RILEY SHUTTLEWORTH

MECHANICAL AND ELECTRICAL SYSTEMS FOR CONSTRUCTION

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Mechanical and Electrical Systems for Construction

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Mechanical and Electrical Systems for Construction

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Preface

The goal of this book is to bring to practitioners and students of construction a fairly complete but nonexhaustive study of the mechanical and electrical systems that are found in modern buildings.

The goal has also been to bring to each of the subjects treated a greater depth of examination than has been true in any of the very few texts of a similar nature available in the literature today. This has made necessary the omission, as a concession to limits of size, weight, and cost, of several secondary subjects, such as elevators, people movers, food preparation and service equipment, pneumatic tube systems, acoustics, sound and signal systems, fire extinguishing systems, and solar energy systems.

The readers that the author has in mind are people of all ages, of somewhat limited technical background, who can recall their high school and early college algebra and physics and who find themselves in one or more of the following situations:

1 A member of a mechanical and/or electrical design team, in an A/E (architect/engineer) organization, who may have extensive training in one discipline but very little training in the many other disciplines with which the team is concerned.

2 An architectural designer who needs greater knowledge of things mechanical and electrical in order to interrelate them more thoroughly with architectural designs, or to assist the designer in passing examinations leading to AIA affiliation and state registration.

3 An A/E "contact" person who in frequent meetings with clients, contracting officers, and building officials may need greater ability to speak the language of construction as it applies to mechanical and electrical work.

4 A third- or fourth-year student in one of the many developing schools of construction (building science) now coming onto the educational scene.

5 A third-, fourth- or fifth-year student of architecture.

6 A civil engineering student who plans to specialize in the field of building construction as a structural or sanitary engineer and needs to round out his background with mechanical and electrical training.

This text is arranged such that a straight-through reading and study from the first page to the last can be efficiently accomplished. However, the author has constantly borne in mind the fact that a reference text on these subjects is badly needed. An effort has therefore been made to make it possible for anyone with a somewhat limited background to jump right into any chapter and make reasonable progress on a specific subject.

To this end, an extensive index with many cross references is provided. The meanings of all symbols in all algebraic formulas are readily determinable. With only a few exceptions, no algebraic symbol is permitted to have one meaning in one chapter and another meaning elsewhere. A complete schedule is given at one location of all symbols and their meanings. To a limited extent, practical examples of the solution of typical problems are given.

A deep, rigorous treatment is not given to any of the many subjects with which this text is concerned; that is not its primary goal. However, to those who have been fully trained previously, it should give refreshment, and should begin and greatly assist the process of recall, when that becomes necessary.

This book's goal, then, is to give enlightenment on many subjects in mechanical and electrical construction, and to do this in a much more than superficial way. It is directed somewhat toward those who will spend their days (and nights) in intimate detail design, but even more toward those in the construction field who must in a secondary manner be extensively conversant and knowledgeable in things mechanical and electrical. For all readers, especially students, and for classroom use, sample problems are given at the end of most chapters.

Riley Shuttleworth

Contents

Chapter 1

HVAC Definitions and Basic Concepts

1-1 GENERALITIES

Throughout this text the expression *heating, ventilating, and air conditioning* will be abbreviated and referred to as HVAC. Everyone in the construction industry routinely uses and understands this terminology.

The HVAC systems in buildings are the most troublesome features in construction. Architects, engineers, and contractors all agree that this is so. They loudly proclaim that the headaches and worries that they suffer from difficulties with their HVAC systems are severe and unending. Difficulties with these systems are the greatest source of complaint and dissatisfaction on the part of building owners and operators.

One of the primary goals of this text is to point out the reasons for the problems and to suggest ways to solve them. A second goal is to set forth proper design principles.

Before proceeding with definitive discussions of this nature, however, it will be necessary to define all the terms and expressions that will be used, and to set forth clearly all the basic technical concepts upon which our discussion will be built.

1-2 HEAT

In HVAC practices, heat is one of the greatest problems. Rarely is heat present naturally in just the right amount. We almost always have too much or too little heat and the purpose of the HVAC system is to remedy that situation.

