification sheets.

By applying good engineering and installation practices, the flowmeter is then calibrated in place, by using the design data and the specification sheet.

Laboratory calibrations of flowmeters are accomplished through the use of time-related, volumetric accountability of the fluid (direct method). Precision manometers are used to measure differential pressure in conjunction with secondary element output.

TABLE 1

ADVANTAGES AND DISADVANTAGES OF THREE PRINCIPAL PRIMARY ELEMENT TYPES

Advantages	Disadvantages
ORIFICE	
1. Lowest cost 2. Easily installed and/or replaced 3. High predictability of coefficient of discharge 4. Will not wear in service 5. Sharp edge will not foul up with scale or dirt 6. Adjustable type capable of wide range metering	1. Unrecoverable head loss sometimes objectionable 2. Suspended matter may build up on inlet side 3. Maximum capacity may be limited 4. Preferably limited to factors below 1000 psi and 800°F 5. Must be mounted between flanges 6. Installation of orifice and pressure connections must be carefully made
FLOW NOZZLE	
1. Handles 60% greater capacity than orifice 2. Can be welded into pipe line 3. Costs less than Venturi tube but handles same capacities 4. Used when piping layout not suitable for orifice	1. Costs more than orifice 2. Same unrecoverable head loss as orifice 3. Throat may foul up with pipe scale or dirt 4. Pressure connections must be carefully made
VENTURI TUBE	
1. Lowest unrecoverable head loss 2. Pressure connection are integral part of element 3. Requires only short length of straight pipe on inlet side 4. Best suited for measuring solids in suspension 5. Can be welded into line	1. Highest original cost 2. Highest installation costs 3. Not recommended for steam 4. Greatest weight and largest size for given line size

TURBINE FLOWMETER

A turbine flowmeter does not rely on any pressure differential but only upon movement of the fluid. It is one of the most commonly used flowmeters

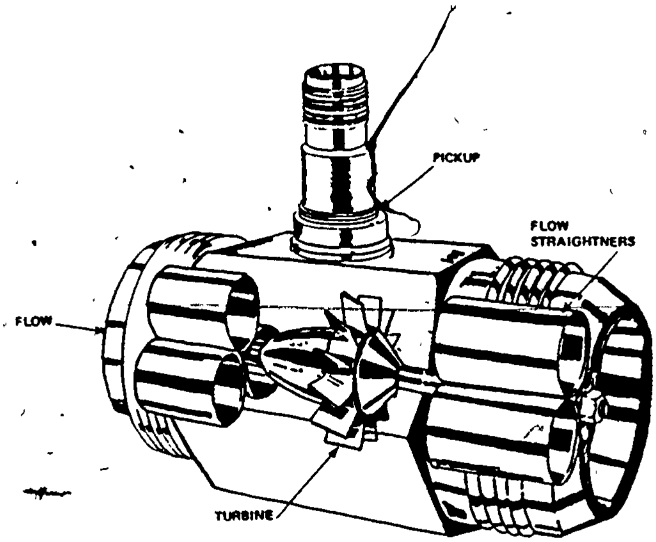


Figure 15. Turbine flowmeter.

in industry and the military. The reason for this is that most turbine meters have an electrical output which makes them useful for providing remote indications while maintaining their accuracy. Due to the type of electrical output that the turbine flowmeter provides, connecting to computerized systems is very easy. (Figure 15)

A turbine flowmeter consists of a straight flow tube containing a turbine or other type of rotor that is free to revolve about the center line of the tube. The speed of rotation of the rotor is directly proportional to the rate of flow of the fluid. The rotation of the rotor is sensed magnetically in such a way that an electrical pulse is generated each time a turbine blade passes a sensor; thus the output frequency of the flowmeter is directly proportional to the rate of flow of the fluid.

Turbine flowmeters are known for their high degree of accuracy. They are linear devices, with good repeatability over wide flow ranges. The major limitation to the use of a turbine flowmeter is that the fluid be clean and noncorrosive, due to physical contact between the rotor and fluid. Pressure losses across the turbine meter can be larger than those experienced with the orifice plate due to the amount of energy being extracted from the system by turning the rotor.

Turbine meter calibration is normally accomplished by inserting the meter into a line where actual flow rate quantities have been determined by a secondary standard. The actual flow quantities are used to calibrate or prepare a calibration curve for the meter under test. A typical calibration loop is shown in block diagram form in Figure 16.

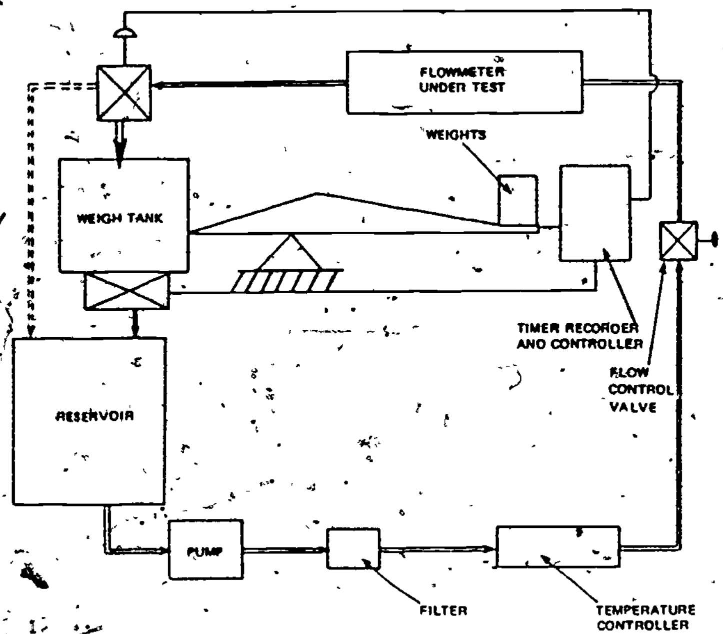


Figure 16. A flowmeter calibration loop.

The calibration loop shown in Figure 16 is known as a dump-weigh system and can be used to calibrate any liquid flowmeter. This system is designed to measure the time interval involved in filling a tank to a preset weight. The system offers the highest degree of accuracy (±0.2%) because both time interval and weight can be measured to very high tolerances, however it is also expensive to construct and operate.

MAGNETIC FLOWMETERS

Magnetic flowmeters are often used in the water and wastewater industry. The operating principal of magnetic flowmeters is based on Faraday's law of induction, that states the following:

> Voltage induced across a conductor as it moves at right angles to a magnetic field is proportional to the velocity of the conductor.

This principle is the basis of operation of generators and alternators. Thus the magnetic flowmeter (Figure 17) is a modified version of an a.c. generator.

A magnetic field (B) in Figure 17 is produced by the magnetic coils. The plane of the magnetic field is perpendicular to the flow axis of the pipe. A disk of flowing fluid with a cross-sectional area equal to that of the pipe moves through the magnetic field and cuts it at a right angle. In accordance with Faraday's law of induction, a voltage is induced into the disc of flowing fluid. The induced voltage (E_S) is the total of all voltage developed within each segment of fluid passing through the magnetic field. This is determined by Equation 12:

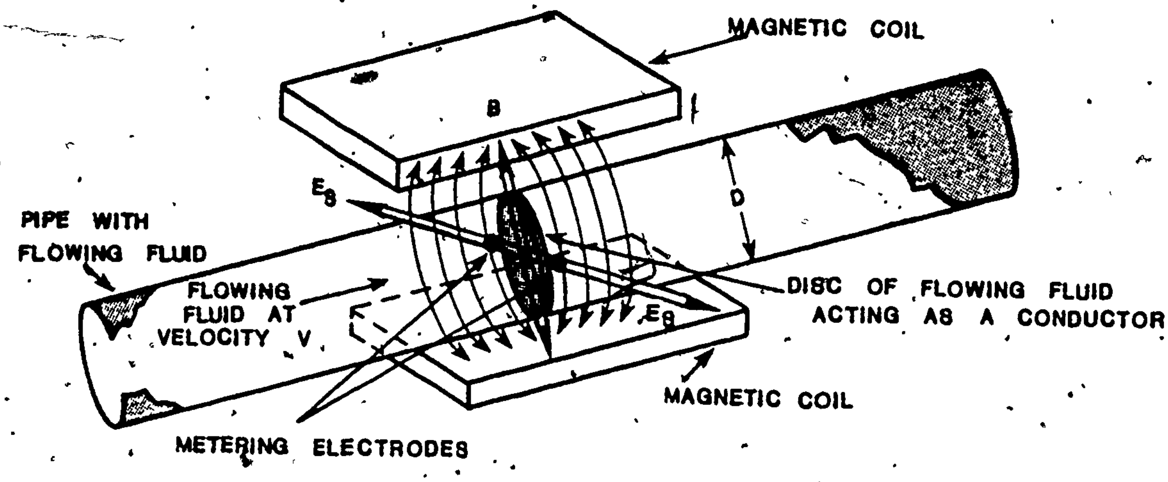


Figure 17. Magnetic flowmeter.

$$E_S = \frac{1}{C} BDV \qquad \text{Equation 12}$$

where: E_S = the induced voltage.
B = the strength of the magnetic field.
D = the diameter of the pipe.
V = velocity.
C = a dimensionless constant.

The flowing fluid through the pipe can be thought of as constituting an infinite series of conductive discs moving through the magnetic field. The greater the flow rate, the greater will be the instantaneous value of signal voltage that is monitored at the meter electrodes.

The field coil is energized by a 60-Hz a.c. signal; thus the induced voltage will have the same frequency. The induced voltage is measured and scaled to represent a flow quantity by the signal conditioner. The signal conditioner is an electronic amplifier system.

The fluid to be measured by magnetic flowmeters must be conductive in the order of 8 to 15 micromhos per centimeter of length. This requirement disqualifies the use of the magnetic flowmeters with petroleum products and some chemicals. The water supply industry is the prime user of the magnetic flowmeter due to the very low nonrecoverable head loss. Care must be exercised to ensure that the fluid passing through the magnetic flowmeter tube does not degrade the performance of the electrodes by corrosion or coating.

The flow tube of the magnetic flowmeter can be mounted either horizontally or vertically as long as the pipe is full of liquid at all times. Fluid characteristics such as viscosity, density, and pressure pose no restrictions on magnetic meter applications.

Calibration of the magnetic flowmeter is simple and does not require the removal of any element from the measurement system. A signal simulating various flow rates is fed into the signal conditioner and adjustments are made at that point so that the readout will agree with the known input.

The relationship between voltage and flow quantity is derived from Equation 12 and shown in Equation 13.

The velocity and flow equation is:

$$V = \frac{Q}{A} = \frac{4\ Q}{\pi D^2}$$

This value of V may be substituted into Equation 11:

$$E_S = \frac{1}{C}(BD)\left(\frac{4\ Q}{\pi D^2}\right)$$

This expression may be solved for Q:

$$Q = \frac{\pi CD}{4}\left(\frac{E_S}{B}\right)$$

as π, C, and D are all constants:

$$Q = K\frac{E_S}{B} \qquad \text{Equation 13}$$

where: Q = a flow quantity.

K = a constant.

E_S and B = the same as explained in Equation 12.

ULTRASONIC FLOWMETER

The final major type of flow measuring device to be discussed in this module is the ultrasonic Doppler-effect flowmeter. The Doppler flowmeter determines the velocity of fluid in a pipe by detecting the frequency change of a signal of ultrasonic frequency that has been injected into the fluid flowing through a pipe. The frequency of the signal is altered by the motion of the fluid in the pipe and is proportional to fluid velocity.

The sensor-transducer utilizes twin piezoelectric crystals that are located in a pipe. One is for transmitting the ultrasonic signal, whereas the other is for detecting the reflected signal.

The principle of operation is based on the Doppler effect which states the following: The frequency of a sound wave is shifted in frequency proportional to the velocity of the medium through which the wave is traveling. The ultrasonic wave injected into the flowing fluid is partially reflected by small bubbles or other particles in the flowing fluid. As the reflectors are traveling at the same velocity as the fluid, the frequency of the reflected wave will be shifted. The frequency of the reflected waveform (Doppler frequency) is a linear function of the flow velocity and the physical characteristics of the flow system that are constant.

Operation of the ultrasonic flowmeter is dependent upon air bubbles or small suspended solids in the liquid. If these are not present, the transmitter signal will not be reflected back to the receiver. Pipes with poor or marginal ultrasonic transmission ability cannot be used with these flowmeters. Concrete pipes or badly corroded metals cannot be used.

The accuracy of flow measurement by ultrasonic flowmeter applications is about 2-5% of full-scale flow values, depending upon calibration and application techniques. There is no pressure drop encountered in this type of flow measurement since there are no obstructions within the flow line.

A major advantage to ultrasonic flowmeters is the relative ease of installation and removal of the sensing and transmitting crystals that are simply attached to the external wall of a pipe. Figure 18 shows an application involving an ultrasonic type of flow measurement.

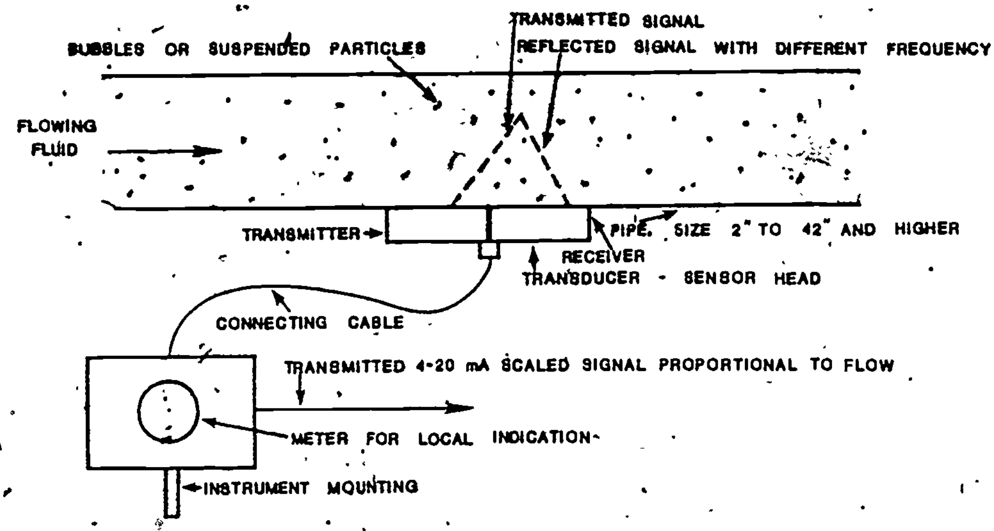


Figure 18. Ultrasonic flowmeter.

The flow measuring techniques discussed in this module are the major types used in modern industrial flow applications. Other types are used, but they are used for special applications and are not of major significance. Several head-type primary devices are used in specific applications, but conform to the general equation used with the orifice meter covered in this module. Open-channel flow measurement techniques employ flumes and wires as head producers and level devices to measure the head loss that is proportional to flow. These are being replaced with magnetic meters in the water industries, but they are still used in industries where it is not convenient to route the flowing fluid through pipes. Pitot tubes, insertion meters, Vortex shedding, positive displacement, and mass flow measurement instruments are used to a limited extent for special applications. The operation of most of these devices is outlined and discussed in the materials designed in the Reference section of this module.

EXERCISES

1. $Q = CA\sqrt{2gh}$ is given as the basic expression for a change in pressure head measured by a head-type flowmeter.
   a. Why is this called a square-root relationship?
   b. If flow rate is doubled and all other variables remain constant, how is pressure head changed?
   c. Identify each function in the above equation.
2. Describe and sketch three principal types of differential-pressure flowmeters; give advantages and disadvantages of each.
3. Sketch and discuss a typical differential-pressure transducer of the force-balance type.
4. Given: 10-inch I.D. stainless steel pipe; average flow of 10 ft/sec of 500°F water; orifice plate $D_0/D_1 = 0.8$.
   Find: Volumetric and mass flow rates.
5. Given: 8-inch (nominal schedule 40) pipe; 70°F water flow; orifice I.D. = 5 inch, Reynolds No. = 3000.
   Find: Differential pressure versus flow (similar to Example A) for the following;
   a. Square-edged orifice.
   b. Venturi tube.
   c. Flow nozzle.

LABORATORY MATERIALS

1 series coupling (orifice plate and venturi tube) in horizontal length with associated scaled (water) manometers and connections at proper tap location. (A commercial classroom apparatus is recommended.)
1 water supply, with variable flow valve and assured constant flow rate.
1 calibrated collection (weighing) tank.
Specification sheet on orifice plate and venturi tube to be used.
Adequate length of straight pipe, upstream from each meter.
1 stopwatch.

If available, this procedure should be performed with a commercial classroom flowmetering device.

1. Assemble orifice plate, venturi tube, piping and manometers as shown in Figure 19. Be sure to follow vendor's instructions.

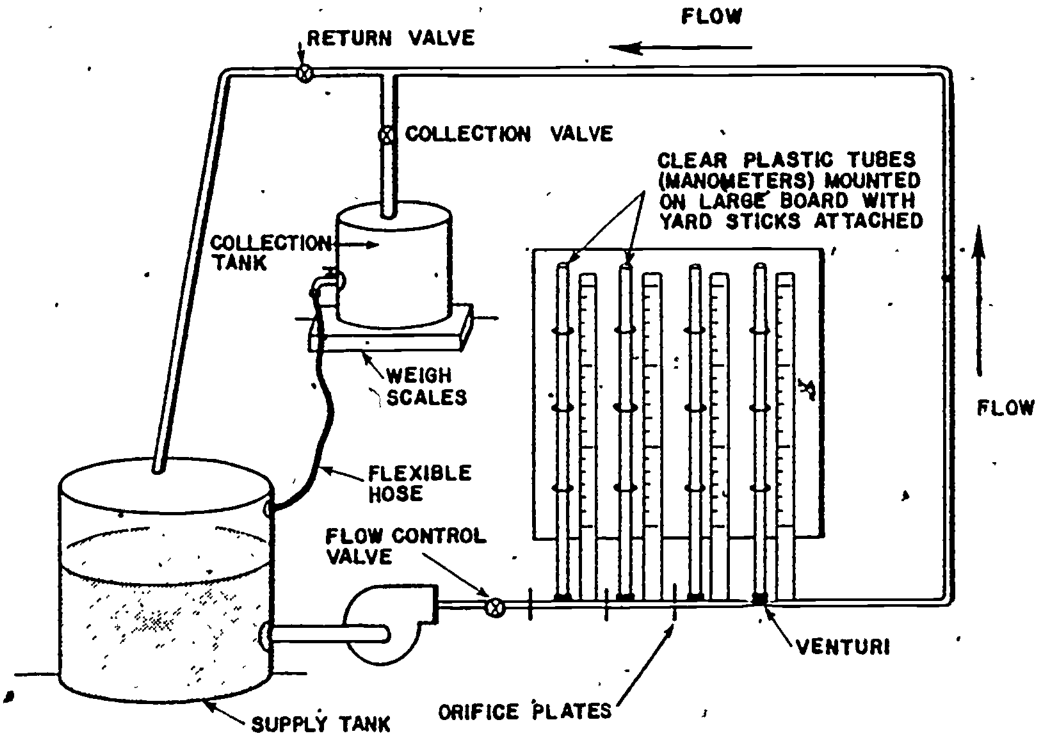


Figure 19. Flowmetering device.

2. Open control valve and return valve; allow water to flow to clear air pockets and sweep out bubbles; close control valve gradually to subject meter to increased pressure; when water level has risen to a convenient height in manometers, close supply valve.
3. Level the manometer water column; open control valve to obtain a reasonably large Δh.
4. Measure pressure drops on meters (take at least 10 readings each); record readings on Data Table 1 (a and b).
5. Note and record pressure losses through metering system.

6. Use vendor-furnished discharge coefficients from specification sheets; calculate flow rates through flowmeters.
7. Explain any differences.

CALIBRATE ORIFICE METER AND DETERMINE ORIFICE COEFFICIENT

1. Arrange orifice meter in manner illustrated above. (Beyond control valve, a flexible hose should lead to a measuring tank.)
2. Admit water from supply valve into meter.
3. To establish orifice coefficient, obtain variations ($h_1 - h_2$) with discharge rate Q: open control and supply valves (to clear out air bubbles and pockets); gradually close control valve to subject meter to increased pressure; when water has risen to convenient heights in manometers, close supply valve; open supply and control valves to obtain flow.
4. Measure the flow rate (collect in weighing tank and take Δh readings); take approximately 10 Δh readings; record readings on Data Table 2; average flow rate.
5. Adjust flow and repeat 4, above.
6. Plot; on the charts provided, a D.P. versus flow curve; calculate orifice coefficient:

$$Q = CA_2 \sqrt{\frac{2g\ (H_1 - h_2)}{[1 - (\frac{A_2}{A_1})^2]}}$$

7. Plot, on charts provided, variation of C with Q.
8. What would be the effect on results if piping were not level?
9. Discuss difference between calculated C and empirical value?

DATA TABLE 1. MEASURE OF ORIFICE AND VENTURI PRESSURE DROPS.

Orifice Plate: I.D. ______ inches, Area _____ sq in, Discharge coefficient C_o = ___________

Venturi Tube: I.D. ______ inches, Area _____ sq in, Discharge coefficient C_v = ___________

Pipe: I.D. _______ inches, Area _______ sq in

Reading No.	A Orifice Meter			B Venturi Meter			% Difference Between A & B
	h_1 (inches)	h_2 (inches)	Q_o (ft^3/sec)	h_1 (inches)	h_2 (inches)	Q_v (ft^3/sec)	
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
Average							

$$\% \text{ Difference between A \& B} = \left| \frac{Q_o - Q_v}{Q_v} \right| \times 100$$

$$\text{Area} = \frac{\pi(\text{I.D.})^2}{4}$$

$$Q = CA_2 \sqrt{\frac{2g\,(h_1 - h_2)}{[1 - (A_2/A_1)^2]}}$$

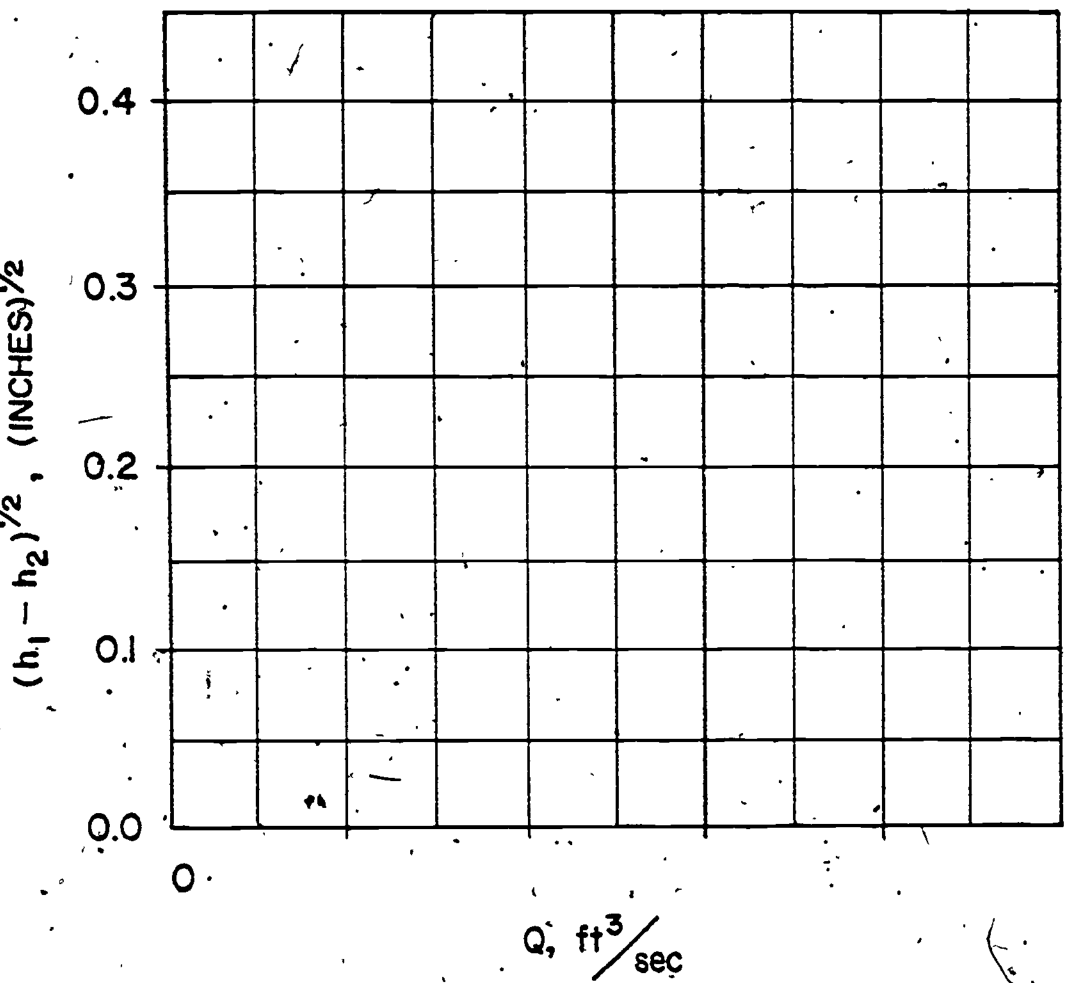
DATA TABLE 2. CALIBRATION OF ORIFICE PLATE.

Orifice Plate I.D. ________ Area ________

Pipe I.D. ________ Area ________

Weight lbf	t sec	h_1 inches	h_2 inches	Q ft^3/sec	$(h_1 - h_2)$ inches	$(h_1 - h_2)^{1/2}$ $(inches)^{1/2}$

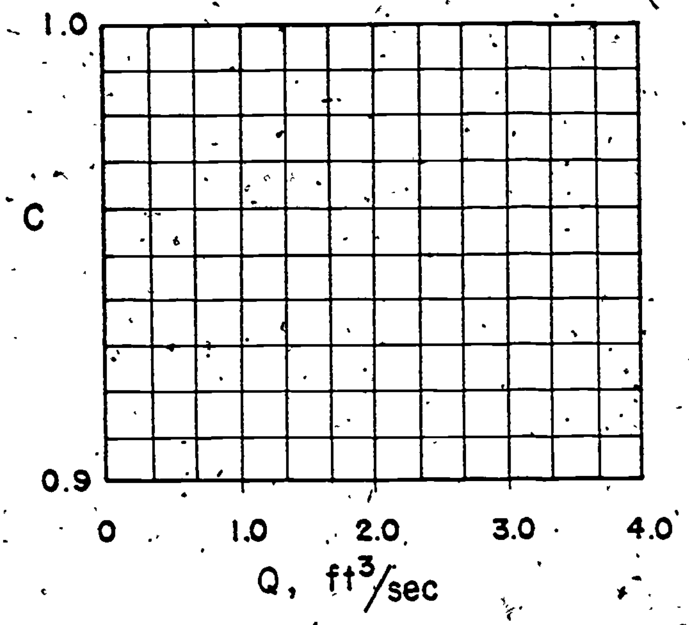
PLOT OF $(h_1 - h_2)^{1/2}$ vs. Q



VALUES OF "C" CALCULATED FROM INDIVIDUAL FLOWS

Q ft^3/sec	$(h_1 - h_2)^{1/2}$ $(inches)^{1/2}$	C

VARIATION OF C WITH Q



TEST

INSTRUMENTATION AND CONTROLS

Module IC-03

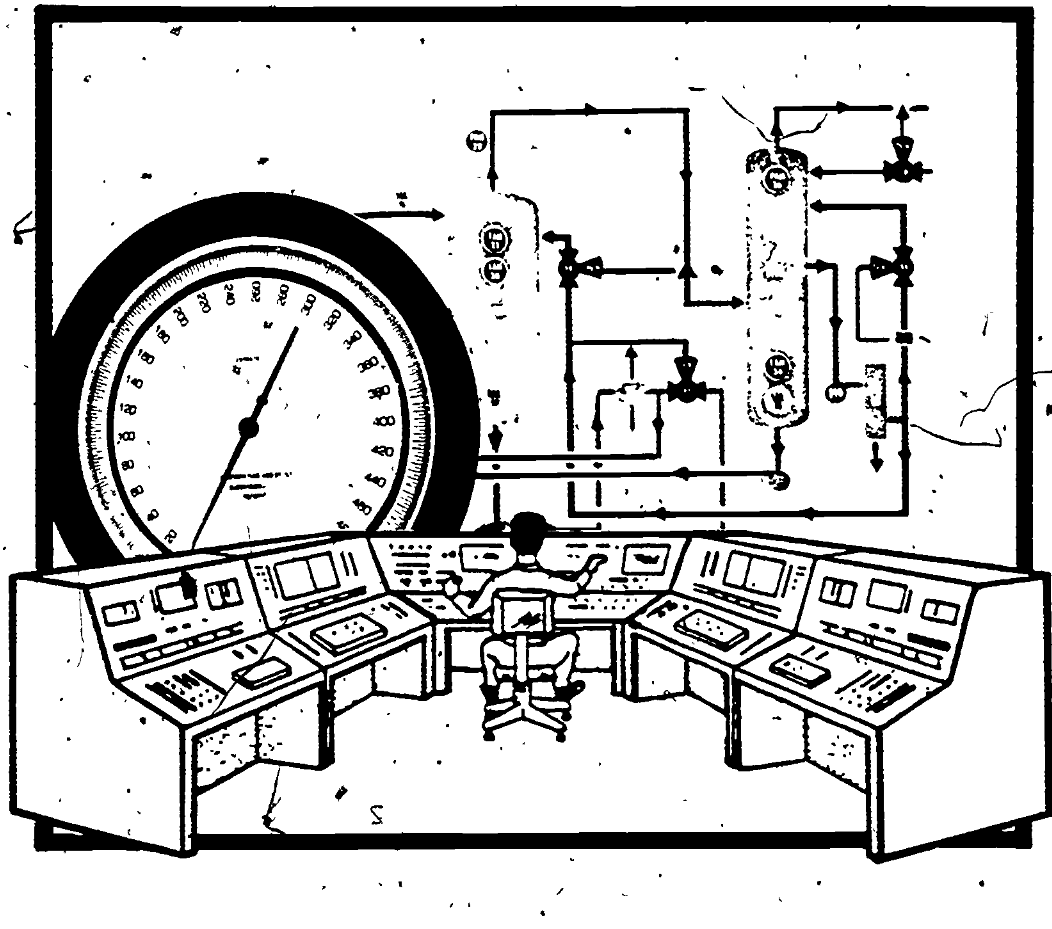
"Fluid Flow Measurement"

1. Define the following, including assigned units where applicable.
   a. Discharge coefficient.
   b. Diameter ratio.
   c. Reynolds number.
   d. Taps.
   e. Throat area.
   f. Streamliners.
2. List and explain operating principles, descriptions, characteristics, and applicability of three differential-pressure sensing flowmeters.
3. Discuss flow measurement secondary elements (transducers).
4. Discuss the hierarchy of flow calibration and standards up to NBS-standards.
5. Relate the hierarchy of flow calibration and standards to the ASME standard design requirements.

ENERGY TECHNOLOGY

CONSERVATION AND USE

INSTRUMENTATION AND CONTROLS



MODULE IC-04

INSTRUMENTS FOR TEMPERATURE MEASUREMENT

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Temperature measurement and control processes are important not only to the process and manufacturing industries, but they have an important effect on everyday life. Automobiles have systems that both monitor and control temperature. Temperature control systems are also present in furnaces, water heaters, stoves, ovens, and other appliances. Most of these applications are based on a few measuring principles that are common to many industrial applications.

A common temperature measurement application includes the expansion and contraction of fluids and metals as a result of temperature variations. The distortion of metal strips and pressure changes of fluids are the result of changes in volume and size that correspond to temperature fluctuations. This process provides the basis of temperature measurement. Changes in electrical quantities that are brought about by corresponding temperature variations also provide the basis of operation for an important class of temperature measuring devices.

PREREQUISITES

The student should have basic understanding of algebra and physics and should have completed Modules IC-01, IC-02, and IC-03 of Instrumentation and Controls.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain the principle of temperature measurement by a filled thermal system.
2. List and define four classes of filled thermal systems.
3. Define the term "inferential measurement" and explain why temperature measurement is based on this principle.

4. Explain the operating principle of the following types of electrical temperature measuring devices:
   a. Thermocouple.
   b. Resistance (RTD).
   c. Optical.
5. List common applications of the above mentioned temperature measuring devices.
6. By use of standard calibrating procedures, explain the means by which calibration is achieved for the devices listed above.
7. List some commonly used temperature scales and explain how they relate to one another.

TEMPERATURE SCALES

Temperature is a quantitative measure of the hotness or coldness of an object. The relative hotness or coldness of an object, as measured by its temperature, simply indicates in which direction heat will flow. Physical laws state that heat will always flow from a hotter body to a colder body, regardless of the masses of the two bodies. Temperature is an indication of the relative amount contained by a body. If a body gets hotter (higher temperature), it has received more heat; if it gets cooler, it has lost heat.

Heat is a form of energy. A hot body has more internal energy than an identical colder body. However, it does not follow that two bodies at the same temperature have the same energy. It is obvious that a cup of sea water does not have near the internal energy of the ocean, even when both are at the same temperature.

Temperature is an arbitrary measure that has been contrived by mankind. Things are judged to be hot or cold as a function of his environment. For example a hot day for a person living in North Dakota might be a cool day for a person living in Texas. Things that have a higher temperature than our body are judged to be warm, while things that have lower temperatures than our body seem to be cool. Relative measure of temperature is unsatisfactory in a technological society, therefore we need quantitative temperature scales.

For a temperature scale to be quantitative we need to be sure that the scale is convenient to use and is capable of being periodically redefined. The need for quantitative temperature measure was recognized in the early 1700s when the first of the four commonly used temperature scales of today were invented. The names and characteristics of the four temperature scales are:

- Centigrade (°C).
- Kelvin (absolute centigrade)(K).
- Fahrenheit (°F).
- Rankine (absolute Fahrenheit)(°R).

Figure 1 is a representation of corresponding points on the four scales.

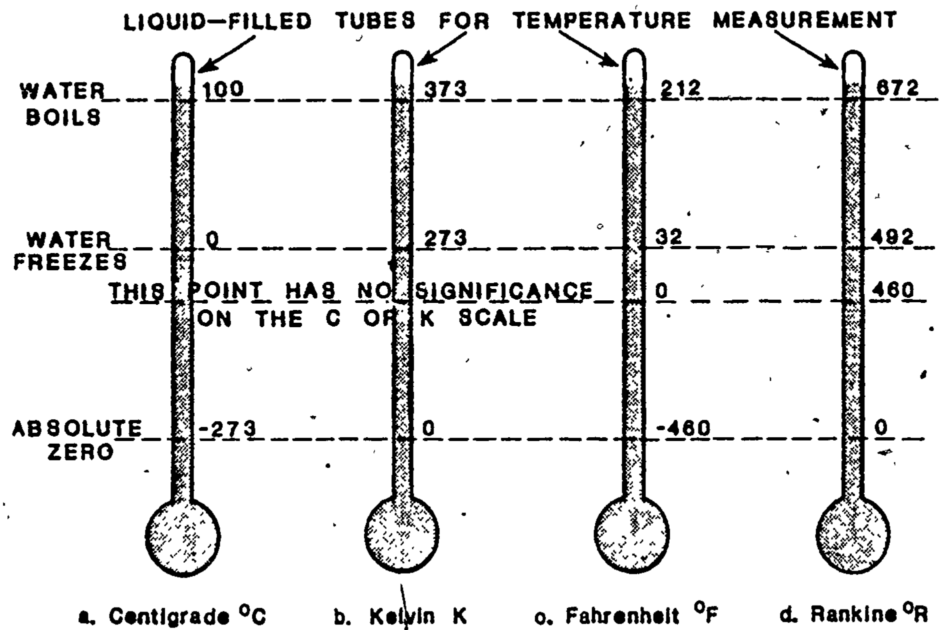


Figure 1. Corresponding points on temperature scales.

As can be seen from Figure 1, temperature conversion from one point to a corresponding point on the absolute scale for another particular scale can be accomplished by adding or subtracting values: 0°C = 273 K and 0°F = 460°R. Therefore, the size of an individual degree on the centigrade scale is equal to a degree on the Kelvin scale. This is also true between the Fahrenheit and Rankine scales. However, conversion between °C and °F is a different matter. The degrees on these scales do not represent the same amount of heat quantity. One hundred degrees on the centigrade scale (100° - 0°) represents the same amount of temperature as 180° (212 - 32) on the Fahrenheit scale, thus 1C° = 1.8F°.* The following equations can be used to convert from one temperature scale to another.

*A convention observed in science and technology is that when the degree symbol (°) preceeds the scale symbol (F, C, or R) that the number represents a position on the scale. If the degree symbol follows the scale symbol then the number represents a temperature interval (difference between the actual temperature values). Thus, 10°F means a temperature measure and 10F° means a temperature difference of 10 degrees between two temperature measures.

$$K = °C + 273 \qquad \text{Equation 1}$$

$$°R = °F + 460 \qquad \text{Equation 2}$$

$$°C = \frac{(°F - 32)}{1.8} \left[= \frac{5}{9}\ (°F - 32)\right] \qquad \text{Equation 3}$$

$$°F = 1.8°C + 32\ \left(= \frac{9}{5}\ °C + 32\right) \qquad \text{Equation 4}$$

EXAMPLE A: CORRESPONDING TEMPERATURES.

Given: The temperature of a material is 40°C.

Find: The corresponding temperature on the other temperature scales.

Solution: From Equation 1:

$$\begin{aligned} K &= °C + 273 \\ &= 40°C + 273 \\ &= 313\ K. \end{aligned}$$

From Equation 4:

$$\begin{aligned} °F &= 1.8\ (°C) + 32 \\ &= 1.8\ (40) + 32 \\ &= 104°F. \end{aligned}$$

From Equation 2:

$$\begin{aligned} °R &= °F + 460 \\ &= 104° + 460 \\ &= 564°R \end{aligned}$$

TEMPERATURE MEASUREMENT

As with most other measurements, the measurement of temperature requires the utliziation of a transducer to change the heat energy of the medium being measured into a more useful form. Transducers for the measurement of temperature are of two broad types: electrical and mechanical.

electrical transducers convert heat energy into electrical energy or electrical properties. Mechanical transducers convert energy into mechanical motion or pressure, which is then converted to motion. Temperature measurement is achieved by inferential means; that is, the measurement results from a secondary effect of temperature.

Temperature is a measurement of the motion or the activity of molecules. The molecular motion, which is directly proportional to temperature, results in some change to the transducer in physical contact with the medium to be measured. The variation in molecular activity results in the transducer response to a temperature variation. The transducer produces energy that initiates a measured response (output) that is scaled and related to temperature.

Temperature measurement in the filled glass tubes (glass thermometers) in Figure 1 results from the change in molecular activity in the liquid in the bulb. An increase in temperature increases the molecular activity in the liquid and causes it to expand or increase its volume. This produces a movement in the liquid surface which infers a corresponding temperature value. Temperature transducers are shown in Figure 2.

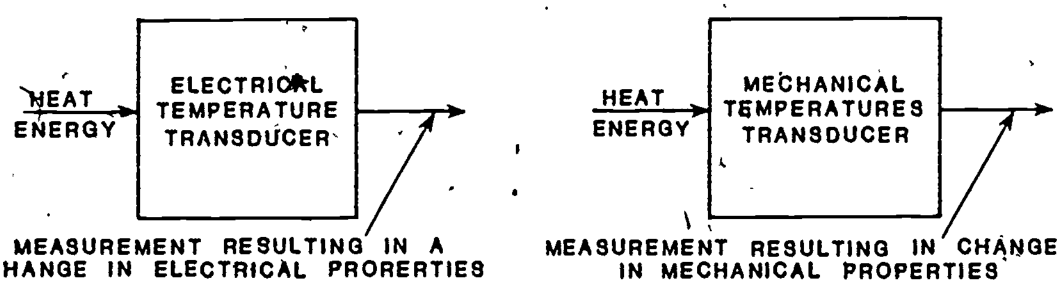


Figure 2. Electrical and mechanical energy transducers.

ELECTRICAL TEMPERATURE TRANSDUCERS

Thermocouples are electrically operated devices capable of measuring temperature a few hundred degrees below zero to several thousand degrees above zero. Thermistor and resistance elements are also used for temperature measurement. They are used with a bridge circuit to measure very small changes in temperature.

