

# REFRIGERATION SYSTEMS AND APPLICATIONS

**Second Edition**

**Ibrahim Dincer**

*Faculty of Engineering and Applied Science  
University of Ontario Institute of Technology (UOIT)*

**Mehmet Kanoğlu**

*Department of Mechanical Engineering  
University of Gaziantep*



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# About the Authors

İbrahim Dinçer is a full professor of mechanical engineering in the faculty of engineering and applied science at University of Ontario Institute of Technology (UOIT). Renowned for his pioneering works in the area of sustainable energy technologies, he has authored and co-authored numerous books and book chapters, more than 500 refereed journal and conference papers, and many technical reports. He has chaired many national and international conferences, symposia, workshops, and technical meetings. He has delivered more than 150 keynote and invited lectures. He is an active member of various international scientific organizations and societies, and serves as editor-in-chief (for *International Journal of Energy Research* by Wiley and *International Journal of Exergy* and *International Journal of Global Warming* by Inderscience), associate editor, regional editor, and editorial board member on various prestigious international journals. He is a recipient of several research, teaching, and service awards, including a Premier's Research Excellence award in Ontario, Canada, in 2004. He has made innovative contributions to the understanding and development of sustainable energy technologies and their implementation, particularly through exergy. He has been working actively in the areas of hydrogen and fuel cell technologies, and his group has developed various novel technologies or methods.

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# Preface

Refrigeration is an amazing area where science and engineering meet for solving the humankind's cooling and refrigeration needs in an extensive range of applications, ranging from the cooling of electronic devices to food cooling, and has a multidisciplinary character, involving a combination of several disciplines, including mechanical engineering, chemical engineering, chemistry, food engineering, civil engineering and many more. The refrigeration industry has drastically expanded during the past two decades to play a significant role in societies and their economies. Therefore, the economic impact of refrigeration technology throughout the world has become more impressive and will continue to become even more impressive in the future because of the increasing demand for refrigeration systems and applications. Of course, this technology serves to improve living conditions in countless ways.

This second edition of the book has improved and enhanced contents in several topics, particularly in advanced refrigeration systems. It now includes study problems and questions at the end of each chapter, which make the book appropriate as a textbook for students and researchers in academia. More importantly, it now has comprehensive energy and exergy analyses presented in several chapters for better and performance improvement of refrigeration systems and applications, which make it even more suitable for industry. Coverage of the material is extensive, and the amount of information and data presented is sufficient for several courses, if studied in detail. It is strongly believed that the book will be of interest to students, refrigeration engineers, practitioners, and producers, as well as people and institutions that are interested in refrigeration systems and applications, and that it is also a valuable and readable reference text and source for anyone who wishes to learn more about refrigeration systems and applications and their analysis.

Chapter 1 addresses general concepts, fundamental principles, and basic aspects of thermodynamics, psychrometrics, fluid flow and heat transfer with a broad coverage to furnish the reader with background information that is relevant to the analysis of refrigeration systems and applications. Chapter 2 provides useful information on several types of refrigerants and their environmental impact, as well as their thermodynamic properties. Chapter 3 delves into the specifics of refrigeration system components and their operating and technical aspects, analysis details, utilization perspectives and so on, before getting into refrigeration cycles and systems. Chapter 4 presents a comprehensive coverage on refrigeration cycles and systems for various applications, along with their energy and exergy analyses. Chapter 5 as a new chapter provides enormous material on advanced refrigeration cycles and systems for numerous applications with operational and technical details. There are also illustrative examples on system analyses through energy and exergy, which make it unique in this book. Chapter 6 deals with a number of technical aspects related to heat pump systems and applications, energy and exergy analyses and performance evaluation of heat pump systems, new heat pump applications and their utilization in industry, and ground source heat pump systems and applications. Chapter 7 is about heat pipes and their micro- and macro-scale applications, technical, design, manufacturing, and operational aspects of heat pipes, heat pipe utilization in HVAC applications, and their performance evaluation.

