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ABSTRACT

This module on heat transfer is one of six in a series intended for use as supplements to currently available materials on solar energy and energy conservation. Together with the recommended texts and references (sources are identified), these modules provide an effective introduction to energy conservation and solar energy technologies. The module is divided into these sections: (1) set of objectives: (2) programed instructional material, consisting of short readings describing ideas and techniques one step at a time, and a question or problem on each reading: (3) review questions and answers at intervals; and (4) posttest. Objectives for this module are for the student to be able to describe heat transfer and compute heat transfer rates. (YLB)

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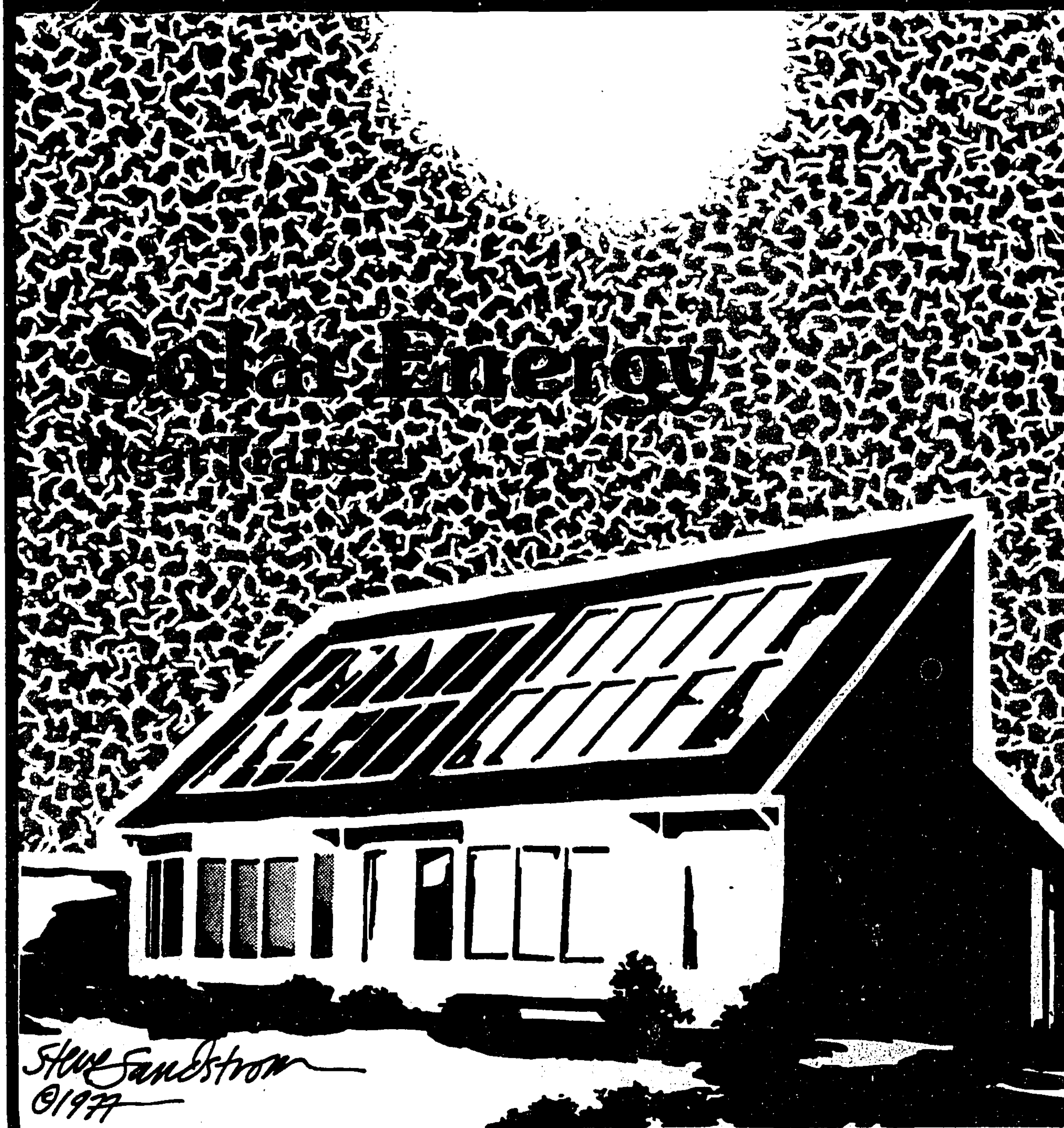
INDIVIDUALIZED LEARNING SYSTEMS

Solar Energy

Heat Transfer



INSTRUCTIONAL LEARNING SYSTEMS

Solar Energy

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Introduction

These modules are intended to be used as supplements to currently available materials on solar energy and energy conservation. The two best available texts are

Leckie, Masters, Whitehouse and Young; Other Homes and Garbage, Sierra Club Books, 1975,

and

Anderson, The Solar Home Book, Cheshire Books, 1975.

There are several reference works that would also be very useful to have on hand. The three most useful ones are

ASHRAE Guide and Data Book, Handbook of Fundamentals, American Society of Heating, Refrigeration and Air Conditioning Engineers, New York, 1977.

U. S. Department of Commerce, Climatic Atlas of the United States, Environmental Data Service, Reprinted by the National Oceanic and Atmospheric Administration, 1974.

U. S. Department of Commerce, Monthly Normal of Temperature, Precipitation and Heating and Cooling Degree-Days (1941-1970) National Oceanic and Atmospheric Administration, Climatography of the United States (by state).

The last two references can be obtained from the National Climatic Center, Environmental Data Service, Federal Building, Asheville, NC 28801. The most important data to have on hand are the per cent possible sunshine and heating degree-day records for locations in Oregon. They're available in the last two references. Some data are also available in the two texts and the modules themselves.

The modules are designed to simplify and supplement the treatment of some of the subjects discussed in the texts and references. In combination, the modules, texts, and references provide an effective introduction to energy conservation and solar energy technologies.

The technique you'll use to learn the skills presented in this module is called programmed instruction. It's a technique which we think will enable you to learn these new skills quickly and easily.

The module is divided into several sections:

1. A set of objectives, which tells you what you should expect to learn from this module.
2. Programmed instructional material which we'll describe later on in this introduction.
3. A post-test, which will help you find out what you were able to learn by using the module.
4. A student evaluation form which you can use to tell us what you liked and disliked about the module, so we can make it better for students who use it later on.

The programmed part of the module consists of short readings which show you the ideas and techniques you need a step at a time. Most are followed by a question or problem which gives you a chance to review what you just read. Depending on your answer to the question or problem, you'll be guided to another short reading which will either help you review a little more, or introduce you to a new idea or technique. Each short reading is called a <u>frame</u>.

To get the most out of the programmed part, you need to follow the directions exactly. Resist any temptations to skip around, and respond in the best way you can to the question in each frame before moving on to the frame you're told to read next.

It'll help to have pencil, paper, and a pocket calculator handy for some of the computations you're asked to do.

Don't forget about your instructor. You don't have to do it all by yourself. Ask for help with any part of the module that you can't get through by yourself. Good luck!

OBJECTIVES

Overall Objective 1:

The student will be able to list and describe the basic ways in which heat can be transferred.

Sub-Objectives:

The student will be able to:

A. describe convective heat transfer, and
B. explain how convective heat transfer is related to sensible heat storage.
C. describe conductive heat transfer, and
D. explain how conductive heat transfer is related to temperature and the properties of materials.
E. describe radiative heat transfer.
F. explain the basic differences between convective, conductive, and radiative heat transfer.
G. explain the operation of heat pumps.

Overall Objective 2:

The student will be able to compute heat transfer rates for two mechanisms of heat transfer.

Sub-Objectives:

The student will be able to:

A. compute convective heat transfer multipliers.
B. compute conductive heat transfer multipliers.
C. compute rates of convective or conductive heat transfer using heat transfer multipliers.
D. compute coefficients of performance for heat pumps.

1. Heat transfer is the movement of heat energy from place to place. The sun transfers some of this heat to the earth in the form of sunlight, or solar energy. The heating system that heats your home has to transfer its heat to the air, the walls, the furniture, and your body.

A solar heating system transfers the sun's heat to a heat storage material, or directly to a heated space. Heat also must be transferred from the heat storage material to the heated space when heat is needed and the sun isn't shining.

Heat transfer is also involved when a building loses heat to the outside air during cold weather. Heat is transferred from the air inside the building to the building's covering materials, and from them to the outside air. In hot weather, heat is transferred from the outside air to the building's covering materials, and from them to the inside air.

Heat pumps also transfer heat. They use a special technique to extract heat from relatively cool surroundings and transfer it to warmer surroundings. When heat pumps are used only for cooling, they're called air conditioners. Refrigerators and freezers use heat pumps to cool their contents.

List three processes which involve heat transfer below:

1.

2.

3.

Go on to frame 2.

---

2. Here are a few:
   1. Transfer of heat to and from thermal storage materials (in a solar heating system, for example).
   2. Winter heat loss from houses.
   3. Refrigeration.
   4. Air Conditioning.
   5. Solar energy transferred from the sun to the earth.
   6. Heating of houses by conventional furnaces.
   7. Heating houses by heat pumps.

If you have trouble seeing where heat transfer is involved in any of those processes, or you couldn't think of three, reread frame 1. Your instructor can help you clear up any confusion you may have about the examples we gave. If the examples all made sense to you, and you had no trouble thinking of your own, go on to frame 3.

---

3. You should have a good idea of what heat energy is from your work on module 1 of this series. We'll remind you. It's the energy in the disorganized motion of the atoms or molecules of everything around us, and us, too. The faster a molecule or atom is moving, the more heat energy it contains, and the higher its temperature.

   Fast moving objects which hit slower moving objects tend to speed them up. The result is that the natural direction of heat transfer or heat flow is from higher temperature objects to lower temperature objects. Your house cools off in the winter because the heat wants to leave its warmer inside for the colder outside.

   Heat naturally flows from higher temperature objects to lower temperature objects, but there are artificial methods to get it to flow in the opposite direction. The heat pump is the main such method. To get heat to behave so unnaturally, the heat pump needs to supply some mechanical energy of its own, so the heat it transfers doesn't come free of charge.

   What's the <u>natural</u> direction of heat flow? Check your answer in frame 4.

