Fast, Computer Supported Experimental Determination of Absolute Zero Temperature at School

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Abstract
A simple and fast experimental method of determining absolute zero temperature is presented. Air gas thermometer coupled with pressure sensor and data acquisition system COACH is applied in a wide range of temperature. By constructing a pressure vs temperature plot for air under constant volume it is possible to obtain - by extrapolation to zero pressure - a reasonable value of absolute zero temperature. The proposed way of conducting experiment allows students to "discover" intuitively the existence of minimal possible temperature and thus to understand the reason for introducing the concept of absolute zero temperature and absolute temperature Kelvin scale. It is a convincing and straightforward method to enhance understanding the general concept of temperature and support teaching thermodynamics and heat - mainly at secondary schools. This experiment was used with our university students who are being prepared to teach physics in secondary schools. They prepared physics lesson based on this material and then discussed didactic value of this material both for pupils and for teachers.
Keywords: Physics education, absolute temperature, absolute zero determination, air gas thermometer.

Introduction

Temperature is a thermodynamic concept characterizing the state of thermal equilibrium of a macroscopic system. Equality of temperatures is a necessary and sufficient condition for reaching thermal equilibrium. In order to measure the temperature, various types of thermometers and temperature scales were developed. Nowadays, most frequently used are thermometers based on thermal dependence of electrical properties, for example electric resistance. Classical, liquid thermometers are designed based on volume thermal expansion of liquids like alcohol, mercury. Volume changes are observed as changes of liquid column in a capillary (Fig. 1).

***Fig. 1.** Thermometer based on liquid thermal expansion.*

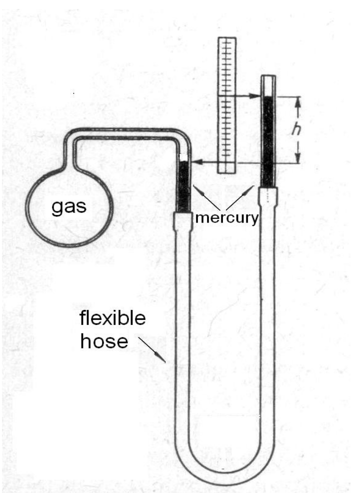

***Fig. 2.** Classical gas thermometer with flexible hose - to ensure constant volume of gas.*

Gas Thermometer

However, a medium that can be theoretically described by simple physical laws is not liquid - but gas, especially gas whose properties can be well described by ideal gas approximation [1, 2]. Hydrogen and helium are good examples but even air, under normal conditions, can be well described by ideal gas approximation. Thermometer, which is based on thermal dependence of gas pressure, is called gas thermometer [2, 3]. It is a gas container with attached manometer (Fig 2). Classical mercury manometer - shown in the figure – enables keeping constant volume of gas closed in a container, independent of temperature change.

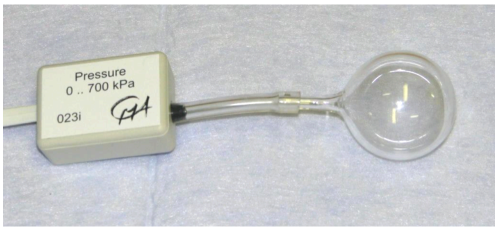

Fig. 4. *Gas thermometer - glass bulb coupled with pressure sensor*

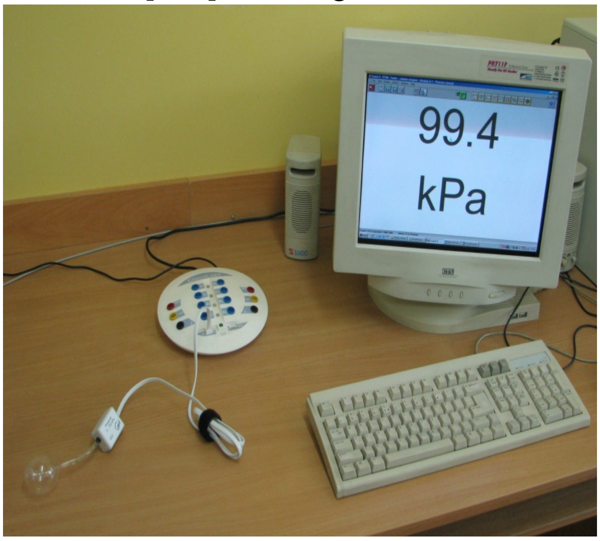

Fig. 3. *Measuring arrangement based on Coach system*

Now it is possible to measure gas pressure using electronic pressure sensor and computer registration system e.g. Coach [4, 5] - Fig. 3. Glass bulb containing air, coupled with pressure sensor can be easily used as a safe and reliable gas thermometer (Fig. 4). It only requires calibration - which is determining the relation between measured pressure and temperature. This can be done using characteristic points: put a bulb (containing air) in ice and water mixture bath, and, subsequently, in boiling water. One can also use a previously calibrated classical thermometer. The registered dependence between air pressure in a bulb and its temperature (Celsius scale) is linear (Fig. 5). The pressure drops with decreasing temperature.

