elements of classical physics

MARTIN C. MARTIN & CHARLES A. HEWETT

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ELEMENTS OF CLASSICAL PHYSICS

PERGAMON PRESS INC.

New York · Toronto
Oxford · Sydney · Braunschweig

PERGAMON PRESS INC.
Maxwell House, Fairview Park, Elmsford, N.Y. 10523

PERGAMON OF CANADA LTD.
207 Queen's Quay West, Toronto 117, Ontario

PERGAMON PRESS LTD.
Headington Hill Hall, Oxford

PERGAMON PRESS (AUST.) PTY. LTD.
Rushcutters Bay, Sydney, N.S.W.

PERGAMON GmbH
Burgplatz 1, Braunschweig

Library of Congress Cataloging in Publication Data

Martin, Martin C
Elements of classical physics.

1. Physics. I. Hewett, Charles A., joint author.
II. Title.
QC21.2.M38 1973 530.1'32 73-3450
ISBN 0-08-017098-6

Printed in the United States of America

Contents

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Preface

This book is being published at a time when many of the nation's leading physicists already have prepared textbooks which implement in an outstanding fashion new approaches developed for the teaching of elementary physics to today's students. The appearance of still another textbook should therefore be accompanied by a presentation of the ideas behind the structure and content of the book.

It has been our experience that students retain an uneven coverage of the various areas of physics from their high school courses. Areas such as elementary heat and light are, in general, more easily understood and remembered than mechanics, thermodynamics, sound, and electricity and magnetism, which necessarily involve a greater degree of abstraction in their presentation as well as greater mathematical sophistication if quantitative discussions are desired.

With very few exceptions, the courses in general physics that have been developed for presentation to entering freshmen begin with mechanics, which represents a relatively serious intellectual challenge for the average student, with or without the use of calculus. This is then followed by heat, light, and sound, which are in turn followed by electricity and magnetism. As a result, the students are confronted by a course that is rather frustrating in the unevenness of its demands upon their understanding. If, in addition, calculus is used from the outset, the average student is initially discouraged, not only by the relatively foreign quantitative concepts of mechanics, but also by the presentation of these concepts in a mathematical "language" that is equally foreign. As a result, many students succumb to these demands and terminate their study of physics or engineering with the mistaken impression that an understanding of the physical world is beyond their grasp.

With these considerations in mind, we have written a text which: (a) begins with the material most readily understood with a minimal mathematical framework, thus providing a smooth transition from high school; (b) progresses as uniformly as possible to areas of increasing conceptual difficulty; (c) introduces at appropriate places the necessary mathematical concepts at a time when they would already have been presented in a typical concurrent mathematical course, and (d) stresses throughout the course the physical concepts and the manner in which these concepts can be used to provide quantitative understanding in a wide variety of specific situations. Many of these are carefully discussed as examples, and the remainder are presented in the problem sections as suitable tests of understanding.

In writing the text, we presume the student has at least a qualitative understanding of the meaning of the terms force, pressure, work, and energy.

After a section devoted to the discussion of dimensions and units, the areas presented are heat, light, mechanics, thermodynamics, sound, and electricity and magnetism, respectively. It is our opinion that this sequence of topics is best suited for achieving the goals outlined above. However, those desiring a more conventional course sequence could with very little difficulty begin with mechanics (Chapter 14), followed by the remaining topics in their usual order. In addition, Chapter 15 on special relativity may be omitted without prejudice to subsequent chapters. No effort has been made to include an extensive presentation of modern physics. There are two reasons for this: first, the material covered represents a thorough coverage of classical physics which is a necessary prerequisite to the proper discussion of modern physics, and second, the mathematical preparation required for modern physics in our opinion necessarily makes it a second year subject in contrast to the contents of this text. It might also be noted that excellent texts covering the subject are available.

We have emphasized the rationalized MKS units throughout the text. We have also made use of some of the various other systems of units in common use today. We introduce the necessary conversions for these systems in an appendix. Every system of units has its proponents and opponents (who are equally convinced of the correctness of their point of view); our choice simply represents a personal preference.

The authors of this book owe much to many people: our teachers; our colleagues; but, most important, our students, whose desire to understand physics has prompted us to try to make their pathway to knowledge as natural as our abilities permit.