Incorporated through this book are many wide-ranging examples which provide useful information for practical applications. Conversion factors and thermophysical properties of various

materials, as well as a large number of food refrigeration data, are listed in the appendices in the International System of Units (SI). Complete references are included with each chapter to direct the curious and interested reader to further information.

İbrahim Dinçer  
Mehmet Kanoğlu

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We are particularly thankful to various companies and agencies which contributed documents and illustrations for use in the first edition of this book. These valuable materials helped cover the most recent information available with a high degree of industrial relevance and practicality. We still keep most of them in the second edition as long-lasting materials.

We are grateful to some of our colleagues, friends and graduate students for their feedback and assistance for the first and the current editions of this book.

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Last, but not least, we would like to take this opportunity to thank our families who have been a great source of support and motivation, and for their patience and understanding throughout the preparation of this second edition.

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# 1

## General Aspects of Thermodynamics, Fluid Flow and Heat Transfer

### 1.1 Introduction

Refrigeration is a diverse field and covers a large number of processes ranging from cooling to air conditioning and from food refrigeration to human comfort. Refrigeration as a whole, therefore, appears complicated because of the fact that thermodynamics, fluid mechanics, and heat transfer are always encountered in every refrigeration process or application. For a good understanding of the operation of the refrigeration systems and applications, an extensive knowledge of such topics is indispensable.

When an engineer or an engineering student undertakes the analysis of a refrigeration system and/or its application, he or she should deal with several basic aspects first, depending upon the type of the problem being studied, which may be of thermodynamics, fluid mechanics, or heat transfer. In conjunction with this, there is a need to introduce several definitions and concepts before moving into refrigeration systems and applications in depth. Furthermore, the units are of importance in the analysis of such systems and applications. One should make sure that the units used are consistent to reach the correct result. This means that there are several introductory factors to be taken into consideration to avoid getting lost inside. While the information in some situations is limited, it is desirable that the reader comprehends these processes. Despite assuming that the reader, if he or she is a student, has completed necessary courses in thermodynamics, fluid mechanics, and heat transfer, there is still a need for him or her to review, and for those who are practicing refrigeration engineers, the need is much stronger to understand the physical phenomena and practical aspects, along with a knowledge of the basic laws, principles, governing equations, and related boundary conditions. In addition, this introductory chapter reviews the essentials of such principles, laws, and so on, discusses the relationships between different aspects, and provides some key examples for better understanding.

We now begin with a summary of the fundamental definitions, physical quantities and their units, dimensions, and interrelations. We then proceed directly to the consideration of fundamental topics of thermodynamics, fluid mechanics, and heat transfer.

### 1.1.1 Systems of Units

Units are accepted as the currency of science. There are two systems: the *International System of Units* (*Le Système International d'Unités*), which is always referred to as the SI units, and the *English System of Units* (the *English Engineering System*). The SI units are most widely used throughout the world, although the English System is the traditional system of North America. In this book, the SI units are primarily employed.

## 1.2 Thermodynamic Properties

### 1.2.1 Mass, Length and Force

Mass is defined as a quantity of matter forming a body of indefinite shape and size. The fundamental unit of mass is the kilogram (kg) in the SI and its unit in the English System is the pound mass (lbm). The basic unit of time for both unit systems is the second (s). The following relationships exist between the two unit systems:

$$1 \text{ kg} = 2.2046 \text{ lbm} \quad \text{or} \quad 1 \text{ lbm} = 0.4536 \text{ kg}$$

$$1 \text{ kg/s} = 7936.6 \text{ lbm/h} = 2.2046 \text{ lbm/s}$$

$$1 \text{ lbm/h} = 0.000126 \text{ kg/s}$$

$$1 \text{ lbm/s} = 0.4536 \text{ kg/s}$$

In thermodynamics the unit *mole* (mol) is commonly used and defined as a certain amount of substance containing all the components. The related equation is

$$n = \frac{m}{M} \quad (1.1)$$

if  $m$  and  $M$  are given in grams and gram/mol, we get  $n$  in mol. If the units are in kilogram and kilogram/kilomole,  $n$  is given in kilomole (kmol). For example, 1 mol of water, having a molecular weight of 18 (compared to 12 for carbon-12), has a mass of 0.018 kg and for 1 kmol, it becomes 18 kg.

