Chapter 2

Heating Fundamentals

There is still considerable disagreement about the exact nature of heat, but most authorities agree that it is a particular form of energy. Specifically, heat is a form of energy not associated with matter and *in transit* between its source and destination point. Furthermore, heat energy exists as such only between these two points. In other words, it exists as heat energy only while flowing between the source and destination.

So far this description of heat energy has been practically identical to that of work energy, the other form of energy in transit not associated with matter. The distinguishing difference between the two is that heat energy is energy in transit as a result of temperature differences between its source and destination point, whereas work energy in transit is due to other, nontemperature factors.

British Thermal Unit

Heat energy is measured by the British thermal unit (Btu). Each thermal unit is regarded as equivalent to one unit of heat (heat energy).

Since 1929, British thermal units have been defined on the basis of 1 Btu being equal to 251.996 IT (International Steam Table) calories, or 778.26 foot-pounds of mechanical energy units (work). Taking into consideration that one IT calorie equals 1⁄860 of a watt-hour, 1 Btu is then equivalent to about 1⁄3 watt-hour.

Prior to its 1929 redefinition, a Btu was defined as the amount of heat necessary to raise the temperature of one pound of water by one degree Fahrenheit. Because of the difficulty in determining the exact value of a Btu, it was later redefined in terms of the more fundamental physical unit.

Relationship Between Heat and Work

Energy is the ability to do work or move against a resistance. Conversely, work is the overcoming of resistance through a certain distance by the expenditure of energy.

Work is measured by a standard unit called the *foot-pound,* which may be defined as the amount of work done in raising one

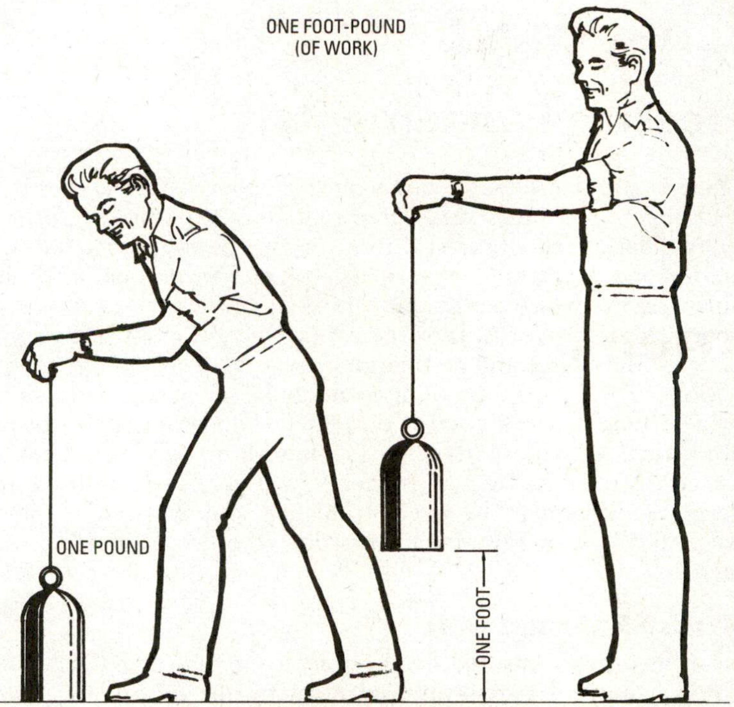

Figure 2-1 Man raising 1 pound 1 foot to illustrate the foot-pound standard unit.

pound the distance of one foot, or in overcoming a pressure of one pound through a distance of one foot (Figure 2-1).

The relationship between work and heat is referred to as the *mechanical equivalent of heat;* one unit of heat is equal to 778.26 ft-lb. This relationship (i.e., the mechanical equivalent of heat) was first established by experiments conducted in the nineteenth century. In 1843 Dr. James Prescott Joule (1818–1889) of Manchester, England, determined by numerous experiments that when 772 ft-lb of energy had been expended on 1 lb of water, the temperature of water had risen 1°F and the relationship between heat and mechanical work was found (Figure 2-2). The value 772 ft-lb is known as *Joule's equivalent.* More recent experiments give higher figures and the value 778 (1 Btu = 778.26 ft-lb). (See the preceding section.)