A basic understanding of heat is therefore mandatory. Although we discuss heat on familiar terms every day, do we really know its basic nature? Many of us do not.

Heat may be defined simply as molecular motion or activity. All matter consists of atoms and molecules, and at normal temperatures, they are in constant motion.

Energy, of which heat is but one form, has been invested in a sample of some material, and as a result, its molecules have motion. Theoretically, if all the heat could be removed from that sample of material, its molecules would fall together in a motionless heap. Add a little heat back to the sample and its molecules begin to stir. Add a lot of heat and those molecules begin to move at tremendous rates of speed, as they do at normal room temperatures.

The molecules of a material at a temperature of 70°F (Fahrenheit) have a rate of motion much greater than those of a material at 0°F whether the materials are similar or different. If brought into contact with each other, the molecular rates will tend to average out at the same rate of speed.

In other words, the warmer material will lose heat, temperature, and molecular motion, and the colder material will gain heat, temperature, and molecular motion. Given time, the heat exchange from one material to the other will result in an equalization of the temperatures and rates of molecular activity.

Swiftly moving molecules coming into physical proximity with more slowly moving molecules will cause the slower molecules to speed up, while the faster molecules, as a result, slow down. This is the process of *heat exchange,* and an understanding of this process must be achieved by the student of HVAC.

As we shall see below, however, heat may take forms other than molecular activity.

1-3 FORMS OF HEAT

In HVAC practices we are concerned with heat in three basic forms:

1 Sensible heat
2 Latent heat
3 Radiant heat

After we discuss these forms a bit, you will probably exclaim—"But two of these forms are not involved with molecular activity"—and you would be right. As we will see, latent heat and radiant heat are not really heat as such; one is vaporized water and the other is an electromagnetic radiation. However, they cause a load on a building cooling system just as sensible heat (molecular activity) does. So even though not technically correct, we do speak of them as heat.

1-4 SENSIBLE HEAT

The first form of heat, *sensible heat,* is, as indicated above, merely molecular activity. It is the form of heat most readily perceived by the human senses. When we feel a blast of warm air coming from some kind of warm air heater, we are sensing sensible heat. The high rate of molecular activity of the heated air that contacts our skin is imparted to the molecules of the tissues that make up the skin. Our senses perceive this increased molecular activity, and a sensation of warmth is transmitted to our brains.

If a person inadvertently places his or her hand on a hot stove, the extremely rapid motion of the molecules of the metal of the stove is instantly imparted to the hand. The molecules of the skin on the hand are then set into such extremely rapid motion that the skin cells cannot contain them. The cells break down and a blister forms—the result of the transfer of sensible heat.

In the same manner, sensible heat is lost from a warm building to the outside atmosphere on a cold day. The comparatively high molecular activity of the interior is transmitted right through the materials of the building walls, windows, and so on, to the comparatively low rate of molecular activity outdoors. This process of sensible heat propagation is called *conduction.* It is characterized by the physical contact of one substance with another, resulting in an exchange of molecular activity from the warmer substance to the cooler substance.

Sensible heat propagation also takes place by another process, called *convection.* In this process, a fluid such as air or water is brought into physi-