The basic unit of length is the meter (m) in the SI and the foot (ft) in the English System, which additionally includes the inch (in.) in the English System and the centimeter (cm) in the SI. The interrelations are

$$1 \text{ m} = 3.2808 \text{ ft} = 39.370 \text{ in.}$$

$$1 \text{ ft} = 0.3048 \text{ m}$$

$$1 \text{ in.} = 2.54 \text{ cm} = 0.0254 \text{ m}$$

Force is a kind of action that brings a body to rest or changes the direction of motion (e.g., a push or a pull). The fundamental unit of force is the newton (N).

$$1 \text{ N} = 0.22481 \text{ lbf} \quad \text{or} \quad 1 \text{ lbf} = 4.448 \text{ N}$$

The four aspects (i.e., mass, time, length, and force) are interrelated by Newton's second law of motion, which states that the force acting on a body is proportional to the mass and the acceleration in the direction of the force, as given in Equation 1.2:

$$F = ma \quad (1.2)$$

Equation 1.2 shows the force required to accelerate a mass of 1 kg at a rate of  $1 \text{ m/s}^2$  as  $1 \text{ N} = 1 \text{ kg m/s}^2$ .

It is important to note that the value of the earth's gravitational acceleration is  $9.80665 \text{ m/s}^2$  in the SI system and  $32.174 \text{ ft/s}^2$  in the English System, and it indicates that a body falling freely toward the surface of the earth is subject to the action of gravity alone.

### 1.2.2 Specific Volume and Density

Specific volume is the volume per unit mass of a substance, usually expressed in cubic meters per kilogram ( $\text{m}^3/\text{kg}$ ) in the SI system and in cubic feet per pound ( $\text{ft}^3/\text{lbm}$ ) in the English System. The *density* of a substance is defined as the mass per unit volume and is therefore the inverse of the specific volume:

$$\rho = \frac{1}{v} \quad (1.3)$$

and its units are  $\text{kg/m}^3$  in the SI system and  $\text{lbm/ft}^3$  in the English System. Specific volume is also defined as the volume per unit mass, and density as the mass per unit volume, that is

$$v = \frac{V}{m} \quad (1.4)$$

$$\rho = \frac{m}{V} \quad (1.5)$$

Both specific volume and density are intensive properties and are affected by temperature and pressure. The related interconversions are

$$1 \text{ kg/m}^3 = 0.06243 \text{ lbm/ft}^3 \quad \text{or} \quad 1 \text{ lbm/ft}^3 = 16.018 \text{ kg/m}^3$$

$$1 \text{ slug/ft}^3 = 515.379 \text{ kg/m}^3$$

### 1.2.3 Mass and Volumetric Flow Rates

Mass flow rate is defined as the mass flowing per unit time ( $\text{kg/s}$  in the SI system and  $\text{lbm/s}$  in the English system). Volumetric flow rates are given in  $\text{m}^3/\text{s}$  in the SI system and  $\text{ft}^3/\text{s}$  in the English system. The following expressions can be written for the flow rates in terms of mass, specific volume, and density:

$$\dot{m} = \dot{V} \rho = \frac{\dot{V}}{v} \quad (1.6)$$

$$\dot{V} = \dot{m} v = \frac{\dot{m}}{\rho} \quad (1.7)$$

### 1.2.4 Pressure

When we deal with liquids and gases, pressure becomes one of the most important components. Pressure is the force exerted on a surface per unit area and is expressed in bar or Pascal (Pa). 1 bar is equal to  $10^5$  Pa. The related expression is

$$P = \frac{F}{A} \quad (1.8)$$

The unit for pressure in the SI denotes the force of 1 N acting on  $1 \text{ m}^2$  area (so-called *Pascal*) as follows:

$$1 \text{ Pascal (Pa)} = 1 \text{ N/m}^2$$

The unit for pressure in the English System is pounds force per square foot,  $\text{lbf}/\text{ft}^2$ . The following are some of the pressure conversions:

$$1 \text{ Pa} = 0.020886 \text{ lbf}/\text{ft}^2 = 1.4504 \times 10^{-4} \text{ lbf}/\text{in.}^2 = 4.015 \times 10^{-3} \text{ in water} = 2.953 \times 10^{-4} \text{ in Hg}$$

$$1 \text{ lbf}/\text{ft}^2 = 47.88 \text{ Pa}$$

$$1 \text{ lbf}/\text{in.}^2 = 1 \text{ psi} = 6894.8 \text{ Pa}$$

$$1 \text{ bar} = 1 \times 10^5 \text{ Pa}$$

Here, we introduce the basic pressure definitions, and a summary of basic pressure measurement relationships is shown in Figure 1.1.

#### 1.2.4.1 Atmospheric Pressure

The atmosphere that surrounds the earth can be considered a reservoir of low-pressure air. Its weight exerts a pressure which varies with temperature, humidity, and altitude. Atmospheric pressure also varies from time to time at a single location, because of the movement of weather patterns. While these changes in barometric pressure are usually less than one-half inch of mercury, they need to be taken into account when precise measurements are essential.

$$1 \text{ standard atmosphere} = 1.0133 \text{ bar} = 1.0133 \times 10^5 \text{ Pa} = 101.33 \text{ kPa} = 0.10133 \text{ MPa} \\ = 14.7 \text{ psi} = 29.92 \text{ in Hg} = 760 \text{ mmHg} = 760 \text{ Torr.}$$

#### 1.2.4.2 Gauge Pressure

The *gauge pressure* is any pressure for which the base for measurement is atmospheric pressure expressed as kPa as gauge. Atmospheric pressure serves as reference level for other types of pressure measurements, for example, gauge pressure. As shown in Figure 1.1, the gauge pressure is either positive or negative, depending on its level above or below the atmospheric pressure level. At the level of atmospheric pressure, the gauge pressure becomes zero.

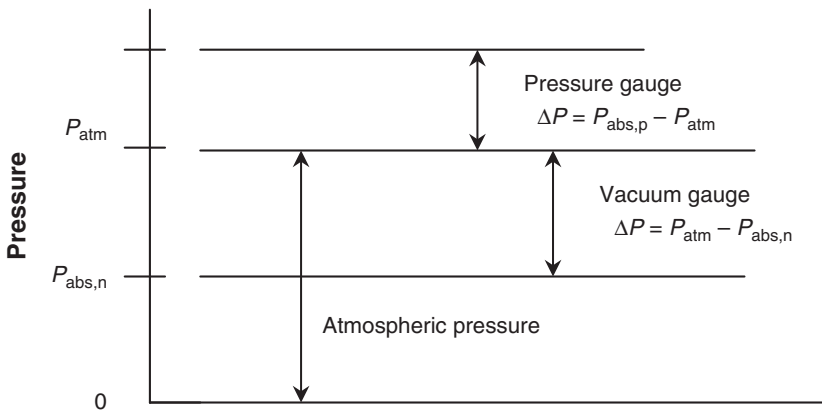


Figure 1.1 Illustration of pressures for measurement.



### 1.2.4.3 Absolute Pressure

A different reference level is utilized to obtain a value for absolute pressure. The absolute pressure can be any pressure for which the base for measurement is full vacuum, being expressed in kPa as absolute. In fact, it is composed of the sum of the gauge pressure (positive or negative) and the atmospheric pressure as follows:

$$\text{kPa (gauge)} + \text{atmospheric pressure} = \text{kPa (absolute)} \quad (1.9)$$

For example, to obtain the absolute pressure, we simply add the value of atmospheric pressure of 101.33 kPa at sea level. The absolute pressure is the most common one used in thermodynamic calculations despite the pressure difference between the absolute pressure and the atmospheric pressure existing in the gauge being read by most pressure gauges and indicators.