Thermocouples

Thermocouples are constructed by connecting two dissimilar metals together and measuring the voltage produced when the ends are at different temperatures. Figure 3 illustrates a thermocouple application. The point at which the two wires are connected is called the measuring, or "hot," junction. The other end of the wires, the point at which the voltage is measured, is called the reference, or "cold," junction. Thermocouples operate on the following principle: A very small voltage is generated when the two junctions are at different temperatures and the voltage is directly proportional to the temperature difference.

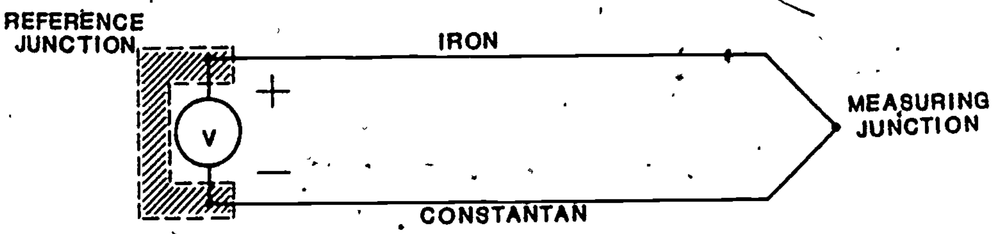


Figure 3. Thermocouple application.

The metal, or metal allow, used for wire construction has an exact relationship between temperature and voltage that is listed in tables supplied by thermocouple manufacturers. Tables are required for EMF-temperature conversion because the relationship is not linear. The amount of voltage generated for a given temperature (EMF/°F) increases with temperature. Typical thermocouple pairs and some of their characteristics are listed in Table 1.

TABLE 1. THERMOCOUPLE PAIRS.

Abbreviations Used In Conversion Tables	ISA Symbol	Conductor Polarity and Color	
		+	-
I/C	J	Iron-white	Constantan-red
C/A	K	Chromel-white	Alumel-red
C/C	T	Copper-blue	Constantan-red
CR/C	E	Chromel-yellow	Constantan-red

Thermocouple tables list the EMF values of different thermocouples with the temperature normally in increments of 5°. For these values, the reference junction is assumed to be at a reference value such as ...

- 32°F or 0°C.
- 75°F or 25°C.

Since the EMF measured at the reference junction is a function of the temperature difference of the two junctions, a change in temperature at either junction is maintained at a constant temperature - 32°F, 25°C, and so forth - in most laboratory applications. However, this practice is not feasible in most process applications. Reference junction temperature compensation is required in most process applications. The need for this will be better understood by the use of Examples B and C:

EXAMPLE B: TEMPERATURE OF MEASURING JUNCTION.	
Given:	The EMF, as measured at the measuring junction of a thermocouple, is 7 mV.
	The thermocouple is type J.
	The reference junction is 25°C.
Find:	The temperature of the measuring junction.
Solution:	Using a thermocouple table based on a 25°C reference temperature, the temperature value corresponding to 7 mV for a type J thermocouple is 155°C.

EXAMPLE C: TEMPERATURE OF MEASURING JUNCTION.	
Given:	The EMF, as measured at the reference junction of a thermocouple, is 8.50 millivolts.
	The thermocouple is a type T.
	The reference junction is at 35°C.
Find:	The true temperature of the measuring junction.

Solution: According to a thermocouple table based on 0°C as the reference a T type thermocouple would have an output of 1.0 millivolts (mV) if its reference junction were at 0°F and its hot junction were at the reference junction temperature of 35°C.

According to procedures recommended by the National Bureau of Standards the correct temperature would be determined by the formula:

$$E_t = E_r + E_m$$

where: E_t = EMF of thermocouple if reference junction is at 0°C and the hot junction is at the measured temperature.

E_r = EMF of thermocouple if reference junction is at 0°C and the hot junction were at the actual reference junction temperature.

E_m = the actual measured output EMF of the thermocouple.

Thus, E_t = (1.0 mV) + (8.5 mV)

= 9.5 mV

and, returning to the same set of reference tables results in finding that 9.5 mV corresponds to an actual hot junction temperature of 204.0°C.

Example C shows how a measurement based on one reference can be changed to another reference. The tables are formulated based on data obtained by maintaining the reference junction at an exact temperature, elevating or decreasing the measuring junction temperature to an exact measured value, and reading and recording the corresponding millivolt value.

The material used to make the thermocouple, the type of insulator used to separate the wires, and the method used to connect the ends that form the measuring junction depend upon the applications. Copper constantan thermocouples are used for temperature ranges of -310°F to 662°F. The mV output is relatively high for this type of thermocouple; but it is erratic at higher temperatures and will suffer from deterioration. Iron constantan is favorable for applications in the lower temperature ranges because it is relatively inexpensive and has excellent output voltage; but it also deteriorates (because of the oxidation of iron) at higher temperatures. Thermocouples made of platinum and a platinum-rhodium alloy have the broadest range (0°C to 1700°C) and are used as a secondary standard in thermocouple calibration. The platinum/platinum-rhodium thermocouple demonstrates the least change of output EMF per degree of temperature over its range. The major disadvantages of this type of thermocouple is that it is expensive and has a EMF output per degree of temperature that is only 1/3 of a type K (chromel/alumel) thermocouple.

Thermocouple Applications

Temperature measurement by thermocouples is a common application in industrial facilities. Figure 4 shows such an application. The thermocouple lead wires are used in such a way that the reference junction is established at the millivolt measuring instrument where electrical reference junction compensation is provided. Thermocouple lead wires can be connected to another material, such as copper wire, if care is taken to see that the same temperature exists at both connections. In modern thermocouple readout instruments the reference junction is unnecessary due to the electrical compensation as shown in Figure 4. Instruments are available that will provide a readout either digitally or by a meter of temperature measurement. For

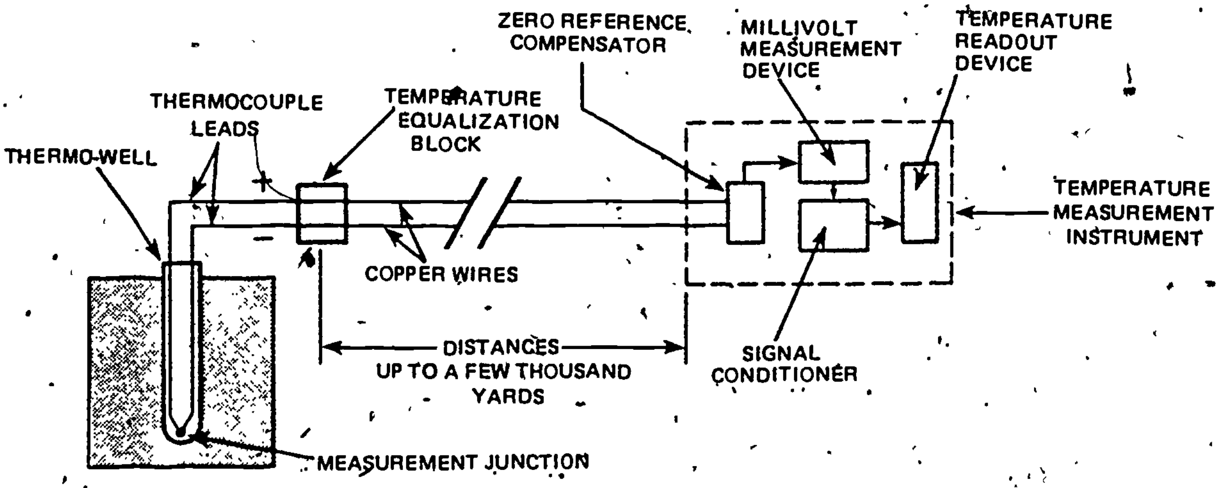


Figure 4. Thermocouple measurement system.

high temperature applications, the thermocouple is constructed from large wire - size 10 or 12. The thermocouple lead wire can be much smaller - size 16 or 18. The larger thermocuple wire size could be connected to the measuring instrument; but the smaller wire size is easier to handle and reduces installation costs.

Read-Out Device (Millivolt Measurement)

Instruments used to measure thermocouple output voltage must be sensitive and acurate with good resolution. The range of millivolt values for 0-400°F, for example, is about 10-15 mV, depending upon the type of thermocouple used. A self-balancing potentiometer has been the most popular millivolt measuring instrument used in industrial applications but is gradually being replaced by other types of electronic measuring devices. The thermocouple measuring instrument must not draw excessive amounts of current from the supply source (the thermocouple) because this could result in voltage drops (IR losses) in the lead wire. This occurrence would present a problem only in small lead wire and for long transmission distances.

Many temperature scales for millivolt measuring thermocouple instruments are slightly nonlinear. This is because the instruments respond linearly with millivolt inputs, and the relationship between temperature and millivolt values are nonlinear.

Thermocouple Reference Junction Compensation

Temperature measurement errors caused by variations in reference junction temperatures, if uncompensated, can be severe if the reference junction temperature approaches the measured value. For a measured temperature range of 100°F, a variation of reference junction temperature of 5° could cause an error in temperature measurement of up to 30% - depending on thermocouple type. For a measured temperature range of 1000°, the same variation in reference junction temperature, with the same thermocouple would be 11%.

Perhaps the simplest means to overcome the error caused by changes in reference junction temperature is to maintain that temperature at the reference value. This is done in some applications, but it is not done in most cases. Instead of this approach, the compensation is done electrically at the measuring instrument.

Special Thermocouple Applications

It is sometimes advantageous to measure a temperature that is the average of two or more values. Thermocouples are connected in a parallel arrangement for this application - a technique which is shown in Figure 5. For the measurement of average temperature (Figure 5), the same type of thermocouples must be used. These thermocouples must be about equal in resistance, and the same size of thermocouple extension wire must be used. Because the resistance of a thermocouple is temperature-dependent, swamping resistors with values that are high compared to the resistance change can be used in the circuit, as shown in Figure 5. Resistance values of about 1500 ohms can be used as swamping resistors.

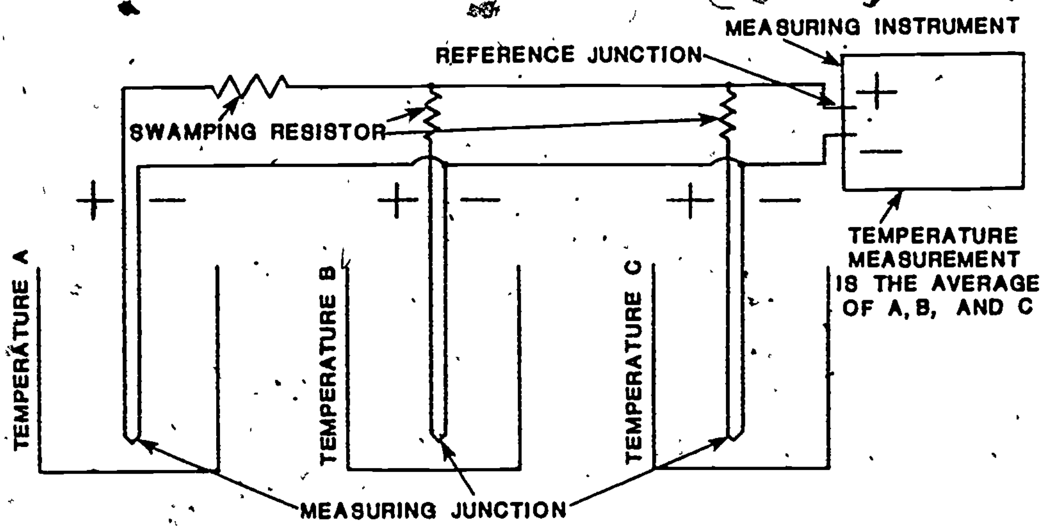


Figure 5. Average temperature measurement with a thermocouple.

Another application involving thermocouples is that of measuring a temperature difference between two values. Thermocouples are connected in series opposition, as shown in Figure 6. Just as with temperature averaging applications, they must be of the same type. The output of one thermocouple is subtracted from the other so that the voltage applied to the measuring instrument is the difference between the two.

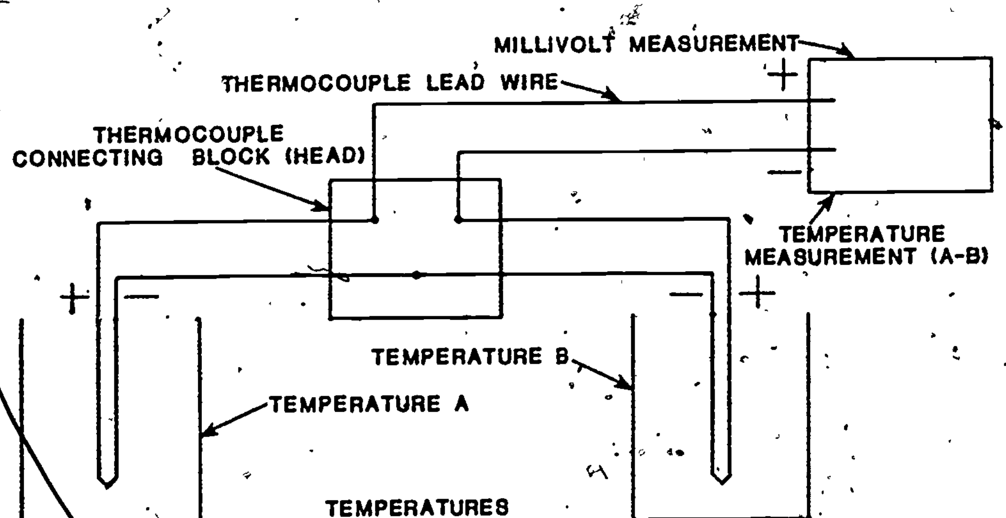


Figure 6. Differential temperature measurement with thermocouples.

RESISTANCE-TEMPERATURE DEVICES (RTD)

Many conductors change resistance when they undergo a change in temperature. This characteristic enables them to be used in temperature measurement. Such devices are called <u>resistance-temperature devices (RTDs)</u>. There are two basic RTD groups - thermistors and conductors.

Thermistors are small semiconductor devices that have a negative temperature-resistance coefficient; that is, their resistance decreases with an increase in temperature. Conductors, on the other hand, increase in resistance values with temperature increases.

RTDs, thermistors, and conductors are commercially available with corresponding curves or tables that give the resistance-temperature characteristics. Temperature values can then be inferred from resistance values. Resistance measurement, using, RTDs, is normally made with Wheatstone bridge circuits. Accurate temperature measurements can be made when using such bridge circuits (Figure 7). Temperature measurements can be made by balancing the bridge with R_3 for a certain value of R_4 corresponding to a temperature. The value of R_4 is then determined by the following formula:

$$R_4 = \frac{R_2}{R_1}(R_3) \qquad \text{Equation 5}$$

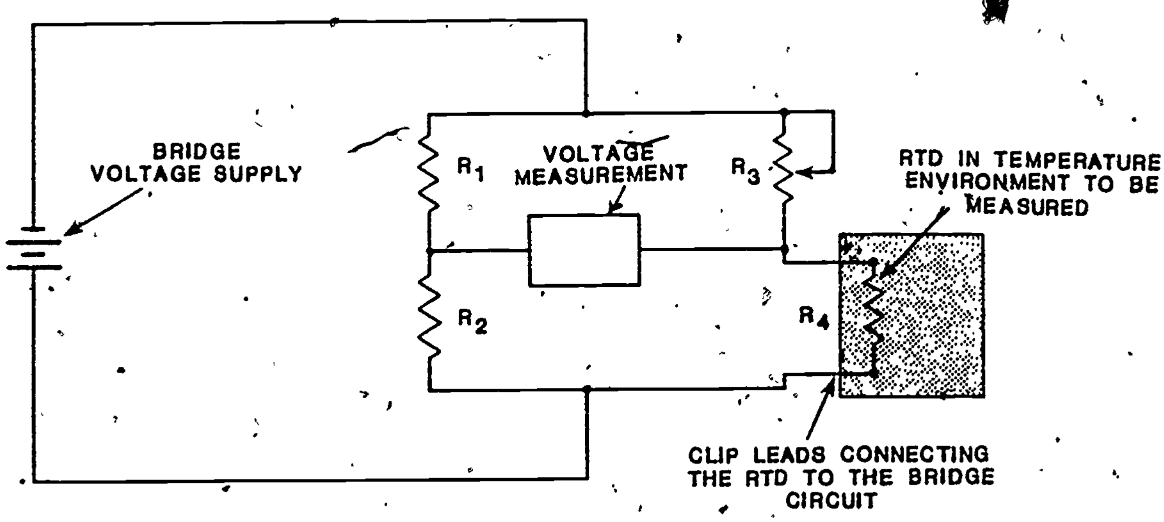


Figure 7. Bridge circuit for temperature measurement with a RTD.

The temperature of R_4 is determined by the use of a resistance-temperature table or curve for the RTD used.

Another, and more common, method of temperature measurement with the circuit shown in Figure 7 is to plot the voltage values of the bridge unbalance caused by corresponding measured temperature values. The scale of the bridge measuring instrument can then be calibrated to read temperature.

OPTICAL TEMPERATURE MEASUREMENT

Electrical and mechanical temperature-measuring devices comprise the bulk of all industrial temperature-measuring systems used in industry. They are used in applications where it is feasible. However, these devices are contact temperature devices, and they must be subjected to the same temperature as that which is to be measured. The upper limit of contact temperature measurement is about 3000°F since, beyond this temperature value, most metals and other materials used as transducers tend to become unstable. For such high temperature applications, noncontact temperature transducers have been developed. The most common is the <u>optical pyrometer</u>.

The principle of operation of optical temperature measurement is based on the relationship between light energy and the wavelength that is a function of the temperature of the object from which the light is emitted. When metals are heated to high temperatures, they emit light in the visible spectrum, beginning with a dull red and progressing through brighter reds to almost white at higher temperatures. In addition, clay, glass, sand, and other solids emit light energy that is not in the visible range. Their wavelengths vary with the temperature of the object.

Optical pyrometers compare the color and brightness of an object with those of a heated tungsten filament. The objective lens forms an image of the hot source in the plane of the filament of an incandescent bulb. The current to the bulb filament is adjusted until the light emitted by the filament is the same color as that emitted by the hot source as detected by the operator. The unknown temperature is then determined by referring to a calibration curve that relates temperature to bulb current or resistance adjusted to produce the current.

It should be understood that the accuracy of the pyrometers, among other factors, depends on the degree to which an exact amount of current in the reference tungsten filament can be measured and controlled. The potentiometric method of current measurement is often used for this purpose. Empirical calibration can also be used. Such a method consists of matching the brightness of the filament against that of a hot substance that has a known temperature.

Optical pyrometers are used to measure high temperatures. Although they are more expensive than many other forms of temperature measurement, their use is justified in many applications. Optical pyrometers were once used strictly for measurement in open-loop control systems; however, closed-loop control devices utilizing optical pyrometers as primary elements are now in use. The accuracy of these devices can approach that of other forms of temperature measurement in higher temperature ranges.

MECHANICAL TEMPERATURE TRANSDUCERS

As previously mentioned, mechanical transducers transform heat energy into mechanical movement or motion. Filled thermal systems are the most common type of mechanical temperature transducer.

The principle of operation of the filled system is based on the change in volume of a fluid that is a result of a change in temperature. The system is sealed with a filled fluid which, when undergoing a temperature variation, produces a volume change caused by expansion or contraction. Figure 8 shows a filled thermal system used for temperature measurement.

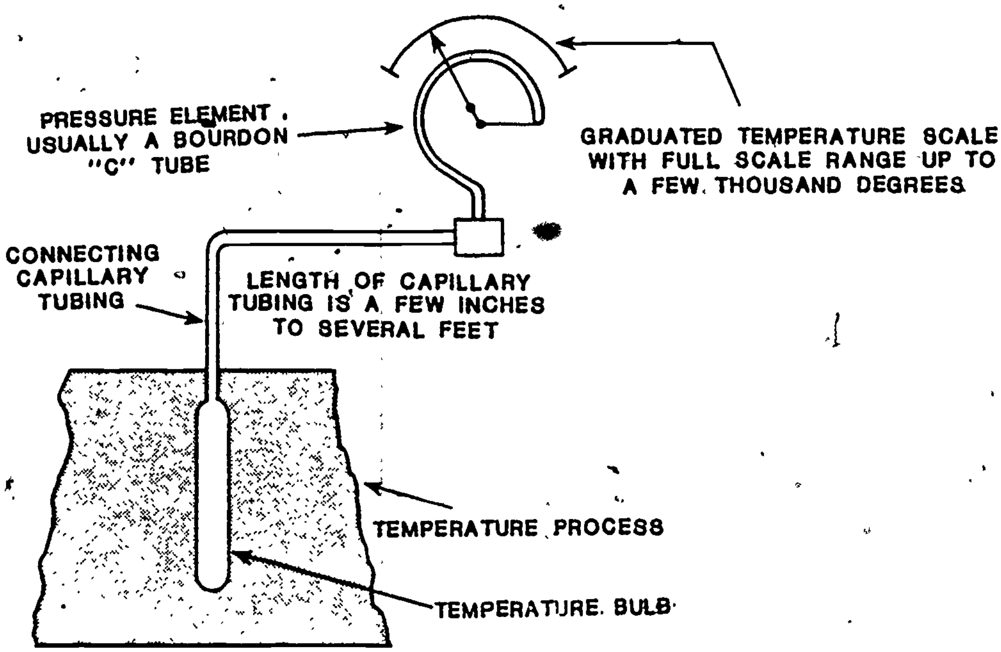


Figure 8. Temperature measurement with a filled thermal system.

FILLED THERMAL SYSTEMS

Filled systems are classified in accordance with the type of fill material that is used. The four general classes are listed below:

- Class I - liquid filled thermometers (except mercury).
- Class II - vapor-pressure thermometers.
- Class III - gas pressure thermometers.
- Class V - mercury filled thermometers.

An earlier system designated Class IV is no longer in use.

The earlier components of a filled thermal system (as shown in Figure 8) consist of the following:

1. A metallic bulb filled with a fluid that undergoes volume or pressure changes in response to temperature changes.
2. Capillary tubing, tubing that has an I.D. $\ll$ O.D., that connects the bulb to the indicating device.
3. An indicating device, usually a pressure element, that produces a scaled measurement in response to the change in temperature at the bulb.
4. Compensating elements to correct for ambient temperature variations.

Filled temperature systems are used in industrial processes because of the many advantages they offer over other temperature-measuring systems. They are easy to manufacture, they require little maintenance, and, while not as accurate as some other devices, they are accurate enough for most industrial processes. A failure in any part of the components, however, renders the complete system inoperative.

The transmission distance, which is limited by the maximum length of the capillary tube to about 100 ft, essentially makes a filled system a remote measuring or controlling device. However, filled systems are used as transducers in trnasmitters when the pressure element is used to generate a scaled signal for transmission. For pneumatic signals, a flapper is positioned in relationship to a nozzle. For electrical transmission, an iron slug is positioned in a LVDT. This application is illustrated by the temperature control system shown in Figure 9 and the block diagram in Figure 10.

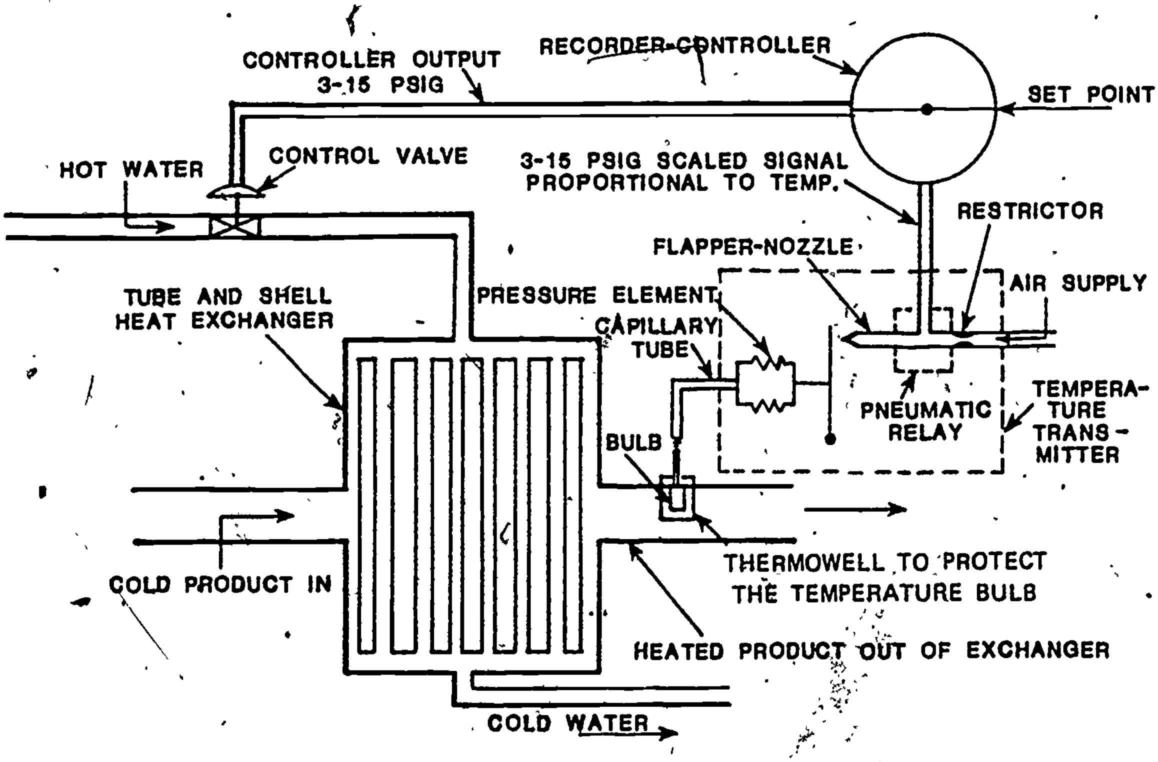


Figure 9. Temperature-controlled process using a filled thermal system as the transducer in the transmitter.

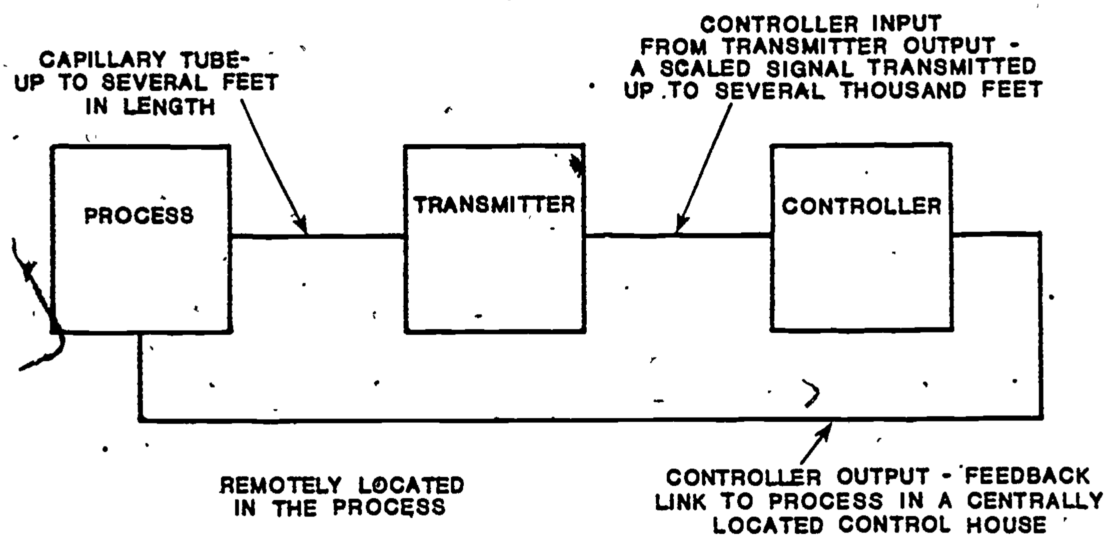


Figure 10. Block diagram of a temperature control system.

Capillary Tubes of the Filled System

The capillary tubes of the filled system are connecting tubes that are usually made of steel or alloy. They are chosen for their inherent characteristics in relation to the fluid used in the system. The temperature bulb and associated pressure element must also be selected for their compatibility with the system fluid. In high temperature applications, pressure inside the tube and bulb may reach a few thousand psig; therefore, a pressure element must be capable of withstanding this pressure. Capillaries must also be selected in accordance with temperature and corresponding pressure ranges. The inside diameter of the capillary tubing is small, usually about 0.025 inches; therefore, the volume of fluid contained within the tube is small compared to that of the bulb.

Error and Compensation in the System

The error introduced into the system by the capillary tubing is caused by both the time lag and the length of the tube exposed to ambient temperature variations. This error can be eliminated, however, when provisions are made to compensate for ambient changes. Two methods of compensation for temperature changes along the capillary tube may be used: case compensation and full compensation.

Case coompensation corrects for temperature variations at the receiving instrument or pressure element only. A temperature change within the case that houses the indicating, receiving, or transmitting instruments usually is the result of variations in the measured temperature as the ambient temperature changes. However, this change is compensated or eliminated by case compensation. Full compensated instruments provide for ambient temperature compensation along the entire length of capillary tubing.

The temperature system shown in Figure 8 is not compensated. Figure 11 shows both a case compensated and a full compensated device. A second capillary tubing is located parallel to the one connected to the bulb for measurement purposes. The two tubes are normally wrapped together in a protecting metal sheath. Both tubes are connected to the pressure element so that the force exerted by each are in opposition and so any element movement will be caused by the bulb only. The compensating tube, which is filled with the same material, is also the same size as the measuring tube.

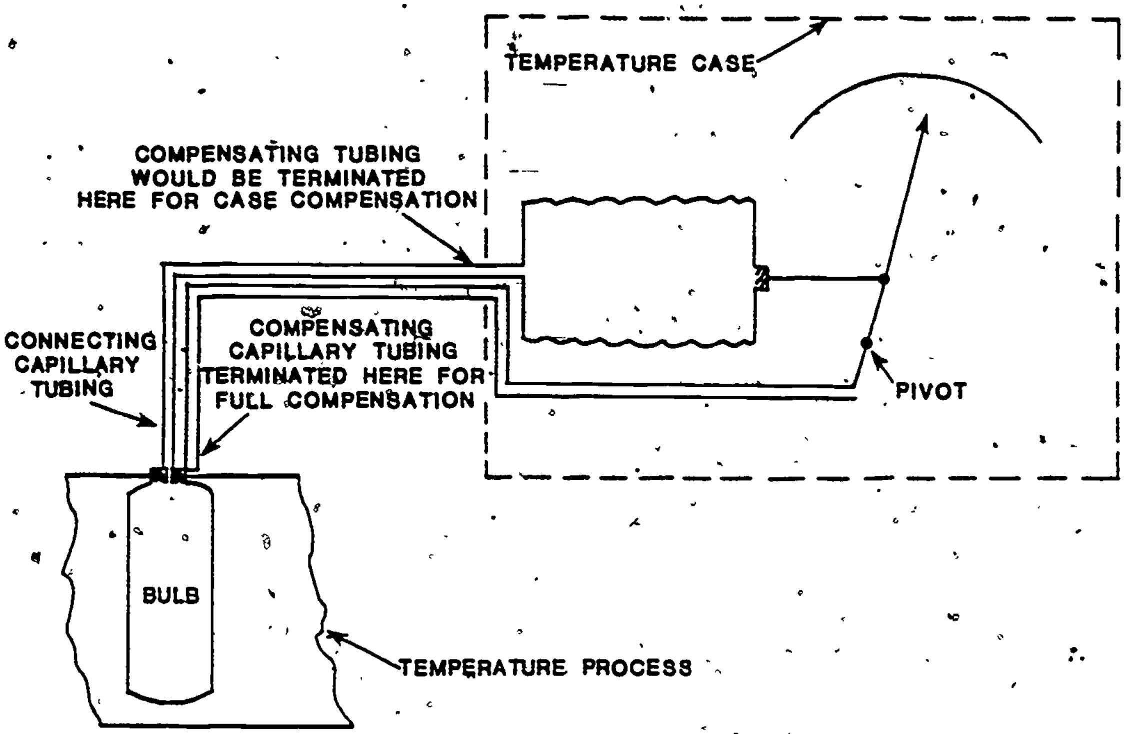


Figure 11. Ambient temperature compensations for filled thermal systems.

Another type of compensation that is used consists of placing a invar wire within the capillary tubing. Invar is a metal that has a negligible coefficient of thermal expansion. Compensation is achieved by the following method: The combined volume of filled material within the tube experiences a change with temperature approximately equal to that experienced by the capillary tube. Therefore, no change in pressure is produced at the pressure element. This type of compensation is used on liquid systems, particularly those that use mercury.

Vapor pressure systems need no capillary compensation. The reason for this is as follows: The vapor pressure of a liquid is a function of temperature, and, as the temperature of a closed system increases, the pressure and quantity of the liquid that is vaporized also increases. A temperature increase on the capillary tube will cause the vapor to expand and will increase the system pressure. However, the increased pressure will also cause some of the vapor to condense, and the pressure on the system is then restored to a value commensurate with the temperature of the liquid in the bulb.

Other sources of error in filled temperature systems are errors in barometric pressure and bulb-elevation. Although these errors are not considered major, one should be aware that they exist. Variations in atmospheric pressure on gas and vapor systems - Classs II and Class III - produce small margins of error and do not significantly affect Class I and Class V systems. Errors caused by barometric pressure usually are less than 0.4%.

Bulb elevation errors affect Classes I, II, and V systems since pressure is exerted on the pressure element as a result of the volume of liquid in the tube and bulb. Such errors are proportional to the density of the filled liquid and to the degree to which the fluid will expand. They are also inversely proportional the the range span. Errors of this type are not significant in Class I systems - unless the bulb is elevated several feet above the pressure element in the case. Bulb elevation is significant in Class V systems because of the high density of mercury. Once elevation is established, however, the error can be compensated by the zero adjustment of the instrument.

Vapor systems - Class II - are further dividied into four groups: A, B, C, and D. Class II-A instruments are designed to measure temperatures that are consistently above ambient; Class II-B instruments are used to measure temperatures that are consistently below ambient. Class II-C and Class II-D instruments are used for temperature measurements that cross ambient. Although Class II-C is similar to Class II-A, it has a larger bulb. When measuring temperatures lower than ambient, all of the liquid will be present in the bulb. The bulb must be large enough to contain the liquid and still have room for a vapor space. When temperature variations across ambient are regular, Class II-C should not be used since erratic action and delay in temperature indications will result. Class II-D instruments should be used when temperature measurements regularly cross ambient. The pressure element and capillary tube are always filled with liquid, and a small amount of vapor is trapped in the bulb. Table 2 shows the various Classes of filled systems, as well as some of their characteristics.

TABLE 2. CLASSES OF FILLED SYSTEMS.

System	Minimum Temperature	Maximum Temperature	Advantages	Disadvantages
Class I (Liquid)	-300°F	700°F	Linear scale small bulb.	Requires full compensation, elevation error.
Class II (Vapor)	-300°F	650°F	Low cost, fast response, no compensation required.	Nonlinear scale, elevation error, erratic response at ambient temperatures.
Class III (Gas)	-450°F	1400°F	Linear scale, temperature capability, withstands overrange.	Large bulb required.
Class V (Mercury)	- 60°F	1200°F	Linear scale, small bulb.	Same as Class I.

BIMETALLIC ELEMENTS

The bimetallic strip is a reliable form of temperature measurement. Though used very little in process temperature systems, bimetallic strips are used in many applications of local temperature indication, ON-OFF control, and alarm devices. They operate on the principle of thermal expansion. As shown in Figure 12, bimetallic devices consist of two connecting strips of metal that have different coefficients of thermal expansion. The different rates of thermal expansion cause a movement at the free end, and this movement is used to drive a pointer on an indicator or move a contact on an electrical switch.

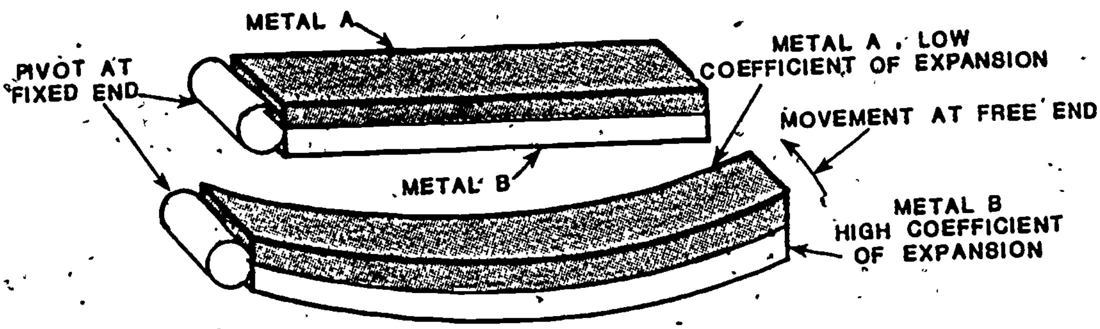


Figure 12. Bimetal elements.

For a particular value of temperature, the bimetal element will be flat and straight; however, because of the dissimilar thermal expansion coefficient of the two metals, temperature variations will cause the strip to bend into an arc. The bending is caused by the expansion of the two metals in accordance with their particular characteristics. One strip will expand to a greater length than the other.

The amount of movement at the free end resulting from temperatures variations is a function of the following characteristics:

- Temperature of element (directly proportional).
- Length of element (directly proportional).
- Thickness of element (inversely proportional).

From the above characteristics, one can assume a long thin strip will produce more movement for a given change in temperature. To obtain more sensitive elements, bimetallic elements are wound in forms of spirals, or helicals, similar to pressure elements.

Most thermometers made of bimetal elements have uniform scales. However, these elements do not have uniform movement over wide ranges of temperature. For temperature ranges up to about 400°F, the nonlinearity is not great; therefore, farily accurate temperature measurements can be made with uniform scales. The limit of the range of temperature measurement made with bimetallic elements is from -300°F to 1000°F. At very low temperatures, the rate of deflection with temperature change decreases sharply because the coefficients of thermal expansion of the two metals approach a common value.

The accuracy of bimetallic thermometers is not perfect, but it is acceptable for indicating purposes. These thermometers are rugged and capable of withstanding over-ranging of up to 100% without damage. Figure 13 shows a two-position control application using a bimetal element.

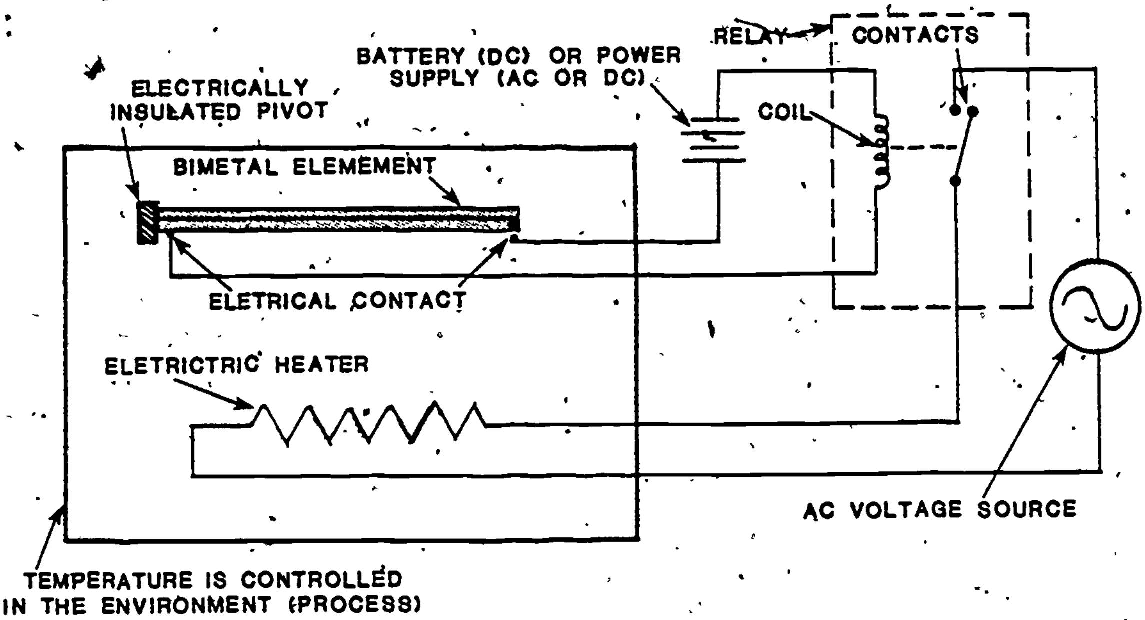


Figure 13. A temperature controlled process using a bimetal strip.