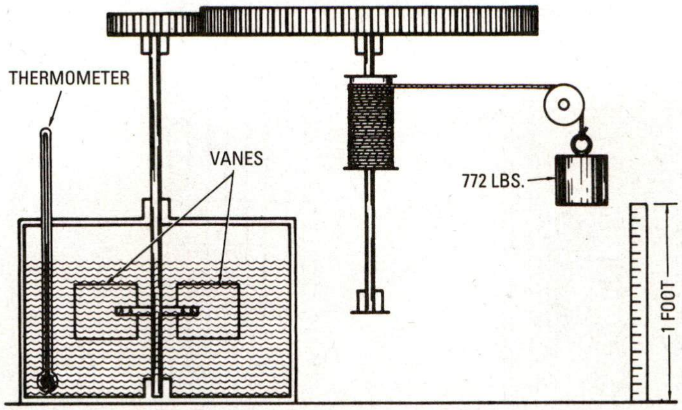

Figure 2-2 The mechanical equivalent of heat.

Heat Transfer

When bodies of unequal temperatures are placed near each other, heat leaves the hotter body and is absorbed by the colder one until the temperatures are equal to each other. The rate by which the heat is absorbed by the colder body is proportional to the difference of temperature between the two bodies—the greater the difference in temperature, the greater the rate of flow of the heat.

Heat is transferred from one body to another at lower temperature by any one of the following means (Figure 2-3):

1. Radiation
2. Conduction
3. Convection

Radiation, insofar as heat loss is concerned, refers to the throwing out of heat in rays. The heat rays proceed in straight lines, and the intensity of the heat radiated from any one source becomes less as the distance from the source increases.

The amount of heat loss from a body within a room or building through radiation depends upon the temperature of the floor, ceiling, and walls. The colder these surfaces are, the faster and greater will be the heat loss from a human body standing within the enclosure. If the wall, ceiling, and floor surfaces are *warmer* than the human body within the enclosure they form, heat will be radiated

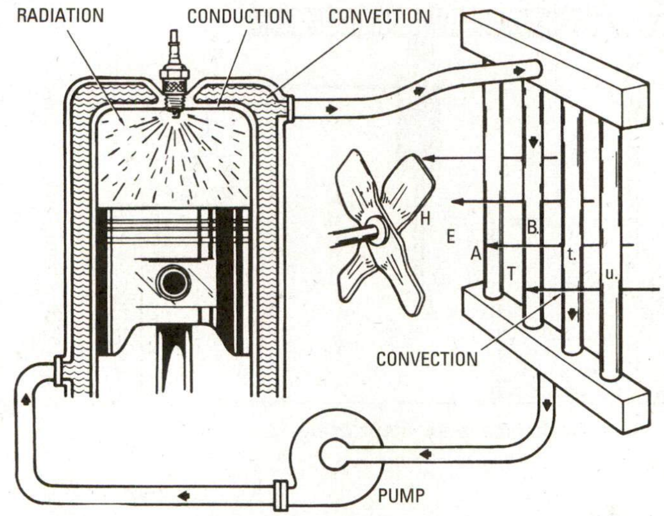

Figure 2-3 The transfer of heat by radiation, conduction, and convection.

from these surfaces to the body. In these situations a person may complain that the room is too hot.

Knowledge of the mean radiant temperature of the surfaces of an enclosure is important when dealing with heat loss by radiation. The *mean radiant temperature* (MRT) is the weighted average temperature of the floor, ceiling, and walls. The significance of the mean radiant temperature is determined when compared with the clothed body of an adult (80°F, or 26.7°C). If the MRT is below 80°F, the human body will lose heat by radiation to the surfaces of the enclosure. If the MRT is higher than 80°F, the opposite effect will occur.