Introduction:
Dimensions and Units

In the study of physics, the dimensions and units to be encountered must be understood. A student must remember that one can only equate the same kinds of quantities. A test on the correctness of an equation can be obtained by checking whether or not the dimensions on one side of the equation are the same as those on the other side.

DIMENSIONS

A dimension may be defined as a name describing certain physical quantities. Therefore, a large number of dimensions are possible. This number can be reduced by the fact that certain descriptions can be expressed in terms of other more basic descriptions (dimensions). For example, length, area, and volume are dimensions, but area can be measured as a length squared and volume as a length cubed. Therefore, the dimensions of area and volume can be stated in terms of the more fundamental dimension of length.

In physics, there are five fundamental dimensions: length, mass, time, temperature, and electric charge, which we shall denote by $[l]$, $[m]$, $[t]$, $[T]$, and $[q]$, respectively. We have already shown how area and volume are expressed in terms of length. Now let us consider a few more physical quantities which should be familiar from high school physics.

$$\text{Velocity} = \text{length} \div \text{time} = [lt^{-1}]$$
$$\text{Acceleration} = \text{velocity} \div \text{time} = [lt^{-2}]$$
$$\text{Force} = \text{mass} \times \text{acceleration} = [mlt^{-2}]$$
$$\text{Pressure} = \text{force} \div \text{area} = [ml^{-1}t^{-2}]$$
$$\text{Work} = \text{force} \times \text{length} = [ml^{2}t^{-2}]$$
$$\text{Power} = \text{work} \div \text{time} = [ml^{2}t^{-3}]$$
$$\text{Density} = \text{mass} \div \text{volume} = [ml^{-3}]$$
$$\text{Current} = \text{charge} \div \text{time} = [qt^{-1}]$$

UNITS

A unit may be defined as a particular amount of the dimension or quantity to be measured. Three different systems are used today in science and engineering. They are the meter-kilogram-second (MKS) system, the centimeter-gram-second (cgs) system, and the foot-slug-second (British) system. The rationalized MKS and cgs systems are used universally in scientific work, with the MKS actually superseding the two other systems.

We shall use the rationalized MKS system throughout most of the book. Much of the literature is still written in the other two systems of units, so we feel that students should eventually become familiar with the three systems of units. In Table 1 are the MKS units for the physical quantities given in Section 1. For comparison purposes, the equivalent cgs unit is also indicated.

Table 1 MKS Units for Some Physical Quantities.

Physical Quantity	MKS Unit	cgs Unit
length	meter	centimeter
mass	kilogram	gram
velocity	meter/second	centimeter/second
acceleration	meter/second^2	centimeter/second^2
force	newton	dyne
pressure	newton/meter^2	dyne/centimeter^2
work or energy	joule	erg
power	watt	erg/second
density	kilogram/meter^3	gram/centimeter^3
charge	coulomb	statcoulomb
current	ampere	statampere

The student should be familiar with the above physical quantities and the MKS units associated with them, even though a detailed discussion of them will not appear until later in the book.

Table 2 then gives some prefixes used to represent divisions and multiples of metric quantities.

Table 2 Prefixes Used for Divisions and Multiples of Metric Quantities.

deci-	10^{-1}	deca-	10^{1}
centi-	10^{-2}	hecto-	10^{2}
milli-	10^{-3}	kilo-	10^{3}
micro-	10^{-6}	mega-	10^{6}
nano-	10^{-9}	giga-	10^{9}
pico-	10^{-12}	tera-	10^{12}

1 Temperature and Thermometry

Consistent with our intent to progress by degrees from the easiest to the most difficult topics, we will begin by discussing various aspects of thermal energy, heat, and temperature.

1-1 THERMAL ENERGY, HEAT, AND TEMPERATURE

The concept of temperature is fundamental to the study of heat. The idea of temperature developed from man's sense of hotness and coldness. Therefore, a body's temperature represents its degree of hotness or coldness. In order to define temperature in a more concrete way than the above, we will first define thermal energy and heat.

We shall define thermal energy as follows:

> Thermal energy is the energy of the atoms in a substance because of their motion on a microscopic scale.

We shall later see in our discussion of kinetic theory that the average motional or kinetic energy of atoms is directly proportional to the temperature.

We shall now define heat as follows:

> Heat is thermal energy transferred between two or more material substances or from one portion of the substance to another on a macroscopic scale.