When the strip is in the flat position as shown, the temperature is low; more heat should then be applied to the temperature process. The bimetallic strip provides a path for current to flow from the a.c. voltage source through the heater that heats the process. When the process is heated to the desired value, the heat will cause the bimetal strip to curve, thereby opening the contact, de-energizing the relay, opening the relay contacts, and stopping the current flow through the heater. When the temperature decreases, the contacts on the bimetal strip closes, and the series of events described above are repeated.

The purpose of the relay shown in the circuit in Figure 13 is to decrease the amount of current traveling through the strip and to its contacts. Without the relay, for large current capabilities, the strip and contact would have to be large enough to operate the heavier contact, thereby reducing the sensitivity of the strip. The sensitivity is inversely proportional to the thickness of the element. A spring or proximity bias arrangement is used to vary the operating temperature (setpoint).

Control circuits like the one shown in Figure 13 are used in home and industrial applications. Most heating and cooling thermostats are based on this operation. The relay normally is not needed in most heating controls circuits since the current required to operate a small solenoid operated valve can be passed through the bimetal strip or through a wire connected to the contact points on the strip. Air conditioning thermostat operation requires the utilization of the relay because of the large current required to operate air conditioning compressors. Industrial bimetal control circuits are limited to processes that can be controlled by two-position or ON-OFF control since proportioning cannot be accomplished by such control circuits.

EXERCISES

1. Make the following temperature scale conversions:
   a. 308°F to °C.
   b. 0 K to °R.
   c. 450°C to °F.
   d. 165°F to °R.
   e. 140°C to K.
2. Using a standard thermocouple calibration table, make the following EMF-temperature conversions:
   a. A type J thermocouple reference junction is 100°F. The measuring junction temperature is 360°F. What is the voltage output?
   b. The voltage output of a type K thermocouple is 5.70 mV. The reference junction temperature is 75°F. What is the temperature of the measuring junction?
3. A bridge circuit similar to the one shown in Figure 7 has the following resistance values: $R_1 = R_2 = 1000$ ohms. R_3 is 500 ohms, and the bridge is balanced. What is the value of R_4?

LABORATORY MATERIALS

A glass thermometer capable of temperature measurement in the 0-400°F range with 2° resolution.

Four feet of type J thermocouple lead wire.

A voltmeter with 0.02-mV resolution on a scale that will measure 50 mV full-scale.

A RTD with a temperature-resistance calibration curve.

A 10-V d.c. power supply.

Two 5000-ohm precision resistors with 1% tolerance with a power rating of one watt.

One 0-5000 ohm wire wound potentiometer with 1% tolerance.

An ohmmeter with one ohm resolution on the R x 10 ohm scale.

1 gallon nonconductive light-weight oil.

A hot water supply up to about 200°F.

Two 30-inch clip leads.

1 quart of ice.

LABORATORY PROCEDURES

LABORATORY 1. TEMPERATURE MEASUREMENT WITH A THERMOCOUPLE.

1. Make a thermocouple by removing the insulation from about 1 1/2" of each end of each wire in the thermocouple pair and tightly twisting the two wires of either end together. This will be a measuring junction.
2. Observing polarity, connect each end of the open end to the voltmeter. This end is the reference junction.
3. With the reference junction and measuring junction at the same temperature, measure the voltage at the reference junction. Note this reading for further explanation. Blow on the measuring junction and note the response of the voltmeter.
4. Immerse the measuring junction in a beaker of water slightly above the reference junction temperature.

5. Measure the temperature of the water by reading the millivolt (mV) value at the reference junction with the voltmeter and the temperature of the reference junction with the glass thermometer. Convert the temperature of the reference junction to a mV value by use of the calibration table. Make certain that the columns on the table correspond to the type of thermocouple used.
6. Add the mV value corresponding to the reference junction temperature from that of the measuring junction temperature. This compensates for the reference junction temperature. If a table referenced to 75°F is used and the temperature of the reference junction temperature is about 75°F, the mV value for the reference junction temperature is 0.
7. Convert the mV value obtained in Step 6 to a temperature value by using the tables.
8. The temperature obtained in Step 7 is the temperature of the measuring junction. Record this value in Data Table 1 (Measured Value of Temperature A).
9. Measure the temperature of the water with the glass thermometer and record this in Data Table 1 (Actual Value of Temperature A).
10. Add some heated water to the water being measured to elevate the temperature.
11. Repeat Steps 5 through 9 and record the value in Data Table 1 (Temperature B).
12. Repeat Step 10.
13. Repeat Steps 5 through 9 and record the value in Data Table 1 (Temperature C).
14. Immerse the measuring junction in ice water.
15. Measure the voltage at the reference junction. Note the voltage value for further discussion and explanation.
16. Repeat Steps 5 through 9 and record this value in Data Table 1 (Temperature D).

LABORATORY 2. TEMPERATURE MEASUREMENT WITH AN RTD.

1. Connect a bridge circuit, as shown in Figure 7, with the following resistance values:
   a. $R_1 = R_2$ 25000 ohms.
   b. R_3 = 0-5000 ohm variable resistor.
   c. R_4 = an RTD.
2. Connect the mV meter and bridge power supply to the bridge circuit.
3. Turn on the bridge supply and adjust R_3 for the bridge balance as indicated by a zero reading on the voltmeter on the most sensitive scale. R_4 is at ambient temperature. Measure the value with the glass thermometer and record it in Data Table 2.
4. Blow on the RTD or fan it with a piece of paper. Note the response of the voltmeter.
5. Immerse the RTD in the nonconductive fluid at the same temperature (ambient) as the other components.
6. Slightly increase the temperature of the nonconduction fluid by mixing it with hotter fluid.
7. Measure the temperature with the glass thermometer and record it in the table under Temperature A.
8. Measure the mV value read on the voltmeter and record it in Data Table 2 (Millivolt-Temperature A).
9. Repeat Steps 6 through 8 and record the values under B in Data Table 2.
10. Repeat Step 9 until the table is complete.
11. Make a plot (on graph paper) of temperature versus the measured millivolt value.
12. This completes the Laboratory section of this module. Secure all equipment.

DATA TABLES

DATA TABLE 1. ACCURACY OF THERMOCOUPLE TEMPERATURE MEASUREMENT.

	Measured Value	Actual Value
Temperature A		
Temperature B		
Temperature C		
Temperature D		

DATA TABLE 2. ACCURACY OF RTD TEMPERATURE MEASUREMENT.

	Measured Value	Millivolt
Ambient Temperature		
Temperature A		
Temperature B		
Temperature C		
Temperature D		

REFERENCES

Anderson, Norman A. Instrumentation for Process Measurement and Control. 2nd ed. Philadelphia, PA: Chilton Co., 1972.

Woodruff, John. Basic Instrumentation. 2nd ed. Austin, TX: University of Texas, 1964.

GLOSSARY

Filled thermal system: Temperature measurement based on a volumetric or pressure change of a fluid.

Inferential measurement: A nondirect means of measurement that is based on the measured value of a related variable.

Optical pryometer: A noncontact form of temperature measurement based on the relationship between a heated object and the frequency of the electron magnetic energy it emits.

Resistance temperature devices (RTD): A device that changes resistance with temperature. The relationship between temperature and resistance when previously established is a basis for temperature measurement.

Temperature transducer: A device that converts heat energy to mechanical or electrical energy in a form that can be measured.

Thermocouple: Two dissimilar metals joined together at one end and producing a voltage at the other end which is proportional to the temperature difference in the two ends (junctions).

TEST

INSTRUMENTATION AND CONTROLS

Module IC-04

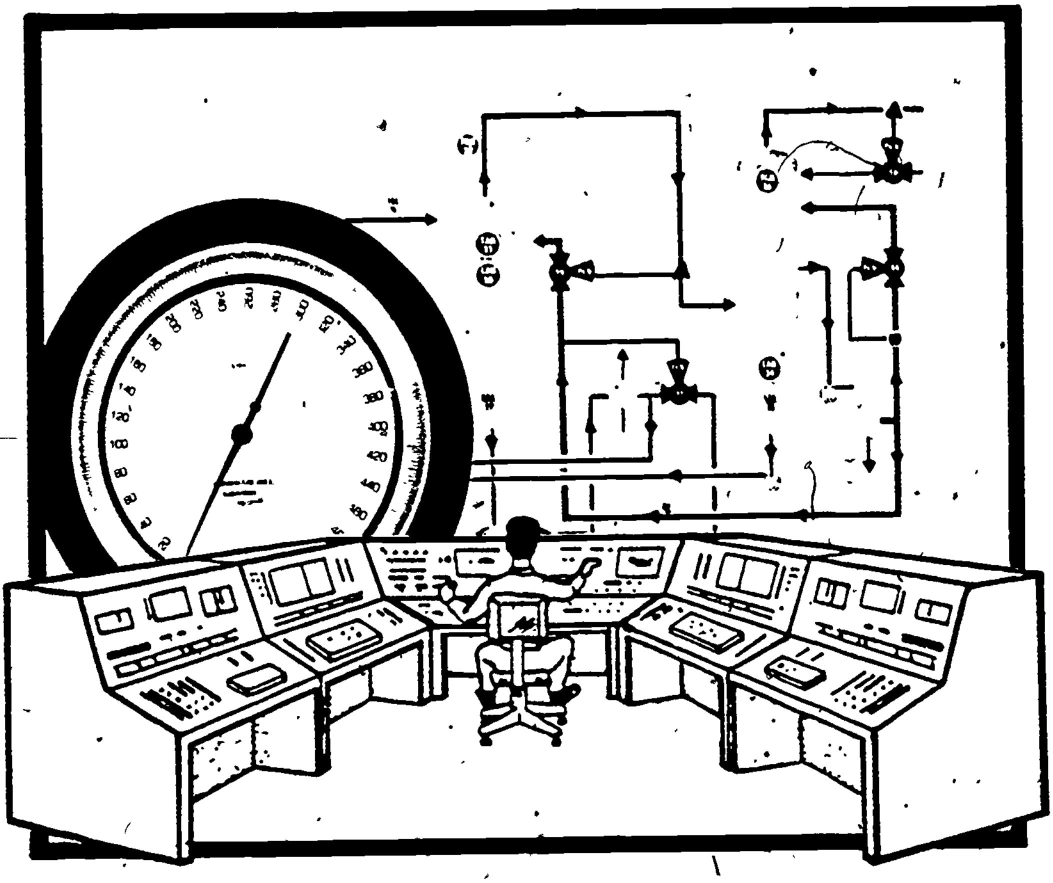
"Instruments for Temperature Measurement"

1. Most temperature measurements are ____________________ values.
2. Three different methods of temperature measurement are.
3. The thermocouple junction in the temperature environment to be measured is the _____________ junction.
4. The thermocouple junction in the controlled environment or at the measuring instrument is the _______________ junction.
5. When both junctions of a thermocouple are the same temperature, the thermocouple output voltage is ____________________.
6. Two methods of reference junction compensation are.
7. The relationship between millivolts and temperature is ______________ (linear or nonlinear).
8. An RTD temperature measuring system is normally ____________________ (more or less) sensitive than a thermocouple application.
9. A device used in many ON-OFF control and alarm applications is a _____.
10. Filled thermal systems are categorized by the ______________________.
11. A noncontact temperature-measuring device is ______________________.

ENERGY TECHNOLOGY

CONSERVATION AND USE

INSTRUMENTATION AND CONTROLS



MODULE IC-05

INSTRUMENTS FOR MECHANICAL MEASUREMENT

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

In the design and operation of any control system it is necessary to measure the variable to be controlled in a process or system. The controlled variable may be pressure, force, temperature, or length or the process variable may be proportional to one of these (such as velocity or flow rate). Measurement of these variables is accomplished by using devices known as transducers.

Transducers convert an input signal containing information in one energy form into an output signal containing the same information in another energy form. Thus, the condition of the process or system found in the pressure, force, temperature, or length can be transferred into electrical or pneumatic signals. Information contained in the output signals of the transducer tells the status of the process and provides the basis upon which decisions affecting that process are made.

Without transducers (or measurement) it would be impossible to accurately or automatically control any process or system. Thus, an understanding of transducers, and their operation and construction, is important to the technician who must operate, repair, or inspect control systems.

PREREQUISITES

The student should have a basic understanding of algebra and physics and should have completed Modules IC-01 through IC-04 of Instrumentation and Controls.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
   a. Force.
   b. Motion.

c. Transducer.
d. Sensor.
e. Scaled signal.
f. Measured variable.

2. Explain the use and operation of the following devices:
   a. Potentiometer:
      (1) Linear.
      (2) Rotary.
   b. Inductor:
      (1) Linear.
      (2) Rotary.
   c. Linear variable differential transformer.
   d. Synchromechanism.
   e. Flyball governor.
   f. Strain gage.

3. Explain how the devices in Objective 2 above can be used to make the following measurements:
   a. Displacement:
      (1) Linear.
      (2) Angular.
   b. Velocity.
   c. Force.

CONTROL PRINCIPLES

The success of a control system is, to a large extent, based on the detection and measurement of force and motion resulting from force quantities. This is true in both open-loop and closed-loop control systems. Many of the components in the control system shown in Figure 1 perform functions based on transducer operations. The measuring means employes a transducer that is physically connected to the process, producing a force of motion as a result of a variation in the process condition. The transducer output is used to generate a scaled signal that is transmitted to the controller. This signal is compared with a standard signal (setpoint equivalent) by the error detection instruments. Then the controller generates a change in an output signal transmitted to the final control element. The final control element usually is a valve that is positioned via a transducer by the controller output to regulate the energy and/or the material entering or leaving the process for the purpose of maintaining a desired process value.

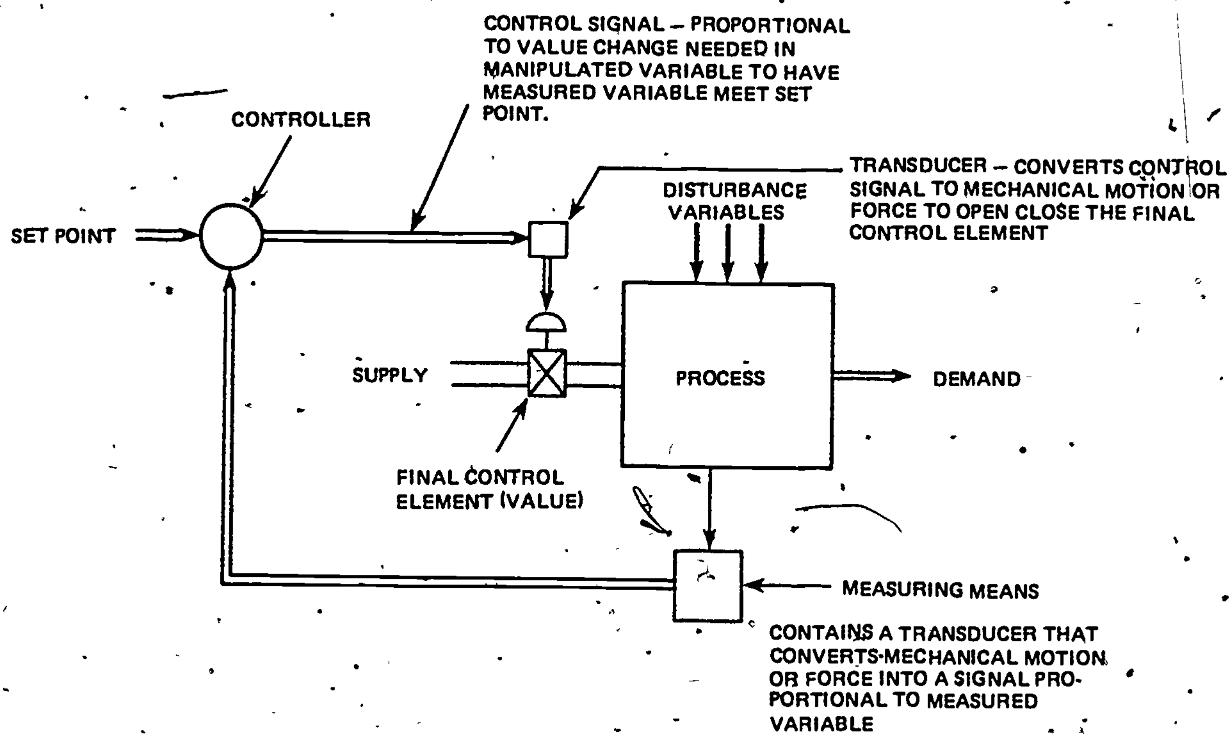


Figure 1. A closed-loop control system showing transducer utilization.

TRANSDUCERS AND TRANSMITTERS

The number and types of transducers used in a control system will vary somewhat with certain applications. However, it is often necessary to convert a process measurement to a mechanical motion and then transform that mechanical motion to an indication or scaled transmitted signal representative of a process condition. Another function of a transducer is to convert one signal proportionally to another type of signal.

Although the two terms are often used interchangeably, technically there is a difference between a transducer and a transmitter (sensor). The transducer is physically connected to the system and produces a response to a variance in the process variable. The transmitter converts this response into an input signal to the controller that is proportional to the value of the process variable. The block diagram in Figure 2 illustrates this function. Many transmitters, especially those of the mechanical type, use a transducer as the input to the transmitter to convert the force to movement. The movement is then used to generate an output signal.

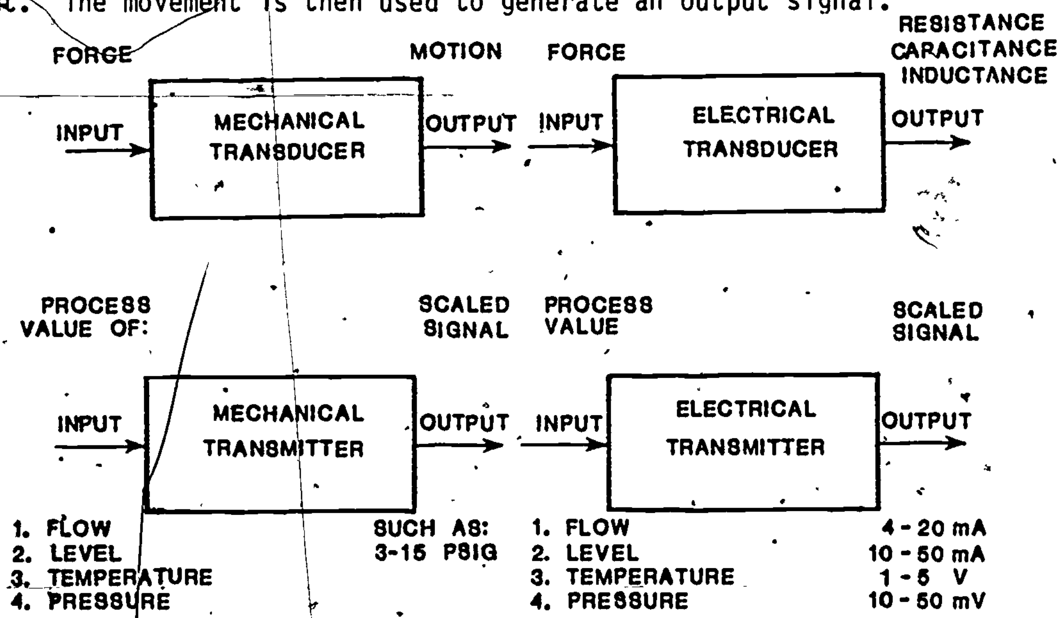


Figure 2. Block diagram of transducers and transmitters.

Transmitters normally are classified according to their function, application, and type. For example, a level transmitter could be a differential pressure-measuring instrument used to measure level and liquid head and to transmit an electrical signal of 4-20 mA. Nothing in the specifications listed gives any details of the means by which the hydrostatic head pressure produces the transmitted signal. This information would be specified by the types of transducers used - which may be a pressure element combined with a variable resistor, inductor, and so forth.

Unless otherwise stated, it will be assumed in this discussion that the movement for the various types of transducers is produced by pressure elements. This concept was previously covered in Module IC-02 of this course. However, a review of that concept is recommended.

MOTION DETECTORS - LINEAR

Motion detectors are used to produce a response to the movement from a pressure element that, in turn, can be used to generate an indication or signal relating to a measured value. Although several different categories can be used to classify motion detectors, they will be referred to in this discussion as either linear or rotary. Linear motion detectors are perhaps the simplest of all types. They are also referred to as displacement transducers when displacement is considered to be a change in movement or position.

Linear Potentiometer - A Linear Motion to Electrical Transducers

The linear potentiometer consists of a slide (or wiper), which is a movable contact that slides across a resistance element. The variable resistance that is a function of the contact arm position produces an electrical signal proportional to mechanical displacement. By the choice of electrical connection, as shown in Figure 3, resistance value can increase or decrease for a given direction of movement. The resolution that defines the relationship between the amount of resistance change with respect to displacment is determined by the spacing of the turns of wire for the wire-wound type of resistors. The resolution of film-type elements is dependent upon the amount of contact friction between a contact wiper and film resistor. When a larger capacity is required, the contact and resistance material must be of rugged construction, thereby requiring a substantial operating force. For most measurement and control applications, the electrical signal level is low and the operating force needed is small.

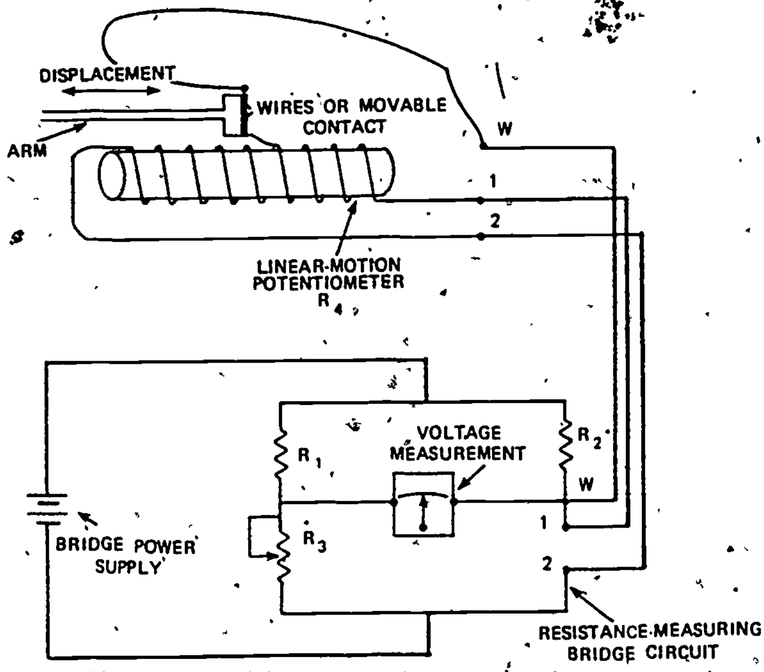


Figure 3. Linear-motion potentiometer and resistance-measuring bridge circuit.

When the contact on the linear-motion potentiometer is in the mid-position R_3 on the bridge circuit is adjusted for a null (or a balanced bridge) condition. When a movement of the wiper occurs, the bridge will be unbalanced, resulting in a voltage measurement on the bridge voltage recorder or indicator. A displacement in one direction will cause a voltage measurement of a particular polarity. When the displacement is in the opposite direction, the voltage polarity will be reversed. For such application - where it is desired to measure displacement in both directions - a center-reading voltage device must be used to measure the bridge unbalance. Most industrial applications involve a unidirectional measurement, whereby a displacement in one direction results in a voltage increase. When the direction of displacement changes, the voltage measurement decreases. With the linear-motion potentiometer described, relative motion as great as six inches can be measured. For very small measurements with extremely reliable and precise results, linear-motion inductors and transformers are used.

Linear-Motion Variable Inductor

A linear-motion variable inductor consists of a spool, or core, that is wrapped with a coil of wire. Relative motion between the core and coil will result in a change in the inductance value of the coil that is proportional to the amount of motion. The circuit used to measure relative motion is an oscillator, and movement of the coil changes the frequency of the output oscillations. This device is more rugged than the potentiometer. It also has little friction and more freedom of movement, with greater life expectancy. Input and output circuits are electrically isolated - which is a great advantage in prevention of spurious voltage disturbances. Although it is used in tuned circuits in the communications industry, the variable inductor is not as common to other industrial applications as the linear variable differential transformer (LVDT).

Linear Variable Differential Transformer (LVDT)

The LVDT contains all of the advantages of the variable inductor, except that it is more expensive. This device is more sensitive to very

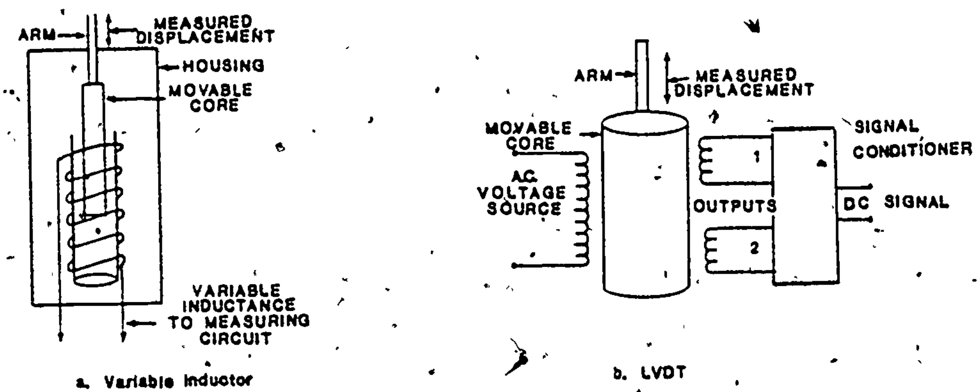


Figure 4. Variable inductor and LVDT.

small movements - to a few ten-thousands of an inch. An additional advantage of the LVDT is that the output voltage, which is d.c., is polarity sensitive to core movement. A variable inductor and an LVDT are illustrated in Figure 4.

The LVDT is used in many industrial process transmitters to measure such quantities as flow, level, and pressure. Figure 5 shows an LVDT with auxiliary circuit components. The primary coil is connected to an a.c. input source. The two output coils, or secondaries - which are mechanically and electricallysimilar - are symmetrically located with reference to the primary coil.

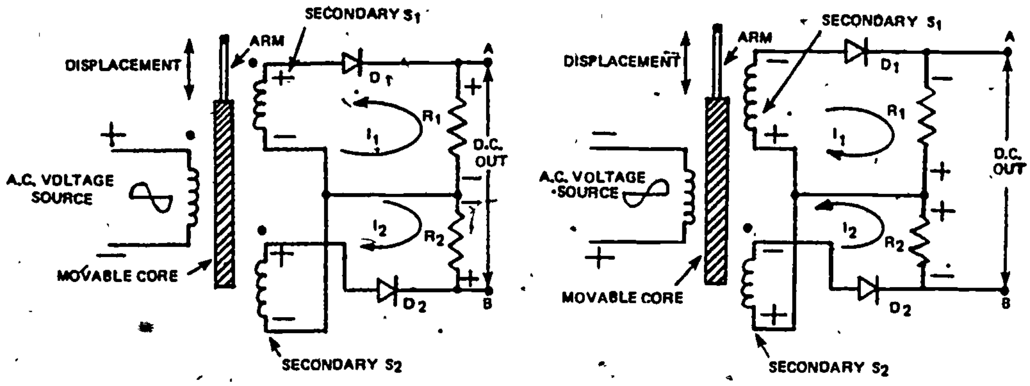


Figure 5. LVDT with signal condition circuits.

With the core positioned so that it is exactly centered electrically between S_1 and S_2 on the positive half-cycle of the input waveform, the output current through R_1 and R_2 will be as indicated in Figure 5a. When the input waveform goes negative on the next 180° phase of generation, current through the output resistors R_1 and R_2 is blocked by D_1 and D_2, and E_{out} is zero. Resistance values of R_1 and R_2 are equal. The current flow through the resistors is equal because of the electrical similarity of the coils (S_1 and S_2) and the symmetrical location of the core with respect to the primary. The voltage drop (I_1R_1) across R_1 is equal to that across R_2. Polarity of the two voltages is opposite because of the opposite direction of current flow. Therefore, for the condition just described - with the core positioned between the secondary coils - the output voltage (E_{out}) is equal to zero.

When the core is positioned more toward S_1, I_1 will be greater than I_2, and the voltage drop across R_1 will be greater than that across R_2. Point A on the output will be more positive than point B, and E_{out} will be positive with respect to common. When the core is positioned more toward S_2, I_2 will be greater; and, for the same reason stated above, E_{out} will be negative.

The magnitude of E_{out} is proportional to the position of the core, with respect to the center or rest position. The greater the displacement, the greater the voltage - the polarity of which indicates the direction of the core from the center position. In practice, it is common to measure the core displacement in only one direction - from the center position. Output voltage is a function of the core movement in one direction and then back to rest position. This movement generates a voltage that changes from zero to a maximum and back to zero.

By the action of the diodes, D_1 and D_2, the waveform of the electrical output is half-wave rectified. When a capacitor is connected from points A and B across the output voltage, a d.c. output voltage is obtained.

However, it may be desirable to use the output as an a.c. waveform. In this case, the rectifying diodes and resistors are omitted from the circuit, and the windings of the secondary coils are connected in a series opposition arrangement. The output will be a phase-sensitive, variable peak voltage, a.c. signal that has a frequency that is the same as that of the input signal. This application - using the output as an a.c. signal - is not as common as that previously described when the output is a half-wave rectified d.c. waveform.

Variable Capacitance for Linear Measurement

A group of linear position detectors operates on the principle of variable capacitance. With other factors that determine the value of a capacitor being constant, the capacitor value is a function of the distance between the capacitor plates. A linear variable capacitance transducer is shown in Figure 6. The capacitance of this transducer is very small. Although the variable capacitance may be measured with a DeSanty bridge, stray capacitance from connecting leads can swamp the transducer capacitance and cause erratic and erroneous measurement values. For this reason,

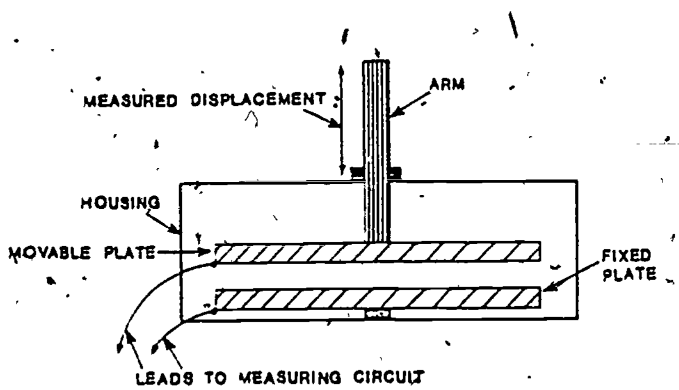


Figure 6. Linear variable capacitance transducer.

the leads of the transducer usually are connected to the tank circuit of an oscillator. A change in capacitance will result in a change in frequency. The variable frequency is then usually converted to a signal having an amplitude that is frequency-dependent. Use of variable capacitance transducers is gaining prominence in transmitters used for process measurement.

MOTION DETECTORS - ROTARY

Rotary position, angular motion, or angular displacement detectors operate on principles simlar to the linear position detectors discussed previously. The following text will reference the operation of rotary motion detectors to that of their linear motion detector counterparts.

Rotary Potentiometers

The angular motion variable potentiometer is perhaps the most common type of rotary motion transducer used commercially. Rotary potentiometers are of either the wire-wound type or the film-composition type, and the type to use is determined by the specific application. The wire-wound potentiometer is used for more precise operations where very small movement or very small increments of resistance change are desired. The motion that drives a rotary potentiometer can be restricted to 360°, or several complete revolutions. Multiple rotation potentiometers (2-, 5- or 10-turn "pots," as they are called) are available for use in many industrial applications.

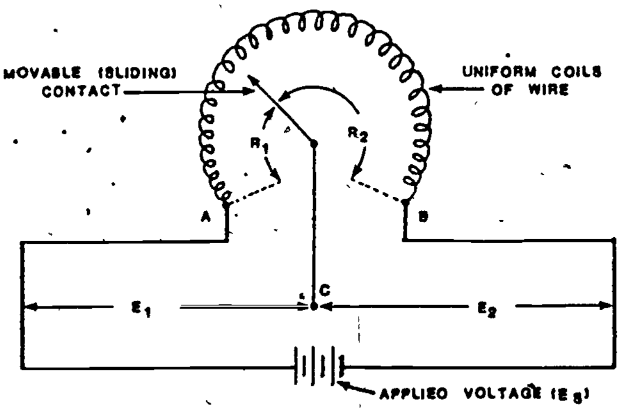


Figure 7. Wire-wound rotary potentiometer.

The term "potentiometer" is derived from the fact that a uniform and proportional drop in voltage (potential) is produced as a result of the displacement of a movable or rotating contact from the displacement of a movable or rotating contact from a reference point. From this result, the voltage at the sliding contact is directly proportional to its distance from the reference end. This concept is illustrated in Figure 7.

The resistance of a potentiometer is the value of resistance, as measured from A to B (Figure 7). Although this value could be any amount, standard values are as follows: 10 Ω, 25 Ω, 100 Ω, 1 kΩ, and so on. The resistance from A to C is R_1; and the resistance from B to C is R_2. The total resistance of the potentiometer is expressed in Equation 1.

$$R_T = R_1 + R_2 \qquad \text{Equation 1}$$

where: R_T = Total potentiometer resistance.
R_1 = Resistance from A to C in Figure 7.
R_2 = Resistance from B to C in Figure 7.

The voltage from A to C in Figure 7 is E_1; and voltage from B to C is E_2. Total voltage is expressed in Equation 2.

$$E_T = E_1 + E_2 \qquad \text{Equation 2}$$

where: E_T = Total applied voltage.
E_1 = Voltage from A to C in Figure 7.
E_2 = Voltage from B to C in Figure 7.

The relationship between voltage and resistance (R_1 and E_1 and R_2 and E_2) is expressed in Equations 3 and 4.

$$E_1 = \frac{R_1}{R_1 + R_2} (E_S) \qquad \text{Equation 3}$$

where: E_1 = Voltage from A to C in Figure 7.
R_1 = Resistance from A to C in Figure 7.
R_2 = Resistance from B to C in Figure 7.
E_S = Applied voltage.

$$E_2 = \frac{R_2}{R_1 + R_2} (E_S) \qquad \text{Equation 4}$$

where: E_2 = Voltage from B to C in Figure 7.
R_1 = Resistance from A to C in Figure 7.
R_2 = Resistance from B to C in Figure 7.
E_S = Applied voltage.

The previous discussion and stated equations indicate that the voltage from A to C in Figure 7 will increase as the sliding contact rotates clockwise and that the voltage from B to C will decrease with a clockwise rotation of the slider. Of course, when rotation of the slider is reversed, the voltage values previously described will assume the opposite values.

Example A will help to explain the concept of rotary potentiometer operation.

EXAMPLE A: ROTARY POTENTIOMETER OPERATION.

Given: The following information:

a. $R_T = 1000\ \Omega$
b. $E_S = 10$ V
c. The maximum rotation of the slider is 0-300°.

Find: Voltage from A to C when the slider rotates 35°.

Solution: By referring to Figure 7, and assuming the relationship between slider movement and resistance from C to A or B is proportional, R_1 will be resistance value proportional to the amount of rotation of the slider from 0-35°.

$$R_1 = \frac{35°}{300°}(1000\ \Omega) = 116.66\ \Omega$$

From Equation 3,

$$E_1 = E_{A-C} = \frac{R_1}{R_1 + R_2}(E_S)$$

$$= \frac{116.66\ \Omega}{1000\ \Omega}(10\ V)$$

$$= 1.166\ V$$

Note: The steps included in Example A to calculate R_1 could be omitted since, in a voltage divider network, voltage and resistance vary in direct proportion to each other. Therefore,

$$E_1 = \frac{35}{300} (10 \text{ V}) = 1.166 \text{ V}.$$

The above demonstrates that, by use of a rotary potentiometer, rotary motion - which can be an inferred value - can be determined by a voltage measurement.

In order to reduce the current flow in the potentiometer and thereby reduce the total maximum power dissipated in the circuit, low voltage and high resistance are often used. This probably will reduce the measured voltage value to the point at which amplification may be required. However, most process instruments will measure voltage in the millivolt range; therefore, when using such devices, amplification may not be required.

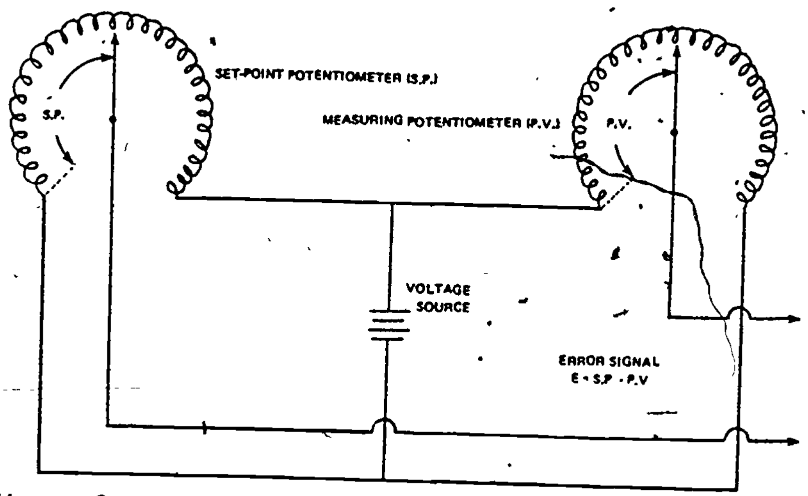


Figure 8. Two-potentiometer error-detecting circuit.

In control and measurement applications, it is often desirable to detect the difference in relative motion. This can be done with two potentiometers. This principle, which involves error-detecting circuits, finds specific use in measuring the error between setpoint value and controlled variable measurement in closed-loop control systems. Such an arrangement is shown in Figure 8.

The error signal, E in Figure 8, is a function of the relative motion of the sliders in the setpoint and measuring potentiometers. When they are at the exact same reference point (50% of maximum rotation, for example), the error voltage is zero. If by some unusual circumstance both sliders moved an equal amount in the same direction, the error voltage would still be zero. When the SP value, which represents the real reference value, is held constant, and the PV slider position changes as a result of a change in the process condition, error voltage will increase by an amount proportional to the difference in the position of the two sliders. In this case, the error signal would provide an input to an amplifier having an output that would position a final control element in the control loop to bring about a change in the process condition. The process would continue to change until the error signal again became zero. This sequence describes the action taken by a controller in a closed-loop control system.

The accuracy of a potentiometer transducer depends upon the proportional change in voltage with respect to resistance. When this relationship is linear - that is, when an increment of shaft rotation of a rotary potentiometer causes an equal increment of voltage variation - the measuring device is said to be linear. The term "linear," as it is used in this case, does not describe the type of motion; instead, it is used to express the degree by which measured voltage is representative of the contact position. The curve in Figure 9 shows linear and nonlinear relationships between measured (output) voltage and contact or slider position. Nonlinearity must be eliminated or held to a minimum.

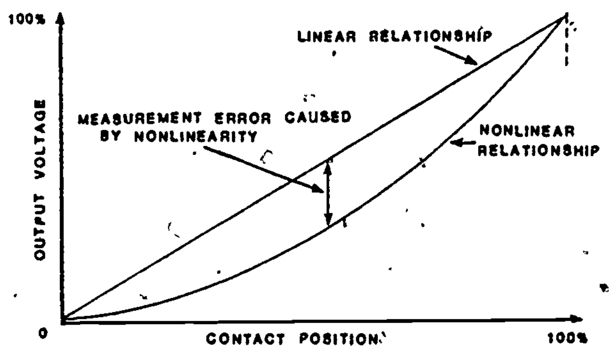


Figure 9. Linear and nonlinear relationships.

When a measuring instrument or load resistor is attached to the measuring circuit, that resistance is parallel with a portion of the potentiometer slidewire and will change the circuit resistance to a value known as the equivalent resistance (R_{eq}). In Figure 7, output voltage measurement is E_1 across R_1, which is a portion of the potentiometer slidewire. This is shown in Figure 10.