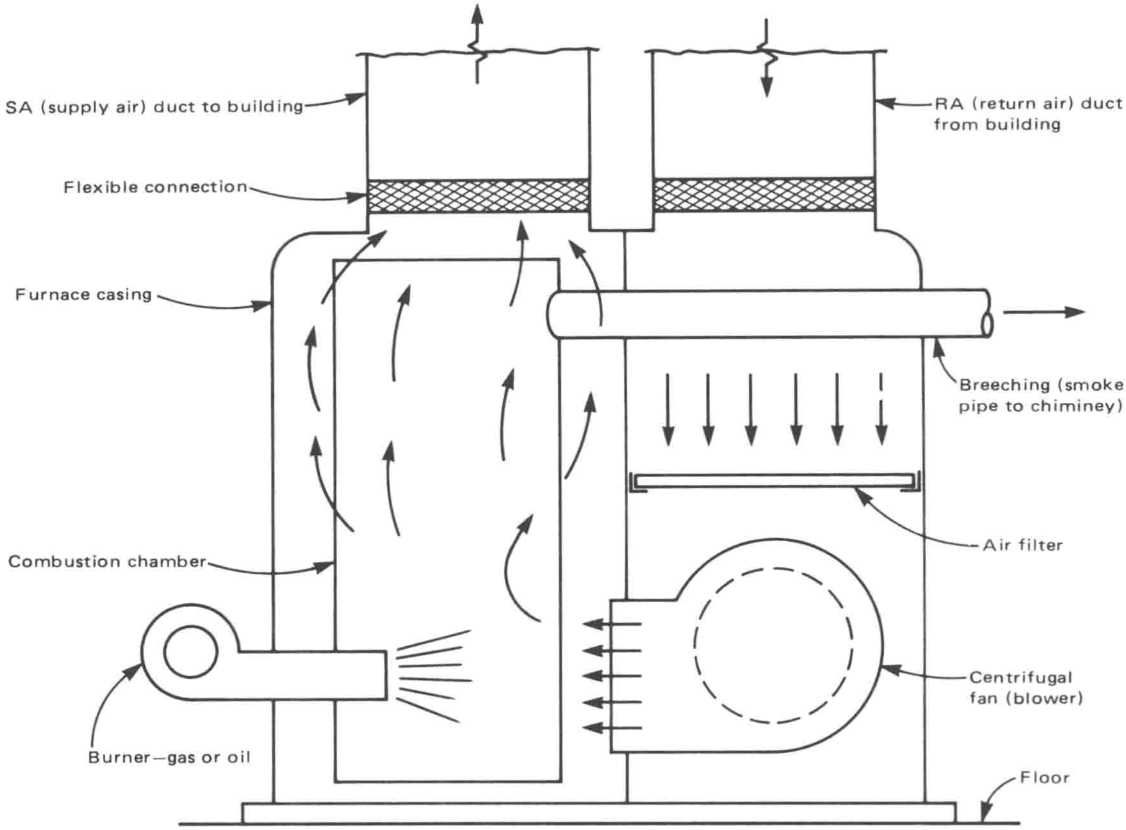

Figure 1-1 Residential warm air furnace.

cal contact with a hot surface, and the fluid is heated by conduction. The fluid is then circulated to an area of lower temperature, and in this process sensible heat is conveyed by the convection process from the hot surface to the area of low temperature.

A good example of sensible heat propagation may be seen in the typical residential warm air furnace (see fig. 1-1). Here, the steel combustion chamber is made very hot by the flame that burns within it. Air is circulated over and around the exterior of this combustion chamber by the motor-driven fan shown.

Sensible heat, molecular activity, is delivered into the moving airstream by conduction; and that heat is conveyed by convection, air movement, through the supply ducts of the heating system to the house.

So sensible heat is molecular activity that is propagated by two methods—conduction and convection.

1-5 LATENT HEAT

As used in HVAC practices, the term *latent heat* has many synonyms. Some of these are: humidity, water vapor, atmospheric moisture, and low-pressure steam. These are all exact synonyms, and as such give a very good indication of the meaning of the term "latent heat."

Latent heat, then, is water which, as the result of the addition of heat to it, has become water vapor. That is what steam is—vaporized water; and the latent heat that was added, and that caused water to change state from a liquid to a vapor, is still stored in the water vapor.

Latent heat, or water vapor, is almost always present in atmospheric air. However, it is not, as is popularly assumed, absorbed by the atmospheric air. It is merely mechanically mixed with the air. The air and vapor just happen to occupy the same space at the same time. There is no chemical interaction between the molecules of the air and the vaporized water.

Latent heat or humidity should be thought of as a pressurized fluid. Consider a steam pressure cooker on the kitchen range at home. When holding pressure with the lid of the cooker tightly in place, the internal steam pressure is perfectly distributed within the cooker. It is not possible to have more steam pressure on one side of the cooker than on another. The same, to a very great extent, is true with the steam pressure (latent heat) in a room in a building. It always distributes itself evenly throughout the room.