---

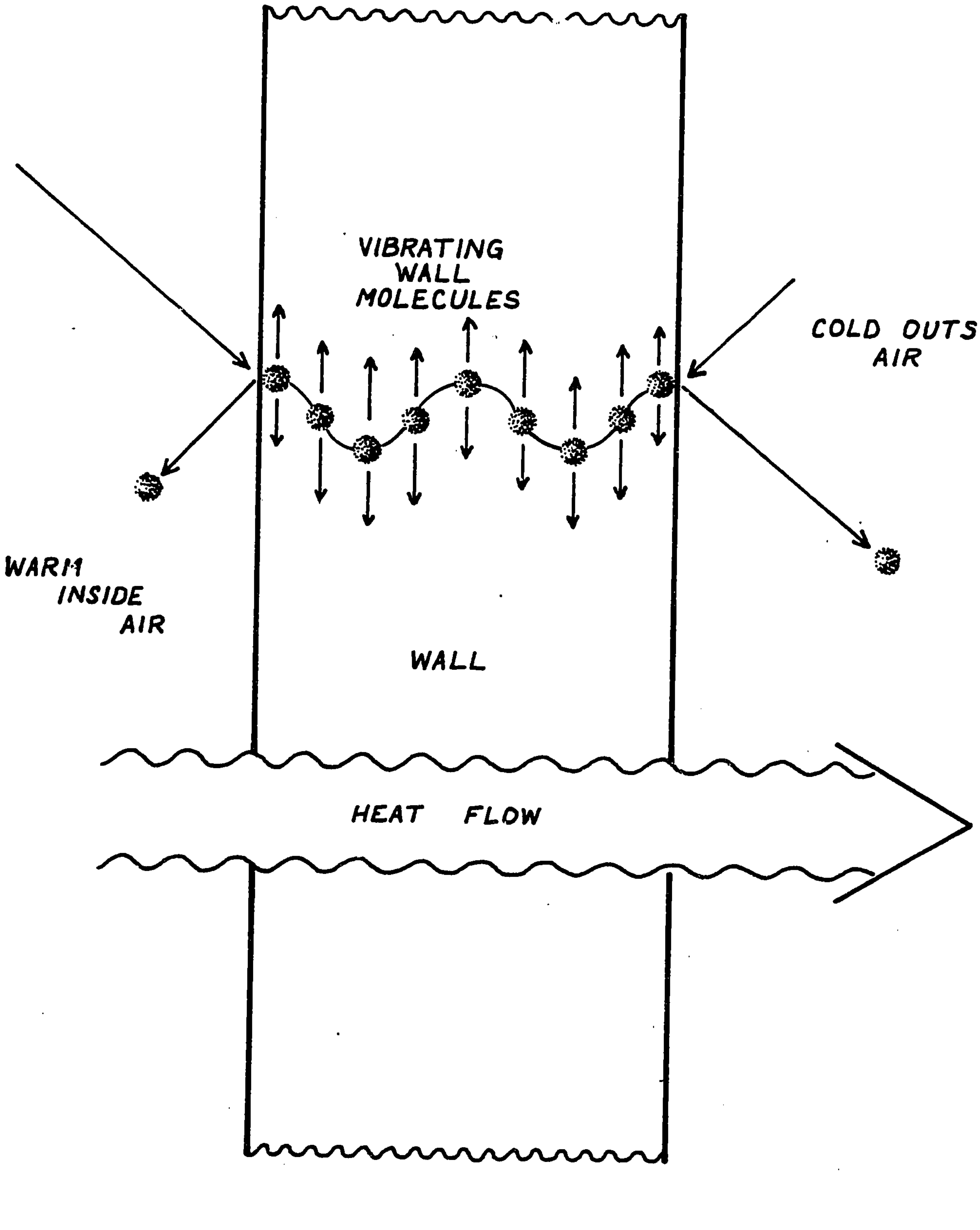
4. The natural direction of heat flow is from higher temperature objects to lower temperature objects. Go on to frame 5.

---

5. The simplest method of transferring heat from one object to another is to put them in contact with each other. Let their atoms or molecules hit each other. The molecules or atoms of the hotter (higher temperature) object speed up the molecules or atoms of the colder (lower temperature) object, transferring heat energy to them. This mechanism of heat transfer is called <u>conduction</u>.

   Conduction can only occur when materials come in direct contact with each other, so their atoms and molecules can collide with each other.

WALL OF HOUSE CONDUCTING HEAT



The name conduction comes from the idea of putting three materials in contact with each other, with one material sandwiched in between the other two. The material in the middle can conduct or lead heat energy from the hotter material on one to the colder material on the other side. It does that by warming up itself because it's in contact with the hotter material, and then transferring some of the heat it's acquired to the colder material.

Describe heat transfer by conduction in your own words, and compare your description with the one in frame 6.

---

6. Conduction, or conductive heat transfer, occurs only when materials touch each other. Collisions between their atoms and molecules result in faster molecules or atoms being slowed down and the slower ones being speeded up. The result is heat transfer from the hotter to the colder atoms or molecules. Go on to frame 7.

---

7. In frame 5, we discussed conduction, or conductive heat transfer involving three objects or substances. The middle substance in the sandwich could conduct the heat from one of the outer substances to the other one.

An example is a wall of a house conducting heat between the air inside the house and the air outside. The rate, or speed, of the transfer of heat through the wall depends on what the wall is made of, its thickness, the temperature difference between the inside and the outside air, and how big a wall area there is for the heat to pass through.

Some materials, especially metals, conduct heat more easily than others, so what the wall is made of has an important influence on how fast heat is conducted through it. The thickness of the wall determines how far the heat has to travel. The bigger the difference in speed of molecules or atoms, the easier it is to transfer energy from the faster ones to the slower ones. The more area the wall has, the more contact there is between the substances, and the more atomic and molecular collisions can occur.

List the four things that determine the speed, or rate, of conductive heat transfer. Check your answers in frame 8.

A.

B.

C.

D.

---

8. You should have written:

   A. type of material

   B. temperature difference

   C. contact area

   D. distance the heat must travel

   If you didn't, or don't know why you did, go back and review frame 7. When you feel confident of these answers, go on to frame 9.

---

9. Good. Now we'll show you how to take all those things into account when you want to compute a rate of heat transfer. Go on to frame 10.

---

10. The first thing we'll take into account is the material the wall or other heat conducting device is made of. The heat conducting ability of a material is described in terms of how much heat will be conducted in one hour through a piece one inch thick with an area of one square foot, if the temperature is 1 ^{o}F. higher on one side than the other. The unit of heat used is the British Thermal Unit (BTU). In module 1, we said that a BTU is the amount of heat energy it takes to heat one pound of water 1 ^{o}F.

    The symbol for heat conducting ability, or <u>thermal conductivity</u> is K. The units of K are BTU-In./Ft.^{2}-Hr.-^{o}F. Ft.^{2} means square foot, and In. means inch.

    A material described by a high value of K conducts heat quickly. A low value of K describes a material which conducts heat slowly.

K is defined for a standard fixed thickness and area of material and a standard fixed temperature difference so that different materials can be compared in the same heat conducting situation. K describes only the physical properties of the material, and doesn't take into account changes in thickness, area, or temperature. The effects of material thickness, area, and temperature on the rate of heat transfer are accounted for in other ways.

Some typical values for K are:

Material	K (BTU-In./Ft.^{2}-Hr.-^{o}F.)
steel	300
aluminum	1400
copper	2685
wood	.8 - 1.0
fiberglas insulation	.25 - .30
cellulose insulation	.22
foam insulation	.20
concrete	5 - 10
water	1.3
rock	1 - 10
earth	5 - 15

You can see the wide variation possible in the rate of heat conduction of a one inch thick wall, depending on what it's made of.

Describe in your own words what the symbol K stands for and give its units. Check your answer in frame 11.

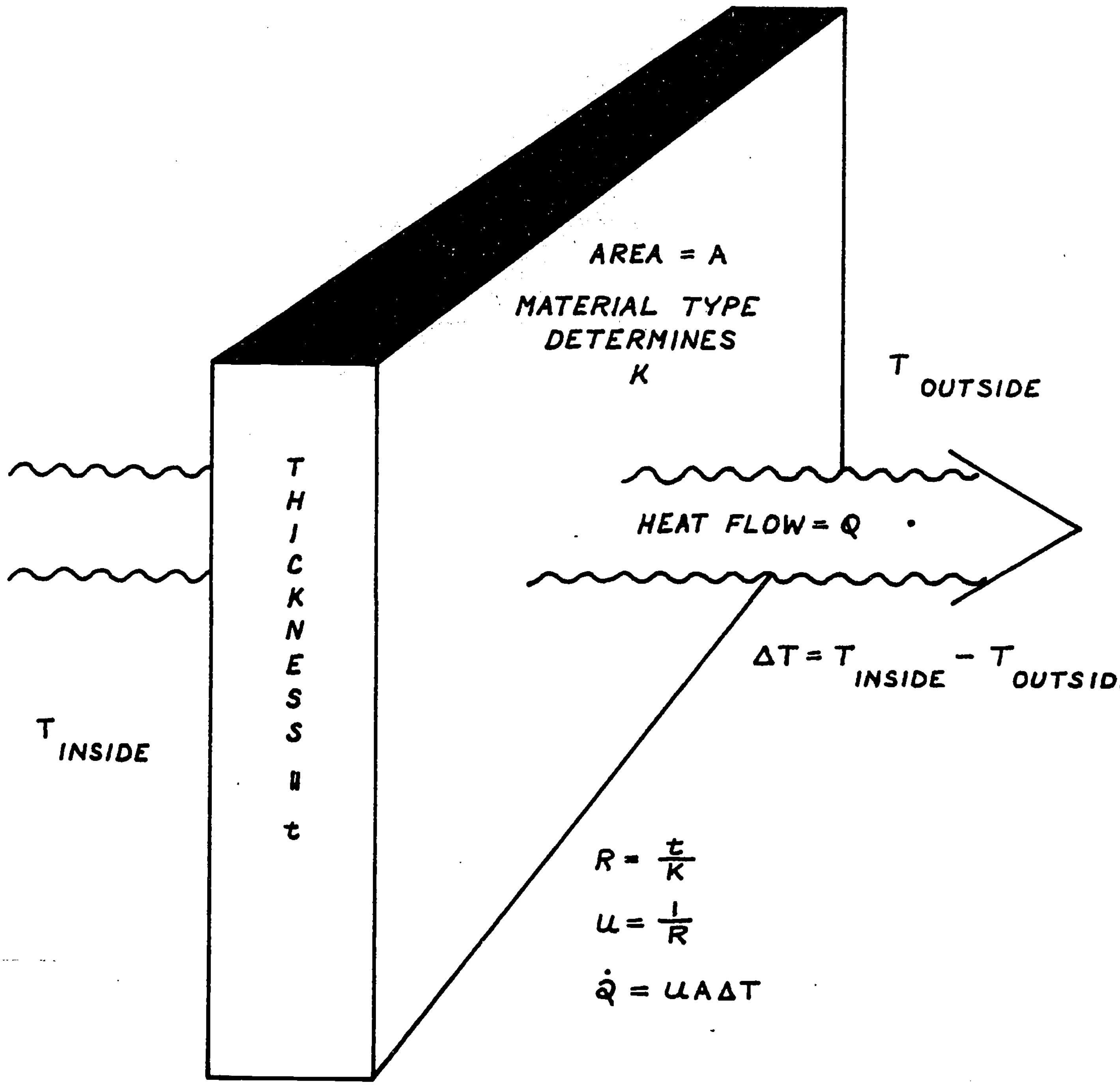
---

11. You should have written something like:

K describes the heat conducting properties of a particular material. It stands for thermal conductivity. It's the number of BTU of heat that will pass through a one-inch thickness of the material in one hour if the area the heat can pass through is one square foot, and the temperature difference from one side of the material to the other is 1 ^{o}F. The units of K are BTU-In./Ft.^{2}-Hr.-^{o}F.

Review this frame and frame 10. Go on to frame 12 when you're sure you can write out a good description of K.