Conduction is the transfer of heat through substances, for instance, from a boiler plate to another substance in contact with it (Figure 2-4). Conductivity may be defined as the relative value of a material, compared with a standard, in affording a passage through itself or over its surface for heat. A poor conductor is usually referred to as a *nonconductor* or *insulator.* Copper is an example of a good conductor. Figure 2-5 illustrates the comparative heat conductivity rates of three frequently used metals. The various materials used to insulate buildings are poor conductors. It should be

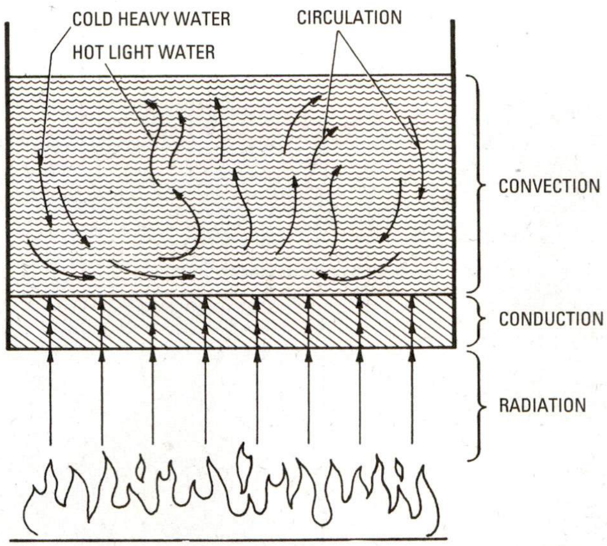

Figure 2-4 Radiation, conduction, and convection in boiler operation.

pointed out that any substance that is a good conductor of electricity is also a good conductor of heat.

Convection is the transfer of heat by the motion of the heated matter itself. Because motion is a required aspect of the definition of convection, it can take place only in liquids and gases.

Figure 2-4 illustrates how radiation, conduction, and convection are often interrelated. Heat from the burning fuel passes to the metal of the heating surface by radiation, passes through the metal by conduction, and is transferred to the water by convection (i.e., circulation). Circulation is caused by a variation in the weight of the water due to temperature differences. That is, the water next to the heating surface receives heat, expands (becomes lighter), and immediately rises as a result of displacement by the colder and heavier water above.

Proper circulation is very important, because its absence will cause a liquid, such as water, to reach the spheroidal state. This, in turn, causes the metal of the boiler to become dangerously overheated. A liquid that has reached the spheroidal state is easy to recognize by its appearance. When liquid is dropped upon the surface of a highly heated metal, it rolls about in spheroidal drops

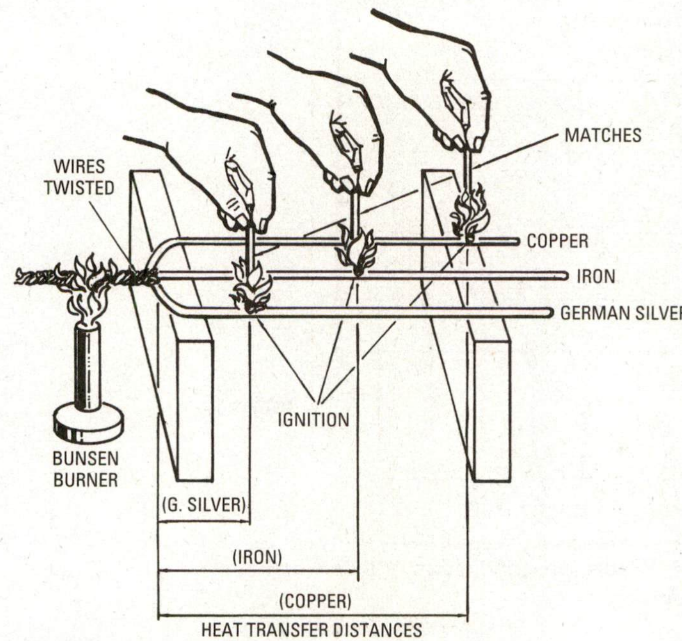

Figure 2-5 Conductivities of various metals.