On a cold winter day, the vapor pressure outdoors is almost always appreciably lower than the vapor pressure indoors. As a result, we find the molecules of water vapor doing their best to migrate, or escape, from the interior to the exterior—thus trying to equalize interior and exterior vapor pressures. The latent heat will migrate (that is the expression usually used) through every door and window crack, and even right through a solid wall or roof, and the rate of latent heat migration will depend on the vapor pressure differential between indoor vapor pressure and outdoor vapor pressure.

1-6 RADIANT HEAT

As mentioned earlier, radiant heat is not molecular activity. It can certainly cause molecular activity, but that is not what it is. *Radiant heat* is infrared radiation. It is part of the electromagnetic spectrum of which visible light is also a part. It is very similar to visible light except that its wavelength is much longer.

All things that surround us are emitters of radiant heat. Some objects have a dull, black surface and are excellent emitters of radiant heat. Some objects have a bright, white, shiny surface; these are very poor emitters of radiant heat.

Consider the two black spheres shown in fig. 1-2. They are of the same size, surface texture, and color. However, one is at a temperature of 150°F and the other is at 100°F. Because of the temperature difference, there will be a net radiant heat exchange from the warmer sphere to the cooler sphere. However, because both spheres are appreciably warmer than the 66°F ambiance (surroundings), both spheres will radiate heat to the ambiance. This will be a wave form of radiant energy, and technically should not be called heat until it strikes something, such as carpeting, furniture, or people. These objects are opaque to the radiant heat; they receive it, absorb it, and convert it into sensible heat (molecular activity).

In fig. 1-2, the 100°F sphere will radiate heat to all surfaces of the room, all of which are at a lower temperature (66°F mean). However, the 100°F sphere also radiates heat to the 150°F sphere, even though the latter is at a higher temperature. Of course, the 150°F sphere, being hotter, will radiate more energy to the 100°F sphere, so there is a *net* radiant heat exchange from the warmer to the cooler sphere.

Radiant heat, like light, is not affected by gravity, and can move in any direction—up, down, or laterally—with equal facility. For example, a ceiling in a room that is heated (by any means) until its temperature is 30°F or so above the other surface temperatures of the room and its furnishings will radiate heat to all parts of the room. It can "shine" downward toward the floor just as easily as it can shine in any other direction. We call it a *ceiling radiant heat panel.*

1-7 SOURCES OF INTERNAL HEAT

Let us consider now a few of the sources of heat that we might find in a typical room which impose a load on the cooling system that cools that room. Further, let us classify the heat that emanates