HEAT TRANSFER and HEAT TRANSFER SYMBOLS



The thicker a wall or a piece of material gets, the harder it is for heat to be conducted through it. The resistance to heat flow is greater, the greater the thickness. The resistance of a certain thickness of material is described by the symbol R. To find a value for R, you divide the material's thickness in inches by the K value corresponding to the type of material:

$R = \frac{t}{K}$, where t is the thickness in inches. The units of R turn out to be ^{o}F.-Hr.-Ft.^{2}/BTU. R describes what the temperature difference between one side of a material and another must be in ^{o}F., if one BTU of heat energy is to pass through a one square foot area of the material in one hour.

The thicker the material, the larger R is. The higher the value of K, the smaller R is. R depends on both the thickness of the material, and on its thermal conductivity, K.

For example, the R value of a four inch thickness of foam insulation is

$$R = \frac{t}{K}$$

$$R = \frac{4 \text{ In.}}{.25 \text{ BTU-In./Ft.}^2\text{-Hr.-}^{o}\text{F.}}$$

$$R = \frac{4 \text{ (Ft.}^2\text{-Hr.-}^{o}\text{F./BTU)}}{.25}$$

$$R = 16 \text{ Ft.}^2\text{-Hr.-}^{o}\text{F./BTU}$$

or $R = 16\ ^{o}\text{F.-Hr.-Ft.}^2\text{/BTU}$

Notice two things:

1. When dividing by K, we reversed the units of K and multiplied by them, just as you learned to do with the units in module 1. The In. units cancelled.
2. The order of the units connected by dashes doesn't matter, as long as they remain on the same side of the slash.

So, the R-value, or thermal resistance, of a four inch thickness of foam insulation is 16 ^{o}F.-Hr.-Ft.^{2}/BTU.

Try this one:

What's the R-value of a three inch thickness of aluminum? Check your answer in frame 13.

13. You should have:

$R = .0021\text{-}^{o}F.\text{-}Hr.\text{-}Ft.^{2}/BTU$ (approximately)

If you didn't get this one, go to frame 14. If you did, go to frame 17.

---

14. O.K. Use $R = \frac{t}{K}$. t was 3 In. K was 1400 BTU-In./^{o}F.-Hr.-Ft.^{2} (See frame 10.)

$$R = \frac{t}{K}$$

Don't forget the unit tricks. Reverse the units of K and multiply by them. The In. units cancel. Just divide the numbers.

$$R = \frac{t}{K}$$

$$R = \frac{3 \text{ In.}}{1400 \text{ BTU -In./Ft.}^{2}\text{-Hr.-}^{o}\text{F.}}$$

$$R = \frac{3 \text{ In. (Ft.}^{2}\text{-Hr.-}^{o}\text{F./BTU-In.)}}{1400}$$

$$R = .0021\text{-Ft.}^{2}\text{-Hr.-}^{o}\text{F./BTU}$$

$$\text{or } R = .0021\ ^{o}\text{F.-Hr.-Ft.}^{2}\text{/BTU}$$

Try this one:

What's the thermal resistance of a two inch thickness of wood with a K value of 1 BTU-In./Ft.^{2}-Hr.-^{o}F? Check your answer in frame 15.

---

15. You should have

$$R = 2\ ^{o}\text{F.-Hr.-Ft.}^{2}\text{/BTU}$$

If you don't, look at our solution; and try the next one:

$$R = \frac{t}{K}$$

$$R = \frac{2 \text{ In.}}{1 \text{ BTU-In./}^{o}\text{F.-Hr.-Ft.}^{2}}$$

$$R = \frac{2 \text{ In. (}^{o}\text{F.-Hr.-Ft.}^{2}\text{/BTU-In.)}}{1}$$

$$R = 2\ ^{o}\text{F.-Hr.-Ft.}^{2}\text{/BTU}$$

What's the thermal resistance of a 6 inch thickness of concrete with a K value of 10 BTU-In./^{o}F.-Ft.^{2}-Hr.? Check your answer in frame 16.

---

16. You should have R = .6 ^{o}F.-Hr.-Ft.^{2}/BTU. If you didn't get this one, review frames 12 - 15. Get help from your instructor if you need it.

If you got it, go on to frame 17.

---

17. Good. Now you understand the relationship between the thickness of a material, described by t, its heat conducting properties, described by K, and its resistance to heat flow, described by R.

$$R = \frac{t}{K}$$

There are two ways to increase a wall's resistance to heat flow. You can increase the thickness of the material the wall is made of, or you can cover, or insulate, the wall with other materials. Walls made out of layers of different coverings are called composite walls, because they're composed of several different materials.

To find the thermal resistance of a composite wall, you just add up the thermal resistances of each of its layers. If a wall has four layers with thermal resistances R_1, R_2, R_3, and R_4, the thermal resistance of the wall is

$$R = R_1 + R_2 + R_3 + R_4$$

Example:

The thermal resistance of a concrete wall (K = 1.0 BTU-In./Ft.^{2}-Hr.-^{o}F.) 6 inches thick is

$$R_1 = \frac{t_1}{K_1} = \frac{1}{\text{1 BTU-In./Ft.}^2\text{-Hr.-}^o\text{F.}}$$

$$R_1 = \frac{6}{1}\ \text{In.}\ (\text{Ft.}^2\text{-Hr.-}^o\text{F./BTU-In.}) = 6\ ^o\text{F.-Ft.}^2\text{/BTU}$$

Adding 2 inches of foam insulation (K = .20 BTU-In./^{o}F.-Hr.-Ft.^{2}) to the outside of the wall adds an additional resistance

$$R_2 = \frac{t_2}{K_2} = \frac{\text{2 In.}}{\text{.20 BTU-In./}^o\text{F.-Hr.-Ft.}^2}$$

$$R_2 = \frac{2\ \text{In.}}{.20}\ (^o\text{F.-Hr.-Ft.}^2\text{/BTU-In.}) = 10\ ^o\text{F.-Hr.-Ft.}^2\text{/BTU}$$

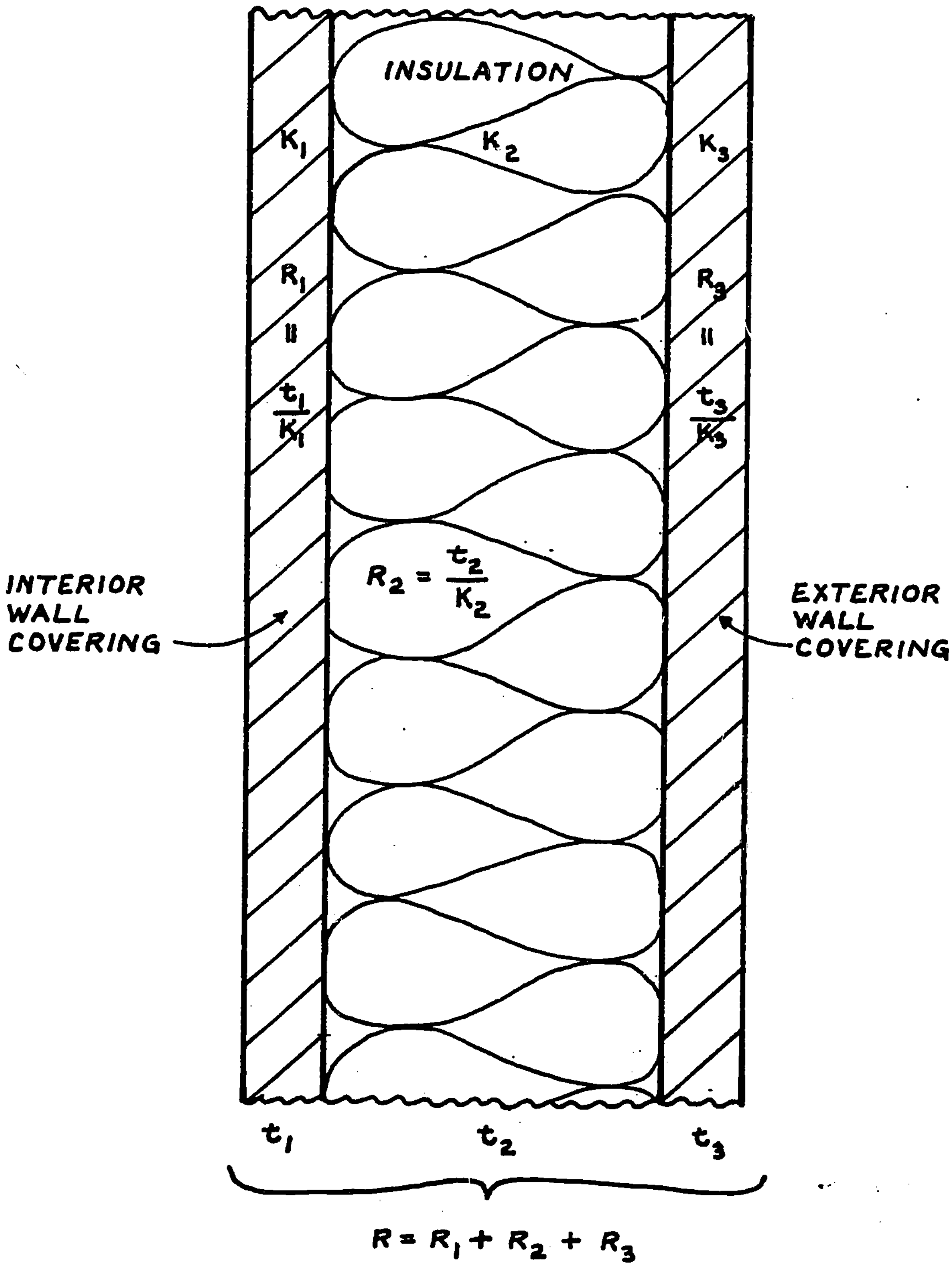
The thermal resistance of the new wal is

$$R = R_1 + R_2 = 16\ ^o\text{F.-Hr.-Ft.}^2\text{/BTU}$$

What's the thermal resistance of a wood frame wall made with 1 inch inner and outer wood skin (plywood and shingles, K = 0.8 BTU-In./^{o}F.-Ft.^{2}-Hr., total wood thickness of 2 inches) and 3-1/2 inches of gypsum insulation (K = .35 BTU-In./^{o}F.-Ft.^{2}-Hr.)?

Check your answer in frame 18. 16

A COMPOSITE WALL



18. You should have

$R = 12.5\ ^oF.\text{-}Hr.\text{-}Ft.^2/BTU$

If you didn't get it, go on to frame 19.

If you did, go to frame 21.

---

19. The idea is to compute the two resistances (wood and gypsum) separately and add

For the wood, the thickness is 2 inches. You get

$$R_1 = \frac{2\ In.}{.8\ BTU\text{-}In./^oF.\text{-}Ft.^2\text{-}Hr.} = \frac{2\ \cancel{In.}}{.8}\ (^oF.\text{-}Ft.^2\text{-}Hr./BTU\text{-}\cancel{In.})$$

$R_1 = 2.5\ ^oF.\text{-}Ft.^2\text{-}Hr./BTU$

For the gypsum (3.5 In. thickness) you get

$$R_2 = \frac{3.5\ In.}{.35\ BTU\text{-}In./^oF.\text{-}Ft.^2\text{-}Hr.}$$

$R_2 = 10\ ^oF.\text{-}Ft.^2\text{-}Hr./BTU$

So the R of the wall is

$R = R_1 + R_2$

$R = 12.5\ ^oF.\text{-}Ft.^2\text{-}Hr./BTU$

Try this one:

What's the thermal resistance of a 2 foot thick earth wall ($K = 2$ BTU-In./$^oF.\text{-}Ft.^2\text{-}Hr.$) with an interior concrete wall 6 inches thick ($K = 10$ BTU-In./$^oF.\text{-}Ft.^2\text{-}Hr.$)?