This means that a hot body can give up some of its thermal energy and therefore affect a neighboring body. The quantity of thermal energy it gives up depends upon the nature and condition of the neighboring body and upon the medium separating the two bodies.

Now we are able to give a somewhat better definition of temperature; we will define it as follows:

> The temperature of a body is a measure of its ability to transfer heat to other bodies.

A body is at the same temperature as another body if there is no net flow of heat from one to the other when they are placed in contact or separated only by a conducting wall. We can also say that a body X is at a higher temperature than a body Y if heat flows from X to Y when they are placed in contact or separated only by a conducting wall.

The above definition of temperature gives us a way of defining absolute zero, which is the lower limit of temperature. That is, no body can be colder or have less thermal energy than a body at absolute zero. Therefore, we can define absolute zero as follows:

> Absolute zero is the temperature of a body that is not capable of transferring any thermal energy to another body.

There is a criticism of the above definitions on the basis that we do not observe the flow of heat. All we can observe is that the cold body gets hotter and the hot body gets cooler. However, many physical processes occur especially in atomic and nuclear physics that we cannot observe directly, so this is not a critical problem. Other definitions of temperature will be given later on in the book which remove this criticism. However, we feel that at the beginning it is good to have a definition of temperature even though it may be subject to later slight modifications.

1-2 TEMPERATURE MEASUREMENT

We shall now discuss thermometry, which is the science of measuring temperatures. A number of physical properties of substances change with temperature. Temperature measuring devices or thermometers make use of these properties. Some of these properties which change with temperature and can be used for thermometric purposes are:

1. Volume of liquids.
2. Length of solids.
3. Volume of gases.
4. Pressure of gases.
5. Pressure of saturated vapors.
6. Electrical resistance of metals.
7. Thermoelectric currents.
8. Color of radiated light.
9. Total radiation intensity.
10. Magnetic susceptibility of paramagnetic salts.

The construction of a useful thermometer requires a choice of some substance whose thermometric properties indicate changes in temperature and a choice of the design of the thermometer. We then require a thermometer scale, which necessitates a choice of one or more fixed temperature points and a selection of numbers to be associated with each division.

1-3 CENTIGRADE AND FAHRENHEIT TEMPERATURE SCALES

The definitions of the Centigrade and Fahrenheit scales involve in each case the same two distinct fixed thermal points. The lower fixed point is the temperature of the melting point of pure ice (ice point), which is the temperature at which pure ice coexists with air saturated water at one atmosphere pressure. The upper fixed point is the temperature of the boiling point of pure water (steam point), which is the temperature of equilibrium between pure water and pure steam at one atmosphere pressure. On the Centigrade scale, the ice point is taken as 0 degrees and the steam point as 100 degrees. On the Fahrenheit scale, the ice point is taken as 32 degrees, the steam point as 212 degrees. There are 100 degrees between the ice and steam points on the Centigrade scale, while there are 180 degrees between the ice and steam points on the Fahrenheit scale. We leave it to the student as an exercise to show that the conversion from the Centigrade scale to the Fahrenheit scale or vice versa is given by the equations

$$t°\text{C} = \frac{5}{9}(t°\text{F} - 32),$$

$$t°\text{F} = \frac{9}{5}t°\text{C} + 32. \tag{1-1}$$

Note that we are using (t) to indicate Centigrade and Fahrenheit temperatures. Later in the text this same symbol will be used to denote time. The double usage of this symbol should not lead to ambiguity if dimensional analysis is used.

Example 1. At what temperatures do the Centigrade and Fahrenheit scales coincide?

SOLUTION

This means the $t°\text{C} = t°\text{F}$. Substitute $t°\text{C} = t°\text{F}$ in Eq. (1-1).