(Figure 2-6) or masses without actual contact with the heated metal. This phenomenon is caused by the repelling force of heat and the intervention of a cushion of steam.

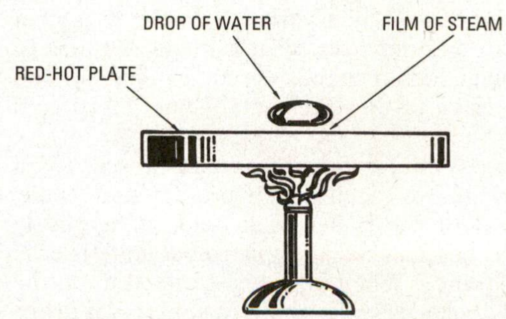

Figure 2-6 Drop of water on a hot plate illustrating the spheroidal state.

Specific, Sensible, and Latent Heat

The *specific heat* of a substance is the ratio of the quantity of heat required to raise its temperature one degree Fahrenheit to the amount required to raise the temperature of the same weight of water one degree Fahrenheit (Figure 2-7). This may be expressed in the following formula:

$$\text{Specific heat} = \frac{\text{Btu to raise temp. of substance 1°F}}{\text{Btu to raise temp. of same weight water 1°F}}$$

The standard used in water at approximately 62 to 63°F receives a rating of 1.00 on the specific heat scale. Simply stated, specific heat represents the Btu required to raise the temperature of one pound of a substance one degree Fahrenheit.

Sensible heat is the part of heat that provides temperature change and that can be measured by a thermometer. It is referred to as such because it can be sensed by instruments or touch.

Latent heat is the quantity of heat that disappears or becomes concealed in a body while producing some change in it other than a rise of temperature. Changing a liquid to a gas and a gas to a liquid are both activities involving latent heat. The two types of latent heat are:

1. Internal latent heat
2. External latent heat

These are explained in detail in the next section under *Steam*.

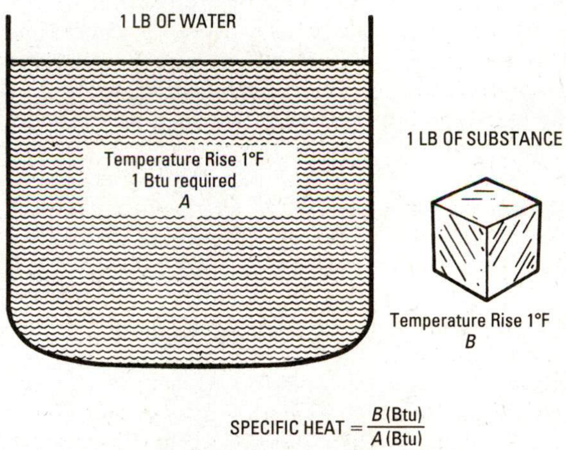

Figure 2-7 The principle of specific heat.

Heat-Conveying Mediums

As mentioned in Chapter 1, several methods are used to classify heating systems. One method is based on the medium that conveys the heat from its source to the point being heated. When the majority of heating systems in use today are examined closely, it can be seen that there are only four basic heat-conveying mediums involved:

1. Air
2. Steam
3. Water
4. Electricity

Air

Air is a gas consisting of a mechanical mixture of 23.2% oxygen (by weight), 75.5% nitrogen, and 1.3% argon with small amounts of other gases. It functions as the heat-conveying medium for warm-air heating systems.

Atmospheric pressure may be defined as the force exerted by the weight of the atmosphere in every point with which it is in contact (Figure 2-8), and is measured in inches of mercury or the corresponding pressure in pounds per square-inch (psi).

The pressure of the atmosphere is approximately 14.7 psi at sea level. The standard atmosphere is 29.921 inches of mercury (in Hg) at 14.696 psi. "Inches of mercury" refers to the height to which the column of mercury in a barometer will remain suspended to balance the pressure caused by the weight of the atmosphere.