Check your answer in frame 20.

18

20. You should have:

$R = 12.6\ ^{o}F.\text{-}Ft.^{2}\text{-}Hr./BTU.$

If you got $R = 1.6\ ^{o}F.\text{-}Ft.^{2}\text{-}Hr./BTU.$, you forgot to convert the thickness of the earth wall into inches. Try again. If you're still stuck, review frames 17, 18, and 19; and get help from your instructor if you need it. When you can do all three problems, including the example, go on to frame 21.

---

21. Good going. Now you can compute the thermal resistance of <u>any</u> wall, if you know the K values and the thicknesses of its layers. K values can be found in the references given in module 1 and most heating, refrigeration and air conditioning handbooks. Go on to frame 22.

---

22. A heat transfer device is called a <u>heat exchanger</u>. A wall is a heat exchanger. Heat exchangers are also used in heating systems.

A wall should be designed to transfer or exchange heat very slowly, because heat transfer through a wall results in a gain or loss of heat in the space enclosed by the wall. That heat gain or loss must be corrected by a cooling or heating system.

You've learned to compute the <u>thermal resistance</u>, or resistance to heat transfer, of a wall. A wall with high thermal resistance transfers heat very slowly, and does its job well. It's a poor heat exchanger.

A heating system should have heat exchangers designed to transfer heat very quickly, because the heat will be used to heat water or air for a building. The more easily a heating system can transfer heat, the more efficient it will be. It should have a good heat exchanger.

The ability of a heat exchanger to exchange or transfer heat is described by a quantity called the <u>heat transfer multiplier</u>, or <u>coefficient of transmission</u>. A high coefficient of transmission indicates a good heat exchanger. The symbol for heat transfer multiplier is U.

As you've discovered by now, thick insulated walls have high values of R, and are poor heat exchangers. You'd expect the value of U for a wall to be low if the wall had a high R value. That's the way it is.

In fact, the formula for U is

$$U = \frac{1}{R}$$

The units of U are the reverse of the units for R: BTU/Hr.-Ft.^{2}-^{o}F.

For composite heat exchangers like walls, or any other heat exchanger built with several different materials, the way to find U is to first compute R, and then use the formula

$$U = \frac{1}{R}$$

For simple heat exchangers involving only one type of material the way to compute U is to reverse the formula for the R-value of a simple material:

$$R = \frac{t}{K}, \text{ so}$$

$$U = \frac{K}{t}$$

U is the opposite of R.

Write the symbol for heat transfer multiplier, and the symbol for thermal resistance below. Write two formulas for each one. Check your answers in frame 23.

Heat transfer multiplier:

Formulas:

Thermal resistance:

Formulas:

20

23. You should have:

Heat transfer multiplier: U

Formulas: $U = \frac{1}{R}$

$U = \frac{K}{t}$

Thermal resistance: R

Formulas: $R = \frac{t}{K}$

$R = R_1 + R_2 + R_3 + \ldots$

If you didn't get everything, review frames 17 through 22. If you did, go on to frame 24.

---

24. Congratulations. Go on to frame 25.

---

25. You should now be able to compute the R or U value of any wall. Try the problem below:

Compute the R value and U value of a wall with a total wood thickness of 2 inches (K = 0.8 BTU-In./^{o}F.-Ft.^{2}-Hr.) and an insulation thickness of 5 1/2 inches (fiberglas, K = .275 BTU-In./^{o}F.-Ft.^{2}-Hr.)

Check your answer in frame 26.

26. You should have

$R = 22.5\ ^oF.\text{-Hr.-Ft.}^2/BTU$

$U = .044\ BTU/^oF.\text{-Hr.-Ft.}^2$

If you didn't get it, go on to frame 27.

If you did, go to frame 30.

---

27. Remember to compute R for each material separately, using $R = \frac{t}{K}$. Then, use $R = R_1 + R_2$ to find the R-value of the wall. The U value is just $\frac{1}{R}$.

Try it again.

What's the U value of a 5 inch concrete wall (K = BTU-In./^{o}F.-Ft.^{2}-Hr.) with 1 inch of foam insulation (K = 0.2 BTU-In./^{o}F.-Hr.) on its outside surface? Check your answer in frame 28.

22

28. You should have

$U = .1$ BTU/Hr.-^{o}F.-Ft.^{2}

If you didn't get it, go back and redo frames 25 through 27, and get help from your instructor. If you did, go to frame 29.

---

29. Good. Now you can compute both R and U. Go to frame 30.

---

30. The R and U values for many heat exchangers, like pipes, walls, windows, and air spaces, have already been computed. They're in tables in heating and air conditioning manuals, such as the American Society of Heating, Refrigeration, and Air Conditioning Engineers Handbook of Fundamentals. All you have to do is look them up.

Some of the tables are reprinted in Leckie, Masters, Whitehouse and Young, Other Homes and Garbage. Sierra Club Books, 1975. Directions for using them are included.

Contractors and architects give the R-values of various types of walls, ceilings, and floors in their building plans, so you can find U-values easily by using $U = \frac{1}{R}$.

The computing procedure you've learned will have to be used for situations where you're designing things yourself or if you can't find something in a table.

Go on to frame 31.

---

31. Once you know U for a heat exchanger, you can compute the rate of heat transfer rather easily. The formula is

$$\dot{Q} = UA\Delta T$$

$\dot{Q}$ is the symbol for the rate of heat transfer. It's pronounced "Q dot". It's units are BTU/Hr. A is the symbol for the area of the heat exchanger. It's units are square feet (Ft.^{2}).

ΔT is the symbol for the temperature difference between one side of the heat exchanger and the other. It's the same ΔT you were using in module 1. Its units are ^{o}F.

Here's an example:

The rate of conductive heat transfer for an R-19 wall with an area of 200 square feet, and an inside-to-outside temperature difference of 40 ^{o}F. is computed using

$$U = \frac{1}{R} = \frac{1}{19\ ^{o}F.\text{-}Ft.^{2}\text{-}Hr./BTU}$$

$$U = .0526\ BTU/Hr.\text{-}Ft.^{2}\text{-}^{o}F.$$

and $\dot{Q} = UA\Delta T$

$$\dot{Q} = (.0526\ BTU/Hr.\text{-}Ft.^{2}\text{-}^{o}F.)\ (200\ Ft.^{2})\ (40\ ^{o}F.)$$

$$\dot{Q} = 420.8\ BTU/Hr.$$

Notice how the ^{o}F. and Ft.^{2} units cancel leaving BTU/Hr.

Now try this one:

What's the rate of heat transfer for an R-40 roof with an area of 1600 Ft.^{2} if the inside-outside temperature difference is 40 ^{o}F.? Check your answer in frame 32.

---

32. You should have:

$$\dot{Q} = 1600\ BTU/Hr.$$

If you got it, go to frame 35. If not, go to frame 33.

---

33. Here's how it works out:

$$U = \frac{1}{R}$$

$$U = \frac{1}{40\ ^{o}F.\text{-}Ft.^{2}\text{-}Hr./BTU}$$

$$\dot{Q} = UA\Delta T$$

$$\dot{Q} = (.025\ BTU/^{o}F.\text{-}Ft.^{2}\text{-}Hr.)\ (1600\ Ft.^{2})\ (40\ ^{o}F.)$$

$$\dot{Q} = 1600\ BTU/Hr.$$

Try this one:

What's the rate of heat transfer through an R-5 floor with 1600 Ft.^{2} area if the temperature difference between the top and underside of the floor is 20 ^{o}F.? Check your answer in frame 34.

34. You should have

$$\dot{Q} = 6400 \text{ BTU/Hr.}$$

If you got it, go on to frame 35. If not, review frames 31 through 33, and try again.

Get help from your instructor if you need it.

---

35. O.K. Now you can compute heat transfer rates for conductive heat transfer using R and U values. Go on to the review questions on the next page.

Review Questions:

1. List three examples of heat transfer.

2. Compute the R value of a wall with 5 1/2 inches of cellulose insulation (K = .22 BTU-In./Hr.-Ft.^{2}-^{o}F.), inch thick wood paneling on the inside (K = 0.8 BTU-In./Ft.^{2}-Hr.-BTU) and inch thick plywood and siding on the outside (K = 0.8 BTU-In./Hr.-Ft.^{2}-^{o}F).

3. The R-Value of the roof of a house is 40 ^{o}F.-Ft.^{2}-Hr./BTU. Compute its U-value.

4. The U-value of a double pane window is 0.69 BTU.Hr.-Ft.^{2}-^{o}F. The window has an area of 35 Ft.^{2}. The window is in the exterior wall of a house with an inside temperature of 65 ^{o}F. The outside temperature is 30 ^{o}F. Compute the rate of heat transfer through the window.

5. Compute the U-value of a piece of aluminum 2 inches thick. (K = 1400 BTU-In./Ft.^{2}-^{o}F.-Hr.)

Answers to review questions:

1. You could have:

   Transfer of heat to or from thermal storage materials in a solar heating system.

   Winter heat loss from a house.

   Refrigeration with a heat pump.

   Air conditioning with a heat pump.

   Solar energy transferred from the sun to the earth.

   Heating of houses by conventional furnaces.

   Heating of homes by heat pumps.

   Electric heating.

2. 27.5 ^{o}F.-Ft.^{2}-Hr./BTU
3. .025 BTU/Hr.-Ft.^{2}-^{o}F.
4. 845.25 BTU/Hr.
5. 700 BTU/Ft.^{2}-Hr.-^{o}F.

If you missed any of these, go back and review frames 1 through 35 until you can do them all. When you can, go on to frame 36.

36. There are other ways heat can be transferred between two substances besides conduction. One of them is convection. Convection is similar to conduction, because it involves contact between the substances transferring heat. However, the contact is less direct than in conduction.

In conduction, the heat moves through a stationary heat transfer device, or heat exchanger. One part of the device is heated by the substance in contact with it. The heat then moves to another part of the device. The device doesn't move or change shape, and the two substances are both in contact with it.

In convection, the heat is first transferred from the higher temperature substance to a fluid, such as air or water, and the fluid then transfers the heat to the lower temperature substance. The heat is transferred to the fluid by conduction, and the fluid moves, carrying the heat with it. When it comes in contact with the other cooler substance, the fluid transfers the heat it is carrying to that substance, again by conduction. (The direct heat transfer between the fluid and both substances is by conduction.) The indirect heat transfer from one substance to the other through the fluid, is called convection.

The main difference between convection and conduction is that the fluid can move. Heat can be transferred long distances to specific locations by convection. It can travel in pipes if the fluid is a liquid, or in air ducts if the fluid is air. The moving fluid carries the heat from place to place.

State in your own words the difference between heat transfer by conduction and heat transfer by convection. Check your answer in frame 37.

37. The difference between conductive and convective heat transfer involves the presence of a fluid (a liquid or a gas). Both means of heat transfer involve the movement of heat from a higher temperature substance to a lower temperature substance through a third substance.