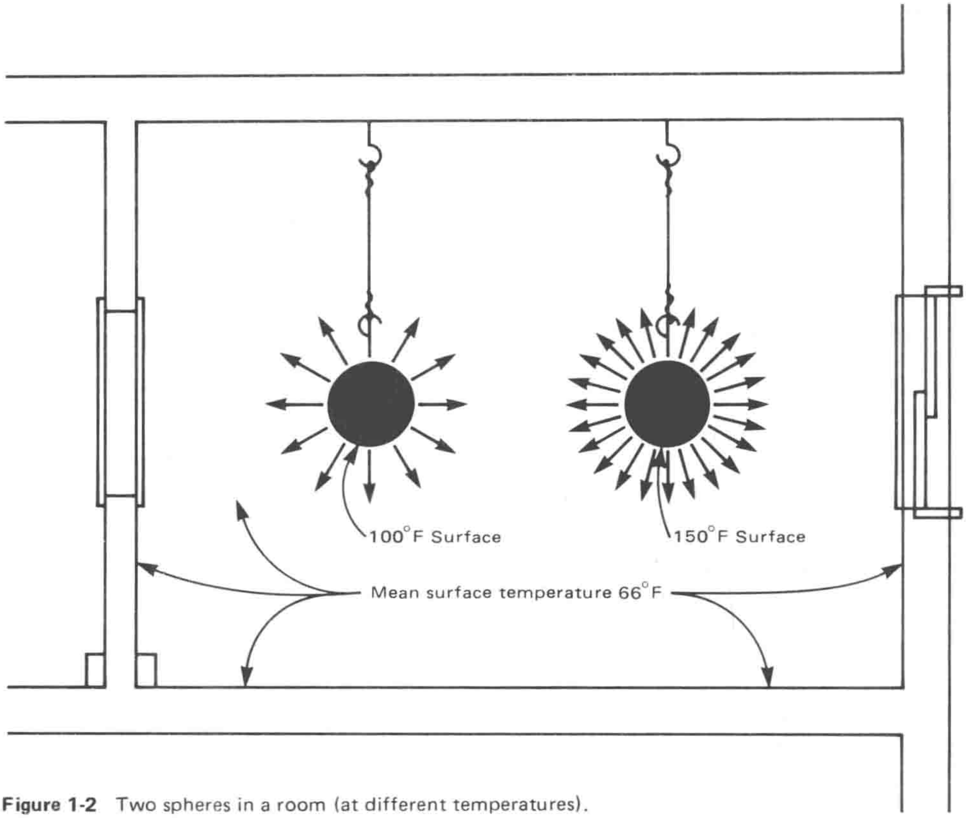

Figure 1-2 Two spheres in a room (at different temperatures).

from each source as to whether it is sensible, latent, radiant, or a combination of these.

Consider first a digital computer; many of these, of considerable size and number, are found in commerce and industry. They emit lots of heat. What kind of heat? It is mainly sensible heat, as a result of the cooling air that is circulated through the computer cabinets. But the external surfaces are often warm to the touch, which means that they are radiating heat to the ambiance. So the heat output is largely sensible, with some radiant but no latent heat.

How about people? As a result of their metabolic processes, people emit heat at all times, and their rate of heat emission depends on their rate of physical and mental activity.

Although the internal body temperature of most people is 98.6°F, the usual skin surface temperature is about 85°F. Since the room surface temperatures that surround us are usually much less than that, the body radiates heat to the ambiance. Also, human beings perspire; and moisture is evaporated from the lungs as a result of respiration. So people emit latent heat.

Most of the time, the air that surrounds us and that we breathe is at a temperature below our lung and skin surface temperatures. So we lose sensible heat by physical contact with the atmosphere as well as with the furniture we sit on and the clothing that we wear. People lose heat, then, in all three forms: sensible, latent, and radiant.

A steam table or serving counter in a cafeteria also loses heat in all three forms.

Lighting fixtures emit sensible and radiant heat but no latent heat.

The sun's heat is all radiant, but that is quickly converted to sensible heat, and sometimes to latent heat when it shines on a body of water.

The heat that transmits through walls, windows, roofs, and so on, on a hot summer day is mostly sensible.

1-8 MEASUREMENT OF HEAT

To deal adequately with heat of all types, we must know how to measure the quantities involved, and for that, we must have units of measurement.

British Thermal Unit

In the United States, the unit of thermal measurement has been, and continues to be, the British thermal unit (Btu). However, as we approach closer and closer to conversion to the metric system, Standard International (SI) units of thermal measurement will become dominant. One such SI unit is the calorie.

The Btu may be defined as that quantity of heat that must be added to or subtracted from one pound of water at 60°F to effect a temperature increase or decrease of 1°F.

Calorie

The calorie may be defined, similarly, as that quantity of heat that must be added to or subtracted from one gram of water at approximately 15°C (Centigrade or Celsius) to effect a temperature increase or decrease of 1°C.