Atmospheric pressure varies due to elevation by decreasing approximately ½ lb for every 1000 ft ascent above sea level. Atmospheric pressure in pounds per square-inch is obtained from a barometer reading by multiplying the barometer reading in inches by 0.49116. Examples are given in Table 2-1.

Gauge pressure is pressure whose scale starts at atmospheric pressure. *Absolute pressure,* on the other hand, is pressure measured from true zero or the point of no pressure. When the hand of a steam gauge is at zero, the absolute pressure existing in the boiler is approximately 14.7 psi. Thus, by way of example, 5 lb pressure measured by a steam gauge (i.e., gauge pressure) is equal to 5 lb plus 14.7 lb, or 19.7 psi of absolute pressure.

When air is compressed, both its pressure and temperature are changed in accordance with Boyle's and Charles' laws. According to Robert Boyle (1627–1691), the English philosopher and founder of

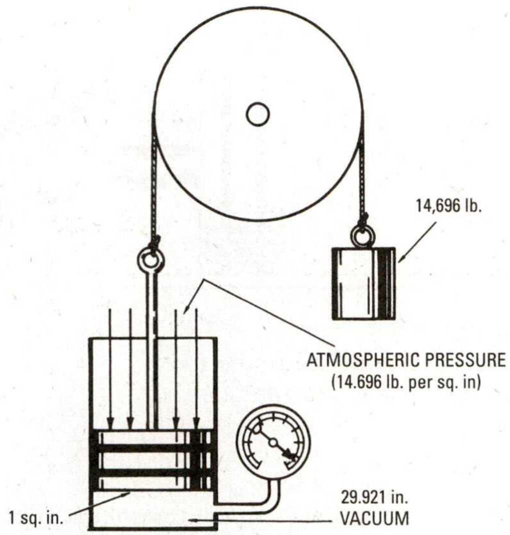

Figure 2-8 Atmospheric pressure.

modern chemistry, the absolute pressure of a gas at constant temperature varies inversely as its volume. Jacques Charles (1746–1823) established that the volume of a gas is proportional to its absolute temperature when the volume is kept at constant pressure.

Table 2-1 Atmospheric Pressure per Square-Inch for Various Barometer Readings

Barometer, in Hg	*Pressure, psi*	*Barometer, in Hg*	*Pressure, psi*
28.00	13.75	29.921	14.696
28.25	13.88	30.00	17.74
28.50	14.00	30.25	14.86
28.75	14.12	30.50	17.98
29.00	14.24	30.75	15.10
29.25	14.37	31.00	15.23
29.50	14.49		
29.75	14.61		

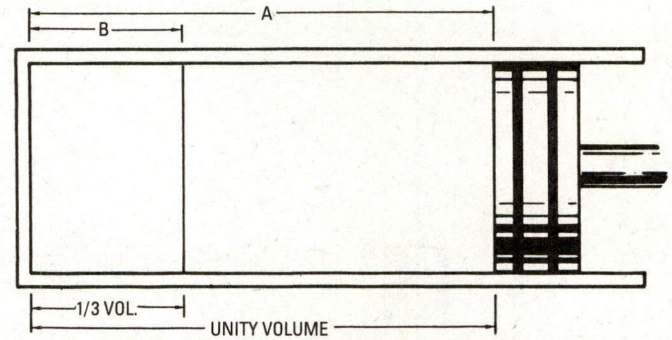

Figure 2-9 Elementary air compressor illustrating the phenomenon of compression as stated in Boyle's and Charles' laws.

If the cylinder in Figure 2-9 is filled with air at atmospheric pressure (14.7 psi absolute), represented by volume A, and the piston B moved to reduce the volume to, say, ⅓ A, as represented by B, then according to Boyle's law, the pressure will be tripled ($14.7 \times 3 = 44.1$ lb absolute, or $44.1 - 14.7 = 29.4$ gauge pressure). According to Charles' law, a pressure gauge on the cylinder would at this point indicate a *higher* pressure than 29.4 gauge pressure because of the increase in temperature produced by compressing the air. This is called *adiabatic compression* if no heat is lost or is received externally.