In conduction, the third substance is an unmoving solid object called a heat exchanger. Repeated collisions with the molecules or atoms of the hotter substance gradually speed up the molecules of atoms of the heat exchanger. Collisions with the heat exchanger molecules or atoms gradually cause those of the cooler substance to speed up. In that way, heat is transferred from the hotter substance through the heat exchanger to the cooler substance.

In convection, the heat exchanger is replaced by a heat exchange fluid (a liquid or a gas). The fluid molecules are speeded up by the collisions with those of the hotter substance. In other words, heat is transferred from the hotter substance to the fluid by conduction. Then the fluid moves, carrying the heat with it, until it comes in contact with the cooler substance. The fluid molecules then speed up those of the cooler substance by colliding with them. The heat they contain is transferred to the cooler substance by conduction. The movement of the heat due to the motion of the fluid is called convective heat transfer.

If you wrote something similar (probably a lot shorter!), go on to frame 38. If not, review frame 36 and this one to be sure you understand the difference between conduction and convection. Get help if you feel doubtful. Then go on to frame 38.

---

38. O.K. Now, you'll learn how to compute the rate of heat transfer by convection. The heat being carried in a moving heat transfer fluid during convective heat transfer is actually stored sensible heat, the same sensible heat that you learned about in module 1.

We hope you remember that the formula for the amount of stored sensible heat in a fluid is

$$Q = \rho V C_p \Delta T$$

and that

Q is the symbol for the amount of heat

ρ is the symbol for the density of the fluid, pronounced "row".

V is the symbol for the volume of the fluid.

C_p is the symbol for the specific heat per unit weight of the fluid, and ΔT is the symbol for the temperature difference between the fluid and its surroundings.

The only difference between the formula for stored sensible heat and the one for the rate of heat flow by convection is that in the one for convection there are dots (.) over the Q and the V. The dots are there to indicate that both the heat and the fluid are moving. Since the heat is contained in a volume of the fluid, the movement of the fluid volume results in the movement of the heat.

$\dot{Q}$ is the symbol for the rate of heat flow. Its units are BTU/Hr.

$\dot{V}$ is the symbol for the rate of fluid flow. Its units are either Ft.^{3}/Hr. (cubic feet per hour) or Gal./Hr. (gallons per hour).

So, the formula for the rate of heat flow in convection is

$$\dot{Q} = \rho \dot{V} C_p \Delta T$$

Explain what the symbols in the formula represent, and give the units of each quantity. Check your answers in frame 39.

---

39. $\dot{Q}$ represents the rate of convective heat flow in BTU/Hr.

ρ represents fluid density in Lb./Ft.^{3} or Lb./Gal.

$\dot{V}$ represents rate of fluid volume movement or fluid flow in Gal./Hr. or Ft.^{3}/Hr.

C_p represents specific heat per unit weight of the fluid in BTU/Lb.-^{o}F.

ΔT represents the temperature difference between the fluid and its surroundings in ^{o}F.

If you got all these things, hooray! Go to frame 40. If not, review the last frame, and module 1, if necessary. When you think your memory has been jogged enough for you to keep the symbols straight, go on to frame 40.

---

40. There's a helpful change that can be made in the formula for convective heat transfer. You can combine the ρ and C_p symbols together in a symbol called C_v, which is the specific heat per unit volume of the fluid. The specific heat per unit volume (C_v) of a fluid is just the product of the density (the weight per unit volume) and the specific heat per unit weight, C_p.

For water,

$C_v = \rho C_p = (8.34\ \text{Lb./Gal.})\ (1\ \text{BTU/Lb.-}^{o}\text{F.})$

$C_v = 8.34\ \text{BTU/Gal-}^{o}\text{F.}$

For air $C_v = \rho C_p\ (.075\ \text{Lb./Ft.}^3)\ (.24\ \text{BTU/Lb.-}^{o}\text{F.})$

$C_v = .018\ \text{BTU/Ft.}^{3}\text{-}^{o}\text{F.}$

Those are good numbers to <u>memorize</u>.

The density of water is 62.4 Lb./Ft.^3. What's the specific heat per unit volume of water in $\text{BTU/Ft.}^{3}\text{-}^{o}\text{F}$? Check your answer in frame 41.

---

41. You use

$C_v = \rho C_p$

$C_v = (62.4\ \text{Lb./Ft.}^3)\ (1\ \text{BTU/Lb.-}^{o}\text{F.})$

$C_v = 62.4\ \text{BTU/Ft.}^{3}\text{-}^{o}\text{F.}$

Remember the values of C_v for water and air:

Water: $C_v = 8.34\ \text{BTU/Gal.-}^{o}\text{F.}$ or $62.4\ \text{BTU/Ft.}^{3}\text{-}^{o}\text{F.}$

Air: $C_v = .018\ \text{BTU/Ft/}^{3}\text{-}^{o}\text{F.}$

You'll use them a lot. Go on to frame 42.

---

42. The formula for convective heat flow is now

$\dot{Q} = VC_v\Delta T$, which is simpler than the earlier formula. The ρ and C_p have been replaced by C_v. Write down translations and units for all the symbols in the new convective heat transfer formula below. Check your answers in frame 43.

43. In $\dot{Q} = \dot{V}C_v\Delta T$

$\dot{Q}$ stands for rate of heat flow in BTU/Hr.

$\dot{V}$ stands for rate of fluid flow in Gal./Hr. or Ft.^{3}/Hr.

C_v stands for specific heat per unit volume of the fluid in BTU/Gal.-^{o}F. BTU/Ft.^{3}-^{o}F.

ΔT stands for the temperature difference between the fluid and its surroundings.

The most common heat transfer fluids are air and water. Their specific heats per unit volume are:

Air: .018 BTU/Ft.^{3}-^{o}F.

Water: 8.34 BTU/Gal.-^{o}F. or 62.4 BTU/Ft.^{3}-^{o}F.

Actually, since fluids expand when heated, the values of C_v for air and water change with temperature. However, they don't change very much, so using the values given won't cause much inaccuracy in computation of heat transfer rates at the temperatures you normally encounter. Go on to frame 44.

---

44. Now we're ready for an example:

How fast is heat being transferred through a pipe with water flowing in it at a rate of 30 Gal./Min (gallons per minute) if the temperature of the water has been raised 40 ^{o}F.?

We use $\dot{V}$ = 30 Gal./Min., ΔT = 40 ^{o}F., and C_v = 8.34 BTU/Gal.-^{o}F. for water.

$\dot{Q} = \dot{V}C_v\Delta T$

= (30 Gal./Min.) (9.34 BTU/Gal.-^{o}F.) (40 ^{o}F.)

$\dot{Q}$ = 10,008 BTU/Min.

Notice that we got BTU/Min. and not BTU/Hr. That's because the fluid flow rate was given in Gal./Min.

That's a common situation. Most fluid flow rates are given in Gal./Min. or $Ft.^3$/Min. and most heat flow rates are given in BTU/Hr. What can we do about it?

We can convert BTU/Min. into BTU/Hr. by converting /Min. to /Hr. To do that, we need a conversion factor that looks like Min./Hr., so we can multiply 10,008 BTU/Min. by (Min./Hr.) and get the Min. symbols to cancel. It's just like the converting ^oC. to ^oF. in module 1.

In that situation, we used 1.8 $^oF./^oC.$, which meant "there are 1.8 ^oF. for every ^oC." to convert ^oC. to ^oF. Here we can use 60 Min./Hr. which means "there are 60 minutes in each hour" to convert /Min. into /Hr. We get

$\dot{Q}$ = (60 Min./Hr.) (10,008 BTU/Min.)

$\dot{Q}$ = 600,480 BTU/Hr.

It makes sense. There should be 60 times as much heat moved in an hour as in a minute.

Try this one:

How much heat is transferred by a column of air heated 20 ^oF. and flowing at 200 CFM (cubic feet per minute or $Ft.^3$/Min.)? Check your answer in frame 45.

---

45. You should have

$\dot{Q}$ = 4320 BTU/Hr.

If you didn't get it, go to frame 46.

If you did, move on to frame 49.

46. You use the C_v for air of .018 BTU/Ft.^{3}-^oF.

$$\dot{Q} = \dot{V}C_v\Delta T$$

$$\dot{Q} = (200 \text{ Ft.}^3/\text{Min.})\ (.018 \text{ BTU/Ft.}^3\text{-}^oF.)\ (20\ ^oF.)$$

$$\dot{Q} = 72 \text{ BTU/Min.}$$

to get into BTU/Hr. you use the conversion factor:

$$\dot{Q} = (60 \text{ Min./Hr.})\ (72 \text{ BTU/Min.})$$

$$\dot{Q} = 4320 \text{ BTU/Hr.}$$

Try this one:

What's the rate of heat flow through a water pipe with a flow rate of 10 GPM (gallons per minute or Gal./Min.) if the water temperature is raised 30 ^oF.? Check your answer in frame 47.

---

47. You should have:

$$\dot{Q} = 150{,}120 \text{ BTU/Hr.}$$

If you didn't get this one, go to frame 48.

If you did, go to frame 49.

---

48. Use C_v for water: 8.34 BTU/Gal.-^oF.

Use $\dot{Q} = \dot{V}C_v\Delta T$

$$\dot{Q} = (10 \text{ Gal./Min.})\ (8.34 \text{ BTU/Gal.-}^oF.)\ (30\ ^oF.)$$

$$\dot{Q} = 2502 \text{ BTU/Min.}$$

Convert to BTU/Hr. using the conversion factor of (60 Min./Hr.):

$$\dot{Q} = (60 \text{ Min./Hr.})\ (2502 \text{ BTU/Min.})$$

$$\dot{Q} = 150{,}120 \text{ BTU/Hr.}$$

Go on to frame 49.

---

49. O.K. Here's another practice problem: You're heating a house with 140 ^oF. air from a rock heat storage bin. The house temperature is 70 ^oF. The fan and ducting system that you're using to move the air can produce an air flow rate of 300 CFM (cubic feet per minute). What's the heating capacity of the heating system in BTU/Hr.? (How fast can it transfer heat to the house?) Check your answer in frame 50.

---

50. You should have:

$\dot{Q}$ = 22,680 BTU/Hr.

If you do, go on to frame 52. If not, go to frame 51.

---

51. You use C_v for air of .018 BTU/Ft.^{3}-^oF. ΔT is 70 ^oF. (140 ^oF.-70 ^oF.)

$\dot{Q} = VC_v\Delta T$

$\dot{Q}$ = (300 Ft.^{3}/Min.) (.018 BTU/Ft.^{3}-^oF.) (70 ^oF.)

$\dot{Q}$ = 378 BTU/Min.

$\dot{Q}$ = (60 ~~Min.~~/Hr.) (378 BTU/~~Min.~~)

$\dot{Q}$ = 22,680 BTU/Hr.

Go on to frame 52.

---

52. Here's one more:

A hot water heating system has a water flow rate of 5 GPM (gallons per minute or Gal./Min.). It uses 180 ^oF. water to heat a 70 ^oF. building. What's the rate of convective heat transfer in BTU/Hr.? Check your answer in frame 53.

36

53. You should have

$\dot{Q}$ = 275,220 BTU/Hr.

If you got it, go on to frame 55.