$$t°\text{F} = \frac{9}{5}t°\text{F} + 32$$

or

$$\frac{4}{5}t°\text{F} = -32.$$

Therefore,

$$t°\text{F} = \frac{5(-32)}{4} = -40°,$$

since

$$t°C = t°F$$

$$t°C = -40°.$$

1-4 GENERAL DEFINITION OF TEMPERATURE

Let us consider a general definition of temperature based on the thermometric properties of a substance. Let X_0 be some thermometric property as, for example, length of a solid or height of a liquid in a capillary tube measured at 0°C, and X_{100} and X_t the thermometric property at 100°C and some unknown temperature t°C. The size of a unit interval or degree is $X_{100} - X_0/100$, and the size of the interval from 0°C to t°C is $X_t - X_0$. By definition, t°C is the number of degrees in the interval $X_t - X_0$, and is given by the equation

$$t°C = \frac{X_1 - X_0}{\frac{X_{100} - X_0}{100}}$$

or

$$t°C = \left(\frac{X_t - X_0}{X_{100} - X_0}\right)100. \tag{1-2}$$

Various thermometric properties can be used. For example, let us consider a mercury in glass thermometer, one with which we are all familiar, and a constant volume gas thermometer, which we will discuss later. If the length of the mercury column is substituted in Eq. (1-2) for the thermometric property X, we have

$$t°C = \left(\frac{l_t - l_0}{l_{100} - l_0}\right)100. \tag{1-3}$$

If the gas pressure of the gas in the gas thermometer is substituted in Eq. (1-2) for X, we have

$$t°C = \left(\frac{p_t - p_0}{p_{100} - p_0}\right)100. \tag{1-4}$$

A word of caution is necessary here. Even though both the above thermometers read the same at 0°C and 100°C, they do not necessarily read the same at in-between temperatures. There is no reason to expect them to be the same since the temperature as defined by Eq. (1-2) depends upon the thermometric property of the substance. Even though two substances like mercury and a particular gas might have the same thermometric property, they might be contained in glass which has different thermometric properties, so the properties relative to the glass would be different. Experiments have shown that if we compare scales of temperatures based on different liquids or gases, or even on the same liquid or gas in different kinds of glass, the scale reads slightly differently. However, in the range between 0°C and 100°C they generally agree to within a few tenths of a degree.

1-5 KELVIN AND RANKINE TEMPERATURE SCALES

We shall see later that there is a limit to the lowest temperature that can ever be attained. This lowest temperature is −273.15°C; it corresponds to absolute zero which we previously defined. The absolute temperature scale has absolute zero as its zero point. The absolute scale with degree intervals equal to those on the Centigrade scale is called the Kelvin or absolute scale, and the absolute scale with degree intervals equal to those on the Fahrenheit scale is called the Rankine scale. The temperature of absolute zero on the Fahrenheit scale is −459.67°F. For most temperature measurements, it is only necessary to have three figure accuracy so as to reduce memory work. We shall in the calculation in this text relate the Kelvin and Centigrade, and the Rankine and Fahrenheit scales by the following equations:

$$T°K = t°C + 273, \tag{1-5}$$

and

$$T°R = t°F + 460. \tag{1-6}$$

Both the ice point and the steam point are difficult to measure with good accuracy. The main difficulty is that when ice melts it becomes surrounded with pure water and causes poor contact between the ice and the air saturated water. This prevents the ice point from being accurately measured. Since the boiling point of water is sensitive to small changes of pressure, the value of the steam point can be in error unless the pressure is kept very constant.

In 1854, Kelvin proposed a temperature scale known as the thermodynamic scale (discussed in Chapter 26), which is independent of the properties of any substance. He pointed out that the scale could be determined by the use of a single fixed point. At the Tenth General Conference of Weights and Measures in 1954, it was decided to choose this fixed point as the temperature and pressure at which ice, water, and water vapor coexist in equilibrium (the triple point of water), and to assign it the value of 273.16°K. This point can be measured with greater accuracy than the ice point and the steam point.

1-6 MERCURY THERMOMETER

The mercury thermometer is the most frequently used thermometer in laboratories because of its simplicity, its fairly large temperature range (−39°C to 357°C), and its quick response to slight temperature changes. It is made by first blowing a bulb at one end of a fine bore glass tube. Mercury is poured into the tube, heated to drive out any air, and the other end of the tube is sealed. When the bulb is brought into contact with a body, the mercury either expands or contracts relative to the glass tube depending on whether the body is hotter or colder than the original surroundings of the bulb.

The chief errors in a mercury thermometer are caused by a non-uniform bore in the tube and imperfections of the glass bulb. However, if these and other smaller errors are corrected, the mercury thermometer is very accurate. A good mercury thermometer is only surpassed in accuracy by a platinum resistance thermometer in the range 0°C to 200°C.