Steam

Those who design, install, or have charge of steam heating plants certainly should have some knowledge of steam and its formation and behavior under various conditions.

Steam is a colorless, expansive, and invisible gas resulting from the vaporization of water. The white cloud associated with steam is a fog of minute liquid particles formed by condensation, that is to say, finely divided condensation. This white cloud is caused by the exposure of the steam to a temperature lower than that corresponding to its pressure.

If the inside of a steam heating main were visible, it would be filled partway with a white cloud; in traversing the main, the little particles combine, forming drops of condensation too heavy to remain in suspension, which accordingly drop to the bottom of the main and drain off as condensation. This condensation flows into

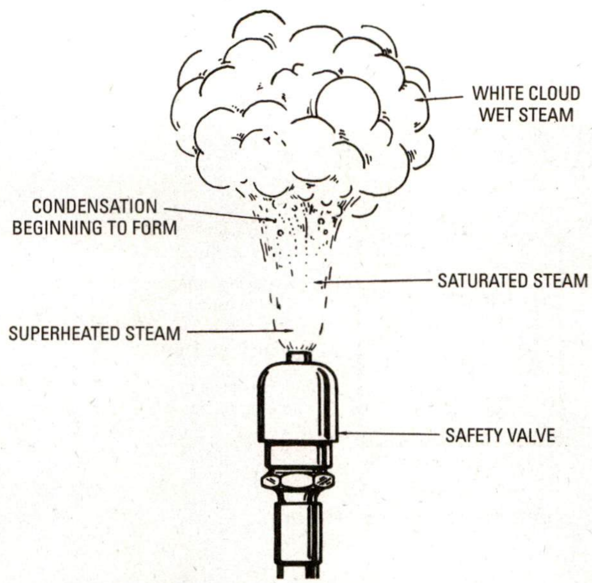

Figure 2-10 Three types of steam.

a drop leg of the system and finally back into the boiler, together with additional condensation draining from the radiators.

Although the word "steam" should be applied only to saturated gas, the five following classes of steam are recognized:

1. Saturated steam
2. Dry steam
3. Wet steam
4. Superheated steam
5. Highly superheated or gaseous steam

Three of these classes of steam (wet, saturated, and superheated) are shown in the illustration of a safety valve blowing in Figure 2-10. It should be pointed out that neither saturated steam nor superheated steam can be seen by the naked eye.

Saturated steam may be defined as steam of a temperature due to its pressure. Steam containing intermingled moisture, mist, or spray is referred to as *wet steam*. *Dry steam* is steam containing no

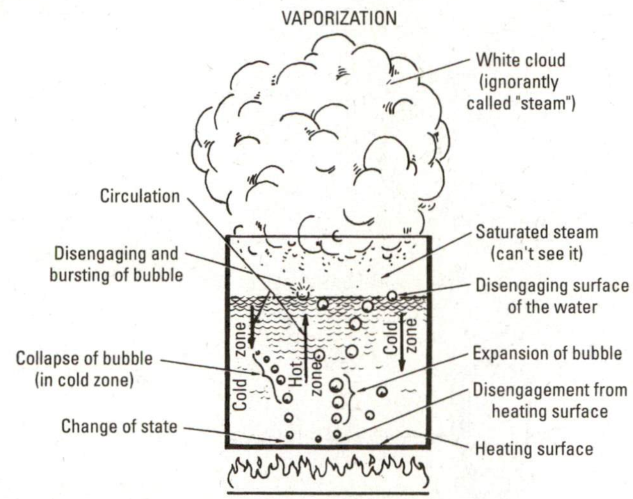

Figure 2-11 The phenomenon of vaporization.

moisture. It may be either saturated or superheated. Finally, *superheated steam* is steam having a temperature higher than that corresponding to its pressure.