### 1.2.4.4 Vacuum

A vacuum is a pressure lower than the atmospheric one and occurs only in closed systems, except in outer space. It is also called the *negative gauge pressure*. As a matter of fact, vacuum is the pressure differential produced by evacuating air from the closed system. Vacuum is usually divided into four levels: (i) low vacuum representing pressures above 1 Torr absolute (a large number of mechanical pumps in industry are used for this purpose; flow is viscous), (ii) medium vacuum varying between 1 and  $10^{-3}$  Torr absolute (most pumps serving in this range are mechanical; fluid is in transition between viscous and molecular), (iii) high vacuum ranging between  $10^{-3}$  and  $10^{-6}$  Torr absolute (nonmechanical ejector or cryogenic pumps are used; flow is molecular or Newtonian), and (iv) very high vacuum representing absolute pressure below  $10^{-6}$  Torr (primarily for laboratory applications and space simulation).

A number of devices are available to measure fluid (gaseous or liquid) pressure and vacuum values in a closed system and require the fluid pressure to be steady for a reasonable length of time. In practice, the most common types of such gauges are the following:

- **Absolute pressure gauge.** This is used to measure the pressure above a theoretical perfect vacuum condition and the pressure value is equal to  $(P_{\text{abs,p}} - P_{\text{atm}})$  in Figure 1.1. The most basic type of such gauges is the barometer. Another type of gauge used for vacuum measurements is the U-shaped gauge. The pressure value read is equal to  $(P_{\text{atm}} - P_{\text{abs,n}})$  in Figure 1.1.
- **Mercury U-tube manometer.** These manometers use a column of liquid to measure the difference between two pressures. If one is atmospheric pressure, the result is a direct reading of positive or negative gauge pressure.
- **Plunger gauge.** This gauge consists of a plunger connected to system pressure, a bias spring, and a calibrated indicator. An auto tire gauge would be an example.
- **Bourdon gauge.** This is the most widely utilized instrument for measuring positive pressure and vacuum. Measurements are based on the determination of an elastic element (a curved tube) by the pressure being measured. The radius of curvature increases with increasing positive pressure and decreases with increasing vacuum. The resulting deflection is indicated by a pointer on a calibrated dial through a ratchet linkage. Similar gauges may be based on the deformation of diaphragms or other flexible barriers.
- **McLeod gauge.** This is the most widely used vacuum-measuring device, particularly for extremely accurate measurements of high vacuums.

Among these devices, two principal types of measuring devices for refrigeration applications are manometers and Bourdon gauges. However, in many cases manometers are not preferred because

of the excessive length of tube needed, inconvenience at pressures much in excess of 1 atm, and less accuracy.

There are also pressure transducers available, based on the effects of capacitance, rates of change of strain, voltage effects in a piezoelectric crystal, and magnetic properties (Marquand and Croft, 1997). All have to be calibrated and the only calibration possible is against a manometer under steady conditions, even though they are most likely to be used under dynamic conditions.

It is important to note at another additional level that the *saturation pressure* is the pressure of a liquid or vapor at saturation conditions.

### 1.2.5 Temperature

Temperature is an indication of the thermal energy stored in a substance. In other words, we can identify hotness and coldness with the concept of temperature. The temperature of a substance may be expressed in either relative or absolute units. The two most common temperature scales are the Celsius ( $^{\circ}\text{C}$ ) and the Fahrenheit ( $^{\circ}\text{F}$ ). As a matter of fact, the Celsius scale is used with the SI unit system and the Fahrenheit scale with the English Engineering system of units. There are also two more scales: the Kelvin scale (K) and the Rankine scale (R) that is sometimes employed in thermodynamic applications. The relations between these scales are summarized as follows:

$$T_{(^{\circ}\text{C})} = \frac{T_{(^{\circ}\text{F})} - 32}{1.8} \quad (1.10)$$

$$T_{(\text{K})} = T_{(^{\circ}\text{C})} + 273.15 = \frac{T_{(\text{R})}}{1.8} = \frac{T_{(^{\circ}\text{F})} + 459.67}{1.8} \quad (1.11)$$

$$T_{(^{\circ}\text{F})} = 1.8T_{(^{\circ}\text{C})} + 32 = 1.8(T_{(\text{K})} - 273.15) + 32 \quad (1.12)$$

$$T_{(\text{R})} = 1.8T_{(\text{K})} = T_{(^{\circ}\text{F})} + 459.67 \quad (1.13)$$