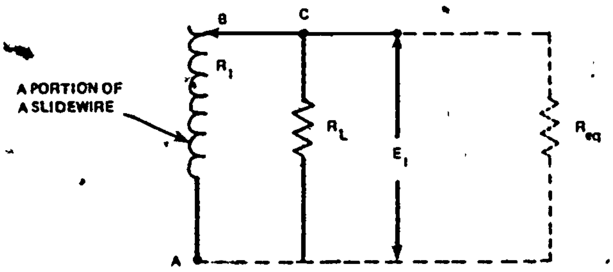


Figure 10. Effect of R_L on a potentiometer measuring circuit.

As a result of the addition of R_L to the circuit, the equivalent resistance value of the circuit in Figure 10 is determined by calculating the parallel combination of R_1 and R_L. This is accomplished by using Equation 5. When the value of R_L is large compared to R_1, the value of R_{eq} will be approximately equal to R_1, and the error caused by the addition of R_L to the measuring circuit will be minimal.

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2} \qquad \text{Equation 5}$$

Rotary Variable Differential Transformer (RVDT)

The rotary variable differential transformer (RVDT) is commercially available for angular motion detection. It operates on the same principle as the LVDT, with the major difference being in the slug or core movement. The core rotates in the RVDT; but it has a linear movement in the LVDT. The core rotation is usually limited to 45° in either direction. The RVDT, as shown in Figure 11a, produces a differential output voltage that is a function of the coil rotation in either direction from the center, or rest position, at which point the output voltage is zero.

A two-coil version of an RVDT is the variable reluctance angular position transducer. This device is the result of omitting the primary coil and connecting the a.c. source, as shown in Figure 11b.

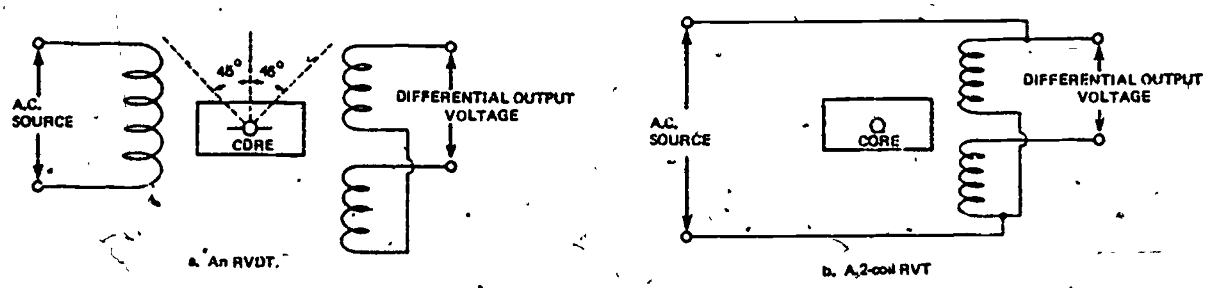


Figure 11. Rotary variable differential transformer.

Synchro Systems

A synchro is a rotary transducer that provides a transformation of angular displacement or motion to a proportional a.c. voltage or an a.c. voltage to a rotary motion.

Synchros resemble a.c. motors in physical construction and operation. They have a rotating armature, or rotor, which is connected to an a.c. excitation voltage source, and a stationary field, or stator. The stator consists of three individual windings, each spaced 120° from the other. The three coils are connected together at one end. Slip rings or brushes are utilized to connect the excitation voltage to the rotor.

The currents induced into each of the stator coils are a function of the position of the rotor coil. They are relative to each of the three stator windings. By comparison of the currents in each of the stator windings, the rotator position can be determined. Changes in the stator current are also an indication of the direction of rotor rotation.

Synchros are also used in pairs to measure angular rotation. In such applications, one synchro is called a control transmitter and one is called a control transformer. Synchro pairs are often used to measure difference in the speed of two rotating shafts in order to produce an error signal that is used to control the speed of one shaft equal to that of another. A typical synchro motor is shown in Figure 12 and a synchro pair is shown in Figure 13.

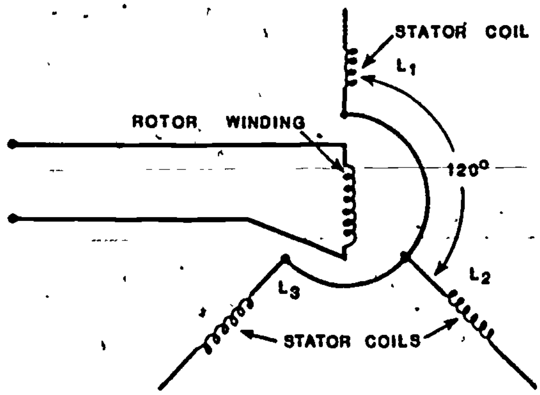


Figure 12. Synchro motor.

In Figure 13, an a.c. voltage is applied to the control transmitter through burshes to the rotor. In turn, an a.c. voltage is induced into the coils (L_1, L_2, and L_3), the amount of which is determined by the angular position of the rotor (relative to each coil) The voltage on each coil of the transmitter also appears on the corresponding coils of the transformer. The coil voltages on the transformer are then induced into the rotor of the transformer - which, through brushes, appears at the transformer output. Therefore, the output voltage is a function of the angular position of the rotor in the control transmitter. Transformer output voltage is described by Equation 6.

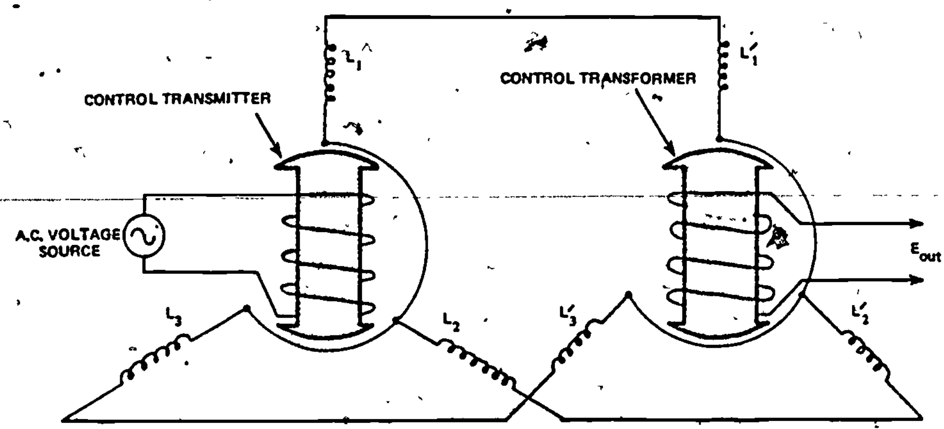


Figure 13. Synchro angular displacement transducer.

$$E_{out} = (E_m \cos \theta) \sin Wt \qquad \text{Equation 6}$$

where: E_{out} = Output voltage of the transformer.

E_m = Maximum output voltage amplitude.

θ = Angular displacement of the transmitter rotor.

W = Frequency, in radians, of the voltage applied to the transmitter rotor.

Flyball Governor

The flyball governor (mechanical angular motion detector) is one of the oldest rotary-motion detecting devices. It was first used in the original steam engine as the measuring means of a closed-loop control system to control engine speed. It still is used to regulate the speed of steam turbines that drive large compressors. Such speed-control devices are known as centrifugal governors.

The centrifugal, or flyball, governor shown in Figure 14 has two spherical weights attached to a rotating shaft by two arms (for each weight). The number of weights can vary from one to four. One arm is pivoted to the

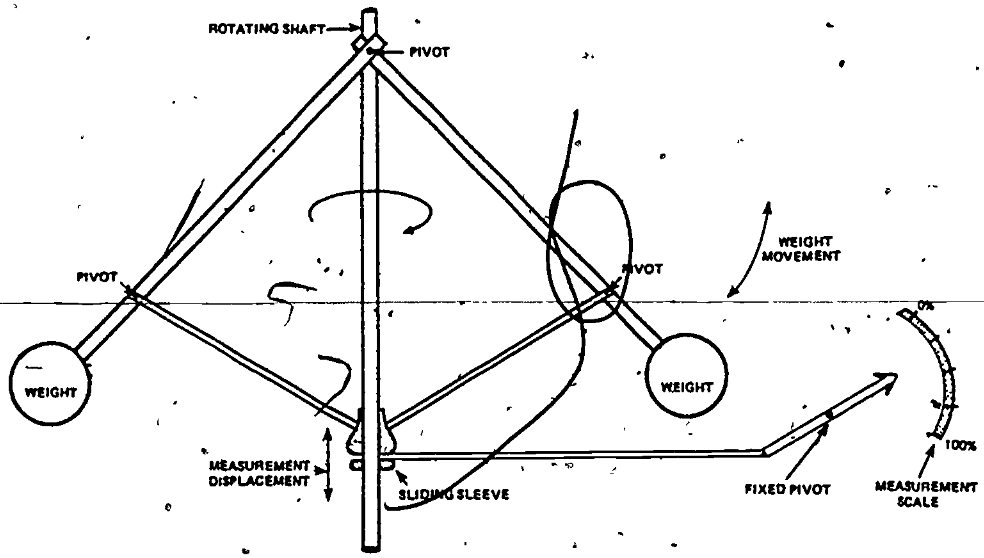


Figure 14. Centrifugal or flyball governor for speed measurement and/or control.

shaft end, and the other arm is free to slide on the shaft. Rotary motion of the shaft creates a centrifugal force on the weights. The force is normal to the shaft (points radially out from axis), and it causes the weight to be hurled outward and upward, creating a motion of the weights. The amount of weight motion is a function of centrifugal force created by the shaft rotation and the opposing force of gravity acting on the weights. At any speed great enough to cause the weights to move, the centrifugal and gravitational forces acting on the weights are out of equilibrium. As gravitational force on the weight is constant, the weight movement is a function of shaft rotational speed. This movement causes a sliding sleeve to be positioned up and down the shaft. Position of the sleeve is an indication of the shaft speed.

VELOCITY MEASUREMENT - ROTARY

Velocity, the rate of change of displacement or distance, is measured in angular rotation per unit of time. Any of the linear- or rotary-motion devices mentioned can be used for velocity measurement, but only when the displacement measurement is made with respect to time. The flyball governor can be used for velocity measurement by simply using a scale graduated to read rotary or angular velocity - r/min, for example. It is strictly a motion, and not a position measurement device. The other devices mentioned in this module are position detectors. To measure velocity from a position indicator, it is necessary to measure the time required to change from one position to another and to express that amount of movement with respect to the amount of time required to make the movement.

Tachometers

A tachometer is a device used to measure angular velocity. The flyball governor is a mechanical tachometer. Electrical tachometers normally are small generators having an output voltage that is a function of this angular velocity of the rotating armature. Output voltage of a generator is expressed in Equation 7.

$$E_L = LBV \qquad \text{Equation 7}$$

where: E_L = Voltage generated by the tachometer.

L = Length of the conductors in the armature.

B = Flux density of the magnetic field established by the field coil.

V = Velocity of the armature.

By designing a generator with all the terms in Equation 7 constant ... and doing the following:

- expressing velocity of the conductors in terms of an average radius (the angular velocity is revolutions per minute),
- establishing the exact number of conductors with their exact length, and
- determining total voltage on the tachometer output by computing the sum of voltages induced in each inductor ...

the tachometer output voltage is determined by Equations 8 and 9.

$$E = K_E S \qquad \text{Equation 8}$$

$$K_E = \frac{2\pi \ RBNL}{60} \qquad \text{Equation 9}$$

where:

E = Tachometer output voltage.

K_E = EMF constant, in V/rpm.

S = Angular velocity of the armature, in r/min.

R = Average radius, in meters (m).

B = Flux density of the magnetic field, in webers per square meter (Wb/m^2).

N = Effective number of conductors.

L = Length of each conductor, in m.

EXAMPLE B: TACHOMETER OUTPUT VOLTAGE.
Given: A d.c. tachometer with the following specification values relating to Equations 8 and 9. R = 0.06 m B = 0.1 Wb/m^2 N = 36 L = 0.2 m

Find: Output voltage for the following speeds:

a. 1000 r/min

b. 2500 r/min

c. 3000 r/min

Solution: Using Equation 9 to find K_E:

$$K_E = \frac{2\pi\ RBNL}{60}$$

$$K_E = (6.28)(0.06\ m)(0.1\ \frac{Wb}{m^2})(36)(0.2\ m)$$

$$= 0.0045\ \frac{V}{r/min}$$

Using Equation 8 to find output voltage:

a. $E = K_E S$

$$= 0.0045\ \frac{V}{r/min}\ (1000\ r/min)$$

$$= 4.5\ V$$

b. $E = 0.0045\ \frac{V}{r/min}\ (2500\ r/min)$

$$= 11.25\ V$$

c. $E = 0.0045\ \frac{V}{r/min}\ (3000\ r/min)$

$$= 13.5\ V$$

EXAMPLE C: REVOLUTIONS PER MINUTE.

Given: A d.c. tachometer with the specifications listed in Example B.

Find: Revolutions per minute for the following output voltages:

a. 3.65 V

b. 4.58 V

c. 7.43 V

Solution: Rearranging Equation 8 to solve for S:

$$S = \frac{E}{K_E}$$

From Example B, $K_E = 0.0045$ V

Solving for S:

a. $S = \frac{E}{K_E} = \frac{3.65}{0.0045} = 811.11$ r/min

b. $S = \frac{4.58}{0.0045} = 1017.77$ r/min

c. $S = \frac{7.43}{0.0045} = 1651.11$ r/min

FORCE SENSORS

Measurement of motion, movement, and displacement has been discussed, and several means to measure both linear and rotary motion have been explained. An equally important measurement is that of force. Force measurements can be - and, in fact, often are - inferred values from both linear- and rotary-motion detectors, where the measurement is based on an amount of force required to produce the measured motion. Other force-measurement devices, though generally operating on the same principle, are not considered to be motion sensors.

STRAIN GAGE

The strain gage is one of the simplest and most prominent types of force sensor in commercial and industrial use. Operation of the strain gage is based upon the effects of physical deformation caused by applied forces on the electrical resistance of a wire conductor.

The electrical resistance of a conducting wire is determined by the equation:

$$R = \rho (L/A)$$

where: R = Electrical resistance, ohms.

ρ = Characteristic resistivity of material, ohms/inch.

L = Length of conductor, inches.

A = Cross-sectional area of conductor, inches^2.

Neglecting temperature changes, the resistance of a conductive wire will remain reasonably constant as long as its physical dimensions are unchanged. When a force is applied that results in a conductor increasing its length, its cross-sectional area will decrease - resulting in a greatly increased resistance. Change in resistance is proportional to the amount of force applied to the wire, thus presenting a means to measure force if the proportionality constant is known.

Strain gages are constructed by attaching a length of wire to a piece of paper or plastic in such a way that no relative motion can exist between the two items. The supporting paper then is fastened to a load column that is subjected to deformation when undergoing an applied force. Bonded wire strain gages have excellent resistance to vibration and mechanical shock. They can be covered with a protective coating for protection from corrosive atmospheres. Some can even be submerged in water. Life expectance can be long when care is taken that the device is not over-ranged or strained beyond its elastic limit. A bonded wire strain gage is shown in Figure 15.

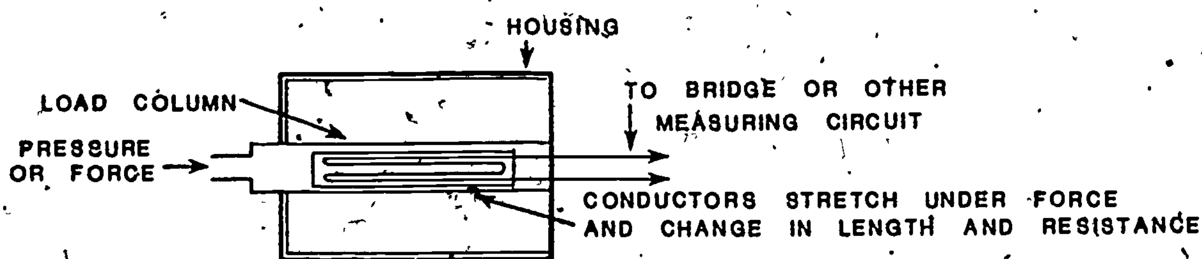


Figure 15. Bonded wire strain gage.

The electrical output usually creates a very small variable resistance. Total resistance of the device may be around 100 ohms, but variations of less than one ohm may result from some applications. The problem of measuring fractions of ohms is solved by using d.c. resistance bridges. With good design and sensitive bridge detectors, accurate and reliable small resistance measurement is commonplace in the industrial instrumentation field.

PIEZOELECTRIC CRYSTAL

A piezoelectric crystal is a device made from Rochille salt. It is a thin slice of quartz that generates a voltage when subjected to a force. When the crystal is distorted by an applied external force, a voltage appears at the crystal surface. The crystal has an extremely low power-generating ability; therefore, the voltage generated is soon dissipated. Thus, voltage appears more as a change in force rather than a static force measurement.

In industrial applications, charge amplifiers that can respond to low-level signals are used to increase the output of the force crystals: Applications involving the piezoelectric crystal and the associated amplifier are (1) vibration monitoring and detection and, in some cases, (2) alarm circuits. A piezoelectric crystal is shown in Figure 16.

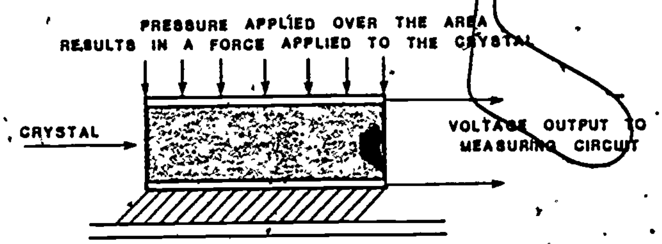


Figure 16. Piezoelectric pressure-force transducer.

PROXIMITY AND LIGHT DETECTORS

The proximity detector does not fit into the linear- or rotary-motion category - or even the motion-detector category. It is used to measure the physical closeness, presence, or proximity of objects. The two types are the contact and the noncontact. Proximity detectors are usually digital-type signal generating devices since the signal is ON or OFF or HIGH or

LOW - depending upon the absolute presence or absence of an object in the proximity of the detector. However, some detectors can monitor the closeness of an object. This type of proximity detector is usually the noncontact type.

CONTACT-TYPE PROXIMITY DETECTORS

Contact detectors normally have a lever of some sort resting on the object or situated close to the object. When the lever is moved after being stroked by the object, a set of electrical contacts operates, thereby generating a signal. This type of device is commonly known as a limit switch. Limit switches are used in the process and manufacturing industries to monitor valve positions as OPEN or CLOSED, to monitor assembly-line objects, and to perform other such functions.

NONCONTACT-TYPE PROXIMITY DETECTORS

In some industrial applications, it is not practical to contact the object of which proximity is being measured. In such cases, a magnetic field, an ultrasonic, or an optical-measuring device is employed. Air jets or air streams have been used. Perhaps the most common type of optical noncontact proximity detector is a light striking a photocell. Presence or absence of the light will cause a switch to be opened or closed and, thereby, sound an alarm or initiate control-circuit action. A very common utilization of this application is the automatic door that operates in supermarkets, hospitals, and so on. Such a device is shown in Figure 17.

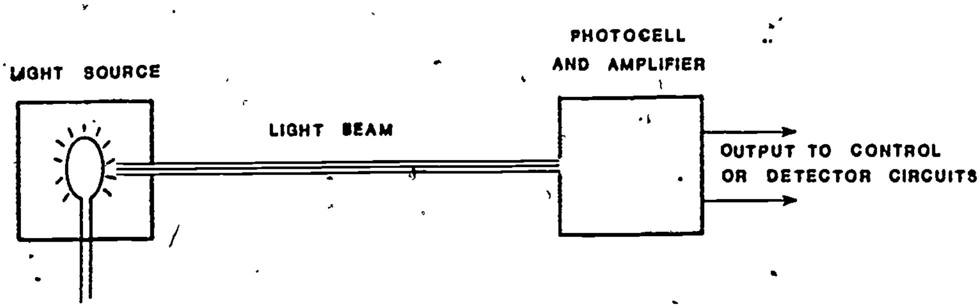


Figure 17. Optical proximity detector.

When an object blocks the light beam from the source, the absence of light striking the photocell causes the amplifier output to decrease. This decrease in signal, through a relay or another type of switching device, generates an output that performs the desired function. The light need not be in the visible region. Ultraviolet and infrared optical de tectors are available.

Industrial applications of optical-proximity sensors include optical-concentration analyzers. In these analyzers, the amplifier output is a proportional signal relative to the amount of light blocked or absorbed by material in the light beam. The property of the turbidity in water is often measured by flowing the water through a transparent cell and focusing a light beam on the wall. The amount of light leaving the cell is a function of the amount of light absorbed or blocked by small, solid impurities suspended in the water.

APPLICATIONS

The previous discussions on detectors were concerned with an output (usually electrical) that was generated or altered in some fashion by a change in motion, force, or some other median on the input. The output signal generated by the detector usually must be conditioned or, at least, scaled before it can be used successfully. When this is accomplished, the transducer input is used to produce a scaled output signal of sufficient amplitude and strength to perform a function. This describes a sensor or transmitter. A pressure transmitter, for example, may employ any of the transducer inputs discussed and transmit a scaled 4-20 mA signal. A scaled input, 0-100 psig for instance, can be used to produce a 4-20 mA output. When this situation exists, the overall device (the transmitter with the transducer input) performs a very necessary and useful function. At this point, a review of the block diagram in Figure 2 would be helpful to the student.

1. By drawing a sketch and using mathematical calculations, show how voltage across a portion of a potentiometer is affected by the position of the slider.
2. Explain how the principle established above can be used in process-measurement applications.
3. Sketch and explain how the variable value of resistance of a potentiometer can be measured with a resistance bridge circuit.
4. Explain the operation of the LVDT shown in Figure 5, and list the specific function of each component.
5. Compare the usefulness of the LVDT device with that of a variable-capacitance transducer with respect to the measuring circuit used. Compare the measuring circuit used with a variable inductor to that used with a variable capacitor. What is the normal output of each measuring circuit?
6. Draw a two-potentiometer measuring circuit. Explain its operation, and list a possible use.
7. List a possible cause of nonlinearity in a variable potentiometer measuring circuit, and explain how this error can be reduced or eliminated.
8. Explain how the velocity of rotary motion can be measured by the following:
   a. A flyball governor.
   b. A d.c. tachometer.
9. How can the flyball governor be used to control the speed of a steam turbine?
10. Sketch and explain how a strain gage can be used for force measurement.

LABORATORY MATERIALS

A differential-pressure transmitter, using a LVDT as the input transducer (a Foxboro brand).

A differential-pressure transducer, using a variable capacitor as the input transducer (a Rosemont brand).

Instruction and service manual with parts list for each instrument used.

A manometer or test gage capable of reading 200 inches of water - 2%.

A 0-100-V variable d.c. power supply.

A time-base oscilloscope capable of frequency and voltage measurement in the audio frequency range and having a sensitivity of 1 mV/cm.

A variable pressure regulator 0-20 psig with 1% regulation.

A 0-50 mA current meter.

Assorted wire, tubing, and fittings for calibration of the d/P cells.

A 0-20 psig air supply.

LABORATORY PROCEDURES

LABORATORY 1. OPERATION OF AN LVDT DIFFERENTIAL-PRESSURE TRANSMITTER

1. Locate the LVDT on the differential-pressure transmitter, and identify the means by which a differential pressure produces a core movement.
2. Using the electrical schematic in the instruction manual, locate the LVDT on the print and note the method of output generation by coil position.
3. Refer to the instruction manual and to Figure 18, and connect the d/P cell to the proper pressure and electrical connections for check-out and/or calibration.
4. Before turning on power supply, check instruction manual for the proper level, and set the voltage to adjust for this value. Apply this voltage to the d/P cell by turning on the power supply.
5. Open both vent plugs on the d/P cell to apply atmospheric pressure to both sides of the capsule.

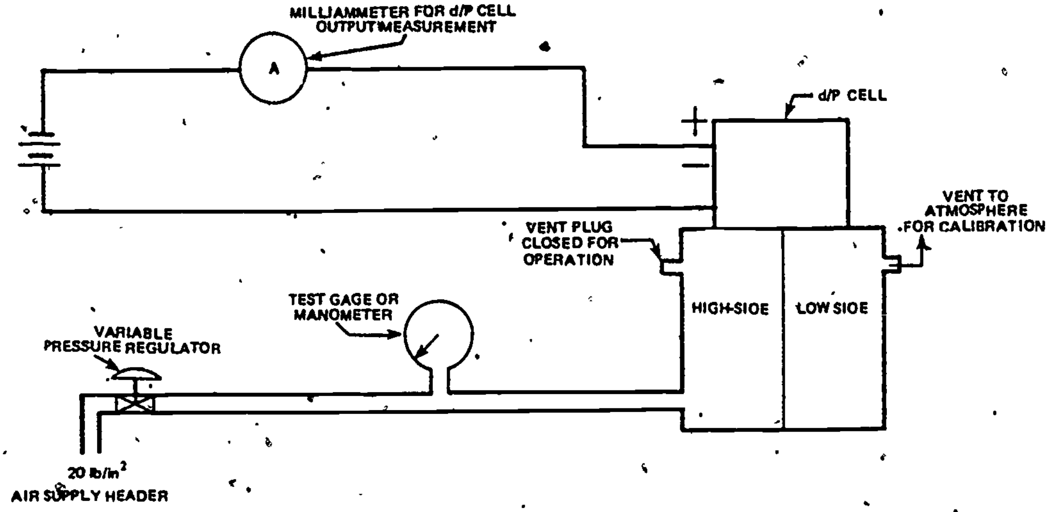


Figure 18. Experimental setup for Laboratory 1.

6. Use an oscilloscope and measure the oscillator voltage on the primary of the LVDT.
7. Use an oscilloscope to measure the output of the secondary of the LVDT.
8. Close the ~~vent on the high~~-side, leaving the low-side vented to atmosphere. With the variable pressure regulator, increase the pressure to the high-side, applying a differential pressure to the d/P cell. Note the change in the secondary output voltage and d/P cell output current, as read in the output meter.
9. Reduce the pressure on the high-side by adjusting the pressure regulator and opening the high-side vent plug.
10. Locate the zero adjustment and, if necessary, adjust for 0% output. Most transmitters have 4-20 mA d.c. output; therefore, this value should be 4 mA.
11. Close the high-side vent plug and apply a pressure to the high-side that is equal to about half of the full-scale adjustable range. The adjustable full-scale range will be listed on the name tag of the instrument, with date and specifications pertinent to the d/P cell. Note the output meter indication. If full output (20 mA on 4-20 mA transmitter) is reached before half the full-scale differential is applied, reduce the differential pressure to zero and increase the range adjustment setting. If the full-scale output does not occur when half of the

full-scale range is applied, reduce the pressure to zero and decrease the range adjustment setting. Continue this procedure until the full-scale output coincides with the pressure of the half-full-scale range.

12. Repeat Steps 9, 10, and 11 for complete calibration of the selected half-scale value of applied pressure.

LABORATORY 2. OPERATION OF A d/P CELL WITH A VARIABLE CAPACITOR.

1. With the use of the instruction manual and a d/P cell with a variable capacitor transducer on the input, locate the input capacitor and associated measuring circuit.
2. Note the method of output generation by displacement.
3. Repeat Steps 3, 4, and 5 of Laboratory 1.
4. Using an oscilloscope, measure the frequency of the variable frequency oscillator. The variable capacitor having value changes as a result of differential pressure is then connected to the tank circuit of this oscillator.
5. Close the high-side vent valve, leaving the low-side vented to atmosphere. With the variable pressure regulator, increase the pressure to the high-side, applying a differential pressure to the d/P cell. Note the change in the oscillator frequency that occurs with a change in differential pressure.
6. Repeat Steps 9, 10, 11, and 12 of Laboratory 1.
7. Procedures are now complete. Turn off the power supply, disconnect the d/P cell, and secure all equipment.

REFERENCES

Bateson, Robert E. Introduction to Control System Technology. 2nd ed. Columbus, OH: Charles E. Merrill Publishing Co., 1980.

Hunter, Ronald P. Automated Process Control Systems, Concepts and Hardware. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1978.

Linear motion: Movement along a straight line.

Rotary motion: Movement in a circular path.

Sensor: A device that often uses a transducer as an input source to generate a scaled signal representing a measured quantity.

Synchro: A rotary transducer that provides a transformation of angular displacement or motion to a proportional a.c. voltage or an a.c. voltage to motion.

Transmitter: Same as sensor.

TEST

INSTRUMENTATION AND CONTROLS

Module IC-05

"Instruments for Mechanical Measurement"

Matching: Match the following terms with the appropriate definition:

_____ Force.

_____ Work (displacement or motion).

_____ Potentiometer.

_____ Transducer.

_____ Flyball governor.

_____ Strain gage.

_____ Linear variable differential transformer.

_____ Transmitter or sensor.

_____ Synchro.

_____ Tachometer.

a. A device used to convert one form of energy to another more useful form.

b. An instrument that generates a scaled signal from a transducer input.

c. A rotary transducer that provides a transformation of angular displacement or motion to a proportional a.c. voltage.

d. The ability to do work.

e. Force operating through distance.

f. A variable resistance device.

g. A variable inductance device.

h. Produce a change in resistance when under force or stress.

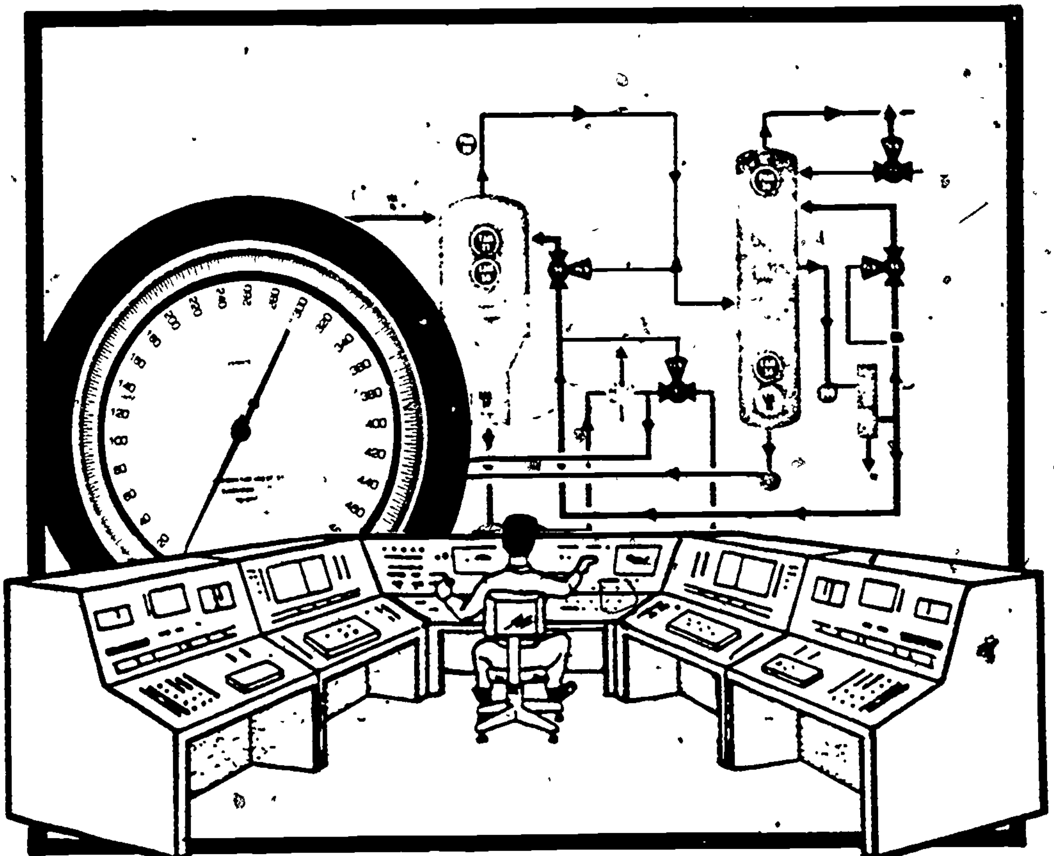
i. Measures circular velocity.

j. A mechanical tachometer.

ENERGY TECHNOLOGY

CONSERVATION AND USE

INSTRUMENTATION AND CONTROLS



MODULE IC-06

PNEUMATIC CONTROLS

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

When control systems were first being developed, mechanical and hydraulic mechanisms were the modern-day marvels of a young industrial era. The first automatic feedback control system was introduced in 1774 when James Watts used a device to control the speed of his steam engine. Oliver Evans used the same technique 10 years later to automatically control a flour mill in Philadelphia. As other industries began to develop, the need for automatic control systems grew; and, by 1930, direct-connected process instruments were being adapted to process control systems. In the 1940s, more complex control systems were developed, along with transmission lines that were used to connect local field-mounted instruments to centrally-located control houses. Pneumatic control systems were popular in this decade and reached their peak of development in the mid-to-late 1950s - when electronic control instrumentation development began. With the widespread use of solid-state electronic devices and the development of integrated circuits and micro-electronics in the late 60s, obsolescence was predicted for the pneumatic instrumentation industry. However, because of some distinct advantages, pneumatic instrumentation continues to be widely used in the control industry.

This module explains the operation and use of pneumatic instrumentation and control systems. Advantages and disadvantages of pneumatic devices are discussed, as well as standard applications and latest developments.

PREREQUISITES

The student should have a basic understanding of algebra and physics and should have completed Modules IC-01 through IC-05 of Instrumentation and Controls.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following component parts of a pneumatic transmission system:
   a. Flapper.
   b. Nozzle.
   c. Restrictor.
   d. Relay.
   e. Feedback bellows.
   f. Variable-gain unit.
2. Explain the operation of a pneumatic transmitter to measure the following variables:
   a. Temperature.
   b. Level.
   c. Flow.
   d. Pressure.
3. Identify the component parts of a pneumatic transmitter.
4. Explain the check-out and calibration procedures of a pneumatic transmitter.

PNEUMATIC TRANSMITTERS - FORCE BALANCE TYPE

Pneumatic instruments have been designed to perform almost any function that can be accomplished by electrical or electronic instruments. In process-control applications, common uses of pneumatic instruments are as transmitters and controllers. These instruments are transducers that convert mechanical motion to a pressure signal. A block diagram of a pneumatic transmitter is shown in Figure 1.

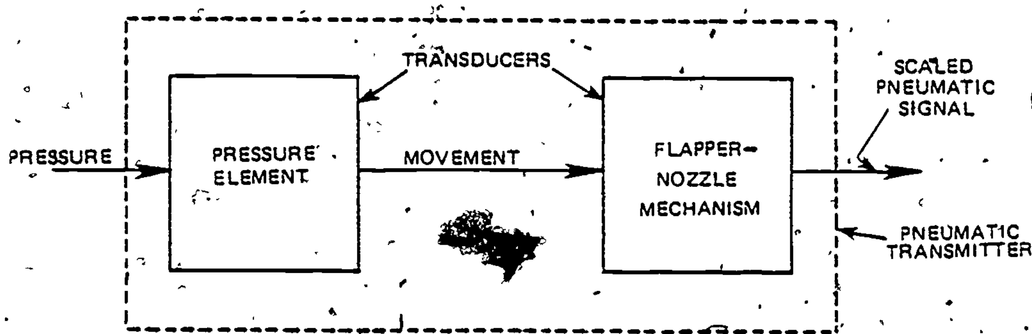


Figure 1. Block diagram of a pneumatic transmitter.

Pressure elements, as discussed in Module IC-02, are used to convert pressure to mechanical motion. Because many types are available, a review of their operation is recommended. A review of Modules IC-02, IC-03, and IC-04 will refresh the memory concerning the principle of process measurement whereby fluid flow, pressure, temperature, and liquid level can all react on a pressure element to produce movement. This movement is then converted to a scaled pneumatic signal by a flapper-nozzle mechanism.

FLAPPER-NOZZLE

All active pneumatic devices (those that generate a scaled signal for transmission) use the flapper-nozzle. This mechanism is shown in Figure 2. The air supplied through the fixed restrictor and nozzle is constant for a given amount of clearance between the flapper and nozzle. When the flapper is closer to the nozzle, the flow is less because of the increased restriction. When the nozzle is moved farther away from the nozzle, the air flow will be greater because of the increased flapper-nozzle clearance. Therefore, the air flow through the nozzle is a function of the flapper position

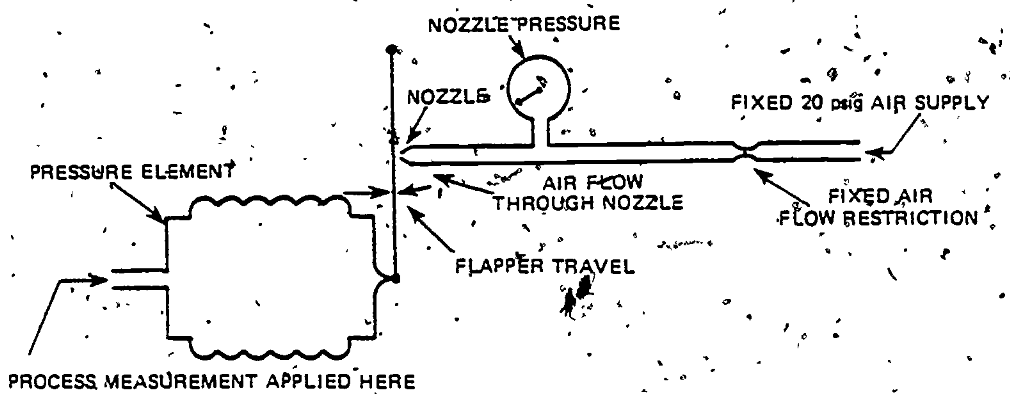


Figure 2. Flapper-nozzle mechanism.

as it relates to the nozzle. This process is a result of the movement of the pressure element, and the movement is a function of the process measurement applied to the pressure element. Because of this, a change in process measurement produces a change in the nozzle back-pressure. To detect very small changes in flapper movement and small changes in the element response, it is necessary to detect very small changes in nozzle back-pressure. For this reason, nozzle pressure is amplified. The amplified nozzle pressure is the output of a pneumatic transmitter. It is a scaled signal representing a process quantity. A pneumatic relay, like the one shown in Figure 3, is used to amplify the nozzle back-pressure. In addition to amplifying nozzle pressure, the relay increases air volume of the instrument's output. Without this boost in volume, the output pressure change would be sluggish because all of the output air would have to flow through the restriction in the nozzle tube. Just as rate of increase in pressure would be limited by the constriction of air flow, the decrease in pressure would similarly be limited by the slow rate of air flow through the nozzle to the atmosphere. The relay overcomes these limitations.

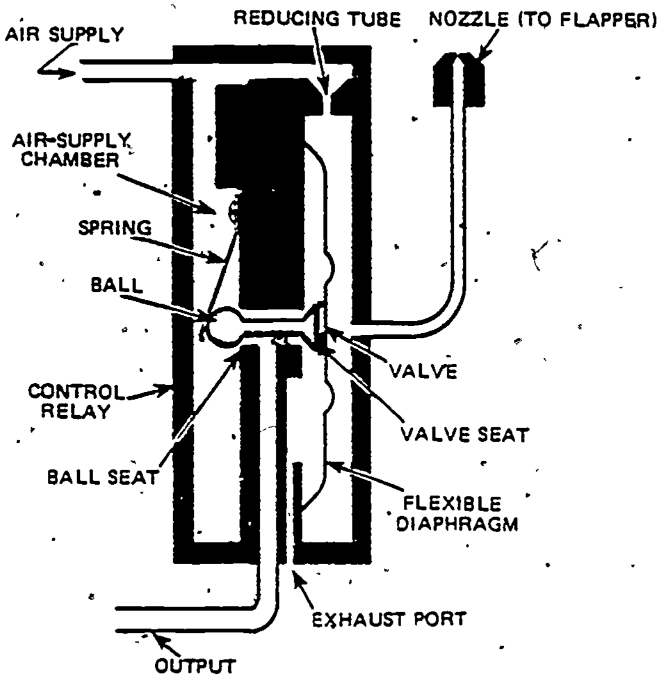


Figure 3. Pneumatic relay schematic.

Relay

An increase in nozzle pressure applied to one side of the relay diaphragm causes the diaphragm to move to the left (Figure 3). This movement positions the ball farther away from the ball seat and allows more air to flow from the relay. The output pressure is also applied to the side of the diaphragm opposite to the nozzle pressure. This increases the pressure on that side of the diaphragm and opposes the nozzle pressure. The pressure does not build up to the full output pressure because the exhaust port vents the pressure to the atmosphere. For any given flapper-nozzle relationship, the diaphragm is in a state of equilibrium with equal pressure on both sides. The diaphragm will move the ball in the correct direction and by the amount required to provide equilibrium.