1-7 GAS THERMOMETERS

Gas thermometers are usually not used in laboratories because they are somewhat elaborate and cumbersome. They are used generally in standardizing other more simple thermometers. For a given temperature rise, gases expand about 20 times as much as mercury and about 120 times as much as the glass in the thermometer. This reduces error due to uneven changes in the volume of the glass. Gas thermometers have a temperature range of −269°C to 1600°C.

There are two types of gas thermometers—namely, constant volume and constant pressure thermometers. With the first type, the temperature is measured by the change in pressure of the gas with temperature. With the second type, the temperature is measured by the change in volume of the gas with temperature. Constant volume thermometers are more satisfactory because it is easier to measure accurately a change of pressure than a change of volume. Figure 1-1 is a simple form of a constant volume gas thermometer.

The volume of the gas in the bulb is kept constant by raising or lowering tube *C* so that the top of the mercury is always kept at point *B*. The pressure is measured by measuring the difference between the heights *h* of the mercury surfaces in the tube. The pressure of the gas in the bulb is equal to the atmospheric pressure plus the pressure due to the height *h* of the mercury in the tube. If we let p_0 be the pressure when the bulb is surrounded by melting ice, p_{100}—the pressure when the bulb is surrounded by steam, and p_t—the pressure when the bulb is surrounded by the substance whose temperature is to be measured, the temperature of the substance is given by Eq. (1-4), namely,

$$t°\mathrm{C} = \left(\frac{p_t - p_0}{p_{100} - p_0}\right) 100. \tag{1-7}$$

Hydrogen is the gas usually used, except for extreme low temperatures where helium is used and extreme high temperatures where nitrogen is used.

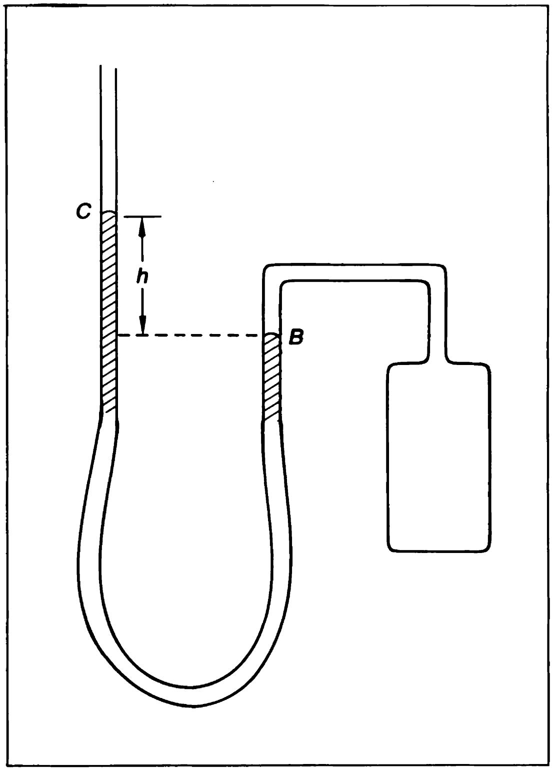

Figure 1-1 Constant volume gas thermometer as described in text.

Helium is used at very low temperatures because it does not liquefy until a temperature of about −269°C is reached. Nitrogen is used at high temperatures because both hydrogen and helium diffuse through the bulb at very high temperatures.

1-8 THE PLATINUM RESISTANCE THERMOMETER

It has been previously stated that the electrical resistance of metals changes with temperature. It is best to use a noble metal for a thermometer so that there is no oxidation. In 1887, Callendar investigated how the resistance of platinum varied with temperature. He showed that the change in electrical resistance of platinum could be used for a very accurate scale of temperatures over a wide temperature range. Today, it is regarded as the most accurate thermometer in the range −190°C to 660°C.

If we define the resistance temperature scale by applying Eq. (1-2), then

$$t\,^\circ\mathrm{C} = \left(\frac{R_t - R_0}{R_{100} - R_0}\right) 100, \tag{1-8}$$

where R_0, R_{100}, and R_t are the resistances of the platinum wire at the ice point, steam point, and the temperature t, respectively. Callendar also showed experimentally that the resistance R_t of a platinum wire at temperature t is given by the equation

$$R_t = R_0(1 + at + bt^2), \tag{1-9}$$

where R_0 is the resistance at the ice point, and a and b are constants. In order to determine the constants a and b, three fixed points are necessary. These fixed points have been chosen as the ice point, the steam point, and the sulphur point which is the boiling point of sulphur (444.6°C) at atmospheric pressure.