Furthermore, the temperature differences result in

$$1 \text{ K} = 1^{\circ}\text{C} = 1.8 \text{ R} = 1.8^{\circ}\text{F}$$

$$1 \text{ R} = 1^{\circ}\text{F} = 1 \text{ K}/1.8 = 1^{\circ}\text{C}/1.8$$

Kelvin is a unit of temperature measurement; zero Kelvin (0 K) is absolute zero and is equal to  $-273.15^{\circ}\text{C}$ . The K and  $^{\circ}\text{C}$  are equal increments of temperature. For instance, when the temperature of a product is decreased to  $-273.15^{\circ}\text{C}$  (or 0 K), known as *absolute zero*, the substance contains no heat energy and supposedly all molecular movement stops. The saturation temperature is the temperature of a liquid or vapor at saturation conditions.

Temperature can be measured in many ways by devices. In general, the following devices are in common use:

- **Liquid-in-glass thermometers.** It is known that in these thermometers the fluid expands when subjected to heat, thereby raising its temperature. It is important to note that in practice all thermometers including mercury ones only work over a certain range of temperature. For example, mercury becomes solid at  $-38.8^{\circ}\text{C}$  and its properties change dramatically.
- **Resistance thermometers.** A resistance thermometer (or detector) is made of resistance wire wound on a suitable former. The wire used has to be of known, repeatable, electrical characteristics so that the relationship between the temperature and resistance value can be predicted precisely. The measured value of the resistance of the detector can then be used to determine the value of an unknown temperature. Among metallic conductors, pure metals exhibit the greatest change of resistance with temperature. For applications requiring higher accuracy,

especially where the temperature measurement is between  $-200$  and  $+800^{\circ}\text{C}$ , the majority of such thermometers are made of platinum. In industry, in addition to platinum, nickel ( $-60$  to  $+180^{\circ}\text{C}$ ), and copper ( $-30$  to  $+220^{\circ}\text{C}$ ) are frequently used to manufacture resistance thermometers. Resistance thermometers can be provided with 2, 3, or 4 wire connections and for higher accuracy at least 3 wires are required.

- Averaging thermometers.** An averaging thermometer is designed to measure the average temperature of bulk stored liquids. The sheath contains a number of elements of different lengths, all starting from the bottom of the sheath. The longest element which is fully immersed is connected to the measuring circuit to allow a true average temperature to be obtained. There are some significant parameters, namely, sheath material (stainless steel for the temperature range from  $-50$  to  $+200^{\circ}\text{C}$  or nylon for the temperature range from  $-50$  to  $+90^{\circ}\text{C}$ ), sheath length (to suit the application), termination (flying leads or terminal box), element length, element calibration (to copper or platinum curves), and operating temperature ranges. In many applications where a multielement thermometer is not required, such as in air ducts, cooling water, and gas outlets, a single element thermometer stretched across the duct or pipework will provide a true average temperature reading. Despite the working range from  $0$  to  $100^{\circ}\text{C}$ , the maximum temperature may reach  $200^{\circ}\text{C}$ . To keep high accuracy these units are normally supplied with 3-wire connections. However, up to 10 elements can be mounted in the averaging bulb fittings and they can be made of platinum, nickel or copper, and fixed at any required position.
- Thermocouples.** A thermocouple consists of two electrical conductors of different materials connected together at one end (so-called *measuring junction*). The two free ends are connected to a measuring instrument, for example, an indicator, a controller, or a signal conditioner, by a reference junction (so-called *cold junction*). The thermoelectric voltage appearing at the indicator depends on the materials of which the thermocouple wires are made and on the temperature difference between the measuring junction and the reference junction. For accurate measurements, the temperature of the reference junction must be kept constant. Modern instruments usually incorporate a cold junction reference circuit and are supplied ready for operation in a protective sheath, to prevent damage to the thermocouple by any mechanical or chemical means. Table 1.1 gives several types of thermocouples along with their maximum absolute temperature ranges. As can be seen in Table 1.1, copper–constantan thermocouples have an accuracy of  $\pm 1^{\circ}\text{C}$  and are often employed for control systems in refrigeration and food-processing applications. The iron–constantan thermocouple with its maximum temperature of  $850^{\circ}\text{C}$  is used in applications in