If not, go to frame 54.

---

54. Did you forget to convert BTU/Min. into BTU/Hr.? What did you use for ΔT? Check your multiplication. If these hints don't help, review frames 44 through 53. Get help from your instructor. Try the problem in frame 53 until you get it.

---

55. Great! You can compute convective heat transfer rates if you know flow rates. Suppose, though, that you wanted to know how big a fan or pump you needed to transfer a certain amount of heat. You'd need to compute the rate of fluid flow for a certain heat flow.

You can do that by reversing the formula for heat flow to get

$$\dot{V} = \frac{\dot{Q}}{C_v \Delta T}$$

Let's go through an example:

Suppose you want to heat a house with a maximum heat loss rate of 90,000 BTU/Hr. You need a heating system that can supply 90,000 BTU/Hr. Suppose the house temperature is going to be 65 ^{o}F., and you're going to use 150 ^{o}F. hot air blown by a fan to heat the house. What air flow rate in CFM (cubic feet per minute) must the fan produce?

You just use:

$$\dot{V} = \frac{\dot{Q}}{C_v \Delta T}$$

$\dot{Q}$ = 90,000 BTU/Hr., C_v = .018 BTU/Ft.^{3}-^{o}F. and ΔT = 85 ^{o}F. (150 ^{o}F.- 65 ^{o}F.). You get:

$$\dot{V} = \frac{90,000 \text{ BTU/Hr.}}{(.018 \text{ BTU/Ft.}^3\text{-}^o\text{F.})\ (85\ ^o\text{F.})}$$

$$\dot{V} = \frac{90,000 \text{ BTU/Hr.}}{1.53 \text{ BTU/Ft.}^3}$$

$$\dot{V} = 58,800 \text{ Ft.}^3\text{/Hr.}$$

But we need $\dot{V}$ in Ft.^{3}/Min. We need to replace /Hr. by /Min. Let's try reversing the conversion factor 60 Min./Hr. and multiplying. We used that trick to convert ^{o}F. into ^{o}C. using (^{o}C./1.8 ^{o}F.) in module 1.

$$\dot{V} = (\text{Hr./60 Min.})\ (58,800 \text{ Ft.}^3\text{/Hr.})$$

$$\dot{V} = \frac{58,800 \text{ Ft.}^3\text{/Min.}}{60}$$

$$\dot{V} = 980 \text{ Ft.}^3\text{/Min.}$$

That's reasonable. We should need to move 60 times more hot air to heat the house for an hour than we need to heat the house for a minute.

Notice that this time we needed to reverse the 60 Min./Hr. conversion factor into Hr./60 Min. to change /Hr. into /Min. That forced us to divide by 60, and made things come out sensibly.

Go on to frame 56.

---

56. Try this practice problem:

Suppose you're going to use water to transfer heat from a solar collector. On a hot sunny day the collector will collect heat at a maximum rate of 250,000 BTU/Hr. How many GPM of water must you pump through it to collect this heat if you let the water temperature rise 10 ^{o}F.? Check your answer in frame 57.

38

57. You should have:

$\dot{V}$ = 50 Gal./Min.

If you got it, congratulations! Go on to frame 62. If not, take a look at frame 58.

---

58. You use:

$$\dot{V} = \frac{\dot{Q}}{C_V \Delta T}$$

ΔT = 10 ^{o}F., C_V = 8.34 BTU/Gal.-^{o}F., $\dot{Q}$ = 250,000 BTU/Hr.

$$\dot{V} = \frac{250{,}000 \text{ BTU/Hr.}}{(8.34 \text{ BTU/Gal.-}^{o}\text{F.})(10\ ^{o}\text{F.})}$$

$$\dot{V} = \frac{250{,}000 \text{ BTU/Hr.}}{83.4 \text{ BTU/Gal.}}$$

$$\dot{V} = \frac{250{,}000 \text{ BTU/Hr. (Gal./BTU)}}{83.4}$$

$\dot{V}$ = 3,000 Gal./Hr.

$\dot{V}$ = (Hr./60 Min.) (3,000 Gal./Hr.)

$$\dot{V} = \frac{3{,}000 \text{ Gal./Min.}}{60}$$

$\dot{V}$ = 50 Gal./Min.

Review the steps and try the problem in frame 59.

---

59. O.K. Here's another one. You plan to use air to transfer heat out of a solar collector. The collector will heat at a maximum rate of 150,000 BTU/Hr. Suppose you're going to let the aire temperature rise 40 ^{o}F. in the collector. How much air will you have to circulate through the collector in CFM (cubic feet per minute or Ft.^{3} Min.)? Check your answer in frame 60.

60. You should have

$\dot{V} = 3472 \text{ Ft.}^3/\text{Min.}$

If you got it, congratulations. Go on to frame 62.

If you didn't, look at the solution in frame 61.

---

61. Here's the solution:

$$\dot{V} = \frac{Q}{C_v \Delta T}$$

$$\dot{V} = \frac{150{,}000 \text{ BTU/Hr.}}{(.018 \text{ BTU/Ft.}^3\text{-}^\circ\text{F.})(40\ ^\circ\text{F.})}$$

$$\dot{V} = \frac{150{,}000 \text{ BTU/Hr.}}{72 \text{ BTU/Ft.}^3}$$

$$\dot{V} = 208{,}333 \text{ BTU/Hr. } (\text{Ft.}^3/\text{BTU})$$

$$\dot{V} = 208{,}333 \text{ Ft.}^3/\text{Hr.}$$

$$\dot{V} = (\text{Hr.}/60 \text{ Min.})(208{,}333 \text{ Ft.}^3/\text{Hr.})$$

$$\dot{V} = \frac{208{,}333 \text{ Ft.}^3/\text{Min.}}{60}$$

$$\dot{V} = 3472 \text{ Ft.}^3/\text{Min. or } 3472 \text{ CFM}$$

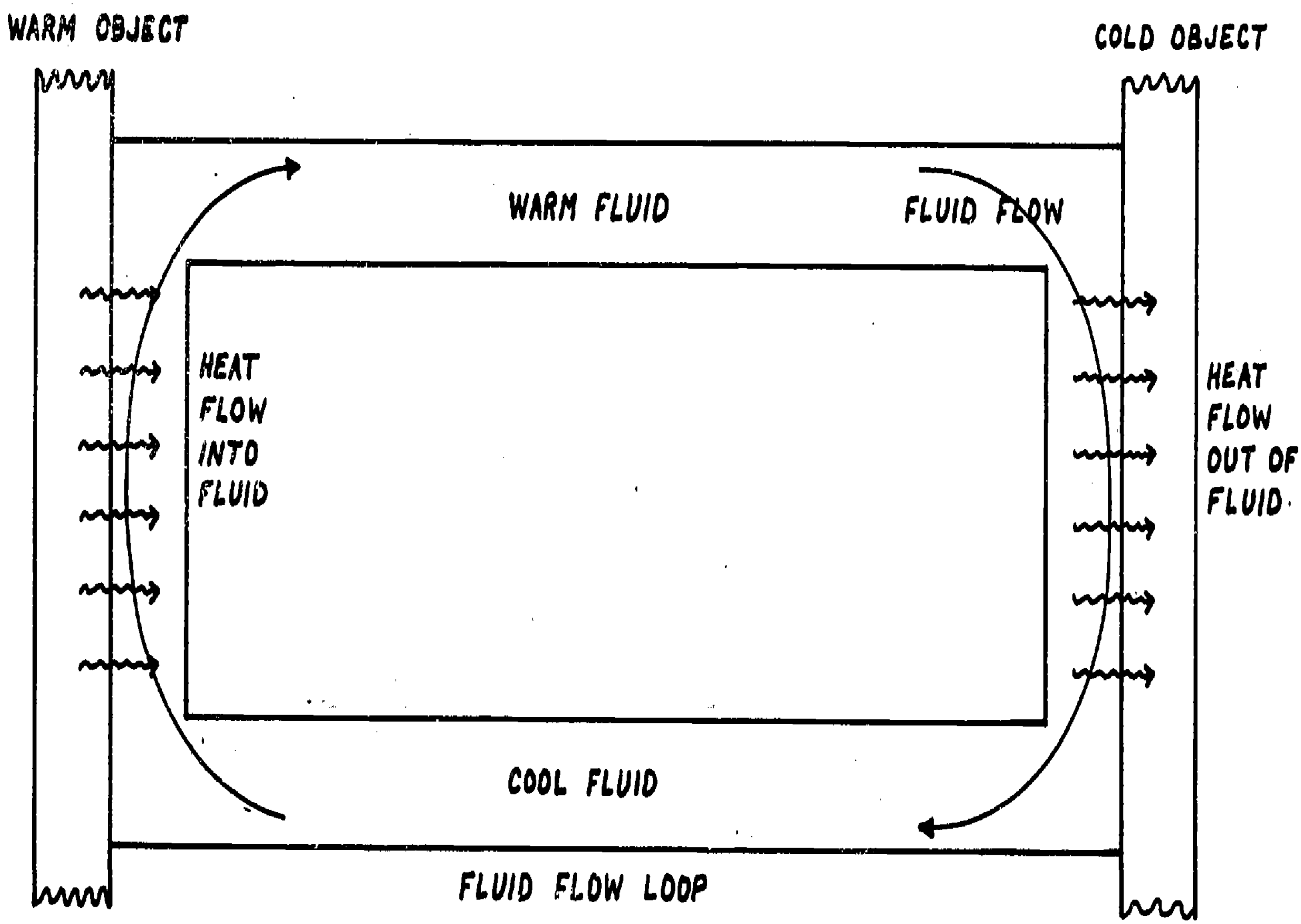
---

62. Here's another problem to try:

You plan to heat a house using water heated by a solar collector. The house temperature will be 65 $^\circ$F. and the water temperature will be 100 $^\circ$F. The house loses heat at a rate of 17,5000 BTU/Hr. What water flow rate will you need through your heating pipes in GPM (Gal./Min.)? Check your answer in frame 63.

40

HEAT FLOW BY FREE CONVECTION



38

63. You should have

$\dot{V}$ = 1 Gal./Min. (almost exactly)

If you got it, nice going! Go to frame 65. If not, don't be too discouraged. Look at frame 64.

---

64. Did you remember that C_v for water is 8.34 BTU/Gal.-^{o}F.? Did you use ΔT = 35 ^{o}F.? Did you remember to use Hr./60 Min. to convert the flow rate from Gal./Hr. to Gal./Min? Try it again and see how you do. Get help from your instructor if you need it. When you have it, go to frame 65.

---

65. O.K. You've just learned the procedure for computing the rates of heat flow and fluid flow in heat transfer by forced convection. Forced convection occurs when a fan or pump is used to move the fluid that's carrying the heat from place to place.

There's another kind of convective heat transfer, called free convection, which occurs when the heat transfer fluid flows naturally from a hotter location to a cooler one and back again. Certain types of heating systems, called gravity heating systems, use it as a means of circulating the heat transfer fluid.

Free convective heat transfer makes use of the fact that almost all fluids tend to get less dense - lighter - when heated, and denser - heavier - when cooled. A hot fluid at the bottom of a closed loop of pipe will naturally rise to the top of the loop and be replaced at the bottom by cooler fluid. If there's a way to heat the fluid at the bottom of the loop and cool it off at the top, the circulation of fluid can be maintained without a pump or fan. Go on to frame 66.