Other resistance thermometers of cheaper metals (for example, copper) are sometimes used where extreme accuracy is not necessary. Also, some semi-conductors whose resistance decreases with temperature increase are used. They are known as thermistors; they have a very large decrease in resistance with increase in temperature and have a greater sensitivity than a platinum thermometer, but they are less accurate.

1-9 THERMOCOUPLES

Thermocouples are based on the principle that electric currents are set up in a closed circuit consisting of two dissimilar metals in contact with one another when the junctions are at different temperatures (Chapter 34). The reference junction is usually put in melting ice and the other junction in contact with the material whose temperature is to be measured. The current (or voltage across a circuit element) is then related to the temperature by appropriate calibrations.

The most common thermocouples are constructed of iron and constantan (an alloy of copper and nickel), copper and constantan, and platinum and an alloy of platinum-rhodium. Thermocouples have the advantage that they can be used for measuring temperatures at a particular point in an experimental system.

PROBLEMS

1. In a certain city the greatest temperature variation recorded during a 24 hour period was 45°F. This corresponds to how many degrees C?
2. (a) A Centigrade degree is what fraction of a Fahrenheit degree?
   (b) The conversion from the Centigrade scale to the Fahrenheit scale is given by the equation
   $$t\,^\circ\mathrm{F} = \frac{9}{5}t\,^\circ\mathrm{C} + 32.$$
   Justify this relation.
3. The reading of a thermometer for the temperature of a room is 77°F. What is the reading on the Centigrade scale?
4. (a) What Centigrade temperature corresponds to 233° Kelvin?
   (b) What Fahrenheit temperature corresponds to 77° Kelvin?
5. At what temperature will the reading of a Fahrenheit thermometer be three times that of a Centigrade thermometer?

6. (a) The temperature of liquid nitrogen is about −196°C. What is its temperature on the Kelvin scale? on the Rankine scale?
   (b) What is the difference between 0°C and 180°F in degrees C? in degrees F?
7. A thermometer was graduated to read 0°C at the boiling point of water, and 155° at the freezing point. Find the reading on the Fahrenheit and Centigrade scale corresponding to 80° on this thermometer.
8. The resistance of a platinum resistance thermometer is found to be 10.000 ohms at the ice point, 13.855 ohms at the steam point, and 25.261 ohms at the sulphur point. Find the constants a and b in Eq. (1-9), and plot R against t in the range 0° to 600°C.

2 Quantity of Heat and Calorimetry

2-1 QUANTITY OF HEAT

When a hot and a cold body are brought into contact, there is a transfer of heat from the hot body to the cold body until they come to the same temperature or reach a state that we term thermal equilibrium. The transference of heat from a hot body to a cold body is analogous to the flow of water from a high level to a low level.

The increase in temperature of a body when heated depends on its mass and the material of which it is composed. For example, to bring a large container of water to the boiling point with a laboratory burner requires a long time. The final temperature may be relatively low, even though it receives a large quantity of heat. If a wire is held in a burner flame, it comes to a very high temperature in a very short time even though it receives only a small quantity of heat. Therefore, the final temperature reached by two bodies in contact initially at different temperatures depends on their masses, the materials of which they are composed, and their initial temperatures.

The net result of heat transfer to or from bodies until thermal equilibrium is reached is given by the relation:

heat gained by cold bodies = heat lost by hot bodies.

In order to make use of this relation, we must define a unit for measuring quantities of heat or thermal energy. The unit we use depends on the system of units we adopt. In the metric system of units, the unit of heat or thermal energy is either the calorie or kilocalorie. If we use centimeter-gram-second (cgs) units, the unit of heat is the calorie; while if we use meter-kilogram-second (MKS) units, the unit of heat is the kilocalorie. The calorie is the quantity of heat required to raise the temperature of one gram of water through one centigrade degree, while the kilocalorie is the quantity of heat required to raise the temperature of one kilogram of water through one centigrade degree.

The above definition of the heat unit depends slightly on the location of the one degree interval. It has been agreed to choose this interval between 14.5°C and 15.5°C.