The various changes that take place in the making of steam are known as *vaporization* and are shown in Figure 2-11. For the sake of illustration, only one bubble is shown in each receptacle. In actuality there is a continuous procession upward of a great multiplicity of bubbles.

The amount of heat necessary to cause the generation of steam is the sum of the sensible heat, the internal latent heat, and the external latent heat. As mentioned elsewhere in this chapter, sensible heat is the part of the heat that produces a rise in temperature as indicated by the thermometer. The *internal latent heat* is the amount of heat that water will absorb at the boiling point without a change in temperature—that is, before vaporization begins. *External latent heat* is the amount of heat required when vaporization begins to push back the atmosphere and make room for the steam.

Another important factor to consider when dealing with steam is the boiling point of liquids. By definition, the *boiling point* is the

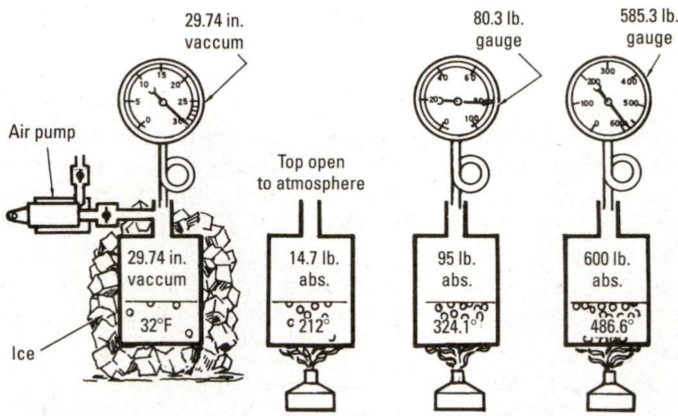

Figure 2.12 Variation of the boiling point when pressure changes.

temperature at which a liquid begins to boil (Figure 2-12), and it depends upon both the pressure and the nature of the liquid. For instance, water boils at 212°F, ether at 9°F, under atmospheric pressure of 14.7 psi.

The relationship between boiling point and pressure is such that there is a definite temperature or boiling point corresponding to each value of pressure. When vaporization occurs in a closed vessel and there is a temperature rise, the pressure will rise until the equilibrium between temperature and pressure is reestablished.

One's knowledge of the fundamentals of steam heating should also include an understanding of the role that condensation plays. By definition, *condensation* is the change of a substance from the gaseous to the liquid (or condensate) form. This change is caused by a reduction in temperature of the steam below that corresponding to its pressure.

The condensation of steam can cause certain problems for steam heating systems unless they are designed to allow for it. The water from which the steam was originally formed contained, mechanically mixed with it, 1⁄20, or 5 percent, of air by volume (at atmospheric pressure). This air is liberated during vaporization and does not recombine with the condensation. As a result, trouble is experienced in heating systems when one attempts to get the air out and keep it out. Suitable air valves are necessary to correct the problem.

Water

Water is a chemical compound of two gases, oxygen and hydrogen, in the proportion of two parts by weight of hydrogen to 16 parts by weight of oxygen, having mixed with it about 5 percent of air by volume at 14.7 lb absolute pressure. It may exist as ice, water, or steam due to changes in temperature (water freezes at 32°F and boils at 212°F when the barometer reads 29.921 in).

One cubic foot of water weighs 62.41 lb at 32°F and 59.82 lb at 212°F. One U.S. gallon of water (231 in^3) weighs 8.33111 lb (ordinarily expressed as 8⅓ lb) at a temperature of 62°F. At any other temperature, of course, the weight will be different (Table 2-2).