A decrease in nozzle pressure, caused when the flapper is positioned away from the nozzle, will cause the diaphragm to move to the right. This movement causes the spring to position the ball more toward the seat. This reduces the air flow from the air-supply chamber to the output port. This reduction, in turn, reduces output pressure until the pressure on the diaphragm is again equal on both sides. When the ball is positioned to allow more air to flow from the air-supply chamber to the output port, the valve is positioned closer to the seat, thereby reducing the amount of air flowing into the exhaust chamber. Conversely, when the ball is moved closer to the seat, reducing air flow into the output port, the valve moves farther from the seat, allowing more air to flow from the output port to the exhaust port.

The output port will be connected to another pressure element in a receiving instrument, and there will be an air flow from the ~~air-supply~~ chamber to the input port only long enough to reach a state of equilibrium after a change in nozzle pressure. Air flowing from the output port to the exhaust port, which is regulated by the valve position with respect to the valve seat, is constant for every condition of equilibrium. This will change only when the nozzle pressure changes. Air flow from the input port to the exhaust port will increase with a decrease in nozzle pressure, and decrease with an increase in nozzle pressure.

The <u>reducing tube</u> that controls air flow through the nozzle also limits the flow to just the amount that can flow through the nozzle when the flapper-nozzle clearance is greatest.

The gain of most pneumatic amplifiers is usually about 15 ~~to~~ 20. A very common amplifier used in many industrial instruments has a gain of 16. For this relay, a change in nozzle pressure of 0.75 psig results in a change in output of 12 psig. This output change results from about 0.006 inch of flapper travel. Figure 4 illustrates a pneumatic relay.

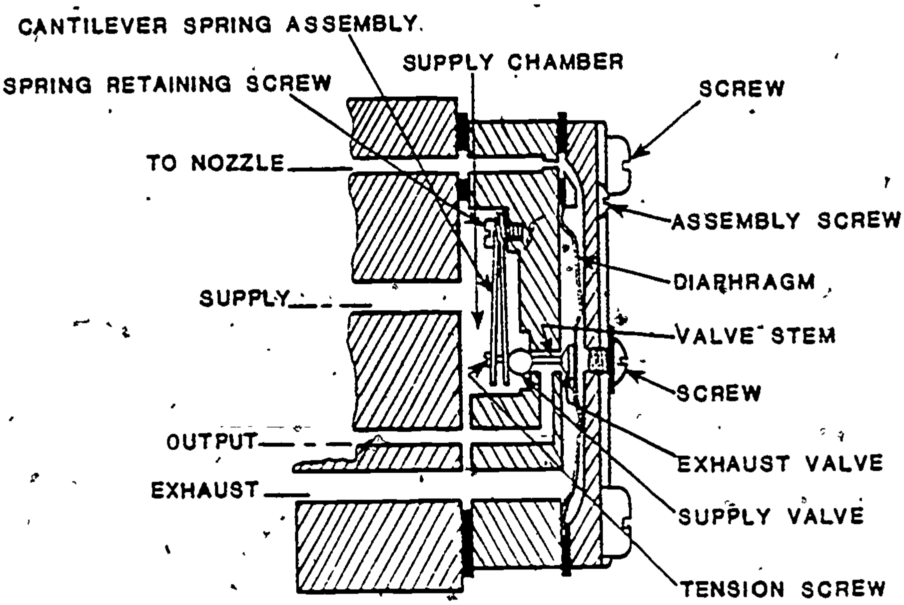


Figure 4. Pneumatic relay.

Feedback

As noted previously, flapper travel required to generate a 100% output span (12 psig) is very small. To eliminate erratic output responses by increasing the stability of pneumatic devices, a technique of applying <u>negative feedback</u> to the flapper-nozzle mechanism is used to achieve an operation principle known as force balance operation. This principle is illustrated in the temperature transmitter shown in Figure 5.

The two forces acting on the force bar (Figure 5) are balanced to create an equilibrium condition in such a way that there is no movement of the bar for a stable operating point. When temperature of the bulb increases, the measurement bellows expands, increasing the measurement force.

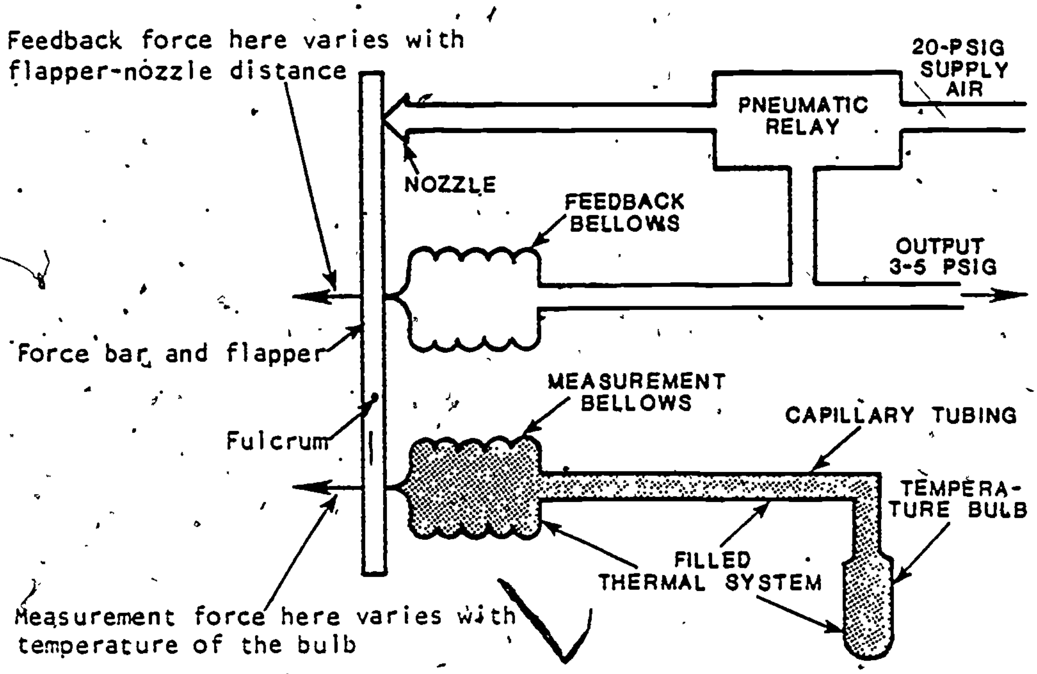


Figure 5. Force-balance temperature transmitter.

This causes the force bar to rotate in a clockwise direction around the pivot point, or fulcrum. This action brings the flapper closer to the nozzle and increases the nozzle back-pressure which is amplified by the relay. The result is an increase in output pressure, which is then applied to the feedback bellows. This increase in pressure causes a force on the force bar - which results in a counterclockwise rotation. The force applied by the feedback bellows will be sufficient to restore the force bar to equilibrium (no movement).

The force bar (flapper) is slightly closer to the nozzle, and output pressure has increased to a new level that is proportional to the temperature that caused the increase in measurement force. In the force balance terminology, the initial measurement force is the force, and the resulting force generated by the feedback bellows is the balance. For every change in temperature, an output will be produced and applied to the feedback bellows that will counter the initial measurement force. It can be seen that the amount of balance needed to counter a given measurement force will be governed by the fulcrum location along the force bar. In practice, the fulcrum point is adjusted to establish the mechanical advantage of one bellows in relationship to another in order to set the measurement span of the instrument.

Force Balance Differential-Pressure Transmitter

The pneumatic d/P cell shown in Figure 6 is used in many industrial applications to measure fluid flow, liquid level, and pressure. The process is connected to the low- and high-pressure connections of the instrument. The pressure connection arrangement must be such that one pressure must always be greater than the other. This causes the d/P cell output always to be positive with respect to a reference level.

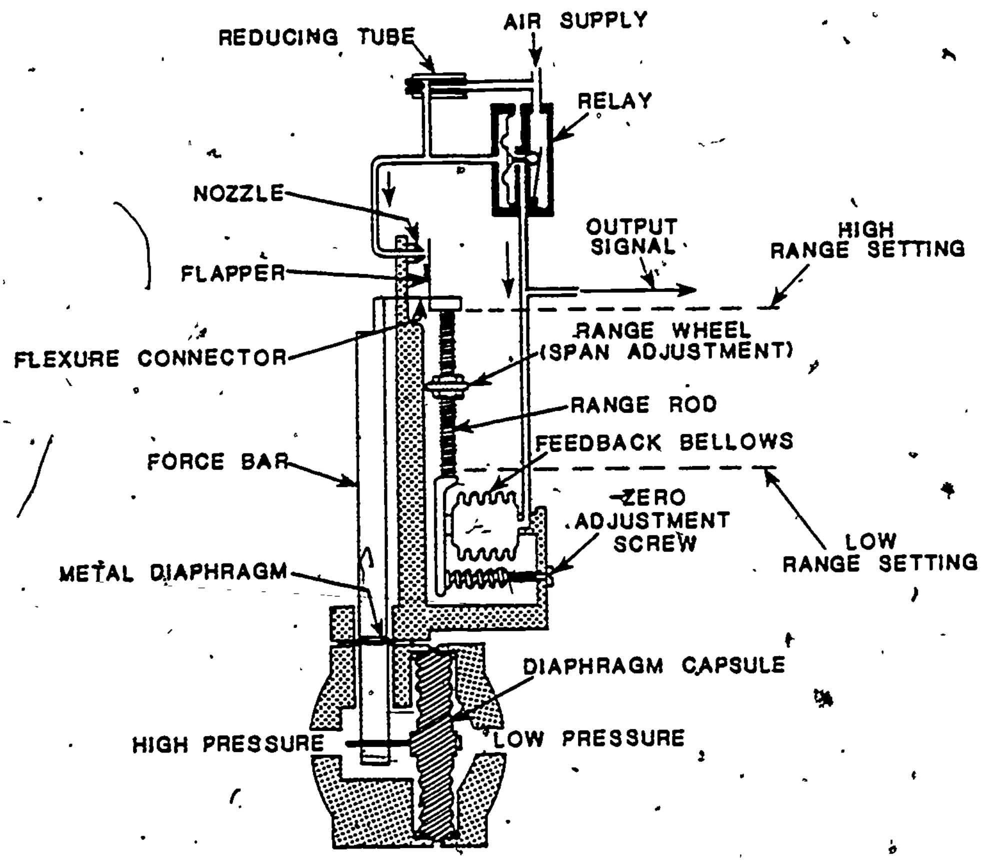


Figure 6. Pneumatic d/P cell.

When pressure on the high-pressure connection is increased, the capsule (which separates the high- and low-pressure chambers) flexes slightly and moves to the right. This causes the upper portion of the force bar to move to the left, bringing the flapper closer to the nozzle, thereby increasing the nozzle back-pressure. After being amplified by the relay, this pressure increase is applied to the feedback bellows, creating a balance force that affects the initial change in measure force on the capsule. Therefore, output pressure of the d/P cell is proportional to the differential pressure on the capsule.

The range wheel or span adjustment can be moved up or down along the range rod to change the mechanical advantage of the feedback or force balance system.

Assuming an initial stable differential pressure on the capsule and an instrument output in the operating range of 3-15 psig, a change in output will occur only when the differential pressure on the capsule is great enough to create a force on the force bar that is sufficient to overcome the force exerted by the feedback bellows. When this is the case, output will change and will continue to change until the force applied by the feedback bellows can restore a state of equilibrium on the force bar. When the range wheel is at the bottom of the force bar, the mechanical advantage of the feedback bellows is the least. Therefore, smaller force is required to overcome the force of the feedback bellows and to position the flapper with respect to the nozzle. This condition represents a low range setting of the instrument. When the range wheel is at the top of the range rod, the instrument is set for a higher range of differential pressure. Commercial d/P cells are available with adjustable ranges from zero to several hundred inches of water pressure.

Pneumatic differential-pressure transmitters, like most pneumatic instruments, have a standard output range of 3-15 psig. The "live zero" of 3 psig is desirable because lag time in transmission lines is reduced from what it would be if the line were empty at 0 psig. In addition it is easier to detect a "dead" instrument, or one that has no output in case of system malfunction.

To determine the relationship between process measurement and a transmitter output, standard scaling and spanning procedures are used. That is, percent of process measurement corresponds to an equal percent of transmitted signal. This will be illustrated by Examples A and B.

EXAMPLE A: DETERMINATION OF OUTPUT VALUE.		
Given:	a.	Input range of a d/P cell is 200" of water.
	b.	Output range is the standard 3-15 psig.
Find:		The output value corresponding to 35".
Solution:	a.	The percent of input range is: 35/200 (100) = 17.5%.
	b.	The output range is 15 - 3 = 12 psig. 17.5% (12 psig) = 2.1 psig. This is the amount of output caused by 35" of differential. The actual output value is 2.1 psig above 3 psig, (zero reference level), or 5.1 psig.

EXAMPLE B: DETERMINATION OF APPLIED DIFFERENTIAL.		
Given:		The input range of a pneumatic d/P cell is 150".
Find:		Differential applied to the instrument when the output is 7.4 psig.
Solution:	a.	To find the output as a result of differential pressure applied, the zero reference level of 3 psig is subtracted from the output. 7.4 psig - 3 psig = 4.4 psig.
	b.	The 4.4 represents 36.6% of the total output $\left(\frac{7.4 - 3}{15 - 12}\right)$ 100 = 36.6%.
	c.	The input that caused this response in output is: (150" water)(36.6%) = 54.9" water.

The pneumatic differential-pressure and temperature transmitters discussed are only two of several types of pneumatic transmitters in use in industrial applications. All operate on the following force balance or motion balance concept: A change in measured variable changes the flapper-nozzle relationship, generating an output response that then is applied to a feedback bellows. This results in a balance that is equal to and opposite the initial measuring force.

PNEUMATIC CONTROLLERS - FORCE BALANCE TYPE

In spite of the many recent advances in control hardware, the principles involved in automatic feedback control that were first developed by pneumatic feedback controllers are still valid and presently being employed. Even in direct digital control applications where a computer solves a control algorithm to control a variable, the procedures involved are similar to those performed by a pneumatic feedback controller. The major difference in the two operations is the speed of response: the computer is much faster. Although speed is an important consideration in fast-acting processes, sophistication beyond that of a pneumatic analog controller is seldom used. However, the discussion at this point is not designed to compare the two methods of control, but to provide a basis for the understanding of control principles. It is felt that this can best be done by presenting the operation of a pneumatic controller. When confronted with other control methods, one realizes that identical functions can be performed by a less complicated pneumatic controller, as shown in Figure 7.

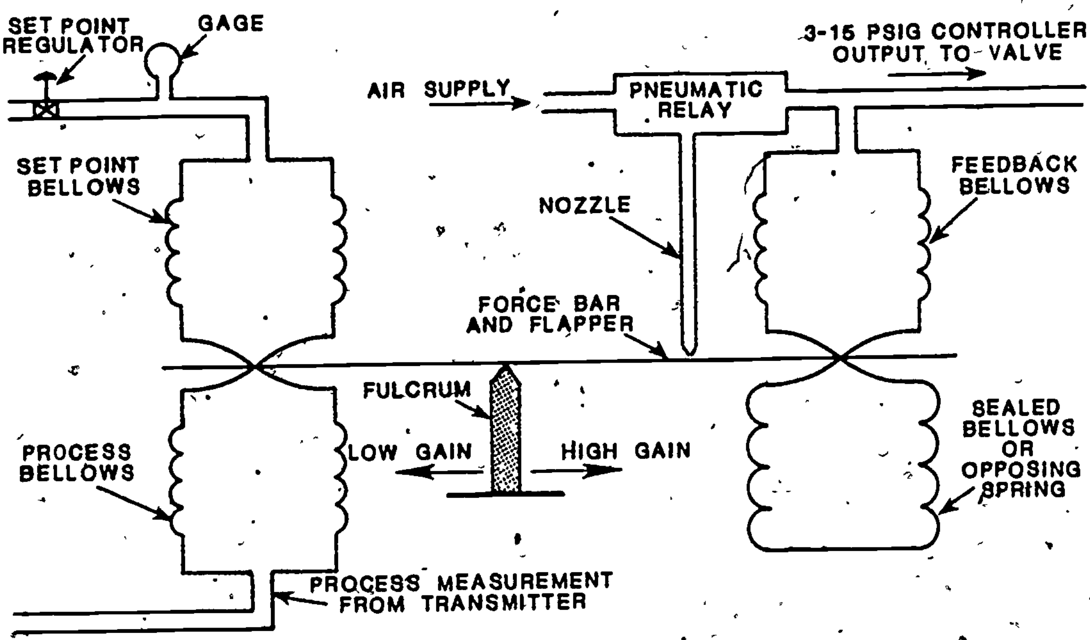


Figure 7. Pneumatic controller.

The purpose of a controller is to balance supply and demand in a process at a desired condition. The principle was discussed in Module IC-01; therefore, a review of that module is recommended at this time. A process supply and demand is achieved when the set point and process bellows in the controller generate equal forces on the force bar to produce an equilibrium state. When this condition is met, the force bar will be stable and the flapper-nozzle relationship will be such that the controller output is positioning the control valve to maintain the process at set point. A load change or set-point change will upset the equilibrium and cause the force bar to move. This changes the flapper-nozzle relationship, and then the controller output changes.

Assume that the controller in Figure 7 is controlling a level process and that the pressure in all bellows is such that the force bar is in equilibrium. If the controller output were connected to a valve, adding material to a level process, the valve would be positioned by the controller to manipulate the liquid supply to the level process equal to the material leaving the process. If flow that goes out of the process is the load or demand, and the controlled flow that goes in is the supply, the level will be maintained when the two flows are equal. The controller's function is to maintain this condition.

If one desires to increase the control point of the level in the process, the operator can increase the controller set point to this new desired value. The controller - if it is performing its function properly - would position the control valve to increase the flow of material to the process to increase the level to the desired control value as specified by the set-point.

Note that in Figure 7 an increase in the set point to the controller (that is, an increase in pressure in the set point bellows caused by changing the set-point regulator) will cause the force generated by the set-point bellows to overcome that of the process bellows, causing the force bar to rotate counterclockwise. This will position the flapper closer to the nozzle and cause the controller output to increase. The output will increase until a force is generated by the feedback bellows to balance the force that produced the output. The force balance principle still works. As explained earlier, the increased controller output will position the valve to increase the level.

PROPORTIONAL CONTROL MODE

Some processes can absorb large, sudden energy bursts; whereas others would be driven beyond control point by such changes. Recall from Module IC-01 that a controller must add material or energy to a process at a rate to which the process can respond. For example, the temperature of a shower cannot be controlled within tolerable limits by turning either the cold or hot water off and on. A bathtub, (with proper mixing), can be controlled by ON-OFF operation of either the hot or cold water valves.

Industrial processes vary in dynamic characteristics; and, to balance the process supply with the process demand (load), controllers also must have different dynamic characteristics. The most important controller characteristic is the gain. Gain of a controller determines the relationship between the controller input and output. Assuming the set-point valve is held constant (Figure 7), controller output is a function of the flapper movement caused by the process bellows. If the fulcrum is moved to the left (lower gain), the mechanical advantage of the feedback bellows is greater and a smaller force is required to balance a change in force caused by the process bellows. Conversely, when the fulcrum is moved to the right (higher gain), a larger balance force is required. Since the balance force is provided by the pressure in the feedback bellows and a greater output is required for a greater force, the controller gain is varied by moving the fulcrum. Moving the fulcrum establishes the mechanical advantage of the feedback bellows for the parallel lever-type controller (Figure 7).

A proportional controller will have a fixed output that is determined by the controller gain and the error signal on the input. This is the difference in pressure on the set point and process bellows. This difference in pressure, or deviation, is called the error signal. The error signal is necesarry for any controller action. The output of a proportional controller is equal to the error signal multiplied by the controller gain (Equation 1).

Output of Proportional Controller = (PV - SP)(Gain) Equation 1

where: PV = Process or measured variable.
SP = Set point.

If a load change on a process required a 10% change in controller output to position the valve enough for the supply to again equal the process demand or load, the amount of process change required to create an error signal large enough to produce the 10% change in output would be determined by the controller gain setting (Equation 1).

$$\begin{aligned} \text{Output} &= \text{Gain (PV - SP)} \\ &= \text{Gain (error signal)} \end{aligned}$$

When the SP value is constant, the error signal can only be a result of a deviation in the process variable. The following is offered as an example (Example C):

EXAMPLE C: CHANGE IN PROCESS VARIABLE.	
Given:	A controller has a gain of 0.5. The required controller output to compensate for a load change on the process is 5%.
Find:	The change in process variable required to produce the desired output.
Solution:	The error signal listed in Equation 1 will be expressed as a percent that is equal to the amount of change in process variable required.
	$$\text{Error signal} = \frac{\text{Output}}{\text{Gain}} = \frac{5\%}{0.5} = 10\%.$$

As shown in Example C, when gain is decreased, the required deviation to produce a given output increases. Thus, the need for automatic reset increases with low-gain controller applications.

In situations where a low controller gain is necesary to maintain process stability, a condition known as residual offset will result. Residual offset is characterized by a variation between the process variable and the set point after a response to a process disturbance or load change. An example of this would be:

> A water tank employs a proportional pneumatic controller to regulate the water level to a depth of 15 feet (set point). The controller has a low gain; thus, when there is a sudden change in the amount of water flowing from the tank, the inlet valve does not open until the level of the water had dropped several feet. This depressed level will be maintained until a decrease demand causes the input to fill the tank faster, thus causing the process variable to approach the set-point level.

PROPORTIONAL PLUS RESET CONTROL

From the previous discussion, one can see that a control action that will cause the controller output to continue to change is needed to eliminate the residual offset. This function is provided by the reset control mode, which repeats the proportional output until the residual offset is eliminated. Reset units are expressed as minutes per repeat, or repeats per minute, where the term "repeat" refers to the proportional output.

The controller in Figure 8 is like the proportional-only controller in Figure 7, except that a reset and derivative control mode is added. This type of controller is commonly referred to as a PID controller. The "I" refers to integral, which is the same as reset.

To explain operation of the reset portion of the controller, assume that the restrictor on the derivative portion is fully open, reset restriction is partially open, set-point bellows pressure is equal to the measurement bellows pressure (9 psig, for example), and the controller is in equilibrium wih a 9-psig output. Suppose, then, that a load change on the process occurs - an increase, for example, which would cause the pressure on the measurement bellows to increase. This sequence of events would cause the force bar to rotate counterclockwise about the fulcrum, thus positioning the flapper closer to the nozzle. Output would increase because of the increase in nozzle back-pressure, and the increase in output would continue until the pressure on the feedback bellows is great enough to create a force on the force bar to offset the initial change in force created by the measuring bellows. The procedure just described defines proportional action of a force balance controller. With a proportional-only controller, the output change produced by the increase in process measurement would establish a new equilibrium condition on the controller, and the output would be stable at this new value. With reset action, however, the controller is not in a stable state after the proportional output has been generated. The reset mode will continue to change the output.

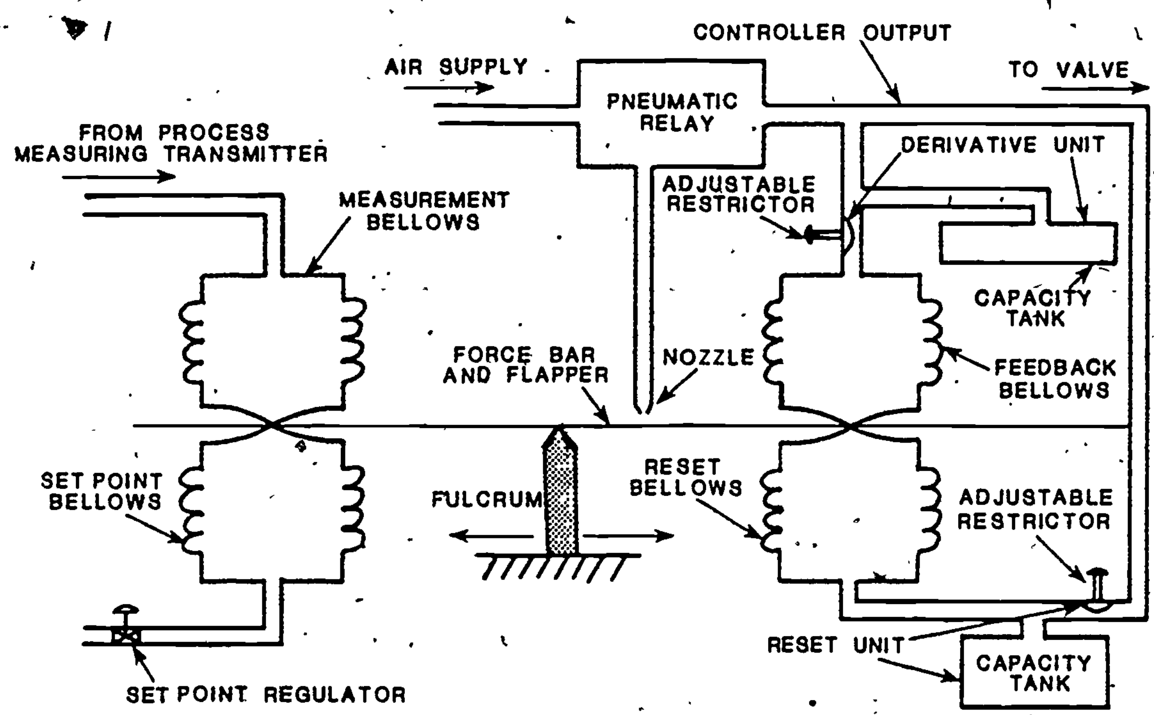


Figure 8. Proportional-plus-reset-plus-derivative controller.

Before the change occurred in the process measurement, the controller was in a stable state. The pressures in the feedback and reset bellows were equal. The proportioning action of the controller - after the change in process measurement - increased the pressure in the feedback bellows. At that instant (at the end of the proportional action) the pressure in the feedback bellows is greater than that of the reset bellows. This is because of the reset restrictor, which limits the flow of air from the output line into the reset bellows. As air continues to flow through the reset restrictor, pressure in the reset bellows will increase, moving the flapper closer to the nozzle. This move will cause controller output to increase beyond the initial proportional output level. The reset action opposes the operation of the negative feedback, or proportional bellows, and, in effect, produces positive feedback in the balance portion of the controller. This additional reset output will continue until the process is returned to set point - at which time the pressure in the reset bellows will equal that in the feedback bellows. The procedure of setting the reset restrictor at a value that will allow the process to change in accordance with the reset output will be discussed in a later module of this course.

A decrease in process measurement will cause a decrease in controller output: first by proportional action, then by reset. Instead of pressure building up in the reset bellows over a period of time to increase output, pressure in the bellows and the reset capacity tank must decrease and cause a continuing decrease in controller output.

When the reset restrictor is fully OPEN, the contoller operates as a high-gain controller. When the reset restrictor is fully CLOSED, the controller acts as a proportional-only controller.

PROPORTIONAL-PLUS-DERIVATIVE CONTROL

The derivative control mode is needed in most temperature processes to increase controller output beyond the proportional level to overcome thermal momentum of the process and equipment. The need for derivative occurs when the process is changing from set point; and it is greatest when the process is changing at a high rate of speed. Because the derivative control mode operates on the rate of change of the process variable, it is sometimes called rate.

In explaining the operation of the derivative control mode (refer to Figure 8), assume the controller is in equilibrium, with all forces balanced and with a stable output. The adjustable derivative restrictor is partially OPEN. An increase in process measurement will cause an increase in output as a result of proportional action. The derivative restrictor will delay negative feedback of the feedback bellows by restricting air flow into the bellows. This will cause the output to be greater than it would be with proportional action only. The controller acts as if it were operating at a different gain caused by the delay in negative feedback. The amount of delay in negative feedback is determined by amount of restriction in the air flow to the feedback bellows. The derivative control mode will respond only to a rate of change of error signal (the difference in process measurement and set point) because the greater the change, the greater the pressure drop across the derivative restrictor. Amount of derivative output is determined by the setting of the derivative restrictor. As with other control-mode adjustments, this amount should be matched to the process. These adjustments are made when tuning the controller.

CONTROLLER ACTION

Controllers may be either the direct-acting type of the reverse-acting type. This concept was covered in Module IC-01. A direct-acting controller will have an increase in output, with an increase in process measurement. Reverse-acting controllers will have a decrease in output, with an increase in process variable. The controller in Figure 7 is a reverse-acting controller because it shows an increase in pressure on the measurement bellows moving the flapper away from the nozzle and, thus, decreasing the controller output. The controller shown in Figure 8 is a direct-acting controller because it shows an increase in process measurement, causing an increase in the controller output. Controller action can be established by instrument connection or, more commonly, by a switching block that selects the desired pressure-bellows orientation. In some controllers - usually the motion balance type - the action is determined by positioning the nozzle with respect to the fulcrum of the force bar.

CONTROLLER SPECIFICATIONS

Most industrial process controllers can be purchased with the following options:

- Proportional-only.
- Proportional-plus-reset.
- Proportional-plus-derivative.
- Proportional-plus-reset-plus-derivative.

Proportional-only controllers seldom are used because of the residual offset in such applications - even with high controller gain. Derivative controllers are used most often with temperature processes. The reset and derivative control modes are independent of each other. Although processes that require derivative controllers will operate at a moderate-to-high gain, they will still need reset; therefore, PID controllers are used. The selection of control modes for controller applications usually will be either proportional-plus-reset or proportional-plus-reset-plus-derivative. When specifying controllers for process control applications, it is best to have the control-mode option available. If, when putting the controllers into operation, it is determined that reset and/or derivative is not needed, these control modes can be eliminated by adjusting each mode for the minimum amount.

MOTION BALANCE PNEUMATIC INSTRUMENTS

The force balance pneumatic instruments that have been discussed comprise one broad classification of pneumatic instruments. Motion balance instruments - divided into angle-motion and linear-motion types - are another classification. Motion balance instruments generally perform the same function and share similar operation principles with force balance instruments. The angle-motion type of motion balance instrument is the more popular of the two.

ANGLE-MOTION BALANCE INSTRUMENTS

A fundamental, Type 3, angle-motion balance mechanism is shown in Figure 9. The measurement motion is produced by a pressure element connected to the process, and the balancing motion is produced by the generated output. The detector, a flapper-nozzle arrangement, is positioned to detect any displacement of the floating lever.

To understand the operation of the mechanism in Figure 9, assume, initially, that the system is in a stable and balanced condition with a steady output. An increase in the measurement signal will rotate the fixed measurement level counterclockwise, thereby lifting one end of the floating lever that rotates about the balancing floating pivot. This raises the center portion of the floating lever. The detector responds to this displacement of the floating lever by decreasing the output pressure - which then is applied to the spring-opposed feedback bellows. This decrease in output pressure produces a change in the balancing motion and, thus, rotates the balancing lever counterclockwise. The balanced end of the floating lever is lowered, balancing that end of the lever. Recall that the measurement signal initially raised the measuring floating point, thereby raising the center

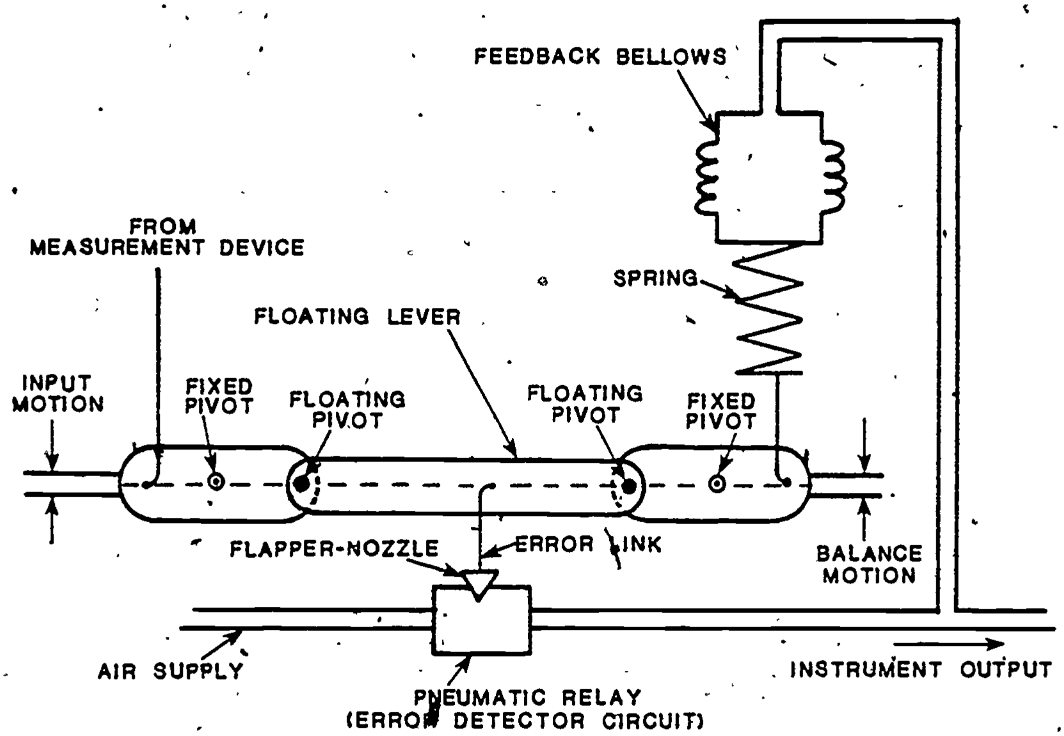


Figure 9. Type 3, Angle-motion balance mechanism.

portion of the floating lever. This action generated an output, which created a balance motion that offset the initial measuring force. Negative feedback is still working.

The motion balance transmitter just described (Type 3) generates a pneumatic output proportional to a measurement input motion. Therefore, output is proportional to input. This action fulfills the purpose of a transmitter - which is to convert a measurement to a proportional pressure.

Besides the Type 3 motion balance mechanism, Type 1 and Type 2 mechanisms are also available. Type 2 has one fixed pivot and one floating pivot operating the floating lever. Both floating and fixed pivot points are eliminated in the Type 1 mechanism. Types 1 and 2 mechanisms are shown in Figure 10. Operation of these devices is similar to that of the Type 3 system; therefore, further discussion on the operation is not necessary.

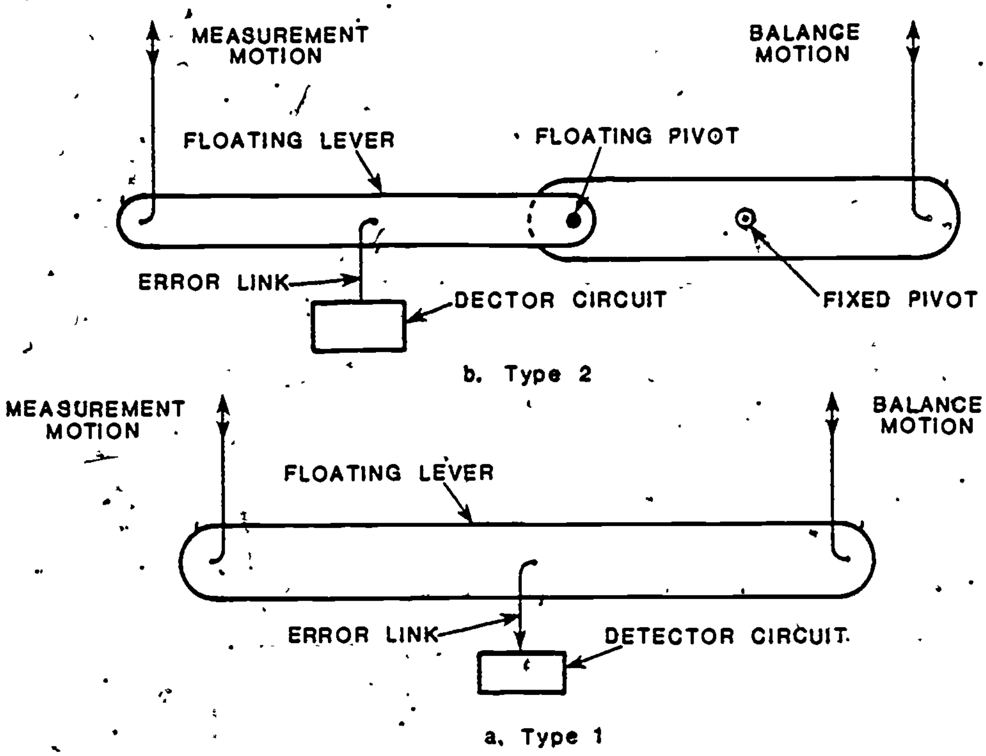


Figure 10. Types 1 and 2 angle-motion balance systems.

SIGNAL TRANSDUCERS

Many control loops utilize both electronic and pneumatic instruments. A diaphragm-operated control valve, which is positioned by a proportional 3-15 psig signal, is used as the final control element in most applications. When electronic transmitters and controllers are employed, it is necessary to convert the electronic signal from the controller to a proportional 3-15 psig signal. A current-to-pressure transducer (I/P) is used for this purpose.

CURRENT-TO-PRESSURE TRANSDUCERS

The block diagram in Figure 11 shows an application using an I/P transducer. The operation of the force balance I/P transducer in Figure 12 is similar to the other force balance discussed. The signal from the controller applied to an electromagnet creates the measuring force on the force bar, which is rotated clockwise about the point. The flapper is positioned toward the nozzle, increasing the back-pressure and output. The pneumatic output is applied to the feedback bellows, creating a balance force on the force bar. For any particular input and corresponding output, the force bar is in equilibrium.

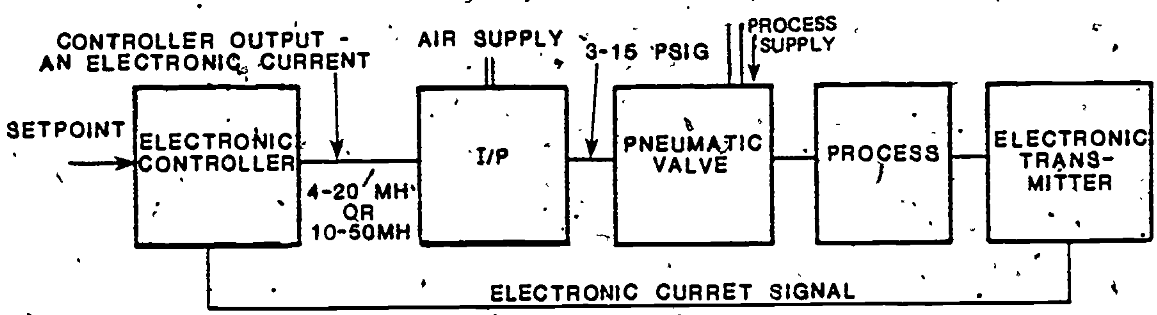


Figure 11. Application of a current-to-pressure transducer in a control loop.

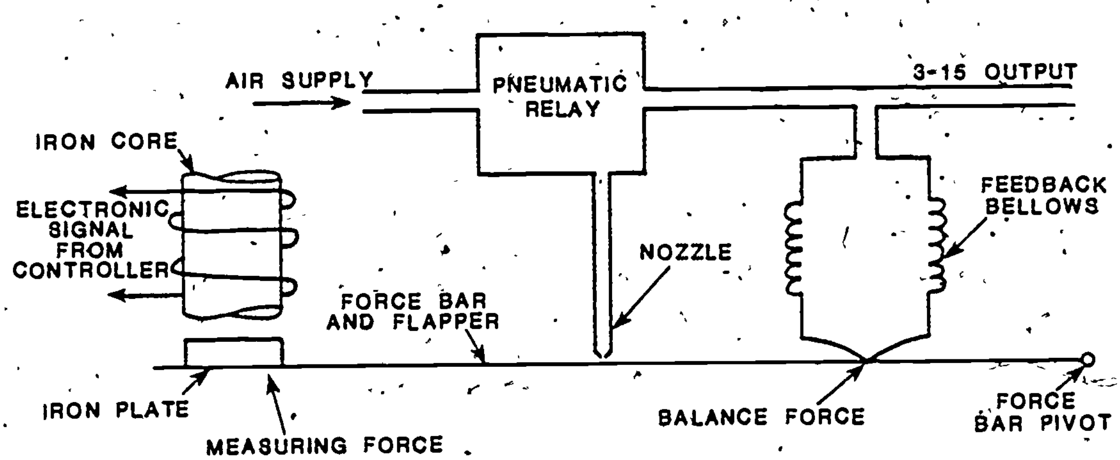


Figure 12. I/P transducer.