**Table 1.1** Some of the most common thermocouples.

Type	Common Names	Temperature Range ( $^{\circ}\text{C}$ )
T	Copper–Constantan (C/C)	$-250$ to $400$
J	Iron–Constantan (I/C)	$-200$ – $850$
E	Nickel Chromium–Constantan or Chromel–Constantan	$-200$ – $850$
K	Nickel Chromium–Nickel Aluminum or Chromel–Alumel (C/A)	$-180$ – $1100$
–	Nickel 18% Molybdenum–Nickel	$0$ – $1300$
N	Nicrosil–Nisil	$0$ – $1300$
S	Platinum 10% Rhodium–Platinum	$0$ – $1500$
R	Platinum 13% Rhodium–Platinum	$0$ – $1500$
B	Platinum 30% Rhodium–Platinum 6% Rhodium	$0$ to $1600$

the plastics industry. The chromel–alumel type thermocouples, with a maximum temperature of about  $1100^{\circ}\text{C}$ , are suitable for combustion applications in ovens and furnaces. In addition, it is possible to reach about  $1600$  or  $1700^{\circ}\text{C}$  using platinum and rhodium–platinum thermocouples, particularly in steel manufacture. It is worth noting that one advantage thermocouples have over most other temperature sensors is that they have a small thermal capacity and thus a prompt response to temperature changes. Furthermore, their small thermal capacity rarely affects the temperature of the body under examination.

- **Thermistors.** These devices are semiconductors and act as thermal resistors with a high (usually negative) temperature coefficient. Thermistors are either self-heated or externally heated. Self-heated units employ the heating effect of the current flowing through them to raise and control their temperature and thus their resistance. This operating mode is useful in such devices as voltage regulators, microwave power meters, gas analyzers, flow meters, and automatic volume and power level controls. Externally heated thermistors are well suited for precision temperature measurement, temperature control, and temperature compensation due to large changes in resistance versus temperature. These are generally used for applications in the range  $-100$  to  $+300^{\circ}\text{C}$ . Despite early thermistors having tolerances of  $\pm 20\%$  or  $\pm 10\%$ , modern precision thermistors are of higher accuracy, for example,  $\pm 0.1^{\circ}\text{C}$  (less than  $\pm 1\%$ ).
- **Digital display thermometers.** A wide range of digital display thermometers, for example, handheld battery powered displays and panel mounted mains or battery units, are available in the market. Figure 1.2 shows a handheld digital thermometer with protective boot (with a high accuracy, e.g.,  $\pm 0.3\%$  reading  $\pm 1.0^{\circ}\text{C}$ ). Displays can be provided for use with all standard thermocouples or BS/DIN platinum resistance thermometers with several digits and  $0.1^{\circ}\text{C}$  resolution.

It is very important to emphasize that before temperature can be controlled, it must be sensed and measured accurately. For temperature measurement devices, there are several potential sources of error such as sensor properties, contamination effects, lead lengths, immersion, heat transfer, and controller interfacing. In temperature control there are many sources of error which can be



**Figure 1.2** Handheld digital thermometers (Courtesy of Brighton Electronics, Inc.).



**Figure 1.3** A data acquisition system for temperature measurements in cooling.

minimized by careful consideration of the type of sensor, its working environment, the sheath or housing, extension leads, and the instrumentation. An awareness of potential errors is vital in the applications dealt with. Selection of temperature measurement devices is a complex task and has been discussed briefly here. It is extremely important to remember to “choose the right tool for the right job.” Data acquisition devices are commonly preferred for experimental measurements. Figure 1.3 shows a data acquisition system set-up for measuring temperatures during heating and cooling applications.