---

66. The situation we've just described occurs naturally in a house with a furnace located in the basement. Heated air from the furnace rises into the house and cools as it comes in contact with the house's outer walls and windows. If floor vents are provided near the outer walls, the cooled air can drop down into the basement to be reheated by the furnace. A natural circulation system is set up which allows heated air to enter the house from the basement and cold air from the house to re-enter the furnace to be reheated and sent back into the house. No fan is needed. Go on to frame 67.

67. The same principle is used in what are called "thermosyphon" solar heating systems. The solar collector is located below the space to be heated. Heated air or water flows up from the solar collector and into the heated space. Cooler air or water tends to fall down into the solar collector through a return air duct or water pipe. Circulation occurs because the solar collector acts like a furnace, reheating the cooler air or water which flows down into it and causing it to rise back into the heated space. Go on to frame 68.

---

68. Free convection also occurs in air space's separating the inner and outer wall coverings in the exterior walls of houses. Air in the air space is heated by conduction when it contacts the warmer inner wall covering and rises to the top of the air space. It's pushed across the air space to the outer wall covering by the pressure of the air rising below it.

It conducts heat to the cooler outer wall covering and gets heavier as it cools, falling to the bottom of the air space. The partial vacuum created by the rising air near the inner wall covering draws the cooler air back across the air space to be reheated. The result is a <u>convective loop</u> composed of cool air falling down the outer wall covering, crossing the air space to the inner wall covering, rising as it's heated, and crossing back to the outer wall covering to be cooled again.

The formation of convective loops in air spaces is the major cause of heat loss through uninsulated walls. Wall insulation's main purpose is to stop the circulation of air inside walls and keep convective heat transfer loops from forming. Go to frame 69.

---

69. Describe the difference between forced and free convective heat transfer, and give three examples of free convection. Check your answers in frame 70.

70. Forced convection involves the forced movement of the heat transfer fluid using either a pump or a fan to move the fluid and the heat it contains from place to place.

Free convection results from the fact that heating most fluids makes them lighter (less dense). Heating the fluid at the bottom of a loop of pipe or duct will cause it to rise to the top, and cooling it at the top will cause it to return to the bottom. The result is a continuous circulation of the fluid which carries heat from the bottom of the loop to the top. Since no pump or fan is required to force the fluid to circulate, the method of heat transfer involved is called free convection.

Some examples:

"thermosyphon" solar heating systems.

"gravity" air heat using basement furnaces.

convective heat loss loops in uninsulated exterior house walls.

"gravity" hot water heat using basement boilers to heat the water.

If you wrote down something similar to what's above and could think of some examples, congratulations. Go on to frame 71.

If you had trouble, review frames 65 through 68, and try again before going on.

---

71. Computing the rate of free convective heat transfer in a particular heat transfer loop is a rather lengthy process. We don't have room in this module to go into it in detail. However, the basic idea is fairly simple.

The hotter fluid moving upward through one half of the loop is less dense than the colder fluid moving downward in the other half. The difference in densities produces a pressure difference between the two halves of the loop which causes the fluid to flow. The magnitude of the pressure difference is roughly equal to the difference in density between the hottest and coldest fluid multiplied by the height of the loop.

The rate of fluid flow is limited by the friction between the fluid and the walls of the loop's piping or ducting. The flow rate will increase until the pressure drop due to friction is equal to the pressure difference due to the fluid temperature rise. The relationship between fluid flow rates, pressure drops, and the interior dimensions of pipes and ducts is complicated. However, tables of pressure drops and flow rates for various pipe and duct sizes can be found in heating and air conditioning manuals.

For a particular circulation loop and a particular fluid temperature rise, you can compute the pressure difference around the loop and look up the fluid flow rate in a table. The flow rate and the temperature rise can then be used in the forced convective heat transfer formula $\dot{Q} = \dot{V}C_v\Delta T$. The result is the heat transfer rate. By varying the interior dimensions of the pipes or ducts in the circulation loop, and varying the temperature rise in the fluid, the fluid flow rate and the heat transfer rate can be varied.

Sometimes it's useful to pick a fluid temperature rise and heat flow rate and compute the necessary fluid flow rate using the reversed convective heat flow formula ($\dot{V} = \frac{\dot{Q}}{C_v\Delta T}$). The temperature rise can also be used to compute the fluid pressure difference. Then you can look up the pipe or duct size necessary to allow the required flow rate without causing a pressure loss greater than the pressure difference you computed.

Both the above methods can be used to design free convective heat transfer systems. The design of forced convective heat transfer systems involves picking a pump or fan and a piping or duct network which will produce the fluid flow rate required by a given forced convective heat transfer rate and a given fluid temperature rise. Tables relating pump sizes, fan sizes, flow rates, pipe sizes, and duct sizes are available in heating and air conditioning manuals. Details of the design procedure, such as balancing air and water flow rates in various branches of networks, are also covered in such manuals. See also Other Homes and Garbage, the reference given in the introduction. Go on to the review questions.

Review Questions

1. Describe the difference between convective and conductive heat transfer.

2. Describe the difference between forced convective heat transfer and free convective heat transfer.

3. Compute the flow rate in GPM (Gal/Min.) required to transfer 100,000 BTU/Hr. using water. The water temperature will be allowed to rise 40 ^{o}F.

4. Compute the flow rate in CFM (Ft.^{3}/Min.) required to transfer 25,000 BTU/Hr. using air with a temperature rise of 50 ^{o}F.

5. Explain how using water as a heat storage material is similar to using it as a convective heat transfer fluid.

Answers to Review Questions

1. Convective heat transfer involves the movement of a fluid, like air or water, which contains heat. The heat can be transferred long distances as the hot fluid molecules move through a pipe or air duct. Conductive heat transfer occurs by direct contact between two substances. The molecules of the hotter substance transfer some of their energy to the molecules of the cooler substance by colliding with them.

2. The fluid flow in free convective heat transfer occurs because the warmer fluid molecules naturally rise and take heat with them. Heat can be transferred upward from a warm object to a cooler one by the naturally rising fluid. Forced convective heat transfer requires a pump or fan to move the fluid either faster or in a different direction than it would ordinarily move when heated.

3. 5 GPM.

4. 463 CFM.

5. In both cases, heat is stored in the water. In convective heat transfer, moving the water moves the heat stored in it.

If you missed any of these, review frames 36 through 71. When you can get all the questions, go on to frame 72.

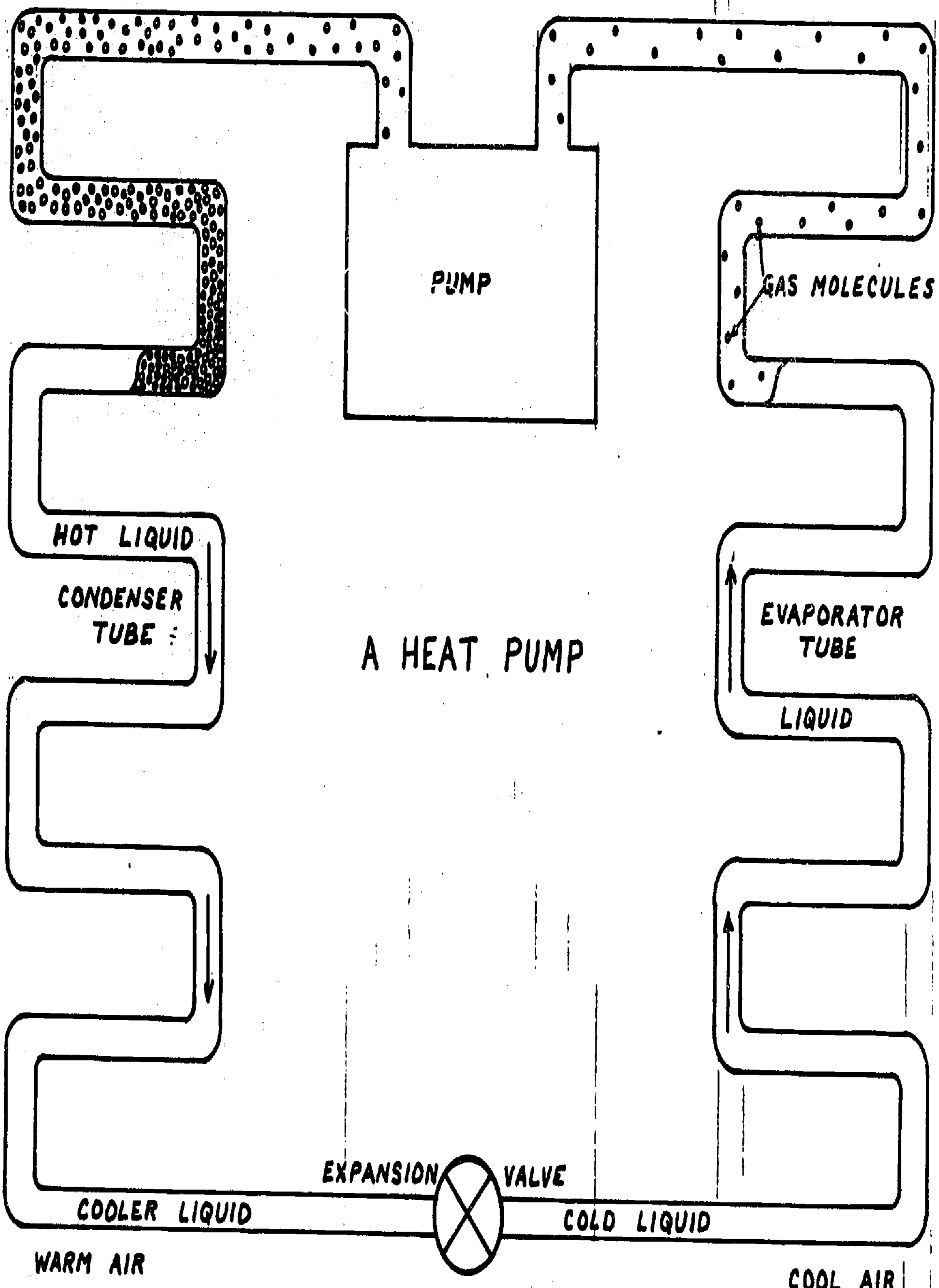
72. There are two other methods of heat transfer that we'll discuss briefly in the rest of this module. The first is the heat pump.

A heat pump is similar to a forced convective heat transfer system. The main difference between a heat pump and such a system is that a heat pump can transfer heat from a low temperature substance to a higher temperature substance. The direction of heat flow is opposite the natural one.

A heat pump consists of an expansion valve, a long coiled tube called an evaporator, a pump which also acts as a compressor and another long coil of tubing called a condenser. The expansion valve, evaporator, pump-compressor and condenser are connected together in a closed loop.