Btu per Hour

In HVAC work we are rarely concerned with static quantities of heat, but we are constantly involved with dynamic situations—in other words, with situations where heat is moving. For example, heat is flowing out of a building in winter, and the heating system must replace that loss with an equal supply of heat. Both that heat loss and the heat supplied are measured as a time rate of heat flow. These are measured in terms of Btu per hour. The expression "Btu per hour" can be written many different ways—such as Btu/hr, Btuh, or just BH, all meaning exactly the same thing. In this text we will generally use the expression BH to mean Btu per hour. This, and variations of it, are set forth in the following list:

BH = Btu per hour

MBH = Btu per hour in thousands;
1 MBH = 1000 BH

BHS = Btu per hour, sensible heat

BHL = Btu per hour, latent heat

BHT = Btu per hour, total heat

In the last entry above, BHT, total heat is simply the arithmetic sum of the sensible heat flow rate plus the latent heat flow rate. Therefore, BHT = BHS + BHL. Another common term for total heat is *enthalpy*.

1-9 SPECIFIC HEAT

In measuring rates of heat flow for various materials, we usually need to know what the *specific heat* of a substance might be. Specific heat may be defined as the amount of heat that must be added to or subtracted from a unit weight of a substance to cause a temperature change of one degree in whatever temperature scale is in use. This definition should sound familiar to the reader, since the thermal value of a Btu (defined above) is identical to the specific heat of water.

One value that we will need to know and to use frequently is the specific heat of air; this is 0.241 (Btu per pound of air) at ordinary room temperatures.

1-10 AIR-WATER VAPOR MIXTURE

The atmosphere almost always consists of a mechanical mixture of air and water vapor (see art. 1-5). The atmosphere normally includes many components, such as nitrogen, oxygen, water vapor, the rare gases such as argon and neon, dust, pollen, carbon dioxide, carbon monoxide, odors, and many other pollutants. However, we are concerned mostly with the air (primarily nitrogen and oxygen) and the water vapor that is mixed with it, and the behavior of these mixtures.

In this connection, there is a group of useful terms which must be carefully defined and completely understood.

1-11 DRY BULB TEMPERATURE

Dry bulb (DB) *temperature* is the temperature reading given by a dry thermometer (some thermometers are wet), which gives a direct indication of the sensible heat content of an air-water vapor mixture.

Dry bulb temperature is just the plain temperature with which you have been familiar all your life. We call it dry bulb temperature to distinguish it from the readings we get from a wet bulb thermometer.

Figure 1-3 is an illustration of a *sling psychrometer,* one of the tools of the HVAC trade. Close examination will show that it consists of two thermometers mounted on a common backing plate to which is connected a chain or a swivel handle. Notice that one thermometer has a cotton wick slid up over the mercury bulb at the bottom end. In use, the cotton wick is kept wet so that, in truth, we have a wet bulb thermometer. The other thermometer has no wick, and the bulb remains dry.

To obtain accurate readings, this instrument must be rapidly swung in a circle around the swivel handle to give the same effect as we would have if the instrument were held steady and a swiftly moving stream of air passed over it.