### 1.2.6 Thermodynamic Systems

These are devices or combination of devices that contain a certain quantity of matter being studied. It is important to carefully define the term *system* as that portion of all matter under consideration. There are three systems that we can define as follows:

- **Closed system.** This is defined as a system across the boundaries of which no material crosses. In other words, it is a system that has a fixed quantity of matter, so that no mass can escape or enter. In some books, it is also called a *control mass*.
- **Open system.** This is defined as a system in which material (mass) is allowed to cross its boundaries. It is also called a *control volume*.
- **Isolated system.** This is a closed system that is not affected by the surroundings at all, in which no mass, heat, or work crosses its boundary.

### 1.2.7 Process and Cycle

A process is a physical or chemical change in the properties of matter or the conversion of energy from one form to another. Several processes are described by the fact that one property remains constant. The prefix *iso-* is employed to describe a process, such as an isothermal process

(a constant-temperature process), an isobaric process (a constant-pressure process), and an isochoric process (a constant-volume process). A refrigeration process is generally expressed by the conditions or properties of the refrigerant at the beginning and end of the process.

A cycle is a series of thermodynamic processes in which the endpoint conditions or properties of the matter are identical to the initial conditions. In refrigeration, the processes required to produce a cooling effect are arranged to operate in a cyclic manner so that the refrigerant can be reused.

### 1.2.8 Property and State Postulate

This is a physical characteristic of a substance used to describe its state. Any two properties usually define the state or condition of the substance, from which all other properties can be derived. This is called *state postulate*. Some examples are temperature, pressure, enthalpy, and entropy. Thermodynamic properties are classified as intensive properties (independent of the mass, e.g., pressure, temperature, and density) and extensive properties (dependent on the mass, e.g., mass and total volume). Extensive properties per unit mass become intensive properties such as specific volume. Property diagrams of substances are generally presented in graphical form and summarize the main properties listed in the refrigerant tables.

### 1.2.9 Sensible Heat, Latent Heat and Latent Heat of Fusion

It is known that all substances can hold a certain amount of heat; this property is their thermal capacity. When a liquid is heated, the temperature of the liquid rises to the boiling point. This is the highest temperature that the liquid can reach at the measured pressure. The heat absorbed by the liquid in raising the temperature to the boiling point is called *sensible heat*. The heat required to convert the liquid to vapor at the same temperature and pressure is called *latent heat*. In fact, it is the change in enthalpy during a state change (the amount of heat absorbed or rejected at constant temperature at any pressure, or the difference in enthalpies of a pure condensable fluid between its dry saturated state and its saturated liquid state at the same pressure).

Fusion is the melting of a material. For most pure substances there is a specific melting/freezing temperature, relatively independent of the pressure. For example, ice begins to melt at 0°C. The amount of heat required to melt 1 kg of ice at 0°C to 1 kg of water at 0°C is called the *latent heat of fusion of water* and equals 334.92 kJ/kg. The removal of the same amount of heat from 1 kg of water at 0°C changes it back to ice.

### 1.2.10 Vapor States

A vapor is a gas at or near equilibrium with the liquid phase—a gas under the saturation curve or only slightly beyond the saturated vapor line. *Vapor quality* is theoretically assumed; that is, when vapor leaves the surface of a liquid it is pure and saturated at the particular temperature and pressure. In actuality, tiny liquid droplets escape with the vapor. When a mixture of liquid and vapor exists, the ratio of the mass of the liquid to the total mass of the liquid and vapor mixture is called the *quality* and is expressed as a percentage or decimal fraction.

*Superheated vapor* is the saturated vapor to which additional heat has been added, raising the temperature above the boiling point. Let us consider a mass ( $m$ ) with a quality ( $x$ ). The volume is the sum of those of the liquid and the vapor as defined below:

$$V = V_{\text{liq}} + V_{\text{vap}} \quad (1.14)$$