PRESSURE-TO-CURRENT TRANSDUCERS

Though not as common as I/P transducers, P/I (pressure-to-current) transducers sometimes are used in control loops. A pneumatic transmitter may be used, and the 3-15 psig signal could be changed to a 4-20 mA signal for an electronic controller. Then, controller output probably would be converted back to a pneumatic signal to operate a valve. This double conversion is not feasible, but it may be necessary in some applications.

Operation of P/I transducers utilizes a force balance principle. The input pneumatic signal is applied to a pressure element that moves the contact on a variable resistor, thereby changing a current value. The current changes the strength of an electromagnet to provide a balance force to offset the measurement force of the pressure element.

GENERAL APPLICATIONS OF PNEUMATIC INSTRUMENTS

Two major advantages of pneumatic instruments are their simplicity and their reliable, safe operation. They can be used in hazardous explosive atmospheres where electrical and electronic instruments could ignite an explosive mixture and cause an explosion. The greatest disadvantage to the use of pneumatic instruments is their slow response time when compared to their electronic counterparts.

TRANSMISSION LAG

Transmission lag in pneumatic instruments is the time required for a pressure change at one end of the line to effect a response on the receiving end. Of course, to reduce the overall instrument response time, the transmission lag time should be held to a minimum. This can be done by reducing the volume of the line and of the receiving instrument and by keeping the transmission distance to a minimum. Standard transmission line size is 1/4" inside-diameter (ID) tubing, and the terminating volume of the receiving instrument should be no greater than two cubic inches for minimum acceptable and reliable results. Maximum transmission distance depends upon specific application, but it is generally less than 2,000 feet. To reduce the effect of transmission lag time, volume boosters and valve positioners should be used.

Volume Boosters

A volume booster is a relay-operated deivce that maintains a pressure at the receiving end of a transmission line by using a supply at that end. This reduces the time required to maintain a pressure at the receiving end from a supply at the transmitting end. Figure 13 illustrates the principle of a volume booster. The much-reduced air flow through the transmission distance greatly reduces the time required to maintain transmitted pressure at the receiving end.

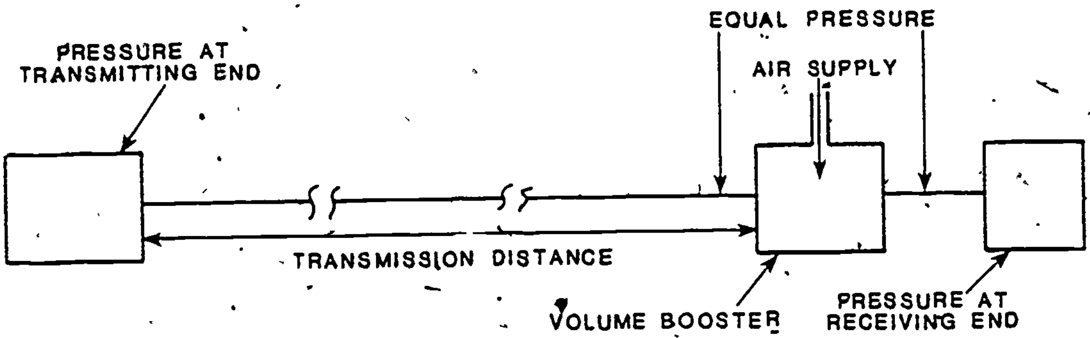


Figure 13. Block diagram of volume-booster application.

Valve Positioners

Pneumatic control valves - particularly those with large diaphragms - greatly increase volume in the controller output circuit. A volume booster sometimes is used for the purpose of reducing time required to position a control valve. However, a valve positioner is more commonly used because it not only can act as a volume booster, but it is a true valve-position controller. A valve positioner is mounted on the valve, with a feedback line connected to the valve stem. It is a motion balance device. Input motion is provided by a bellows that receives the controller output signal. The bellows positions a pilot valve (similar in function to a pneumatic relay) which produces an output. The pilot valve output is applied to the valve diaphragm, and the valve diaphragm positions the valve until a balance motion is generated by travel of the valve stem. A block diagram of a valve positioner is shown in Figure 14.

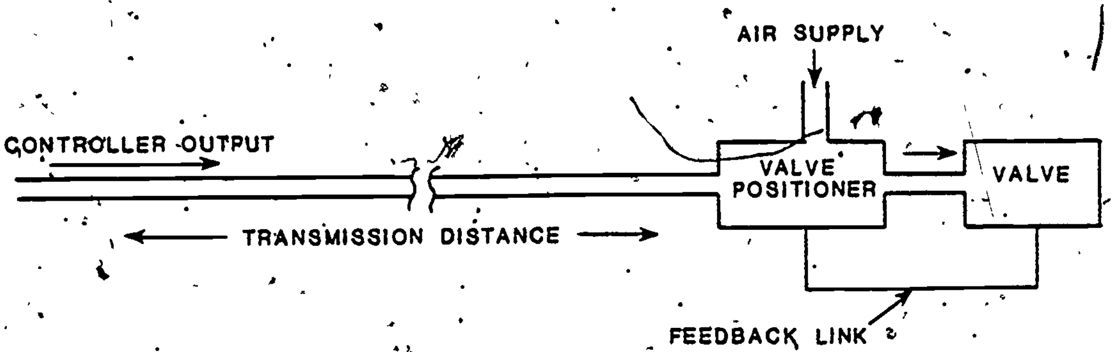


Figure 14. Block diagram of a valve positioner.

CONCLUSION

No attempt has been made in this module to discuss use and operation of all pneumatic devices. General operating principles of all active pneumatic instruments - those that generate a signal or output proportional to one or more inputs - have been presented. Those operating principles are either a force balance operation or a motion balance operation. When these concepts are realized and applied to appropriate devices, understanding of pneumatic instruments can be demonstrated.

EXERCISES

1. Draw a functional diagram of a pneumatic transmitter. List and describe operation of the following components:
   a. Flapper.
   b. Nozzle.
   c. Air-flow restrictor.
   d. Feedback bellows.
2. Answer the following questions:
   a. Why is the flappler sometimes called a baffle?
   b. Why is the feedback bellows sometimes called a proportioning bellows?

    c. How is feedback action related to instrument gain?

3. Draw a functional diagram of a pneumatic controller. List and describe the operation of the components listed in Exercise 1.

4. Answer the following questions.
    a. What is an error signal, and how is it detected?
    b. Explain the proportional action of the controller.
    c. Explain the operation of reset with regard to feedback.
    d. What causes the derivative output? Is this negative or positive feedback?

5. A controller can be divided into four mechanisms:
    a. Detection mechanism.
    b. Comparison mechanism.
    c. Feedback mechanism.
    d. Gain mechanism.

   Identify and explain the operation of each mechanism on the controller drawn in Exercise 3. How does operation of a pneumatic controller compare with that of a Wheatstone bridge?

LABORATORY MATERIALS

A moment balance version of a force balance pneumatic transmitter, such as a Foxboro Model 13A d/P cell or a Taylor Model d/P cell. It is important that a complete calibration and instrument manual be available.

A moment balance version of a force balance pneumatic controller, such as a Foxboro Model 58 with field-mounted connection block; a Taylor Transcope series; or a Fischer and Porter Model 45. It is important that a complete instruction manual be available.

A pneumatic test bench with the following:

2 - 0-20 psig pressure regulators.

1 - mercury manometer ~~or pressure gage to~~ read inches of water.

1 - mercury manometer or pressure gage to read pounds per square inch of pressure (0-30 psig).

Assorted tubing and piping to connect the equipment and test instruments for calibration and alignment procedures.

LABORATORY PROCEDURES

LABORATORY 1. OPERATION AND CALIBRATION OF A d/P CELL.

1. Connect the pneumatic d/P cell, as shown in Figure 15. Instructions given are general in nature to outline standard calibration procedures. Actual calibration procedures for a specific instrument are given in the instrument's instruction manual; they should be followed in exact procedures.

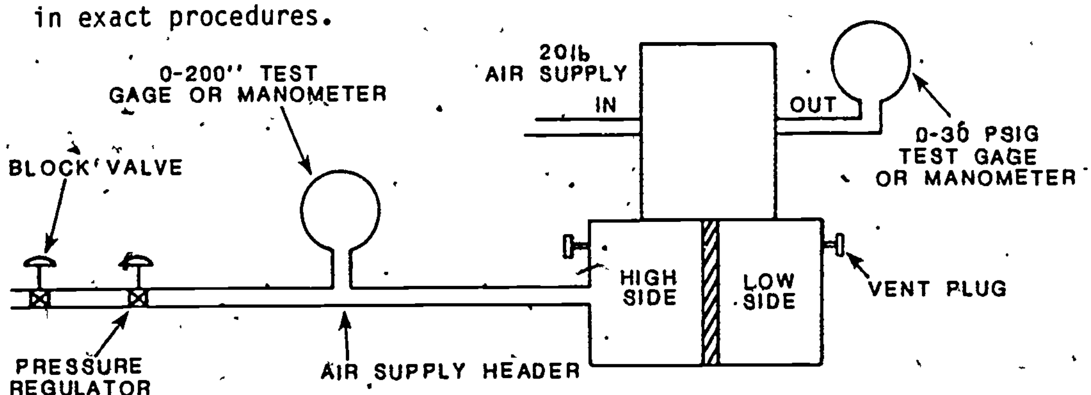


Figure 15. Pneumatic d/P cell.

2. Visually inspect the d/P cell; and, with the aid of the instruction manual, locate and identify the following:
   a. Range adjustment.
   b. Zero adjustment.
   c. Feedback bellows.
   d. Relay.
   e. Restrictor.
   f. Force bar.
   g. Flapper.
   h. Nozzle.

3. Using calibration procedures listed in the instruction manual, calibrate the d/P cell for two different ranges within the variable full-scale range.
4. Observe (and note for later discussion) the following:
   a. Range-change mechanism.
   b. Zero mechanism.
   c. Force bar operation.

LABORATORY 2. BENCH-CHECKING A PNEUMATIC CONTROLLER.

The following procedure is to demonstrate operation of bench-checking a pneumatic controller. In checking a controller, the following calibration procedures are performed:

- Calibration of input or measuring portion.
- Calibration of set-point adjustment.
- Calibration of manual output generation and measuring portion.
- Controller alignment.

The first three functions can be performed by simple calibration procedures outlined in previous modules of this series. Because actual procedures vary with controller types, calibration procedures in the instruction manual for the controller in use should be followed. General calibration procedures are (1) to apply a measured simulated input to the device under test, (2) to accurately measure output or response, and (3) to make appropriate zero and range adjustments as needed to cause output to coincide with the corresponding input.

Controller alignment is needed to make certain that the comparison mechanism, feedback mechanism, detector mechanism, and gain mechanism all are properly related to each other. This usually can be done in either open-loop or closed-loop applications. The actual procedure used will depend upon the controller and the instruction manual.

1. Connect the controller to the test equipment used in Laboratory 1, and calibrate the measuring portion of the controller. The controller should be in the manual mode of operation for this and all following procedures.

2. Calibrate the manual output regulator and valve loading indicator.
3. Calibrate the set-point regulator and set-point indicator.
4. Perform controller alignment procedures, as given in the instruction manual.
5. Disconnect and secure all equipment. Procedures are now complete.

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Instrumentation Training Course. Vol. 1, "Pneumatic Instruments." Howard W. Sams Technical Staff, ed. Indianapolis, IN: Howard W. Sams and Co., 1978.

GLOSSARY

Active pneumatic instrument: Devices that generate a signal, usually for transmission.

Control mode: Controller characteristics that determines the relationship between a controller's input and output.

Derivative control mode: Control mode that generates a controller output proportional to the rate at which the error signal is occurring (also called rate).

Flapper nozzle: A device used to detect a small amount of movement and, by doing so, generate a usable signal.

Force balance: The operating principle of most active pneumatic instruments. A change in measurement generates an output applied to the feedback mechanism. Output continues to change until feedback force is equal to measuring force.

Force bar: A lever used in pneumatic instruments with the measuring force applied to one end and the output force applied to the other end. An unbalance in forces causes movement that changes the flapper-nozzle relationship.

Pneumatic relay: A device used to amplify nozzle pressure and increase volume.

Negative feedback: The means of utilizing a portion of an instrument's output signal for stabilization by generating a force equal and opposite to that which produced the initial output.

Proportional controller: A controller that generates an output proportional to the amount of deviation between process variable and set point (error signal).

Reducing tube (restrictor): A restriction port in the relay, usually removable for cleaning, which limits air flow to the nozzle to an amount that can flow through the nozzle without creating a back-pressure.

Reset control mode: Control mode that generates a controller output proportional to the time of error signal (also called integral).

Residual offset: Difference between process measurement and set point after a proportional response to a process disturbance or load change.

Transmission lag: Time required for a signal change to effect a response on the receiving end.

Valve positioner: A position controller mounted on a control valve to cause the valve to assume the position specified by the controller output.

TEST

INSTRUMENTATION AND CONTROLS

Module IC-06

"Pneumatic Controls"

Matching: Match the following terms with the appropriate definition:

_____ Reset

_____ Negative feedback

_____ Positive feedback

_____ Proportional

_____ Force Balance

_____ Derivative

_____ Controller Tuning

_____ Residual offset

_____ Transmission lag

_____ Controller gain

a. Feedback applied to an instrument input that opposes the change that initiates an original output.

b. An instrument system that produces an output, generating a force equal to and opposite the measuring force that caused the output.

c. Control mode that acts on the amount of deviation.

d. Control mode that acts on the time of deviation.

e. Control mode that acts on the rate of change of deviation.

f. Derivative output is a result of delayed negative feedback or ...

g. Delay time in signal transmission.

h. Reset control is used to eliminate ...

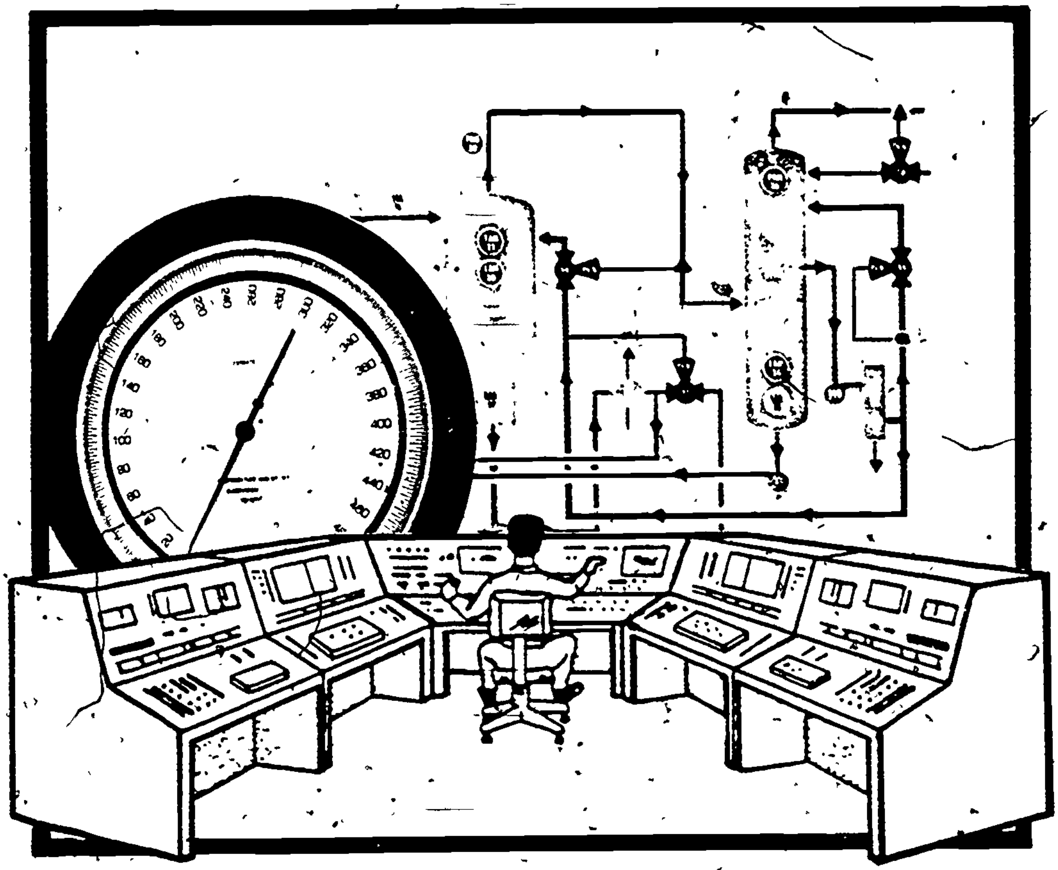
i. The need for reset control is inversely related to ...

j. The procedure for determining the correct control mode settings is accomplished by a method of ...

ENERGY TECHNOLOGY

CONSERVATION AND USE

INSTRUMENTATION AND CONTROLS



MODULE IC-07

AUTOMATIC CONTROL SYSTEMS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Equipment, systems, and processes can be controlled by a variety of techniques and instrumentation control systems. Some techniques, systems, or components will provide a "higher quality" of control than others.

The "quality" of an instrumentation control system is a relative measure of quantitative variations in the process parameters. The ideal, or perfectly-controlled, system or process would be in a steady state; i.e., the controlled parameters of pressure, temperature, speed, and so on, would be held to constant desired levels (set points). In practice, system operation is not ideal; parameters will vary between some upper and lower boundaries. (For example, temperature may fluctuate between 100°C and 110°C.) The width of these variations and the frequency with which a parameter oscillates between the boundaries determine the degradation in control quality.

The purpose of this module is to describe the procedure by which the dynamic performance of each control component is evaluated. Control-quality evaluation is discussed, and methods are presented for matching the dynamic properties of the controller to the process.

PREREQUISITES

The student should have a basic understanding of algebra and physics and should have completed Module IC-01 through IC-06 of Instrumentation and Controls.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Implement the operation of a closed-loop control system by performing the following:
   a. Install closed-loop control components on a combination level-flow process.
   b. Connect the instruments to perform closed-loop control functions.
   c. Make instrument adjustments to provide optimum process control. This includes controller tuning, transmitter range selection, and adjustment.
2. Describe a method of control quality evaluation and relate the effect of each control-loop component on the quality of the process. This will include a definition and explanation of the following terms:
   a. Gain:
      (1) Process.
      (2) Instrument.
   b. Capacity.
   c. Dead time.
   d. Lag time.
   e. Process stability.
   f. Process disturbance.

CLOSED-LOOP CONTROLS VERSUS OPEN-LOOP CONTROLS

The principles of closed-loop and open-loop controls were discussed in Module IC-01, and an open-loop control was implemented on a level process. For stable process operation containing few load changes or disturbances, open-loop control techniques may be adequate. However, this condition cannot be assumed in most industrial porcesses. Although some open-loop control applications exist in industry, they are the exception. Most control systems are closed-loop automatic feedback systems.

When properly adapted to a process, a closed-loop control system will perform its function of maintaining a balance between the supply and demand of a process.

CLOSED-LOOP OR AUTOMATIC FEEDBACK CONTROL AND CONTROL MODES

Most processes contain material and energy inputs and outputs. A single variable control system, the most common type, can control a balance between material or energy; but it cannot control both. Level processes are controlled by maintaining a material balance; whereas temperature processes are usually controlled by manipulating a material quantity - fluid flow, for example.

The principles of closed-loop control should be briefly reviewed. Consider the concept involved: A process will be stable when material entering (the supply) is equal to material leaving (the demand). To illustrate the principle involved, refer to the process in Figure 1. The level will be constant when flow leaving the tank is equal to flow entering the tank. Since flow entering the tank is an uncontrolled variable as far as the controller is concerned, the only means of controlling a material balance is by manipulating the flow leaving the tank. The control loop will perform this function.

Review Module IC-01 for the function of each component used in the control system. Although instruments discussed in this module can be of any type and can operate by either electrical or pneumatic transmitted signals, operating functions are the same as those explained in previous modules.

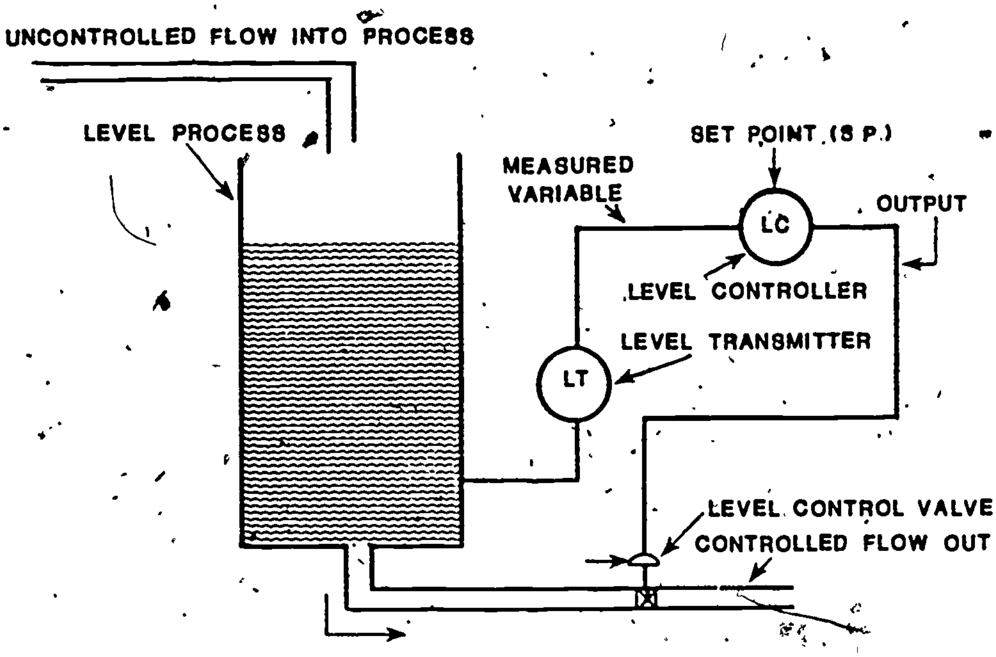


Figure 1. Closed-loop level process.

Assume that initial operating conditions are such that flow entering the tank is equal to flow leaving the tank and that level is stable. Consider the effect that an increase in the uncontrolled flow entering the tank would have on the process. With flow out being unchanged, the level would, of course, increase. Control action now begins.

The increase in level is detected by the level transmitter, which sends an increase signal to the controller. Prior to this level increase, the process was at the control point. The measuring bellows and set-point bellows of the pneumatic controller discussed in Module IC-06 were in equilibrium. As a result of the level increase, the increase in signal to the measuring bellows upsets this balance, and the controller output will change to open the control valve. This action increases flow out of the tank to compensate for increased flow into the tank. The operation just described makes automatic feedback control sound very simple - which it actually is. However, the explanation did tend to oversimplify the concept; several important considerations were overlooked.

When the set-point value is contant (as it was in the previous example) the only variable that will cause a stable controller output to change is the process - by way of the signal to the input bellows from the trans- mitter. The relationship between the input and output of a controller is described by the controller's transfer function. This depends on the control mode used and its settings. The following paragraphs explain how the process would react to a high-gain controller without reset or deviation.

ON-OFF CONTROL

A controller with a high gain will function as an ON-OFF, or two-position, controller. This concept specifies that the control valve will be either fully open or fully closed. When the level in Figure 1 increases above the set point, the error signal causes the valve to open completely. This will reduce the level; but with the valve in the wide-open position, flow out will exceed flow in. In this case, the level will fall below set point, at which time the valve again will close. Then the level process is in an unstable, or cyclic, condition. Amplitude of the cycle will depend on several factors, the most prominent being the physical and dynamic properties of the process itself.

It can be seen that, if the tank is narrow, the level will respond more to valve operation than it would if the tank had a relatively larger diameter. Actual size (volume) is not so much of a determining factor considering the flow-level relationship as is the volume-to-height ratio. A wide tank, for example, would undergo a much smaller change in level with sudden flow changes than a tank that had a low volume-to-height ratio (such as a very narrow tank). The size of the valve and piping will also affect the level-flow relationship. Regardless of specific process characteristics, when dynamic characteristics are such that an ON-OFF control can be used with an acceptable amount of process instability, it should be - and probably will be - used. However, most industrial processes require more stable control than the ON-OFF type can provide.

Many processes around the home are controlled by ON-OFF controllers. A furnace or air conditioner is turned on or off as required to maintain a temperature. The temperature is not controlled at an exact value, and cycling always will exist with two-position control. But temperature instability is within tolerable limits. Another example of ON-OFF control applications is control of level in a tank by controlling a pump motor on and off by a pressure or level switch.

PROPORTIONAL CONTROL

A much more stable control can be accomplished when the material can be more evenly balanced. The ON-OFF controller is able to control the process, as illustrated by the previous explanation. However, this cannot be done at an exact point. If flow out of the tank were caused to increase by an amount equal to flow entering the tank, the level would not cycle; but it would reach a stable condition following a change in load or disturbance variable. In other words, flow out should be in proportion to flow in or, more precisely, proportional to the error signal. Remember that controllers react to the error signal or deviation in process and set point. If there is no deviation, the controller output will not change. Output of a proportional controller will be in proportion to deviation.

In Module IC-06, it was explained that the output of a proportional controller is equal to the product of the deviation (error signal) and controller gain. This product is the instantaneous output that results from an error signal caused by a load change or set point change. When there is no error signal the controller will not function and does not seem to have a purpose. Actually, for this condition, the controller is doing exactly what it is supposed to do: maintaining a balance between supply and demand at a desired value. The real function of a controller is to compensate for load changes. The following examines operation of a proportional controller with respect to load change (causing a deviation or error signal) and controller gain.

Proportional Output and Gain

For a controller with a gain of one, output will change the same amount as input. A 1% deviation caused by a 1% change in either the process or the set point will cause a 1% change in output. A 100% change in deviation will cause a 100% change in output. Thus, output is in proportion to a change in deviation, with the proportion being governed by the controller gain. Equation 1 expresses the relationship between gain, output, and deviation - which is the error signal applied to the controller input and is the difference between process measurement (variable) and set point (PV - SP).

$$C_O = (PV - SP)\ G + K \qquad \text{Equation 1}$$

where: C_O = Controller output.
PV = Process variable.
SP = Set point.
G = Controller gain = output/input.
K = Previous output of the controller, or the value before a change occurred.

Gain of a controller can also be expressed as the percent of change in process variable needed to cause the controller output to change 100%. This gain expression, called proportional band, is the inverse of gain. It is expressed as a percent. If the output of a proportional controller changed 100% when the process changed 50%, the proportional band of the controller would be 50% and the gain would be two. The relationship between proportional band and gain is expressed in Equation 2.

$$\text{Proportional band (PB)} = 1/\text{gain}\ (100)$$

$$\text{Gain} = \frac{1}{PB}\ (100) \qquad \text{Equation 2}$$

The terms are as previously explained.

EXAMPLE A: CONTROLLER GAIN.		
Given:	a.	A controller has a span of 4-20 mA.
	b.	The controller has an output of 18 mA.
	c.	A process change of 10% causes output to go to 15 mA.
Find:	Controller gain.	

Solution: To avoid unit conversion requirements, this and all such scaling problems should be carried out with the signal levels converted to a percent of full-scale value.

a. $\frac{18 \text{ mA} - 15 \text{ mA}}{20 \text{ mA} - 4 \text{ mA}} (100) = 18.75\%$ of total change

b. The deviation (PV - SP = 10%), assuming that the deviation was caused by the process change.

c. From Equation 1:

$$G = \frac{C_o}{(PV - SP)}$$

$$G = \frac{18.75}{10} = 1.875$$

Note: The "K" term was not needed in this exercise because it was included in the given information.

EXAMPLE B: PROPORTIONAL BAND OF CONTROLLER.

Given: Values in Equation 1.

Find: Proportional band of the controller.

Solution: Using Equation 2 and solving for PB,

$$PB = \frac{1}{\text{Gain}} (100)$$

$$= \frac{1}{1.875} (100) = 5.3\%$$

Proportional Control Application

To explain how to overcome the disadvantage of cycling in the ON-OFF level control system (Figure 1), proportional control will be discussed.

The level process is shown again in Figure 2. To illustrate proportional control principles, make the following assumptions:

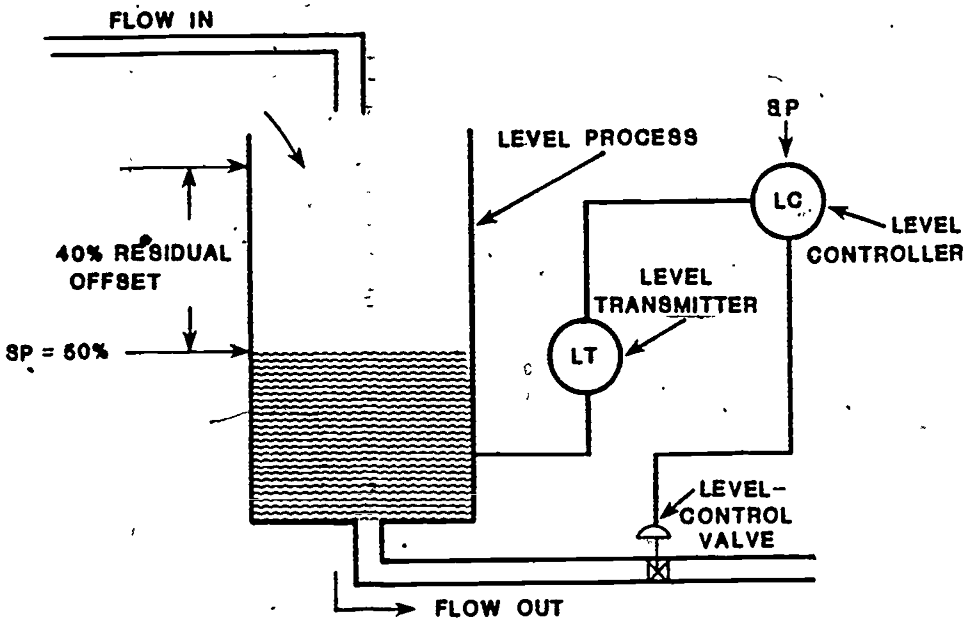


Figure 2. Level process on proportional control.

1. Controller is direct acting with a gain of 0.5, or PB = 200%.
2. The valve is air-to-open and changes the flow rate at 2 gal/min/5% opening.
3. Initial conditions: Flow in = flow out = 20 gal/min; SP = PV = 50%; and valve is 50% open.
4. Flow in is suddenly increased by 8 gal/min.

When flow into the tank is increased, the level will increase because flow out is still at the 20-gal/min value when the flow in is increased to 28 gal/min. For flow out to increase to 28 gal/min, an 8-gal/min increase to balance the increased flow in, the valve must move 20%.

$$\frac{8 \text{ gal/min}}{2 \text{ gal/min/5\%}} = 8 \text{ gal/min} \left(\frac{5\%}{2 \text{ gal/min}}\right) = 20\% .$$

This 20% change in output from the controller will require a 40% change in input.

$$\text{Deviation} = \frac{\text{Output}}{\text{Gain}} = \frac{20\%}{0.5} = 40\%$$

This means that the level must change 40% to change the controller output 20% to increase the flow out by 8 gal/min. The level is then at a 90% value, or 40% above set point. This is called residual offset.

If controller gain were higher, the process would not need to deviate as far from set point to change controller output the required amount. If gain were increased by a factor of four to a value of two, the residual offset would be decreased by the same factor to a value of 10%. Gain of a process controller should be as high as possible to reduce the amount of <u>residual offset</u>. Maximum allowable gain will be determined by the overall process and equipment gain, and will be determined when the controller is tuned to the process. Regardless of controller gain, proportional control will be characterized by residual offset because, operating on a feedback principle, offset is required for corrective controller action. Even with ON-OFF controllers (which, in theory, have infinite gain) an amount of process deviation is required to initiate control action. If the gain value were infinitely large, zero deviation would produce a 100% controller output. Reasoning will dictate that this is an impossibility. It should be derived from the previous discussion that residual offset is inversely related to controller gain - which should be the maximum value that will maintain stable process operation. To eliminate residual offset, the reset control mode is used.

RESET CONTROL

When the controller has made a proportional response to a load change, the reset control mode will continue to change controller output in the same direction as the proportional action ... and at a rate that is determined by the reset value set on the controller.

Reset output is a function of the time of deviation between process variable and set point. This control mode repeats the proportional output. The reset adjustment determines the amount of time required to repeat the proportional output. In the previous discussion, proportional output was 20%. This 20% change in controller output was not sudden, because the increase in flow into the tank (in view of tank capacity) would not result in a sudden change in level. This change would occur over a period of time. In fact, the valve would open gradually, and the deviation would be continuously decreasing because of the gradual valve opening. Exact conditions given in the previous explanation would exist in theory only if the change on the controller input were sudden (a step change in set point, for example). If proportional output suddenly changed by the 20% value indicated, the reset control mode would repeat this 20% value by the reset setting on the controller.

Reset units are expressed as minutes per repeat, or repeats per minute, depending upon the brand of controller use. If reset units were repeats per minute and the proportional output were 20%, the output would continue to change at a rate of 20% per minute, and it would continue at this rate until the process was back at set point. If, for some reason, the controller increases to a 100% value and the process has not returned to set point because of equipment malfunction (a stuck or undersized valve, for example), a condition known as "reset wind-up" exists. In this condition, the controller is out of control. This, of course, is an abnormal condition and should be avoided for the following reason: When normal operation of the process reoccurs, the controller will be out of correct operation for as long as the reset wind-up condition exists. Some later-model controllers have an anti-reset wind-up feature to avoid this problem.

EXAMPLE C: RESET CONTROL.	
Given:	The reset of a controller is set for four minutes per repeat.
Find:	Corresponding reset value in repeats per minute.

Solution: The two reset units are reciprocals of each other.

$$\frac{\text{Repeats}}{\text{min}} = \frac{1}{\text{min/Repeat}}$$

$$\frac{\text{min}}{\text{Repeats}} = \frac{1}{\text{Repeats/min}}$$

$$\frac{4\ \text{min}}{\text{Repeat}} = \frac{1\ \text{Repeats}}{4\ \text{min}} = 0.25\ \frac{\text{Repeats}}{\text{min}}$$

DERIVATIVE CONTROL

It should be emphasized that the control modes required are determined by the process characteristics, especially the dynamic qualities (process behavior with respect to a disturbance). It has been shown that the controller gain and reset requirements depend upon the process gain - which is determined by the physical design and relates input to output with respect to amplitude. The derivative control mode is concerned with the time required to measure a process disturbance, to change the process, and to measure that change. These time-related characteristics are important in proportional and proportional-plus-reset control; but they are not great enough to warrant special consideration. If they are, derivative control is necessary.

Recall from Module IC-06 that the derivative action of a controller is caused by a delay in response of the feedback mechanism. Furthermore, remember that the amount of negative feedback that results from an input disturbance affects the instrument gain. In effect, the derivative control mode changes the controller gain for the amount of time of the delay in the negative feedback. This operation will result in an increased controller response greater than that which would be generated by the proportional response alone.

Derivative control is used in processes that are slow to respond to a change. Temperature processes are typical of this type of process. The characteristic that depicts the slowness to respond has been referred to as thermal momentum. Thermal momentum is related to the flywheel effect of rotary motion. To help to overcome this sluggish response, the derivative control mode adds an additional burst of energy to the process.

Controller output caused by the derivative control mode is used to give a lead in the controller output to compensate for <u>dead time</u> in the process. In all controllers, derivative response is measured in minutes. It is the time that derivative output leads proportional output. For a step change in set point or process measurement, derivative output will go to a very high value (probably to the level of maximum output) and will return to the proportional level when there is no longer a change in error or derivation between set point and process variable. Because derivative controller output is a function of the rate of change of deviation, it will be present only during the time of a changing value. Because of the very fast rate of change of error signal caused by step changes or spikes in the process, derivative output for such a situation will be large and will decay when the error ceases. However, derivative response to a slower change in error signal causes derivative output to continue and to be proportional to the rate of change of error signal.

The additional controller output caused by derivative action is useful in processes with large capacitance time constants and large dead time. This helps the process to recover faster from upsets for the following reason: controller output changes a large amount when a change is first detected and changes by a lesser amount when the process is changing at a slower rate.

The advantage of the derivative control mode can be realized by referring to the temperature process in Figure 3. Assume that the cold product flowing in is at a constant rate and temperature, and that temperature of the product flowing out is maintained at a desired value by a constant steam flow rate through the valve and steam coil. The controller therefore is positioning the steam value in order to maintain a balance in the heat energy in the process. Consider the effect of an increase in flow of the cold product into the process. This cools the product, which then must result in an increase in steam flow. This increase will not be immediate,

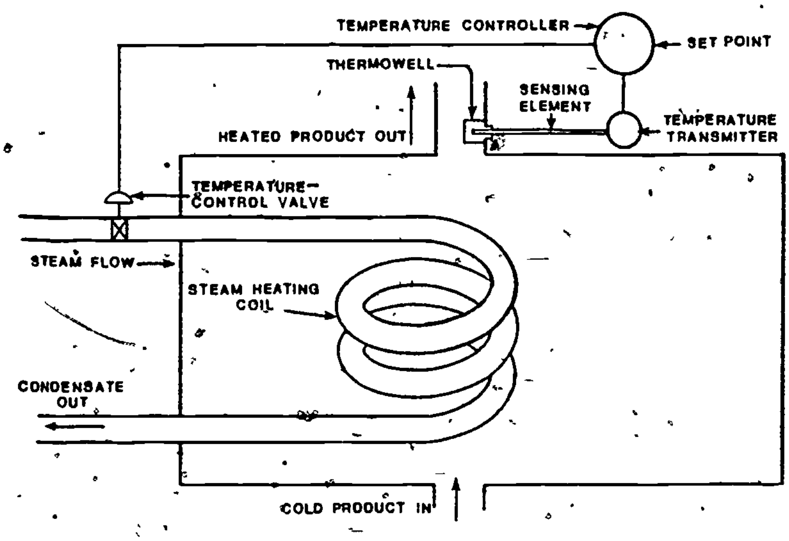


Figure 3. Temperature process.

however, because the change in temperature is not instantaneous. The heat energy in the process must be absorbed by the colder incoming product, the thermowell must lose heat energy to the cooler product, and the sensing element of the temperature also must lose heat energy to the thermowell. All of these energy transfers must take place before the output of the temperature transmitter can change. Once this change occurs, a deviation will exist between the value of the process variable and set point, and controller output will change. With proportional-only control, output will be proportional to the magnitude of the deviation. If the increase in cold product flowing in were very great, temperature of the product passing the surface of the steam coil would be less than the temperature of the product at the thermowell. In this case, a change in controller output caused by an amplitude of deviation would not result in a valve opening to a sufficient amount to heat the product to the desired value. Additional heat energy is required because of the difference in temperature of the product that is caused by time lost in the transfer of energy throughout the system. The derivative control mode supplies this additional energy. The amount of additional energy needed is dependent upon the dynamic error in temperature measurement, or the rate at which the temperature is changing. This concept is illustrated in Figure 4.

The controller output curve shows that the proportional output follows, and that it is proportional to the controller error. However, total controller output is the sum of proportional and derivative control action. Derivative output is significant when the maount of error is changing.

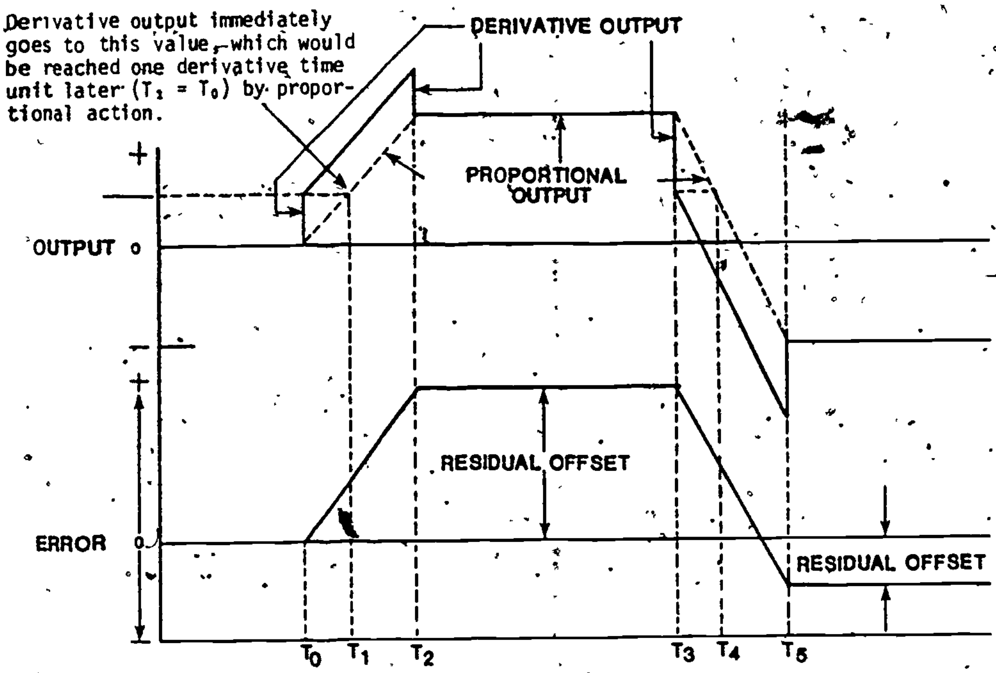


Figure 4. Derivative response to a process change for a proportional-plus-derivative controller.