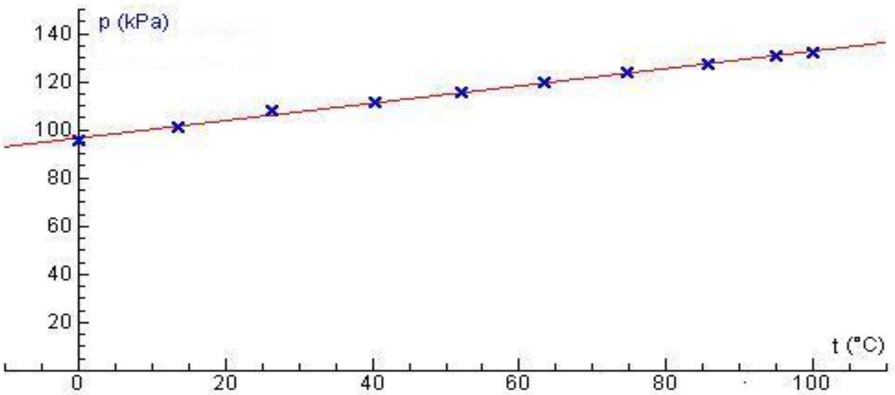

Fig. 5. *Dependence of air pressure in a bulb on temperature. Straight line is a fit to experimental data.*

Absolute Zero Temperature

The pressure of gas is a consequence of gas molecules hitting the walls of a bulb. Using the relation between momentum change and force, one can obtain [1, 2] the dependence between gas pressure p and average kinetic energy of a single molecule, E_k

$$pV = \frac{2}{3} N E_k \quad (1)$$

** N is the number of gas molecules in volume V.*

The observed decrease of gas pressure with decreasing temperature (Fig. 5) illustrates decreasing of an average kinetic energy of molecules. By extrapolation to low temperatures, one can find the temperature in which gas pressure is equal zero (Fig. 6). It is the temperature in which, based on classical physics, the molecules have zero kinetic energy; they do not move. This temperature, determined from our results, is -267(±15) ^{o}C. Precise laboratory measurements give value -273.15 ^{o}C. Since molecules at this temperature do not posses any kinetic energy, it is not possible to draw energy (heat) from them: gas cannot be cooled any further. Such determined temperature is the lowest possible - it is called absolute zero temperature.

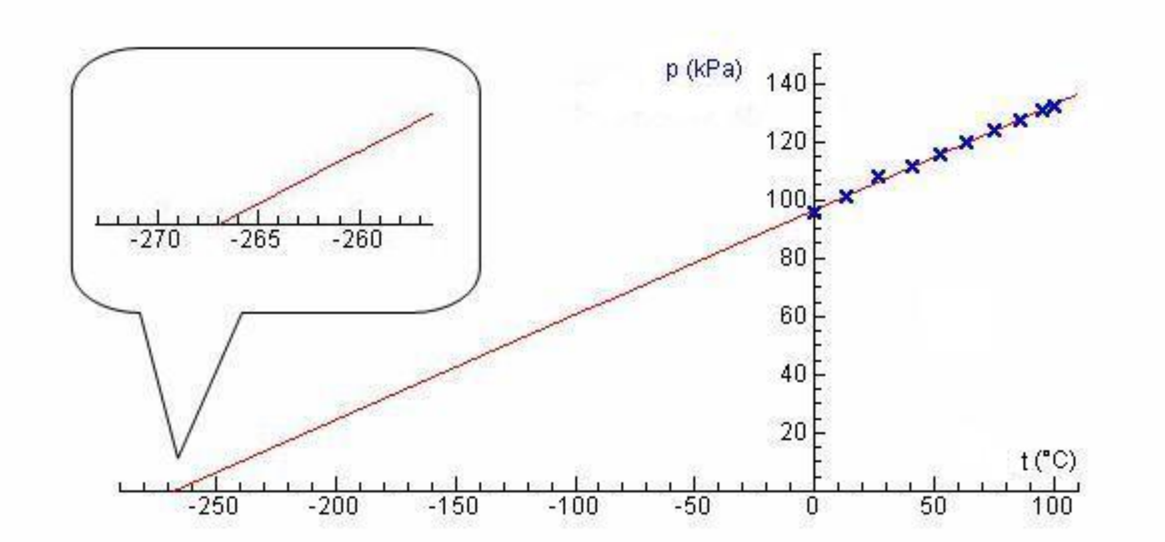

Fig. 6. *Absolute zero temperature - as a result of extrapolation to p=0*

In the year 1848 William Thomson (Lord Kelvin) proposed introducing the concept of temperature, as quantity proportional to average kinetic energy E_k of translational motion of a single molecule

$$T \equiv \frac{2}{3k} E_k \quad (2)$$

thus, the concept of absolute temperature and its scale. The temperature -273.15 ^{o}C constitutes zero of absolute temperature scale. The unit in this scale, called absolute scale, is

Kelvin [K]. The selection of proportionality constant $\frac{2}{3k}$, (k in reality) determines the value of unit in this scale. Coefficient "k" was chosen in such way - that units in "absolute scale" and in Celsius scale would be the same. According to SI System of units the triple point of water has the temperature 273.16 K. The value of "k" - called Boltzmann constant - in fact results from intrinsic properties of water - was determined experimentally to be:

$$k = 1.38 \cdot 10^{-23} \frac{J}{K} \qquad (3)$$

Zero in Celsius scale corresponds to 273.15 K.