2-2 SPECIFIC HEAT AND HEAT CAPACITY

The specific heat of a body is the heat required to raise the temperature of a unit mass of the body one degree.

In the MKS system of units, it is the heat required to raise the temperature of a one kilogram mass of the body one degree centigrade. From this definition and the definition of the kilocalorie, we see that the specific heat of water is 1 kilocalorie per kilogram per degree centigrade. Although we are concerned here with the MKS system of units, it seems noteworthy to mention that the numerical value of the specific heats is the same in the cgs system of units.

The quantity of heat necessary to raise the temperature of a body of mass m and specific heat c by Δt degrees is given by

$$Q = mc\Delta t. \tag{2-1}$$

The specific heat of a substance is roughly constant at ordinary temperatures provided the temperature interval is not too great. As the temperature is lowered, the specific heats of all substances show a decrease. The specific heat of a substance is changed by (1) change of state such as from a solid to a liquid, liquid to a vapor, and vice versa, (2) presence of impurities, and (3) change in temperature.

It is convenient, as we shall see in calorimetry, to define a quantity called heat capacity.

> The heat capacity of a body is the quantity of heat required to raise the temperature of the body one degree. It is the product of the mass of the body and its specific heat.

In the MKS system, the unit of heat capacity is kilocalories per degree centigrade.

2-3 CALORIMETRY

Calorimetry refers to the laboratory science of making measurements of quantities of heat. In making measurements of quantities of heat, a container called a calorimeter is used. The ordinary calorimeter is a vessel placed within another larger vessel, with the two vessels insulated from one another. In this way, exchange of heat to the surroundings is minimized. The inner vessel of the calorimeter must be provided with a stirrer so as to keep its contents at a uniform temperature.

The fact that when two bodies at different temperatures are placed in contact, heat is transferred from the hotter one to the cooler one until their temperatures are equal, gives us one of the most convenient methods of determining specific heat, known as the *method of mixtures.*

2-4 METHOD OF MIXTURES

(a) Determination of the Specific Heat of a Solid

Let a solid of mass m, temperature t, of unknown specific heat c_x be immersed in a mass m_1 of water at temperature t_1 less than t contained in a calorimeter of mass m_2, known specific heat c, and also at temperature t_1. Let t_2 be the final temperature after thermal equilibrium is reached.

Heat lost by the solid $= mc_x(t - t_2)$.
Heat gained by the water $= m_1(t_2 - t_1)$.
Heat gained by the calorimeter $= m_2c(t_2 - t_1)$.

Heat lost by the solid = heat gained by the water + heat gained by the calorimeter. Therefore,

$$mc_x(t - t_2) = m_1(t_2 - t_1) + m_2c(t_2 - t_1), \tag{2-2}$$

from which c_x can be determined.

(b) Determination of the Specific Heat of a Liquid

The specific heat of a liquid may be determined in the same way by the method of mixtures. If a solid of known mass, specific heat, and temperature is immersed in a known mass of the liquid contained in a calorimeter at a known temperature, the specific heat of the liquid can be calculated.

Example 1. A 0.10 kg calorimeter of specific heat 0.090 kcal/kg°C contains 0.15 kg of a liquid at 20°C. Into this container is placed a 0.20 kg block of copper of specific heat 0.095 kcal/kg°C and temperature 100°C. The final temperature is 40°C. What is the specific heat of the liquid?

SOLUTION

Heat gained by liquid + heat gained by calorimeter = heat lost by copper block.

$$\begin{aligned}(0.15\ \text{kg})(c_x)(40-20)^\circ\text{C}& \\ + (0.10\ \text{kg})(0.090\ \text{kcal/kg}^\circ\text{C})(40-20)^\circ\text{C}& \\ = (0.20\ \text{kg})(0.095\ \text{kcal/kg}^\circ\text{C})(100-40)^\circ\text{C}&\end{aligned}$$

$$(c_x)(3.0\ \text{kg}^\circ\text{C}) + (0.18\ \text{kcal}) = 1.14\ \text{kcal}$$

$$c_x = \frac{0.96\ \text{kcal}}{3.0\ \text{kg}^\circ\text{C}} = 0.32\frac{\text{kcal}}{\text{kg}^\circ\text{C}}.$$

The method of mixtures also can be used to determine the specific heat of gases, but it is very difficult to perform experimentally.