When the error is a steady value, derivative output is zero, and total controller output of the proportional-plus-derivative controller is caused by the proportional control response.

At T_0, when change in deviation is just detected by the controller, the derivative output goes to a level (shown in Figure 4) that would be reached one derivative time unit later by proportional action. The derivative time unit is the time interval between T_0 and T_1. Derivative output leads proportional output by the amount of time that is one derivative time unit. Derivative units normally are measured in minutes. After the initial derivative response at T_0, there is no further change in derivative output until T_2 -- at which time the error signal becomes stable. Derivative output at T_2 decreases, returning controller output to the proportional level that is maintained until T_3. The error signal again starts to change at T_3, but in a different direction. The derivative response to this change immediately decreases controller output to a level that would be reached at T_4 by proportional action. The time interval $T_4 - T_3$ is one derivative time unit because the derivative control mode causes output to go to a level that would be reached at T_4 by proportional action. At T_5, derivative control returns controller ouput to the stable proportional value.

It should be emphasized that a derivative response occurs only when there is a change in error signal and that amount of derivative output is a function of rate of change. Each time there is a change in this rate of change, derivative output will go to a new level.

Derivative action (as explained and illustrated in Figure 4) will compensate for the dead time in the process and <u>lag time</u> - usually measurement lag - in the instruments. Referring back to the temperature process in Figure 3, derivative response will add the sudden burst of energy required to compensate for the difference between actual temperature of the process and measured temperature value. Derivative also helps to overcome dead time in the process - which is the time required for the process to respond to a change in energy supply.

Although helpful, derivative control in processes with long dead time can be detrimental to control quality. This type of control should never be used in processes that respond quickly to disturbance variables and that are likely to have spurious response: Derivative control is not compatible with erratic process behavior and soon can cause the process to cycle violently and go out of control. The selection of proportional and reset control for processes is also important; but it is not as critical as derivative control.

PROCESS DYNAMICS AND CONTROL-MODE SELECTION

Optimum control for a process will be realized when the proper selection of control-mode combinations has been made and when they are used in the required amount. This is done by tuning the controller. Controller tuning is a process used to match the dynamic controller qualities with the quality of the process. For this matching, it is necessary to determine the dynamic behavior of the process and to obtain data that can be used to establish compatible dynamic qualities in the controller.

For the dynamic behavior of a process to be observed, it must be in a state of change. Although it is desirable to maintain process stability, it is necessary to initiate small disturbances in the process to study reaction to these changes.

PROCESS REACTION TO A STEP CHANGE

To determine the process reaction to a step change, a step change is introduced into a stable process system on open-loop control. This can be done by having the controller on manual or open-loop control and by slightly moving the control valve with the manual control adjustment. The process response to this step change will reveal dynamic process characteristics that determine the required controller dynamic response to correct for process disturbances. Response curves shown in Figure 5 are typical for the associated types of processes.

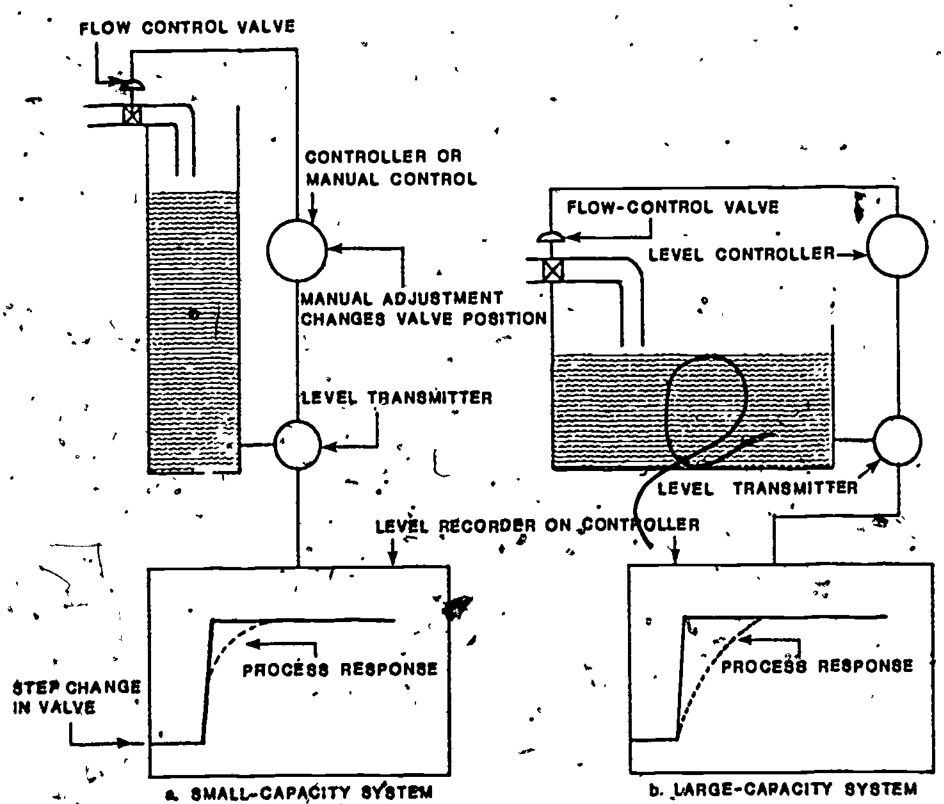


Figure 5. Level responses to a step change.

Process Gain

Process gain is the first important process dynamic quality to be considered. It determines controller gain, and the gain determines the reset. Process gain is characterized by the slope of a line drawn tangent to the response curve at its inflection point, or the point of maximum rate of rise. The process in Figure 5a has a higher gain because it has a slope that indicates the ability to reach new levels of stability quicker than processes that have slow rates of reaction or take longer to reach stability levels. Processes that start to react immediately following a step change or other changes in input exhibit low dead time and lag time. They can be controlled by control modes based on gain principles - namely, proportional and reset. The process reaction curve in Figure 6 suggests other considerations.

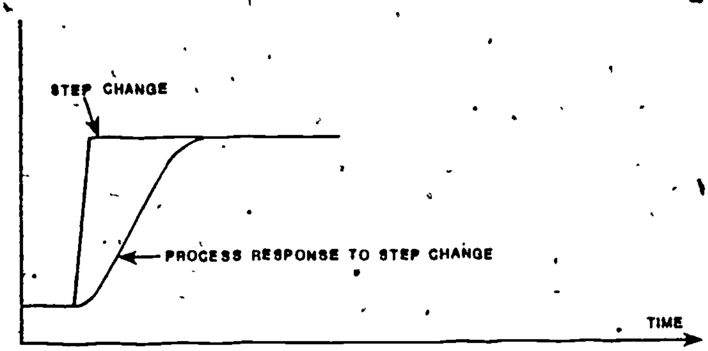
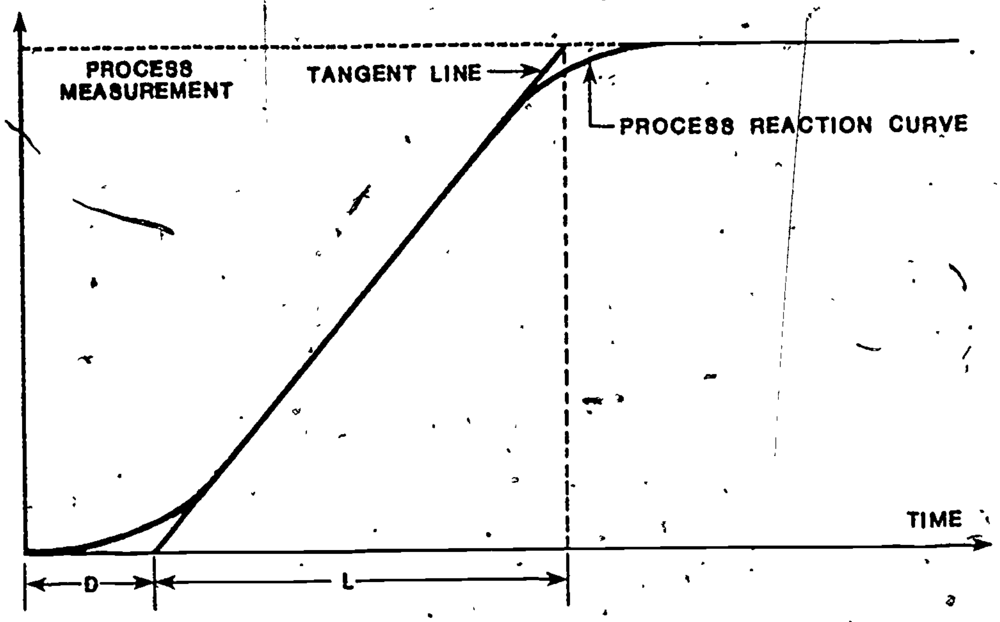


Figure 6. Process response of a temperature system.

Dead Time

It can be seen in Figure 6 that the temperature process does not react immediately to energy changes. Reasons for this were given in a previous discussion. The combination of dead time and lag time results in an overall phase shift in the control system. This characteristic is detrimental to the control quality of a process and dictates the necessity for the derivative control mode. The control characteristic depicted by Figure 6 represents a more difficult control situation that is compounded when rate of rise is high, representing a high gain process and a large delay time or time required for the process to respond to a change in input. This is illustrated in Figure 7. D, the time delay, is measured from zero time point (when the step change was introduced into this system) to the point at which the tangent line intercepts the time axis. L, the time period, extends from the end of the delay line to the point at which the tangent line intercepts the point of 100% process measurement.



$R = \frac{L}{D}$

Figure 7. Loop dynamics determined by response to a step change.

R, which is equal to L/D, is the ratio of the time period of the process to the time delay. This ratio describes the dynamic behavior of the process. Process gain was related to the slope of the tangent line. Plant gain includes every component of the control loop except the controller - the process, transmitter, valve, and pipe.

Transmitter Gain

The range of the transmitter to provide process measurement affects the overall loop gain. Because transmitter output provides the recorder response that is the process reaction to a step change, amount of measurement response is determined by the transmitter range (gain). It usually is expressed as a decimal value or a percent; and it is determined by dividing the measurement response resulting from the step change by the full-scale response.

EXAMPLE D: DETERMINATION OF PLANT GAIN	
Given:	Full-scale measurement of a temperature transmitter is 300°F. Temperature variation caused by a step change is 40°F. Percent of valve travel required to cause the 40°F change was 4%.
Find:	Plant gain.
Solution:	a. Gain of a component is determined by dividing output by input. Percent of transmitter output is as follows: $\frac{40}{300} = 13.3\%$. b. Plant gain is: $\frac{\text{Output}}{\text{Input}} = \frac{\text{Transmitter change}}{\text{Valve change}} = \frac{13.3}{4} = 3.3$

Loop Gain

Total loop gain is the product of the following:

1. Valve and piping gain.
2. Transmitter gain.
3. Process gain.
4. Diaphragm or valve actuator gain.
5. Controller gain.

The value of the total loop gain should be slightly less than one. This describes a passive system that will not oscillate. If total loop gain were greater than one, the system would not be passive, but would oscillate or be unstable. Therefore, it is desirable to adjust controller gain to a value to make total loop gain as close to one as possible and to maintain process stability. The optimum value of controller gain is determined during a process of controller tuning. This will be discussed later.

It can be seen that a value of controller gain can be optimally determined for a given set of process and associated hardware conditions. When any condition is changed (a transmitter range change, for example), the total loop gain is changed - which requires a new value of controller gain.

CONTROLLER TUNING

The controller must be tuned and control-mode values set in order to match the controller's dynamic qualities with the quality of the process. Many methods are used to determine the best control-mode settings for a given control situation. Some are purely analytical; whereas others are strictly empirical in nature. Analytical methods are used more frequently in process modeling situations. Most technicians use empirical methods that sometimes are based on analytical data.

CONTROLLER TUNING BY STEP ANALYSIS

When values of L, D, and G are determined by step analysis, dynamic process characteristics are revealed. By substituting these values into empirically-derived equations, optimum control-mode settings for a given situation can be determined. Formulas used for determination of the control-mode settings are given in Table 1. A 20% overshoot response is desired when it can be tolerated without causing undesirable or unsafe process conditions. This condition, representing a better control quality, will be explained later.

Data needed to make the calculations to determine the control-mode settings is easy to obtain - an advantage to this method of controller tuning. A disadvantage is the fact that a true quality of control is not tested until the settings have been made and the process is controlled by the controller. Control quality is verified only when the process is controlled to optimum. Although not exact, this method of control-mode determination yields empirical approximations that serve as a fairly complete identification and determination of dynamic behavior.

TABLE 1. FORMULAS FOR CONTROL-MODE SETTINGS BY STEP ANALYSIS.

Type of Control			Quickest Response With 20% Overshoot	
	Step Change in Manipulated Variable	Step Change in Load	Step Change in Manipulated Variable	Step Change in Load
Straight Proportional Proportional band (percent) =	$\frac{333\ C}{R}$	$\frac{333\ C}{R}$	$\frac{143\ C}{R}$	$\frac{143\ C}{R}$
Proportional + Reset Proportional band (percent) =	$\frac{286\ C}{R}$	$\frac{167\ C}{R}$	$\frac{167\ C}{R}$	$\frac{143\ C}{R}$
Reset (time units of D) =	3.33 DC	$\frac{6.67\ DC}{R}$	1.67 DC	$3.33\ \frac{D}{R}$
Proportional + Reset + Derivative Proportional band (percent)	$\frac{167\ C}{R}$	$\frac{105.2\ C}{R}$	$\frac{105.2\ C}{R}$	$\frac{83.3\ C}{R}$
Reset (time units of D) =	1.67 DC	$2.5\ \frac{DC}{R}$	1.43 DC	$1.67\ \frac{DC}{R}$
Derivative (time units of D) =	$0.3\ \frac{RD}{C}$	$0.4\ \frac{RD}{C}$	$0.45\ \frac{RD}{C}$	$0.5\ \frac{RD}{C}$

CONTROL-MODE SETTINGS BY THE ZIEGLER-NICHOLS METHOD

A method of controller tuning, developed by J.G. Ziegler and N.B. Nichols, is known as the Ziegler-Nichols method. There are many modifications and variations of this approach - which is a combination analytical-empirical technique. This method presents a classic approach to controller tuning. It, or one of its variations, is commonly used. Control-mode settings are based on process and controller conditions that just produce process instability or cycles. The Ziegler-Nichols method also has been known as the ultimate sensitivity method.

Procedures used for the Ziegler-Nichols method of controller tuning will be discussed in the Laboratory section of this module.

CONTROL-QUALITY EVALUATION

The term "optimum control" has been used in this module without definition to this point. There is almost an infinite number of possible control-mode settings. One may ask "What defines optimum control or the best selection of control-mode settings?" To answer this question, remember that the purpose of a controller is to balance the process supply and demand at a process condition. This also means to return a process to set point after an upset in the shortest possible time. Consider process response to a step change, as shown in Figure 8. In each case, assume the set point value was

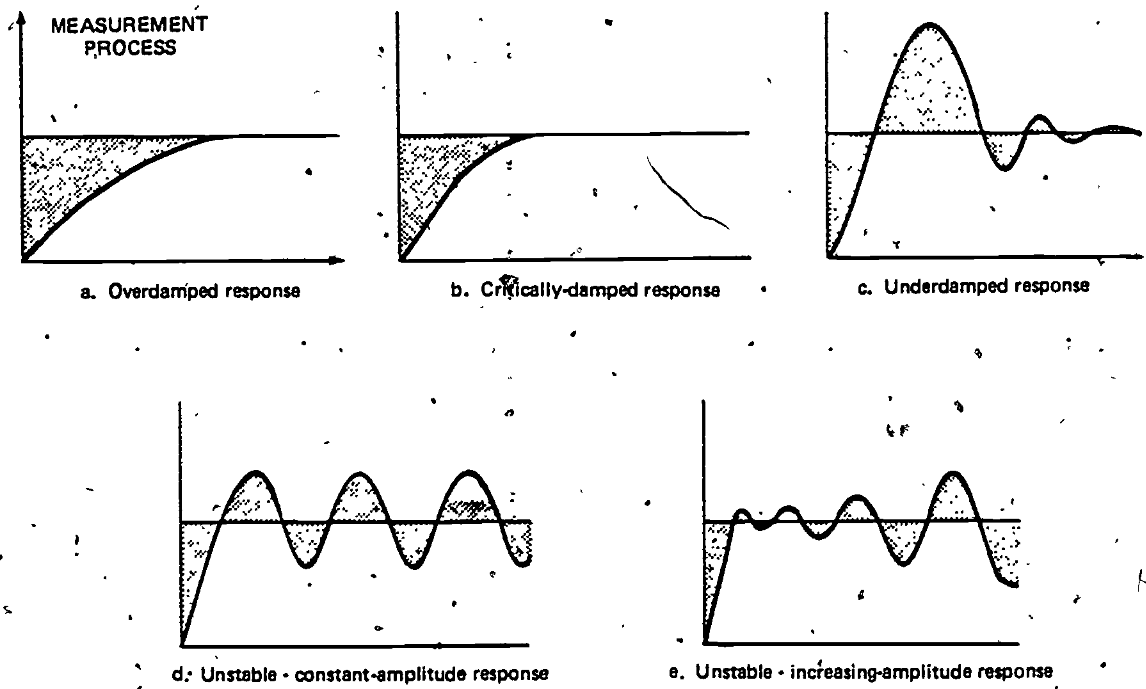


Figure 8. Controlled process responses to a step change.

on the x axis, or at the bottom of the curve, and that the set point was moved to a new level at the center portion of the curve. The total amount of time that the process is away from set point is represented by shaded areas of the curve. The response shown in Figures 8a and 8b returns the process to set point without overshoot, but the total time that the process is away from set point is greater than the condition represented in 8c. Conditions shown in 8d and 8e are not acceptable for obvious reasons. The underdamped response in 8c is considered to represent optimum control quality because underdamped response returns the process to set point more quickly, and it should be used for a test of optimum control when overshoot can be tolerated. It is termed "quarter-amplitude decay damping" because the amplitude of each successive cycle is 25% of the previous cycle, and the process is returned to set point after four cycles.

EXERCISES

1. Using graphical analysis, show the following controller responses:
   a. Proportional controller response to a step change.
   b. Proportional controller response to a gradual load change.
   c. Proportional-plus-reset response to a step change.
   d. Proportional-plus-derivative response to a step change.
   e. Proportional-plus-derivative response to a gradual load change.

   What determines the output of each mode?
2. Use a process on closed-loop control to determine residual offset.
3. Show how residual offset is a function of controller gain.
4. Explain how reset eliminates residual offset.
5. What are the limitations of reset control? (Hint: Remember reset wind-up.)
6. List advantages and disadvantages of on-off or two-position control.
7. What type of processes can be satisfactorily controlled by an on-off or two-position control scheme?
8. How is on-off controllability related to the dynamic process characteristics?
9. List the reason for controller tuning.
10. List two methods of controller tuning.
11. List a means of identifying or determining control quality.

LABORATORY MATERIALS

1 pump (P_1): an electrically-operated pump that will deliver 10 to 20 gal/min of flow against a 20 pisg head

2 control valves diaphragm operated by 3-15 psig. The valves can be single seated air to open or close with a 1" body and 1/2" trim. ($C_v \cong 0.5$)

2 strip chart recording controllers with a fast (1 in/min) and a slow (1 in/hr) chart speed. The controllers should be pneumatic with conventional 3-15 psig input and output.

2 tanks with approximately a 20-gal capacity for use as the reservoir and process. The reservoir should be flat (about 10-12" high), and the one used for the process should be cylindrical (about 8-10" in diameter and 8' high). Volume of the reservoir should excess that of the tank.

1 level transmitter with an adjustable range of approximately 0-20" to 0-20" of H_2O. (Pneumatic 3-15 psig input and output.)

1 flow transmitter with an integral orifice approximatley 0.250" and an adjustable range of approximately 0-20" to 0-200" of water.

Assorted hoses, pipe, tubing, and wire to connect the process and instruments.

Manometer or pressure gage to read 0-200" of water.

20-psig air supply for pneumatic test bench.

0-30-psig test gage.

Presssure regulator having 0.1% regulation with 30-psig input and regulation up to 20 psig.

Vendors' instruction manuals and parts lists for all instruments and equipment.

1 tank 8-10" in diameter and approximately 10" high. This is used as added capacitance for the process.

LABORATORY PROCEDURES

LABORATORY 1. OPEN-LOOP CONTROL.

1. Construct the process in Figure 9. Mount the instruments in accordance with mounting instructions provided in instrument instruction manuals.

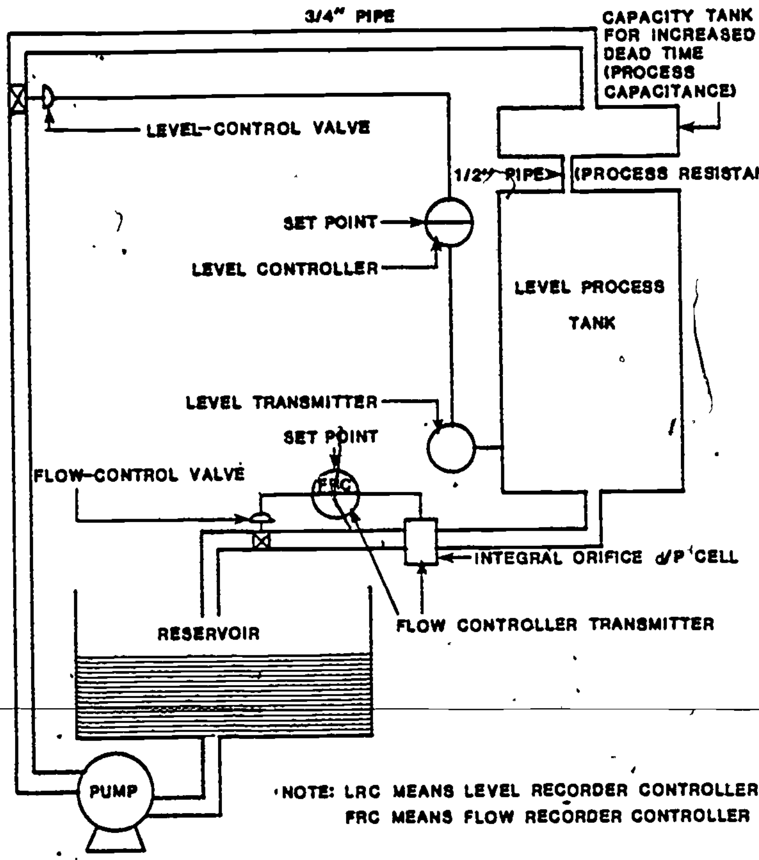


Figure 9. Flow-level process with dead time.

2. Using standard calibration procedures, as outlined in the instruction manuals and as covered in Modules IC-02, IC-03, and IC-06, calibrate the level transmitter for a full-scale range of 0-50" of water and the flow transmitter for a full-scale range of 147.3" of water. This will give a full-scale flow range of 3.5 gal/min when using the 0.250-inch integral orifice.
3. Using 1/4-inch plastic tubing, connect the instruments as required in accordance with instructions in the instrument manuals.

4. By referring to procedures for open-loop control given in Module IC-01, establish a level in the process level tank of approximately 50%, with the flow rate at about 50% of full-scale value. This is done by operating the valves on manual control from the controllers, opening the flow control valve 50%, filling the reservoir with water, and opening the level-control valve about 50%. The pump is then started, and the flow- and level-control valves are adjusted for 50% level at 50% flow rate.

LABORATORY 2. TUNING FLOW CONTROLLER BY THE ZIEGLER-NICHOLS ULTIMATE-SENSITIVITY METHOD.

1. Remove all reset and derivative from the controller, and set gain adjustment for a low value. If reset is measured in minutes per repeat, the reset is eliminated with the highest setting. For repeats per minute, the setting should be the lowest setting. If gain is expressed as proportional band, the setting should be a high value - 300% or higher. For a controller with gain or sensitivity settings, a low value should be used. Put the controller on "automatic."
2. Gradually increase proportional gain by decreasing the proportional setting or by increasing the gain setting until the process just begins to oscillate or cycle, as indicated on the recorder on the high chart speed range. To start oscillations, it may be necessary to introduce small disturbances by slight movement of the set point.
3. Note controller gain that just produces the oscillations. This is the critical gain: G_C.
4. Measure period of oscillation on the strip chart recorder. Note this time, which is T_C.
5. Because dead time is not significant on the flow controller, derivative will not be used. The controller will be proportional-plus-reset.

6. Compute the optimum gain and reset values by the following equations:
   a. Optimum gain = 0.45 G_c.
   b. Reset time = $T_i \; \frac{T_c}{1.2} \; \frac{\text{min}}{\text{Repeat}}$

      Reset time = $T_i = \frac{1.2}{T_c} \; \frac{\text{Repeat}}{\text{min}}$

   c. If proportional-only control is used, optimum gain is 0.5 G_c.
7. Set gain and reset control-mode settings to the value determined in Step 6.
8. When the process is stable, introduce a small step change into the system by increasing set point by about 5 to 10%.
9. Check for quarter-amplitude damping.
10. Touch-up the control-mode settings if necessary to achieve quarter-amplitude damping. Adjust gain for the correct number of cycles, and adjust reset until residual offset is eliminated.

LABORATORY 3. TUNING LEVEL CONTROLLER BY THE ZIEGLER-NICHOLS ULTIMATE SENSITIVITY MEHTOD.

1. Repeat Steps 1 through 4 of Laboratory 2 for the level controller. Level controllers normally do not require derivative control, but the added capacitance and resistance at the top of the level process will introduce significant dead time in the system.
2. Derivative controll will be added. Level control will be proportional-plus-reset-plus derivative. Compute control-mode settings by the following formulas:
   a. Optimum gain = 0.6 G_c.
   b. Reset time = $\frac{T_c}{2} \; \frac{\text{min}}{\text{Repeat}} = \frac{2}{T_c} \; \frac{\text{Repeat}}{\text{min}}$
   c. Derivative time = $\frac{T_c}{8}$ min

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3. Repeat Steps 9 and 10 of Laboratory 2.

4. Procedures are now complete. Stop the pump, put the controller in the manual operation mode, and close both the level and flow valves.

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GLOSSARY

Controller tuning: The procedure involved in matching dynamic properties of a process with those of a controller.

Dead time: Time between a change in process disturbance or input and a process change.

Process gain: Ratio of output to input of a process. More specifically, the amount of process change with respect to an input change.

Lag time: Time between a process change and an instrument response.

Loop gain: Total gain of all components in a control loop.

Optimum control: Control-mode settings that produce quarter-amplitude damping of a process.

Reset wind-up: Condition that exists when a controller output has reached either of the two extreme conditions without returning or maintaining the process to set point.

Residual offset: Difference between process measurement and set point after a proportional response to a process disturbance or load change.

TEST

INSTRUMENTATION AND CONTROLS

Module IC-07

"Automatic Control Systems

Matching: Match the following terms with the appropriate definition:

_____ Lag time.

_____ Total loop gain.

_____ Cyclic action or process instability.

_____ Dead time.

_____ Residual offset.

_____ Process gain.

_____ Reset wind-up.

_____ Ziegler-Nichols.

_____ Capacity.

_____ Quarter-amplitude damping.

_____ Controller tuning.

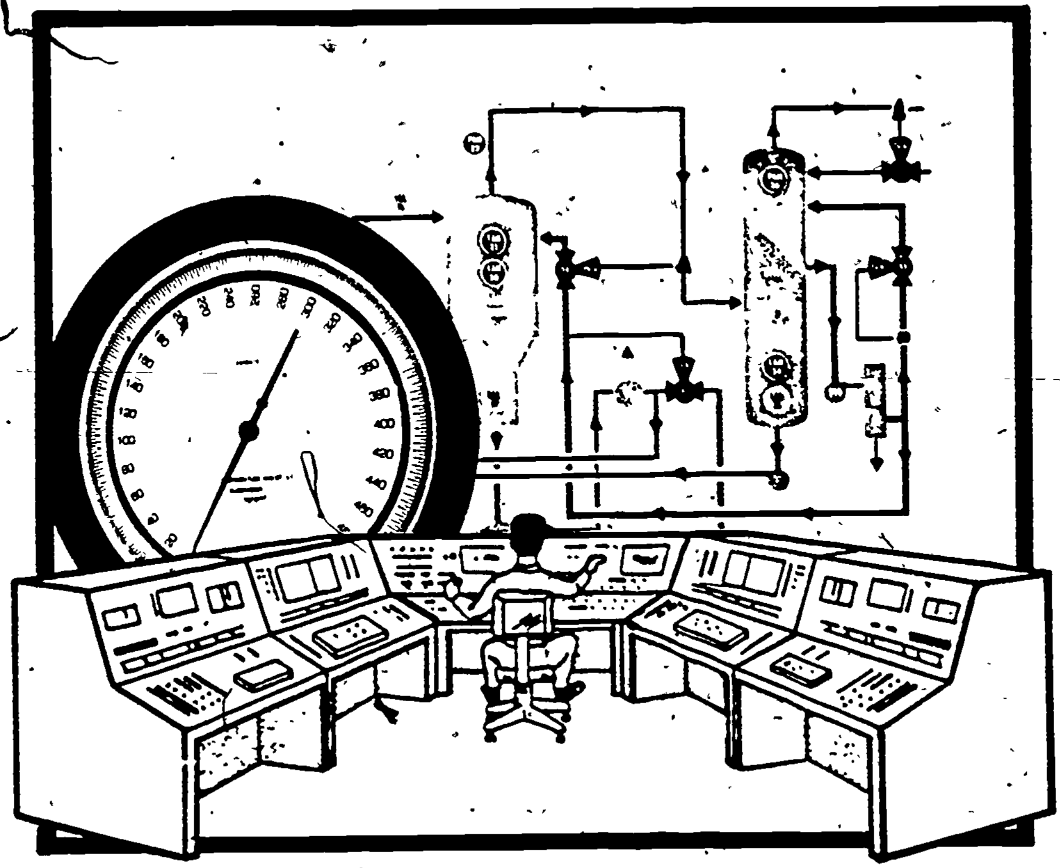
_____ L/P.

a. Characteristic of on-off control.
b. Characteristic of proportional control.
c. ~~Characteristic of reset control.~~
d. Measure of control quality.
e. Matching controller dynamic characteristics with those of the process.
f. Ability of process to store material or energy.
g. Instrument response time - cause of dynamic measurement error.
h. Describes the dynamic behavior of a process.
i. Method of controller tuning.
j. Characterizes or determines the need for derivative control.
k. Related to proportional control.
l. Product of the gain of all components in a closed-loop system.

ENERGY TECHNOLOGY

CONSERVATION AND USE

INSTRUMENTATION AND CONTROLS



MODULE IC-08

BOILER AND OTHER SPECIAL CONTROL SYSTEMS

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

The theory, application, and operating principles of a simple, single-variable, feedback control loop system have been discussed in previous modules of this series. Although many control applications utilize this method of control, process control has been shown to be enhanced by refining, combining, or altering the basic feedback loop. The refinements, combinations, and alterations were discussed in Module IC-07, "Automatic Control Systems."

This module explains the concept of cascade, ratio, and feedforward control and shows how these control systems can be incorporated in boiler control applications. Although most modern boilers rely on computer control techniques, the basic premise to be developed in this module can be understood by students who do not possess a knowledge of computer applications or operating principles. The boiler control concepts presented in this module were utilized long before digital or even sophisticated analog computers were developed. Pre-existing control technique has been refined by the use of process control computers, but the basic principles still hold.

PREREQUISITES

The student should have a basic understanding of algebra and physics and should have completed Modules IC-01 through IC-07 of <u>Instrumentation and Controls</u>.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
   a. Cascade control:
      (1) Primary control (master).
      (2) Secondary control (slave).

b. Ratio control:
   (1) Wild flow.
   (2) Controlled flow.

c. Feedforward control (and feedforward control equation).

d. Feedback trim control.

2. Explain the principles of operation of each of the control types listed in Objective 1 above, and explain their use in a boiler control system.
3. List an auxiliary fuel control technique for boiler control.
4. Describe the operation of fuel and air cut-back systems or overrides used in maintaining boiler operation safety.
5. Explain the purpose and operation of a method of feedback trim control for boiler operation.
6. List boiler shutdown conditions.
7. Explain the purpose and operation of a three-element drum level-control system.

CONTROL QUALITY

The test of true control quality is the degree to which a process condition is maintained at a desired value. The occurrence of load changes; time rate of the changes; and interval of occurrence, along with static (physical) and dynamic characteristics, define the difficulty of obtaining and maintaining an acceptable degree of control quality. This usually can be accomplished by proper selection and adjustment of control-mode combinations. Some processes require additional control system design beyond that of a simple single-variable feedback control system. Cascade control systems are based on the feedback control principles discussed thus far; however, they generally are concerned with controlling two variables.

CASCADE CONTROL

Although not precisely defined as such, a cascade control system usually involves at least two controllers that are connected in such a way that the output of one controller drives the set point of a second controller. Each controller, which is the controlling means of an independent closed-loop control system, controls separate but related variables. Cascade control systems discussed in this module are of the general type. In these systems, primary quantity is measured, and then variations change the set point of one or more secondary controllers that control a second quantity by operation of a single, final control element.

The four primary purposes for use of a cascade control system are as follows:

1. To maintain a desired relationship between variables.
2. To accurately limit a secondary variable.
3. To reduce load changes, nonlinearities, and discontinuities near their source.
4. To improve the control circuit to reduce effective time lag.

A desired relationship between variables is accomplished by a special cascade application (called ratio control), which will be discussed later.

The second purpose, to limit a secondary variable, is a fairly uncommon application - at least in boiler control applications. A valve positioner is a true position controller that is mounted on a control valve to assure that a valve will assume a position as specified by the output of a centrally-mounted controller. This application is defined by the third purpose listed above. The fourth purpose - the most common and useful application - is discussed in the following paragraphs.

NEED FOR CASCADE CONTROL

A temperature process, as shown in Figure 1, utilizes a steam reboiler or heat exchanger to maintain a process temperature. The temperature is controlled by manipulating the flow of steam into the tubes of the reboiler to regulate heat energy. The purpose of the control system is to maintain a balance on energy in the process.

On the cascade system shown in Figure 1b, the quantity of steam flow is regulated by the flow controller that has a set point that is determined by the output of the temperature controller. In Figure 1a, the set point of the flow controller is set manually by an operator.

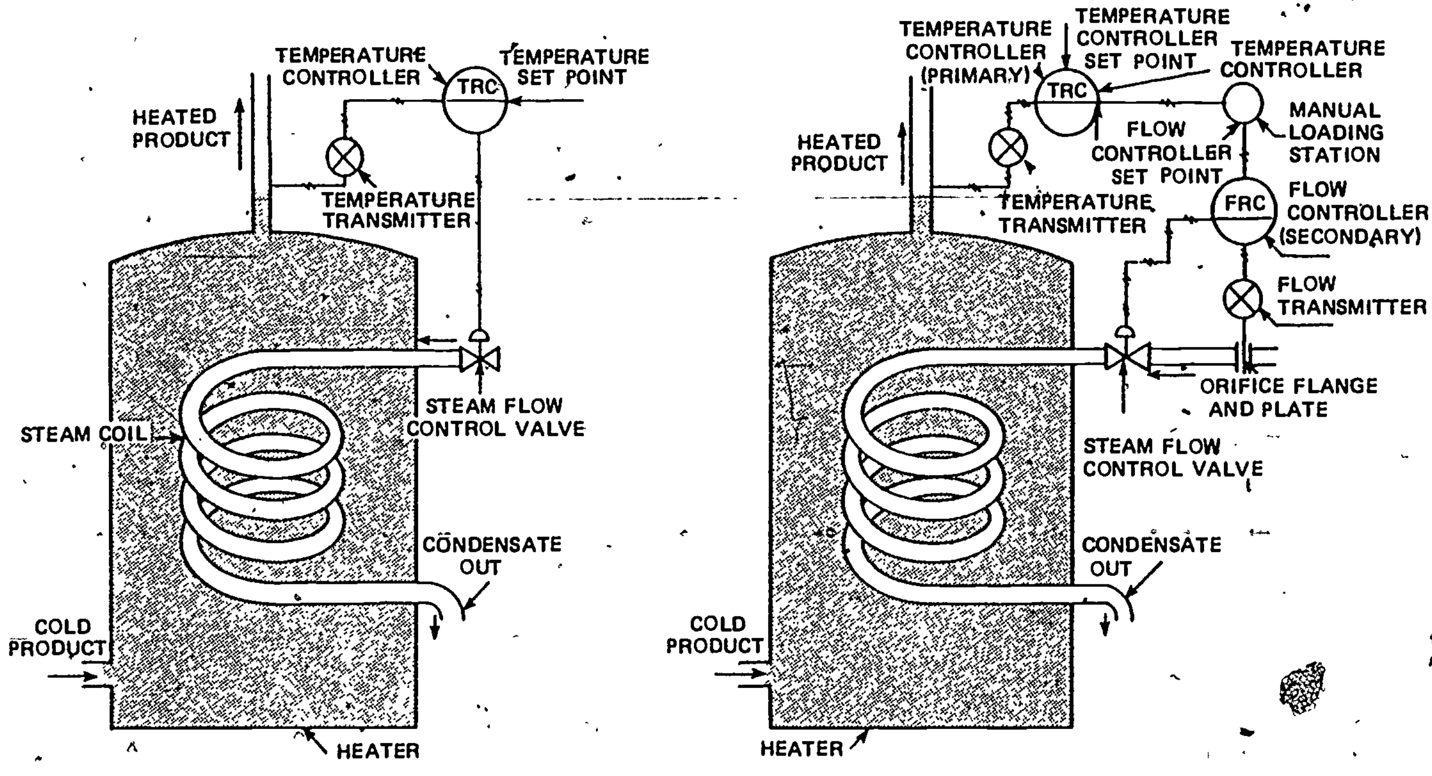
Assume that initial conditions in Figure 1a, are such that the temperature of the product is stable at a desired value for a given load on the process (that is, a given product flow rate through the heater). A change in product flow rate - for example, an increase in cold product flowing in - will cause a cooling in the process. As is true with nearly all temperature processes, the process will not change immediately because of the large capacitance (or thermal momentum, as it is called) of the process. A transfer of heat energy must take place in the product. When the product temperature changes, heat energy must be transferred between the temperature-measuring element and the process. This is a double-capacitance process: the capacitance of the process and that of the measuring means. The temperature transmitter cannot immediately detect a process disturbance. By the time the controller senses a process change, the disturbance may have receded, causing the process to return to normal operation. Cyclic action probably will result.

Another disadvantage of the single-variable temperature control system shown in Figure 1a is the effect of load changes near the source. The steam valve, which is positioned by the controller to maintain a process temperature, will change only when a load causes an unbalance in the process. This results in a temperature change. If a disturbance in the steam flow process (such as a variation in steam header pressure) causes steam flow to change, the steam value will not be repositioned to correct for this disturbance until process temperature changes. Therefore, the control system cannot correct for steam load changes near the source. This is another disadvantage of the single-variable temperature control process. A cascade system will provide better control by doing the following:

- Improving control quality by reducing the effect of lag time, and ...
- Reducing the effect of load changes near the source.