By replacing in relation (1) average kinetic energy by temperature, one receives the equation of state for ideal gas - famous Clapeyron equation

$$pV = NkT \qquad (4)$$

Fig. 7. *Measurement of liquid nitrogen temperature with air gas thermometer.*

which describes relation between pressure, volume, temperature and number of molecules of ideal gas. It shows that pressure of ideal gas and its temperature are proportional for constant mass (constant number of molecules) and constant volume of gas.

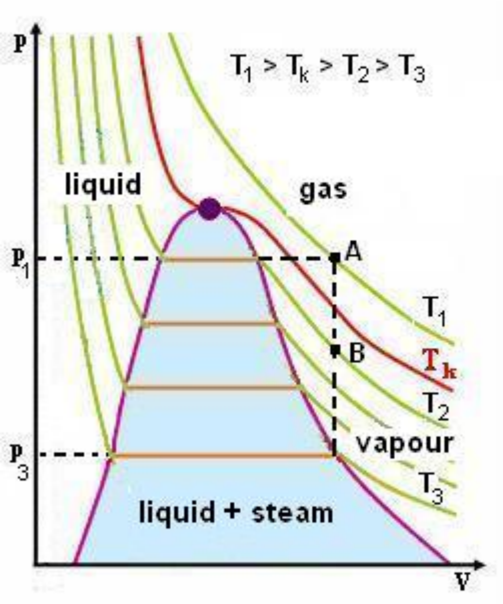

Fig. 8. *Isotherms of real gas. Liquefying processes are indicated (starting from point A): by cooling gas under constant pressure and by cooling under constant volume.*

In order to fully investigate the possibility of our air gas thermometer, we tried to measure the boiling temperature of liquid nitrogen. It was successful (Fig. 7). The pressure in a thermometer bulb placed in liquid nitrogen drops to 25 kPa which is about 1/4 of normal atmospheric pressure. This pressure is small enough that under such pressure neither nitrogen nor oxygen contained in the air inside the bulb does not change into liquid, so the air retains properties close to ideal gas. When trying to liquefy gas by cooling it under constant volume one must cool it down to lower temperature than in case of cooling it under constant pressure (Fig. 8).

Evaluation

This experiment and accompanying text have been used during one (2 hours) hands-on exercise class with a group of 18 third year university students who study to become teachers of physics. The class was held in a regular teaching cycle (2 hours per week, 30 h in a semester). Each student received the text several days before the class and one student was assigned to prepare a high school physics lesson using this experiment. This student was given a detailed instruction about the experiment and - knowing earlier the computer system COACH- he prepared and conducted a "lesson" in front of his colleagues. The discussion after the class was very vivid. All comments were very positive ("Pitty that I had no such experiment in my school!").

Formal evaluation of the material was conducted in the form of simple question " How would you rate this material (scale 1-low, 5 - high): to what extent does it help understand the concept of temperature". Average score was 4.8

Didactic Comments

The concept of temperature is known to pupils intuitively from early childhood, based on everyday experience. However, the existence of the lowest possible temperature in nature does not come from everyday experience and can be very surprising (because there are no limits on high temperature value).

The use of the presented system allows for fast measurements of pressure and temperature and automatic, simultaneous presentation of the p vs t plot. This gives opportunity for teacher to steer discussion in class in such a way that pupils can formulate observations and conclusions on their own. Inquiry based teaching (“pupil – discoverer”) is an excellent method to apply here.

The first and fundamental observation should be the linear relation between air pressure and its temperature. The second observation should be noticing that pressure decreases when decreasing temperature (Fig. 5) (so the bulb with air inside can be a good thermometer !). The teacher should remind pupils that gas pressure is a consequence of motion of gas molecules. The slower they move, the lower is the speed they hit the bulb walls (lower momentum transfer) and the lower is gas pressure. This allows pupils to conclude, based on the observed p vs t plot (Fig. 5), that gas molecules move slower and slower with decreasing temperature.

Extrapolation to low temperatures (Fig. 6) gives important material to discussion. Pupils have a chance to notice that there exists the temperature in which gas pressure reaches zero. They should conclude that in this temperature the molecules stop their motion - and hence it is impossible to lower the temperature any more. The conclusion on the existence of the lowest possible temperature and determination of its value should be the most important and possibly "own discovery" of pupils.

Introduction of absolute temperature and Kelvin scale and, finally, measurement of temperature of boiling liquid nitrogen can be a good summarize of the lesson. Few remarks on impossibility of reaching absolute zero temperature is recommended.

Close coupling of temperature concept with motion of molecules (their kinetic energy) is fundamental for pupils’ proper understanding of this concept and develops good physics intuition.

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