A heat pump works by using a liquid heat transfer fluid that can be vaporized at very low temperatures in the evaporator. By pumping away molecules of the vapor as fast as they break free of the liquid, the pump can make the liquid evaporate. If the temperature of the liquid is lower than that of its surroundings, heat will flow into the liquid from the surroundings and cause more molecules to break away from it. The molecules that break free are immediately pumped away by the pump. That prevents them from re-entering the liquid in the evaporator and raising its temperature by speeding up the motion of the remaining liquid molecules. All the fast-moving molecules are removed from the liquid and the evaporator remains cooler than its surroundings. The heat that's removed from the liquid is latent heat of vaporization, the same as the latent heat you studied in module 1. The vapor molecules pass through the pump and are compressed together on its compressor side. They're pressed together so tightly that they stick together, and become a high temperature liquid instead of a vapor. The latent heat of vaporization that they gained when they evaporated in the evaporator is turned into sensible heat when they're pressed together and condensed into a liquid in the condenser. The liquid temperature in the condenser is higher than the temperature of the condenser's surroundings, so the condenser transfers heat to its surroundings.

After losing most of its heat in the condenser, the now warm liquid flows to the expansion valve, which lets it trickle slowly back into the


PUMP
GAS MOLECULES
HOT LIQUID
CONDENSER TUBE
A HEAT PUMP
EVAPORATOR TUBE
LIQUID
EXPANSION VALVE
COOLER LIQUID
COLD LIQUID
WARM AIR
COOL AIR

evaporator to be pumped back down to a low temperature by having its high speed molecules pumped away.

The heat transfer fluid continuously vaporizes in the evaporator and is liquefied in the condenser. Latent heat of the vaporization is continuously moved from the evaporator to the condenser by the pump as it transfers and compresses the vapor molecules. Heat is being pumped from the cooler surroundings of the evaporator to the warmer surroundings of the condenser.

Describe the operation of a heat pump briefly in your own words. Check your answer in frame 73.

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73. A heat pump transfers heat from a low temperature substance to a higher temperature substance. It does so by pumping on a liquid that can vaporize at a low temperature in a long tube called an evaporator, and transferring the vapor molecules to another long tube called a condenser, where it compresses them into a liquid (at a high temperature.) The latent heat of vaporization of the fluid is carried from the evaporator to the condenser by the vapor molecules. Since the evaporator is at a low temperature and the condenser is at a high temperature, heat can be transferred from a low temperature substance to the evaporator, then to the condenser and from the condenser to a high temperature substance. If you said something similar to what we said, go on to frame 74. If not, review frames 72 and 73; and correct your mistakes.

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74. The heat transfer rate of a heat pump is called its capacity. The capacity is usually described in units called tons. A ton corresponds to 12,000 BTU/Hr. The measure of a heat pump's efficiency is called its coefficient of performance, or COP. The COP is the ratio of its heat transfer rate, or capacity, to the amount of energy required to move the pump's heat transfer fluid. The COP is almost always greater than 1, because the heat is drawn from the pump's surroundings, rather than from the energy source that runs the pump.

A kilowatt (1000 watts) of electric power corresponds to 3413 BTU/Hr. of energy flow, so a heat pump with a capacity of 1 ton which requires a kilowatt of electricity to run its pump/compressor has a COP of about 3.5

$$COP = \frac{(1\ \cancel{Ton})\ (12{,}000\ BTU/Hr.\text{-}\cancel{Ton})}{(1\ \cancel{KW})\ (3413\ BTU/Hr.\text{-}\cancel{KW})} = 3.51$$

Notice that the units come out the same on the top and the bottom of the fraction and cancel. A COP has no units.

What's the COP of a heat pump that has a capacity of 2 tons and uses 2505 watts of electric power to drive its pump/compressor?

Check your answer in frame 75.

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75. You should have

COP = 2.8

If you got it, go to frame 77. If not, go to frame 76.

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76. Here's how it works out:

$$COP = \frac{2 \text{ Tons}}{2500 \text{ Watts}} = \frac{(2 \text{ Tons})(12{,}000 \text{ BTU/Hr.-Ton})}{(2500 \text{ Watts})(\text{KW}/1000 \text{ Watts})(3413 \text{ BTU/Hr.-KW})}$$

$$COP = \frac{24{,}000 \text{ BTU/Hr.}}{8532.5 \text{ BTU/Hr.}} = 2.8$$

Notice how we used the conversion factor (KW/1000 Watts) to convert 2500 watts into KW. Go on to frame 77.

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77. Heat pumps which draw heat into their evaporators from the cool air outside a house and use it to heat the air inside a house usually have COP's of between 2 and 3. That makes them two to three times as efficient as conventional electric space heaters. The higher the COP, the more efficient the heat pump. A lot of the power that goes into running such heat pumps is used to drive fans which move air past the evaporator and condenser coils. It takes a lot of outside air to provide enough heat to heat the air inside a house, and the inside air must move rapidly past the condenser coils to extract all the heat from them.

The colder the outside air is, the harder a heat pump must work to extract heat from it. If the outside air temperature is much below freezing, a heat pump is less efficient than a conventional electric heater. If the outside air gets too cold, a heat pump won't be able to heat the inside air fast enough to replace the heat lost to the outside. For that reason, heat pumps are usually used together with conventional heating systems that can back them up when it gets really cold outside.

What's the normal range of the COP of an air-to-air heat pump? Check your answer in frame 78.

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78. The normal COP of an air-to-air heat pump is between 2 and 3. Go on to frame 79.

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79. Why are heat pumps usually used together with conventional heating systems? Check your answer in frame 80.

80. The colder the outside air, the less efficient the heat pump. If the outside air gets too cold, the heat pump won't be able to heat the inside air fast enough to replace heat lost to the outside. When that happens, a conventional heating system must be used to heat the house.

In some mild climates, such as that of the Willamette Valley, a backup conventional heating system won't be necessary in a well-insulated house.

Go on to frame 81.

81. Three types of heat pump can be used to heat the air inside a house: air-to-air, water-to-air, and ground-to-air.

The heat pumps that pump heat from water into air, or from the ground into air, use underwater or underground evaporator pipes. Ground-to-air systems are usually more expensive than air-to-air systems because very long evaporator tubes must be used to spread the collection of heat over a large volume of soil. Collecting a large amount of heat from a small volume of soil will soon cause it to freeze, and reduce the efficiency of the heat pump below a useful value. Water to air heat pumps face the same problem unless the water is circulated past the evaporator tubing.

Compute the COP of a 4 ton capacity heat pump which uses 4 KW of electric power. Check your answer in frame 82.

82. You should have COP = 3.5. If you didn't get it, review frames 71 through 80. Get help from your instructor if you need it. If you got it, go on to frame 83.

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83. Good! You remembered how to do it. Now list 3 types of heat pumps according to where the heat pump evaporator collects the heat. Check your answers in frame 84.

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84. You should have:

    air-to-air

    ground-to-air

    water-to-air

    Why are ground-to-air and water-to-air heat pump systems usually more expensive than air-to-air systems? Check your answer in frame 85.

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85. The evaporator tubing in ground-to-air heat pump systems needs to be much longer in order to spread out the collection of heat and prevent freezing. That's also true of water-to-air systems unless the water flows past the evaporator tubing. Go on to frame 86.

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86. Another way heat can be transferred is by <u>thermal radiation</u>. Visible light is a form of thermal radiation.

    Thermal radiation, like visible light, can travel extremely long distances through a vacuum or the air, but is blocked by solid objects. Objects which are connected by a natural line of sight can send thermal radiation to each other. Go on to frame 87.

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87. All objects give off thermal radiation, even very cold objects. Hotter objects just radiate more heat than colder ones.

To be cold enough not to radiate any heat at all, an object would have to be at a temperature called absolute zero. Absolute zero is about 460 ^{o}F. below 0 ^{o}F. or 273 ^{o}C. below 0 ^{o}C.

Objects don't need to be touching to transfer heat by thermal radiation. They can be separated by empty space and still radiate heat to each other.

The hotter object radiates more heat than it receives by radiation from the colder one. The result is a net transfer of heat from the hotter to the colder object. In that way, a warm room wall, ceiling or floor can transfer heat to the rest of the room. Go on to frame 88.

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88. Our eyes were made to sense the heat radiation of the sun, which is at a temperature of about 10,000 ^{o}F. Light is what we call heat radiation from objects at about the same temperature as the sun.

We can't sense the heat radiation from cooler objects with our eyes, but sometimes we can feel it on our skin. A black wood stove radiates heat which you can't see, but you can feel.

The wavelength of the heat radiation depends on the temperature of the object radiating the heat. Our bodies radiate heat radiation with an average wavelength of a thousandth of a centimeter (.001 cm.). Our eyes can't sense it. The sun's heat radiation has an average wavelength about 250 times shorter, just right for our eyes to see.

Why can't we see the heat radiation from all objects? Check your answer in frame 89.

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89. Our eyes are made to see the heat radiation of the sun, which has a different wavelength than the heat radiation from cooler objects. Go on to frame 90.

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90. Describe the main features of heat transfer by thermal radiation in your own words. Check your answer in frame 91.

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91. Thermal radiation travels in straight lines, and can pass through empty space. It's invisible unless it's coming from an object at about the same temperature as the sun (thousands of degrees Fahrenheit).

All objects, hot or cold, radiate thermal radiation. Hot objects radiate more heat than they receive from cooler ones, so they can transfer their heat to the cooler ones by radiation without having to actually touch them.

If you understood the main points, congratulations! You've finished the programmed material and can go on to the review questions. If you missed a point or two, review the main points in frames 86 through 89 before going on.

Review Questions

1. Briefly explain the operation of a heat pump.

2. A heat pump with a 3 ton capacity uses 4 kilowatts of electric power. Compute its coefficient of performance.

3. List three types of heat pumps.

Answers to Review Questions

1. A heat pump transfers heat by pumping free molecules away from a liquid heat transfer fluid as it evaporates in an evaporator tube. The remaining liquid is cooled, and absorbs heat from its environment through the walls of the evaporator tube. The pump compresses the evaporated molecules in a condenser tube until they condense into a liquid again, releasing their latent heat of vaporization to their surroundings through the walls of the condenser tube.
2. 2.64.
3. Air-to air, water-to-air, ground-to-air. If you had trouble with any of these questions, review frames 72 through 85. When you feel ready, go on to the post test.

Post-Test

1. Compute the R-value and the U-value of a wall with 5-1/2 inches of foam insulation and 1 inch of wood covering on both the inside and the outside. Use a K-value of .20 BTU-In./Ft.^{2}-Hr.-^{o}F. for the foam insulation, and .8 BTU-In./Ft.^{2}-Hr.-^{o}F. for the wood.

2. Compute the rate of heat transfer through an exterior door with an R-value of 8 and an area of 21 square feet. The temperature inside the door is 70 ^{r} . and the temperature outside is 25 ^{o}F.

3. Describe convective heat transfer, and explain how it's related to sensible heat storage.

4. Describe conductive heat transfer, and explain how it's related to temperature, type of heat transfer material, thickness of the material, and area.

5. Compute the rate of convective heat transfer of a column of air moving at 2500 CFM (Ft.^{3}/Min.) with a temperature rise of 50 ^oF.

6. Compute the coefficient of performance of a 10 ton capacity heat pump that uses 12 KW of electric power.

7. List the main features of heat transfer by radiation.

8. Explain how a heat pump operates.

9. Compute the flow rate of water in GPM (Gal./Min.) necessary to transfer 600,000 BTU of heat with a water temperature rise of 10 ^{o}F.

10. A double pane window with a U-value of .69 is covered with an insulating curtain with an R-value of 4. Compute the total R-value of the window and curtain together.