CASCADE CONTROL THEORY

The cascade control system has one final control element, with one manipulated variable, two measuring elements, and two controllers. The temperature controller is the master, or primary controller because the prime function of the system is to control temperature. The steam-flow controller is the slave, or secondary, controller. The purpose of the master controller is to generate a set point for the slave that maintains a steam flow at a value dictated by the master. When steam flow is controlled at a value required to maintain a product temperature, a disturbance in the steam flow process will be detected immediately by the steam-flow transmitter and will be corrected by the slave controller before temperature of the process changes. In theory, because of the nature of feedback control systems, a disturbance variable in the flow process will cause a variation in steam flow before correction. This, then, will cause a change in process temperature. However, because of the magnitude of capacitance in the temperature process, this temperature variation will be negligible when the system is tuned properly.



a. Single-variable temperature control

b. Cascade temperature control

Figure 1. Temperature process.

OPERATION OF A CASCADE CONTROL SYSTEM

Control systems are designed and adjusted to control a process under normal load conditions at the normal operating point. Therefore, processes usually are started by manual or open-loop control. When they are stable, they are switched to automatic feedback control by the "auto-manual" select switch located on the controller.

Cascade control systems generally are started, checked out, and tuned by decoupling the temperature and flow controllers. A manual loading station provided for this purpose is located in the secondary controller set point circuit. To decouple the cascade control loop, a signal manually regulated from an external source supplies the set point for the secondary controller. Output of the temperature controller is dead-ended, and it has no way of altering control of the temperature process. To prevent a reset wind-up condition of the temperature controller, it should be in the manual mode of operation when the cascade loop is decoupled.

With the manual-loading station set so that the secondary controller set point is supplied from an external source and both controllers are in the manual mode of operation, the system is started by positioning the steam-control valve with the manual adjustment from the secondary controller. The manipulated variable - steam flow, in this case - is regulated to establish process temperature at a desired value as indicated by the temperature controller-recorder or indicator. When the process is stable, the secondary controller is switched to automatic, using standard, bumpless transfer procedures. The secondary controller then is tuned as a flow controller to maintain steam flow at a value specified by the external set point. Regardless of steam-flow disturbance, steam-flow value will be maintained by the secondary controller. For constant loads on the temperature process, the temperature value will be maintained by the steam flow as controlled by the secondary or steam-flow controller. However, the set point of the secondary controller must be changed as load on the temperature process varies as evident by a change in process temperature. The function of the primary or temperature controller is to change the set point of the secondary controller as required to maintain process temperature.

When process temperature is stable with the secondary controller in the automatic mode, manual output of the primary controller can be made equal to the set point value of the secondary controller. Process temperature now is controlled by the manual output of the primary controller. Again, using bumpless transfer procedures, the primary controller is switched to automatic and tuned as a temperature controller. The cascade loop is now in service, and the primary controller is controlling process temperature by generating a set point for the secondary controller. The secondary controller maintains steam flow at a value specified by the output of the temperature controller. This cascade operation improves control quality by reducing the effect of lag time, and it corrects for load changes near the source. It will be explained later in this module how cascade systems are used to improve quality of boiler control.

RATIO CONTROL

As the name implies, ratio control is the process of maintaining one variable as a fixed ratio of another variable. The most common application of ratio control is maintenance of two flow values in a fixed relationship. One flow rate (Q_1) is controlled by means other than the ratio controller; the second flow rate is maintained at a value that is a multiple (N) of Q - such that $Q_2 = NQ_1$. More common terms to define variables in a ratio control loop are "wild flow" and "controlled flow" - where the wild flow is not controlled by the ratio controller. A typical application of a ratio-control system is to regulate flow rates of material into a vessel to obtain a proper or desired mix or blend.

The ratio-control system shown in Figure 2 is used to control flow Q_B in exact proportion to flow Q_A. The ratio controller has two inputs, one from each of two flow transmitters. One output is generated, and it is used to position a valve that regulates the controlled flow value Q_B. When the flow rates are measured by head-type flow-metering devices, such as orifice

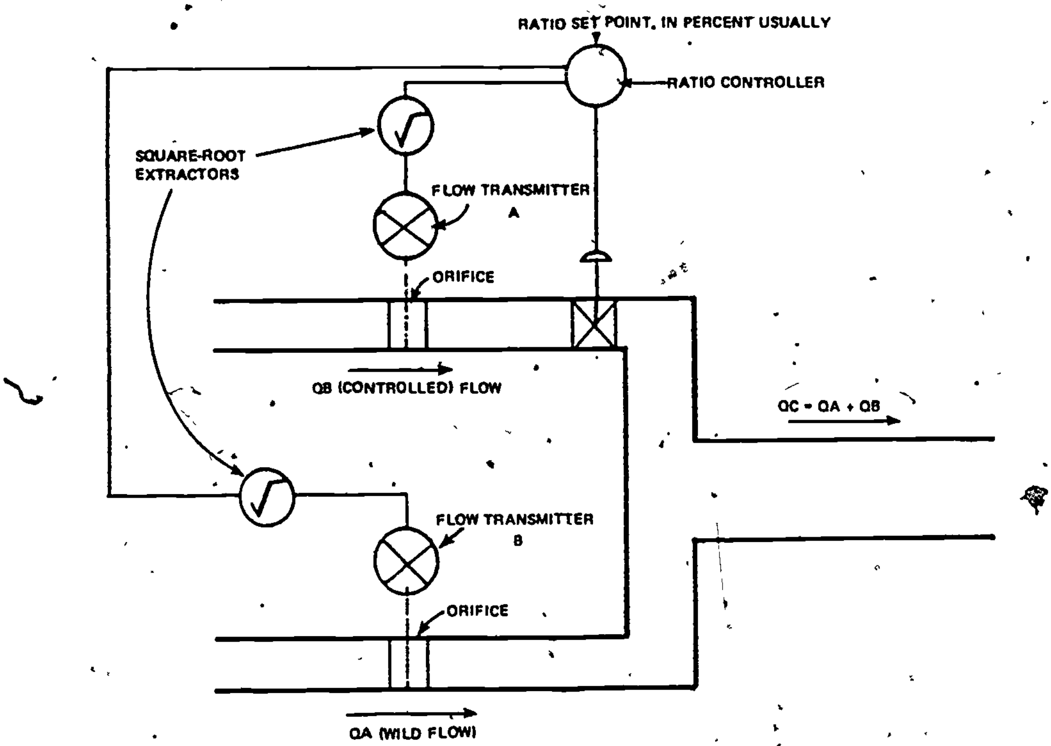


Figure 2. Ratio control system.

plates and d/P cells, square-root extractors are needed to linearize exponential signals from the flow transmitters. When one flow rate is controlled proportional to another flow rate, scaled signals must have a linear relationship between actual flow and magnitude of the measured value. The signal level from a head-type flow transmitter varies as the square root of the differential pressure across the differential producer, as covered in Module IC-02.

THEORY AND DESIGN OF RATIO-CONTROL SYSTEMS

When designing ratio-control loops, it usually is desirable to have a ratio flow setting as close to 100% as possible. Refer to Figure 2; suppose it is desired to maintain flow Q_B at a value four times as great as flow Q_A. The ratio of Q_B to Q_A is therefore 4:1, and the span of the flow transmitters should be in the same ratio. If the span of flow transmitter A (controlled) is set to measure a full-range flow of 100 standard cubic feet per minute (SCFM) and the wild flow meter range is 400 SCFM, the actual ratio may be determined from Equation 1.

$$\text{Actual ratio} = \frac{\text{Controlled-flow range}}{\text{Wild-flow range}}(100\%)$$

$$= \frac{100 \text{ SCFM}}{400 \text{ SCFM}}(100\%) = 25\% \qquad \text{Equation 1}$$

The dial of the ratio controller would be set at 100% to control ratio of flow Q_B to flow Q_A at 4:1.

EXAMPLE A: DETERMINATION OF ACTUAL FLOW RATIO.
Given: a. Wild-flow range of a ratio-control system is 1200 SCFM. b. Controlled-flow range is 300 SCFM. c. The setting on the ratio controller is 100%. Find: Actual flow ratio. Solution: From Equation 1: $\text{Actual ratio} = \frac{\text{Controlled-flow range}}{\text{Wild-flow range}}(100\%)$ $= \frac{300 \text{ SCFM}}{1200 \text{ SCFM}}(100\%) = 25\%.$

EXAMPLE B: DETERMINATION OF ACTUAL FLOW RATIO.
Given: Conditions in Example A, with a setting of 50% on the ratio controller. Find: Actual flow ratio. Solution: $\text{Actual ratio} = \frac{300 \text{ SCFM}}{1200 \text{ SCFM}}(50\%) = 12.5\%.$

FEEDFORWARD CONTROL

Feedforward control applies to control systems where a balance between supply and demand is accomplished by measuring both demand potential and demand load. From these measurements, information is obtained that can be used to regulate supply at an amount to control the process.

To apply feedforward control, the controlled process must be completely understood so that equations can be written that state the material and energy balance required. Any interaction between material and energy balance also must be understood. In a sense, feedforward control systems correct for a load variation before a process disturbance exists. Consider a simple level process with two input flows, A and B, and three output flows C, D, and E. When total flow into the level process is equal to total flow leaving the process, the level will be maintained. The following expression must be satisfied:

$$A + B = C + D + E \qquad \text{Equation 2}$$

where: Terms refer to flow rates, as explained.

Normally, one variable will be selected to correct for a change in any of the other variables. If it were desired to manipulate flow C to maintain a material balance on the level process, the feedforward equation (similar to Equation 2) would be solved for flow C with the following results:

$$C = A + B - (D + E) \qquad \text{Equation 3}$$

where: Terms define flow rates, as previously discussed.

To implement the feedforward control system defined by Equation 3, flow rates would be measured: A and B would be totalized, as would D and E. The sum of D and E would be subtracted from A and B. When either flow changed values, the amount of change would be reflected in a corresponding value of C. Level is then controlled, based on load changes instead of an actual process change. It should be pointed out that, if any variable changes - other than those expressed in the feedforward equation - no correction will be made. It is also significant that measurement of the process is not required for feedforward control because corrections are based on variables that cause the process to change, not on the actual process change. The obvious advantage to this arrangement is that corrections for load variations can be made before the process is affected. In most feedforward applications, however, the process is measured and feedback corrections are made based on the error between the process value and set point. This correction, called feedback trim, is applied to correct for disturbance variables that are not foreseen or are not included in the feedforward equation.

Feedforward control is most advantageous in processes where time lags are significant and where process instability caused by over- or under-correction resulting from lag time is critical. Otherwise, the added expense and complexity of feedforward control is not justified. The basic concept of feedforward control has been used for many years. One such application - boiler control - has been used with much success.

BOILER CONTROL

With rising fuel costs, increased emphasis on plant operation and personnel safety, and increased competition of manufacturing costs and methods, boiler operation efficiency is an important consideration. This is not to say that interest in boiler controls and boiler control theory is new. Boiler control principles and applications have formed a prominent class of process control systems. These systems have been the forerunner to, and perhaps even spawned, development of those used in other process applications.

BOILER CONTROL THEORY

Automatic systems for the control of boilers can range from a simple ON-OFF pressure switch to a sophisticated computer program with several hardware components. Most boiler control systems possess a complexity that is a compromise between the two extremes.

Need for Special Control Considerations

A boiler is a device that converts water into steam. In this context, a teakettle could be classified as a boiler. However, because generation of steam is the prime function of a boiler, relating a teakettle to a boiler is not an adequate comparison. A pressure cooker more closely simulates boiler operation. Suppose the purpose of a pressure cooker operation were to generate low-pressure, saturated, or wet steam. In this analogy, steam would be taken out of the vessel and water would be added to maintain water level so the cooker would not overflow or run dry. Of course, normal operation of the device in question is to maintain a steam pressure with no steam flow (that is, the steam is not consumed). The only steam consumption is that which is vented by the pressure regulator (a weight that covers a small opening in the lid). As pressure increases, it creates a calculated force on the weight. This force causes the weight to be lifted from the opening (valve seat), venting the steam and reducing pressure. This process concerns a simple ON-OFF pressure control system.

Now, consider a different situation. Instead of merely maintaining the steam pressure at a value to raise the boiling point of the water above 212°F at 0 psig, suppose it were desired to take steam at undetermined rates from the pressure cooker and, at the same time, keep the pressure constant. This set of conditions complicates the control techniques required. Control possibly could be implemented by ON-OFF operation; but the feasibility of this would, as mentioned in previous modules, depend upon the degree of cycling that could be tolerated. The control system - whether ON-OFF or proportional - must have a means of level control to maintain the flow of water into the vessel at the same quantity as the steam that is being generated and removed. This is a material balance. To maintain the steam pressure constant and independent of varying steam flow rate, fuel (energy in) must be added to the boiler at an exact amount needed to generate the required amount of steam (energy out). This is an energy balance. In many instances material and energy balance for boiler control (low pressure, less than 50 psig, and low-volume boilers) can be achieved with an ON-OFF level-control switch that controls a pump. An ON-OFF pressure switch also can be used to control fuel flow to the burner. However, most industrial boiler applications require a more sophisticated means of boiler control. A block diagram of a boiler control system is shown in Figure 3.

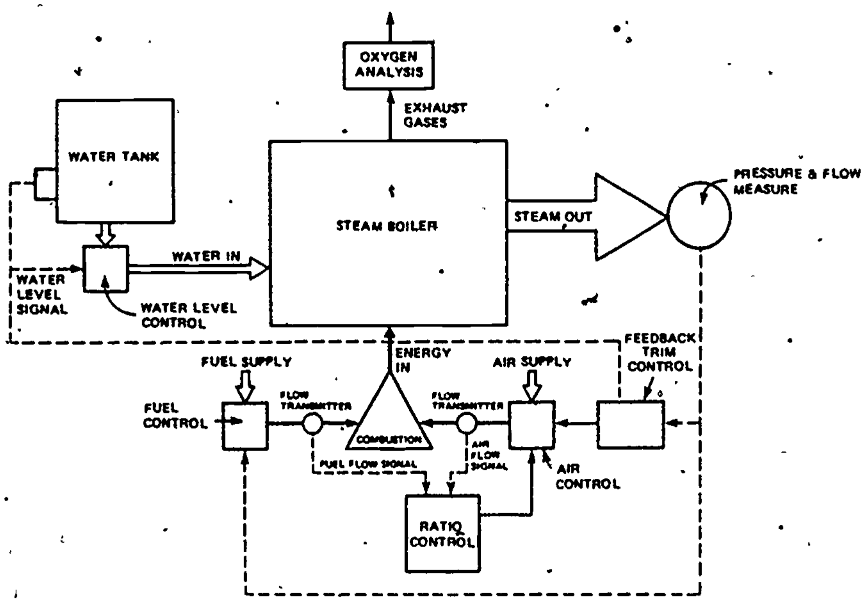


Figure 3. Block diagram of a boiler control system.

Combustion Air Control

The steam production rate of industrial boilers is great enough that static atmosphere around the burners does not contain enough oxygen to support combustion of the fuel. Air must be either blown or forced into the firebox of the boiler by blowers or fans; or it must be pulled through. When blowers force air through the boiler, the term "forced draft" is used to define the boiler. When air is pulled or sucked through, the term "induced draft" is used in the boiler definition. Therefore, boilers are the induced-draft (ID) type, the forced-draft (FD) type, or they operate on both principles. Regardless of type, air flow must be measured and controlled to keep an exact combustible mixture of air and fuel. If air flow is excessive, the air-fuel mixture will be lean; and could result in a loss of flame. When the amount of air flow is too small, the mixture is rich. A rich mixture could result in undesirable conditions such as a loss of flame or a combustible mixture entering the boiler stack that could cause an explosion or a costly pollution of the atmosphere. The ratio of air to fuel flow must be controlled in exact proportions to provide fuel combustion at optimum efficiency and to avoid the conditions listed above. Because any air that enters the boiler and is not used in the combustion process acts to draw heat energy from the steam generation process, the combustion air flow is controlled as the ratio to the fuel flow.

Steam from the boiler and steam drum pressure are measured, with a change in either reflecting a change in boiler load, which in turn will affect the combustion process. For example, an increase in steam flow or a decrease in steam drum pressure (either or both) would indicate a need for an increase in the boiler firing rate. This increase means more gas for energy, more air for combustion, and more water to make the steam. The air, gas, and water must be added quickly, at a rate that will maintain the critical material and energy balance. A method to do this will be explained later in the module.

Drum Level and Feedwater Control

Drum boilers utilize a steam drum where the water - which passed through the tubes in the firebox and was heated - is in equilibrium with the generated steam. Remember the reference to the pressure cooker (steam drum) in which the steam and the water from which the steam was formed were in equilibrium. If a steam quantity were allowed to escape from the cooker, more water would be vaporized to replace the steam that left the vessel. In a drum boiler, the steam and water are in equilibrium; the steam and water are at the same temperature; and the steam is saturated or wet. Most commercial boilers have a superheater section where the wet steam is passed through another section of the boiler and is heated above the saturation temperature to make superheated steam. Regardless of the particular arrangement, when more steam is used from a boiler, an amount of water equal to the steam usage must be added to the boiler drum.

The boiler drum level is usually a three-element control arrangement. The three elements measured to control drum level are steam flow, feedwater flow, and the drum level itself. A simple single-element level system relies on the drum-level measurement only. However, this is not adequate in boiler applications because a sudden change in boiler load could result in extreme variations in level when controlled by a single-element feedback control. The three-element level-control system will maintain the feedwater flow rate equal in mass flow values to that of the steam leaving the boiler. An increase in steam flow from the boiler will result in an increase in feedwater to the boiler tubes. The drum-level value is measured, and an error signal between the actual value and desired value is used to correct feedwater flow rate. This is known as feedforward control with feedback trim.

Auxiliary Fuel Control

Most industrial boilers are powered by two different fuel sources. Some boilers utilize an alternate fuel supply; but this supply is not always available. These alternate fuels are produced on an irregular basis as a result of a product that does not possess a quality high enough for sale. In most cases, these fuels can be used in this way more efficiently than recycling them through the process. Other boiler applications, such as the ones found in hospitals, require an auxiliary or backup fuel. The auxiliary fuel is usually fuel oil, which can be stored in large tanks to provide emergency operation during times of main fuel supply interruption. Though this situation is changing somewhat with increased emphasis on the curtailment of natural gas consumption, standard, conventional-fueled boilers use natural gas a primary fuel source and fuel oil as a secondary or standby source.

Because of the difference in fuel requirements, boiler control systems are designed for the primary and, usually, the auxiliary fuel. Sometimes, however, the boiler must be controlled (partially at least) by open-loop control methods when the standby fuel source is used. Flame detectors, control system, for air and fuel, and burners normally will not accommodate both gas and oil combustion. In some cases, auxiliary control equipment is designed for the secondary fuel.

Fuel flow to boilers is supplied at a rate that will allow it to mix with the air to make a suitable air-fuel ratio. This is normally done by feedback controllers that utilize a feedforward concept. Fuel and air flow limiting techniques are provided to avoid hazardous mixtures that would result in unsafe boiler operation.

WATER TUBE DRUM BOILER

Water tube drum boilers, like the one shown in Figure 4, have one or more relatively small steam drums that have several tube arrangements. A mixture of steam and water flow through these tubes, which are heated on the outside surface. The boiler feedwater is pumped into a steam drum that supplies water to several passes of the generating tubes. Steam is generated in the tubes, and then a mixture of steam and water circulates through the tubes and returns to the steam drum. The mixture is separated in the drum, which furnishes a steam supply to a header for consumption. Pressure and flow rate are measured. These measurements determine the boiler firing rate which, in turn, maintains the pressure at a desired value. A water tube drum boiler is shown in Figure 4 and its schematic in Figure 5.

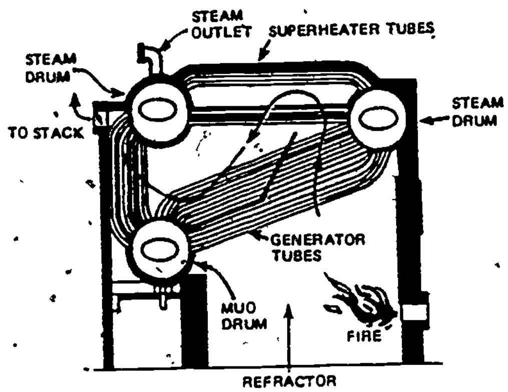


Figure 4. A water tube drum boiler.

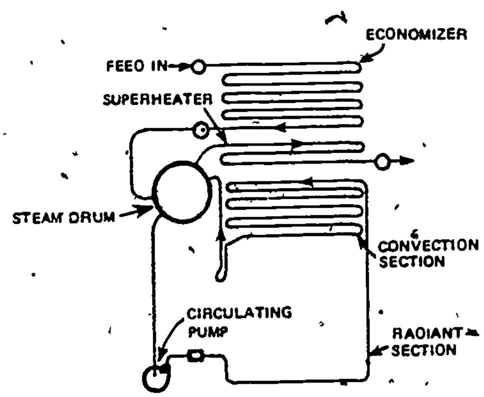


Figure 5. Schematic diagram of a forced-draft water tube drum boiler.

CONTROL SYSTEM FOR A DRUM BOILER

The control schematic of a water tube drum boiler is shown in Figure 6, and the measurement and control points are shown in Figure 7. It should be stressed again that the primary function of the control system in Figure 7 is to regulate the supply of fuel, air, and feedwater at the exact rate and in the exact proportions needed to generate a desired amount of steam at the desired pressure.

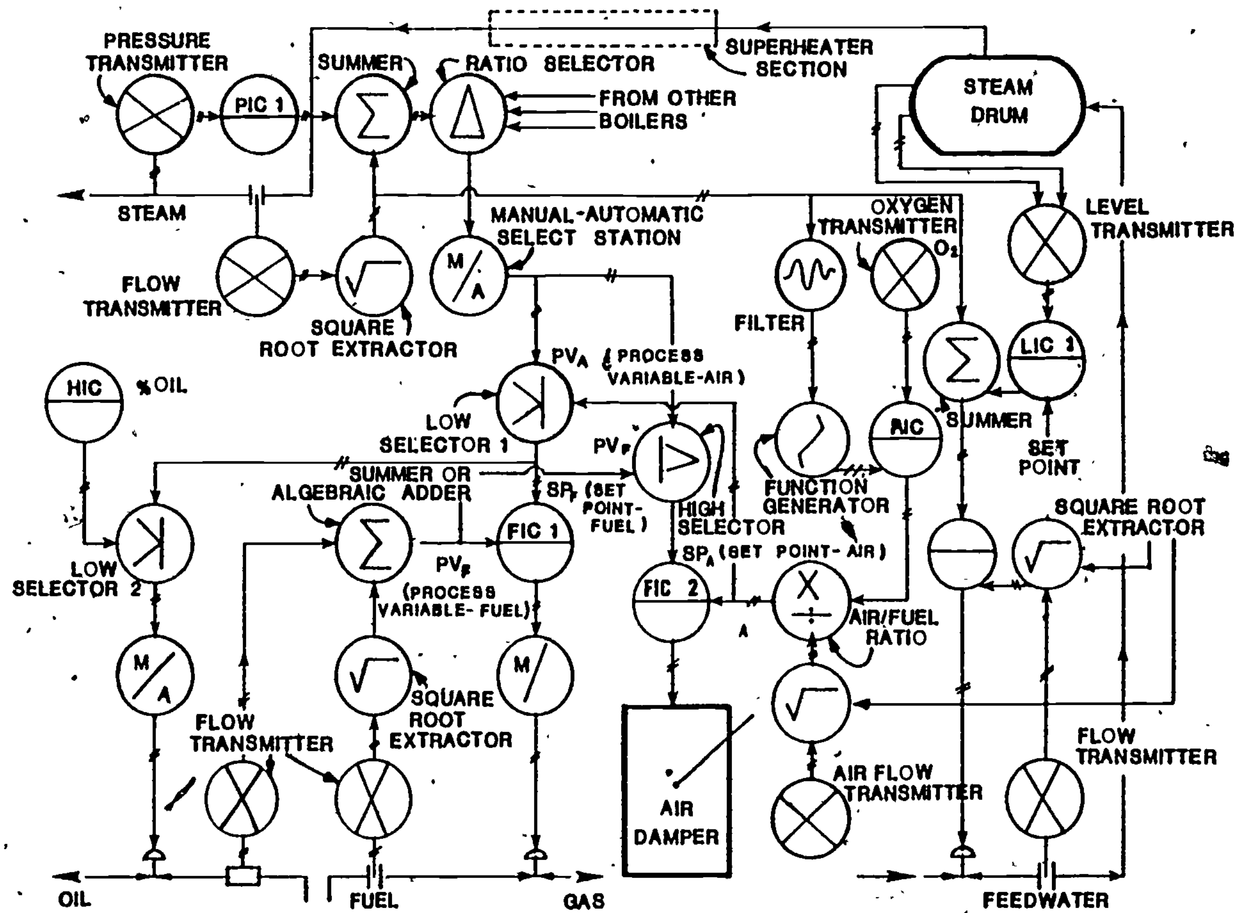


Figure 6. Control schematic of a water tube drum boiler.

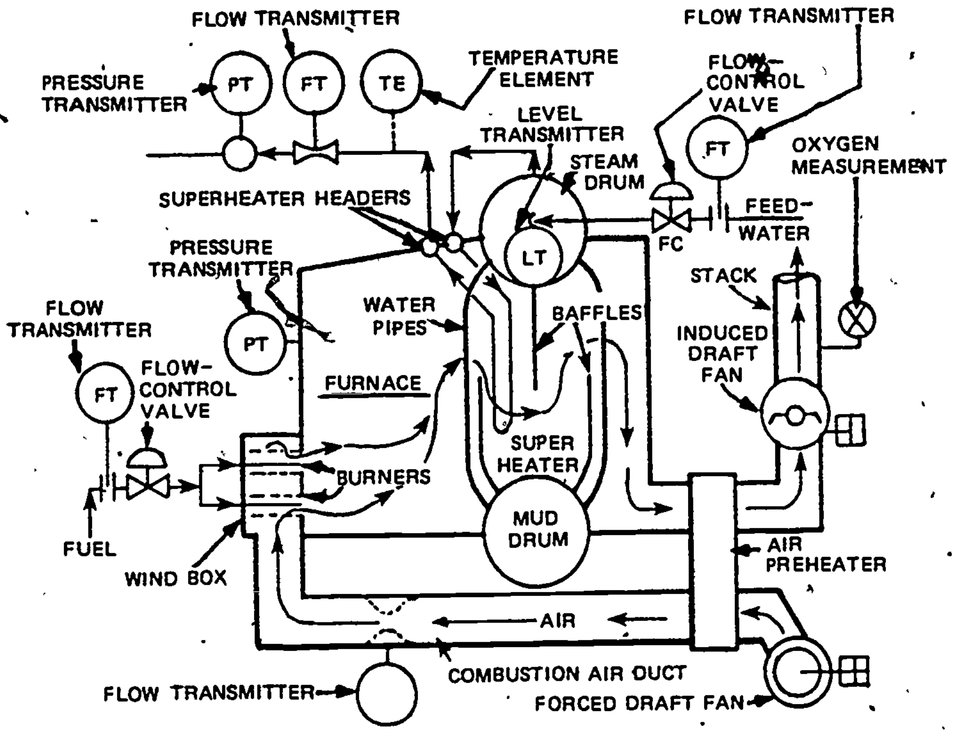


Figure 7. Drum-type boiler with measurement and control points.

Air and Fuel Control

Assume that the boiler is generating steam at a constant rate and pressure that is equal to the demand or steam load on the steam header. An increase in steam consumption will result in an increase in steam flow and a decrease in steam pressure. To compensate for this load change, the firing rate must be increased, more fuel and air must be added, and the feedwater flow must be increased. The steam pressure controller (PIC 1) reacts to a decrease in steam header pressure and generates a signal that is transmitted to the summer. A linear signal from a square root extractor that is proportional to flow also is transmitted to the summer. The output of the summer is adjusted by a ratio controller to bias the boiler firing rate when other boilers are supplying steam to the same header. If, for example, four boilers are supplying steam to a common header, a particular boiler can be biased by the ratio controller to carry any desired percentage of the total load. The signal leaving the ratio controller determines the firing rate of the boiler and, for normal operation of the manual-automatic select switch, passes unattended through the high selector and low selector 1 to drive the set point of the fuel-flow controller FIC 1 and the air-flow controller FIC 2. Both flow controllers are slave controllers of a cascade loop, and they determine flow rates at amounts determined by the master controller PIC 1.

The low selector 1 selects the lower of the two signals - the output of the PIC 1 or the air flow feedback signal - that is altered by the air-fuel ratio selector. During times of abnormal boiler operation (when the air damper may stick, or for some reason the air flow amount would be limiting) the PV_A would be lower. Under such conditions, the air flow would pace the fuel flow.

The high selector in the set point circuit to FIC 2 receives a signal, PV_F, which is the fuel-flow feedback signal representing the total fuel flow. This signal is compared to the set point from PIC 1, and the higher of the two is the set point to FIC 2, which determines the combustion air flow rate to the boiler. The purpose of the high selector is to allow air flow to follow fuel flow if the fuel valve sticks open and fuel flow is excessive.

Any circumstance that would result in the air-flow feedback signal driving the set point to the fuel-flow controller or the fuel feedback signal driving the set point of the air flow would define a stop-gap control situation. The high and low selectors are used to safely control the air-fuel mixture until the abnormal condition is eliminated or until the boiler can safely be shut down.

Dual Fuel Control

The primary fuel for the water tube drum boiler is natural gas, with fuel oil being used as the auxiliary fuel. Although some boilers can be fired completely on a secondary fuel, this boiler and control system cannot. The hand-indicating controller (HIC) in the fuel control circuit is an open-loop controller. There is no feedback loop from the oil flow transmitter to the HIC. An amount of oil flow to the oil burner, usually less than about 25% of the total fuel flow, is set on the manual controller. A variation in oil flow is measured by the oil-flow transmitter, where output is added with the linear feedback signal from the square root extractor in the gas-flow feedback loop. The output of the summer provides the fuel-flow feedback signal. Therefore, an increase in oil flow will cause a proportional decrease in gas flow to maintain the total fuel flow constant. If the oil-firing rate set point is increased by the operator, the oil-flow signal will increase. This increases the process variable to the fuel-flow controller which, in turn, provides negative feedback and reduces the gas flow.

The low selector in the oil-control circuit allows the master signal from the PIC 1 (which is the set point to FIC 1) to cut back on oil flow, and it keeps the oil firing rate less than the gas firing rate.

Drum Level and Feedwater Control

The three-element feedwater-control system is the material balance control that keeps the feedwater flow equal to the steam flow, FIC 3 (feedwater flow transmitter). The control valve is a conventional feedback flow-control loop which controls the feedwater flow rate. For a given flow rate, variations in flow rates will be measured and compensated in a way that is similar to any flow loop. The set point for the controller comes from the LIC 1, which controls drum level at a desired value. LIC 1, then, is a master controller in a cascade loop; and FIC 3 is the slave. The set point for FIC 3 from LIC 1 goes through a summer which combines the output from LIC 1 with the steam-flow variable from the steam-flow transmitter. A change in steam flow will alter the feedwater flow to maintain a material balance on the steam drum. This action occurs before the drum level changes. This control scheme is a feedforward concept implemented by feedback control means.

Feedback Trim Control of Air-Fuel Ratio

The AIC (analyzer indicating controller) is a feedback controller. It receives a process variable signal from an oxygen analyzer that monitors the oxygen content in the flue stack. The boiler firing rate determines the amount of oxygen required for combustion; and the AIC set point is supplied by a function generator with an output that varies with the steam-flow rate. The function is nonlinear because the amount of oxygen needed varies nonlinearly with firing rate. The filter in the set point of the AIC is filtered to make the load compensation a gradual process, thereby avoiding upsets and oscillations. In steam boiler applications, where load demands are fairly constant, the oxygen set point usually is manually adjusted.

The output of the AIC corrects ~~the~~ air-flow ratio by biasing the feedback signal from the air-flow transmitter to FIC 2. For stable operating conditions, this ratio is set by the ratio controller to control the air-fuel ratio content in the flue stack, and the constant readjustment of the ratio helps to maintain the ratio to establish maximum efficient operation.

Safety Shutdown Procedures and Conditions

In addition to a control system that supplies variables to a boiler at exact values and proportions, a shutdown control system must be provided. This shutdown system causes the boiler to shut down safely when abnormal boiler operations or control-system malfunctions result in hazardous boiler operating conditions.

The best and surest way to shut a boiler down is to close the fuel valve. Normally, a solenoid-operated valve (SOV) is mounted in the fuel line that leads to the burners. The valve's quick, sudden action results in positive shut-off of the fuel flow. A loss in signal resulting from any switch opening in the shutdown circuit causes the valve to close immediately. Restoration of the signal will not open the valve; it must be opened manually.

Conditions that cause a boiler to shut down may vary with particular boiler operation; but they usually include the following:

- High and low steam header pressure.

- Flame failure.
- High or low oxygen content in the stack.
- High or low drum level.
- High combustible content, or explosive mixture in the flue stack.

Special sensors normally are used to detect a shutdown condition. Pressure, level, and flow switches are commercially available to monitor critical conditions. The measurement of these variables is made by process transmitters, and the scaled output signals are sometimes used in the shutdown circuit. Auxiliary shutdown devices are sometimes desired for redundant operation. If one system malfunctions, a backup shutdown system is available to assure the safe operating shutdown of equipment.

A typical fuel shutdown system is shown in Figure 8. The normally-closed trip valve is opened manually and is held open (or energized) by the startup switch. When the boiler is operating at normal conditions, the startup switch is secured, and sometimes locked, in the open position. This action averts an override of the shutdown system.

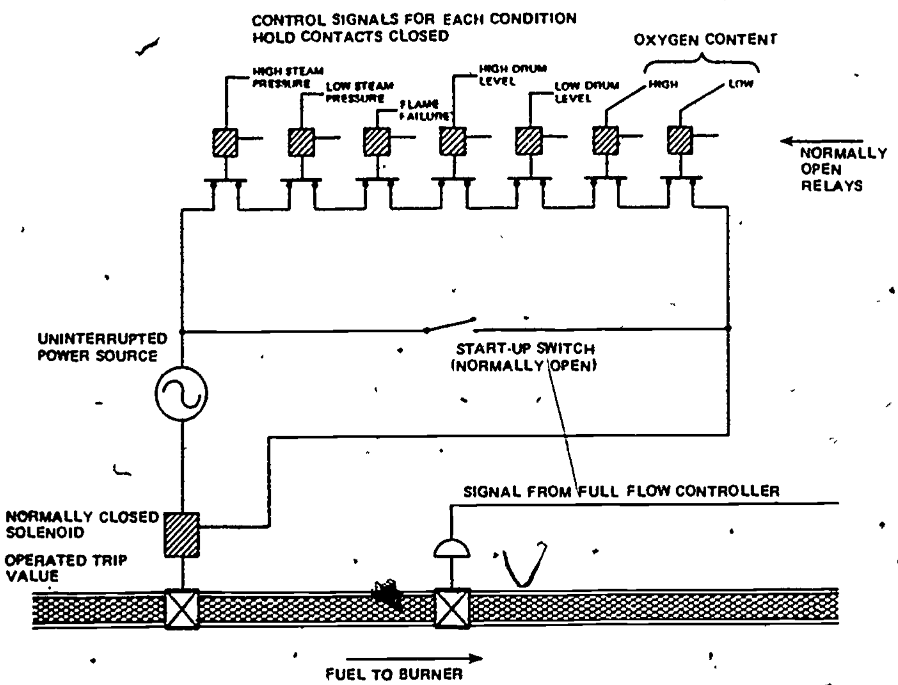


Figure 8. Typical fuel shutdown circuit.

The normally-open relay switches in Figure 8 are held closed by safe process conditions. A relay in the output circuit of a combustion analyzer causes the associated switch to be closed only when the mixture of exhaust gases in the flue stack is not combustible (that is, when boiler combustion is complete and no unburned fuel is entering the stack).

The flame failure switch is held closed by an optical flame analyzer that measures electromagnetic radiation from the flame. The light from the flame, usually measured in the infrared or ultraviolet wavelength region, is detected by a photodetector. Current from the detector is amplified to a level that is sufficient to energize a switch. When the flame is extinguished, energy to the photodetector ceases, and the switch opens. An intermittent flame failure will close the trip valve. This valve remains closed until opened manually. If the shutdown feature were not provided, an intermittent flame failure could fill the firebox with gas, causing a hazardous condition. An optical flame detector is used because of the very fast response time. A thermocouple would not respond to a flame failure quickly enough to close the trip valve if interruption in the gas flow were instantaneous and gas flow were suddenly restored.

The boiler control system discussed in this module is only moderately complex; there are several more sophisticated systems used in some applications. Programmed startup and shutdown systems are provided for some boilers to eliminate or reduce the necessity of operator drudgery in the startup and shutdown of boilers. Other, more advanced control systems utilizing microprocessor control techniques are also employed in modern boiler operation. However, such control techniques do not deviate from the basic principles of boiler control presented in this module.

EXERCISES

1. Draw a cascade control loop that controls the temperature of a process, and then perform or answer the following:
    a. Indicate the primary and secondary controllers.
    b. Explain the function or purpose of the two controllers.
    c. Explain the advantage of a cascade control system over a single-element control system.
    d. Give the procedure to startup and tune a cascade control loop.
    e. Explain the purpose of the manual loading station.
2. Draw a ratio control loop that controls one flow in a direct ratio to another flow.
3. Explain when and why square root extractors are needed in a ratio control system.
4. Explain the concept of feedforward control.
5. Explain the feedforward control concept and why it is advantageous to boiler control.
6. Describe feedback trim, and tell why it is necessary.
7. How is the material and energy balance on a boiler maintained?
8. How are ratio and cascade control used in a boiler control system?
9. How is feedback trim provided for the control system, as discussed in this module?
10. Why are optical flame detectors used in boiler shutdown systems?

LABORATORY MATERIALS

None.

LABORATORY PROCEDURES

LABORATORY 1. BOILER VISITATION.

Visit a conventionally fired boiler installation to observe boiler operation and control. The following items should be considered or observed.

1. Type of boiler - water tube, fire tube, drum, or straight through.
2. Fuel system - auxiliary or backup provided.
3. Drum level control (if applicable), two- or three-element.
4. Identify a cascade and ratio control loop.
5. Identify a method or methods to ensure optimum control operation.
6. Identify a boiler as either an induced-draft type or a forced-draft type.

LABORATORY 2. FILM PRESENTATION.

View the film produced by the Instrument Society of America entitled "Boilers and Their Control - Parts 1 and 2."

REFERENCES

Elonka, Sephan M. and Kohan, Anthony L. Standard Boiler Operators' Questions and Answers. New York: McGraw-Hill Book Company, 1965.

Liptak, Bella G. Instrumentation in the Processing Industries. Philadelphia: Chilton Book Company, 1973.

GLOSSARY

Boiler: A device to generate a quantity of steam for consumption at a desired pressure.

Cascade control: A system that involves two controllers, where the output of one furnishes the set point of another.

Combustion air: The air a boiler requires to burn the fuel.

Drum boiler: A boiler type in which water is supplied to a drum that supplies water to tubes. Water is heated in the tubes and returned to the drum. Wet steam from the drum is passed through a superheater.

Feedforward control: A control system in which both demand potential and demand load are measured. A supply amount is determined from the measured values of potential and load and is used to maintain the desired balance.

Ratio control: The scheme by which two variables, usually flow, are controlled in exact proportion to each other.

Straight-through tube boiler: A boiler that has water supplied to one end of a series of tubes, and steam taken from the other end of the tubes. It contains no steam drum.

Water tube drum boiler: A boiler that contains water on the inside of tubes, and heat is applied to the outside of the tubes.

TEST

INSTRUMENTATION AND CONTROLS

Module IC-08

"Boiler and Other Special Control Systems"

1. List the four general boiler classifications.
2. A three-element drum level control consists of the following:
   a.
   b.
   c.
3. The controllers in a cascade loop are called __________ and ________.
4. The two flows of a ratio-control loop are called ________________ and ________________.
5. The component used to decouple a cascade control system is called ________________.
6. In tuning a cascade control loop, a general procedure is to tune the controller in an exact order. List the order in which the controllers are tuned.
7. Flame detectors for boiler shutdown circuits are generally of the ____________ type because of the __________________.
8. The feedback trim control discussed in this module is provided by which measurement.
9. List four boiler conditions that normally would constitute a shutdown condition.
10. Boiler control is based on maintaining one variable constant. That variable is ____________________.