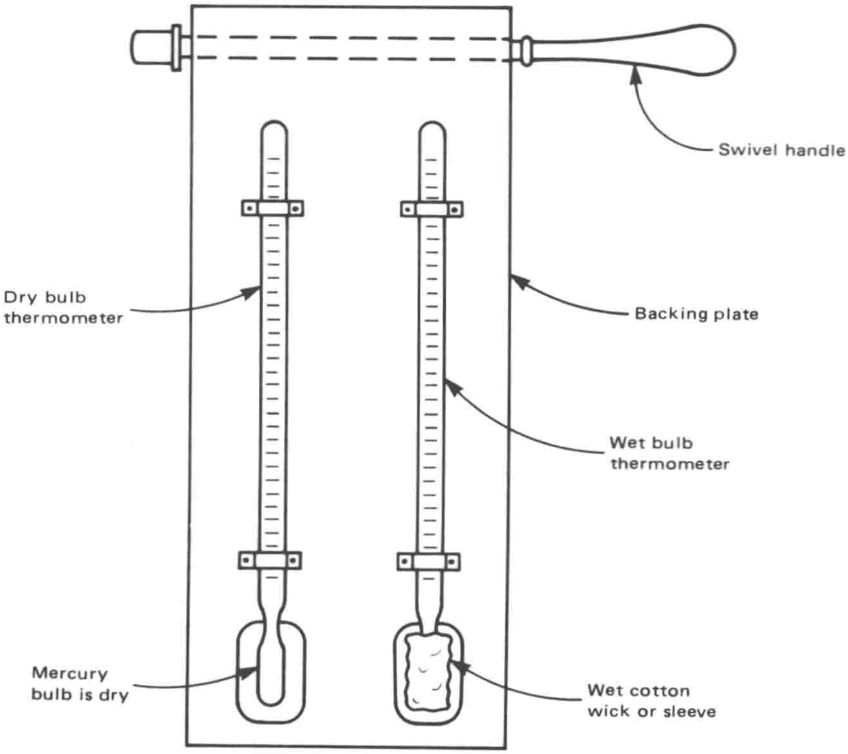

Figure 1-3 Sling psychrometer.

Obviously, from this instrument we get dry bulb and wet bulb temperature readings simultaneously.

1-12 WET BULB TEMPERATURE

Wet bulb (WB) *temperature* is the reading we get from a thermometer with a wetted bulb, immersed in a stream of rapidly moving air, which gives us a direct indication of the *total heat content* of an air-water vapor mixture.

Remember, we said in art. 1-8 that total heat is merely the arithmetic sum of the sensible heat and the latent heat content of an air-water vapor mixture. We may speak of the total heat as the Btu content per pound of a certain stationary sample of air, but more frequently we will speak of total heat as the BH (Btu per hour) in a moving stream of air. In the latter case, the total heat flow per hour (BHT) is the sum of the sensible heat flow per hour (BHS) and the latent heat flow per hour (BHL): thus, BHT = BHS + BHL.

Wet bulb temperature is so important to the study of HVAC that an effort should be made to achieve an understanding of what it basically means, as well as how wet bulb temperatures are measured. Consider a glass mercury type of wet bulb thermometer as shown in fig. 1-3, and the fact that the swiftly moving molecules of the surrounding air are beating on the wet wick and, through the wick, the glass of the thermometer and, through the glass, the mercury inside. The air molecules are trying to impart their energy to the mercury molecules and set them in more rapid motion. To the extent that this is done, the mercury molecules zip around a little faster and as a result, they require more space in which to maneuver. The volume of the mercury increases, the mercury rises higher in the stem of the thermometer, and the result is a higher temperature reading.

In opposition to this action, the water that is evaporating from the wet wick requires heat, since heat must be added to water to make it boil or evaporate from a liquid to a vapor. The necessary heat is drawn partly from the atmosphere and partly from the thermometer. Removal of heat from the thermometer cools it, causing the mercury molecules to slow down and contract—thus "trying" to give a lower temperature reading. The rate at which the water evaporates depends on the level of humidity in the atmosphere—the lower the humidity, the faster the water evaporates, and vice versa.

So we see that the wet bulb thermometer is subject to opposing forces. The sensible heat in the atmosphere tries to increase the reading up to to the dry bulb temperature as a limit, while the cooling effect of the evaporating water tries to reduce the reading down to the dew point temperature of the atmosphere as a lower limit. (Dew point temperature is defined in the following section.)

The resultant effect of the opposing forces is to balance out the thermometer reading at a point somewhat below the dry bulb reading and somewhat above the dew point temperature. It is a compromise between these two values.

It is important to realize that to the extent that moisture is constantly being evaporated from the human body's external surfaces, its nasal passages, bronchi, and lungs, the body behaves very much like a wet bulb thermometer. That is why many people feel that wet bulb temperature is a better indicator of human comfort conditions than is dry bulb temperature.

1-13 DEW POINT TEMPERATURE

Dew point (DP) *temperature* is that temperature at which an air-water vapor mixture, when cooled, will begin to yield liquid water. In other words, if a sample of an air-water vapor mixture is somehow cooled, at some point as the dry bulb temperature falls, some of the water vapor in the mixture will condense and become liquid. This is the dew point temperature of that mixture.

If in the cooling process, the dry bulb temperature fell only a few degrees before liquid water appeared, we can conclude that the moisture content of the mixture was very high. However, if