Table 2-2 Weight of Water per Cubic Foot at Different Temperatures

Temp., °F	*lb per ft^3*	*Temp., °F*	*lb per ft^3*	*Temp., °F*	*lb per ft^3*	*Temp., °F*	*lb per ft^3*
32	62.41	55	62.38	78	62.23	101	61.98
33	62.41	56	62.38	79	62.22	102	61.96
34	62.42	57	62.38	80	62.21	103	61.95
35	62.42	58	62.37	81	62.20	104	61.94
36	62.42	59	62.37	82	62.19	105	61.93
37	62.42	60	32.36	83	62.18	106	61.91
38	62.42	61	62.35	84	62.17	107	61.90
39	62.42	62	62.35	85	62.16	108	61.89
40	62.42	63	62.34	86	62.15	109	61.87
41	62.42	64	62.34	87	62.14	110	61.86
42	62.42	65	62.33	88	62.13	111	61.84
43	62.42	66	62.32	89	62.12	112	61.83
44	62.42	67	62.32	90	62.11	113	61.81
45	62.42	68	62.31	91	62.10	114	61.80
46	62.41	69	62.30	92	62.08	115	61.78
47	62.41	70	62.30	93	62.07	116	61.77
48	62.41	71	62.29	94	62.06	117	61.75
49	62.41	72	62.28	95	62.05	118	61.74
50	62.40	73	62.27	96	62.04	119	61.72
51	62.40	74	62.26	97	62.02	120	61.71
52	62.40	75	62.25	98	62.01	121	61.69
53	62.39	76	62.25	99	62.00	122	61.68
54	62.39	77	62.24	100	61.99	123	61.66

(continued)

Table 2-2 *(continued)*

Temp., °F	*lb per ft³*	*Temp., °F*	*lb per ft³*	*Temp., °F*	*lb per ft³*	*Temp., °F*	*lb per ft³*
124	61.64	160	60.99	196	60.21	380	54.47
125	61.63	161	60.97	197	60.19	390	54.05
126	61.61	162	60.95	198	60.16	400	53.62
127	61.60	163	60.93	199	60.14	410	53.19
128	61.58	164	60.91	200	60.11	420	52.74
129	61.56	165	60.89	201	60.09	430	52.33
130	61.55	166	60.87	202	60.07	440	51.87
131	61.53	167	60.85	203	60.04	450	51.28
132	61.51	168	60.83	204	60.02	460	51.02
133	61.50	169	60.81	205	59.99	470	50.51
134	61.48	170	60.79	206	59.97	480	50.00
135	61.46	171	60.77	207	59.95	490	49.50
136	61.44	172	60.75	208	59.92	500	48.78
137	61.43	173	60.73	209	59.90	510	48.31
138	61.41	174	60.71	210	59.87	520	47.62
139	61.39	175	60.68	211	59.85	530	46.95
140	61.37	176	60.66	212	59.82	540	46.30
141	61.36	177	60.64	214	59.81	550	45.66
142	61.34	178	60.62	216	59.77	560	44.84
143	61.32	179	60.60	218	59.70	570	44.05
144	61.30	180	60.57	220	59.67	580	43.29
145	61.28	181	60.55	230	59.42	590	42.37
146	61.26	182	60.53	240	59.17	600	41.49
147	61.25	183	60.51	250	58.89	610	40.49
148	61.23	184	60.49	260	58.62	620	39.37
149	61.21	185	60.46	270	58.34	630	38.31
150	61.19	186	60.44	280	58.04	640	37.17
151	61.17	187	60.42	290	57.74	650	35.97
152	61.15	188	60.40	300	57.41	660	34.48
153	61.13	189	60.37	310	57.08	670	32.89
154	61.11	190	60.35	320	56.75	680	31.06
155	61.09	191	60.33	330	56.40	690	28.82
156	61.07	192	60.30	340	56.02	700	25.38
157	61.05	193	60.28	350	55.65		
158	61.03	194	60.26	360	55.25		
159	61.01	195	60.23	370	54.85		

Water changes in weight with changes of temperature. That is, the higher the temperature of the water, the less it weighs. It is this property of water that causes circulation in boilers and in hot-water heating systems. The change in weight is due to expansion and a reduction in water volume. As the temperature rises, the water expands, resulting in a unit volume of water containing less water at higher temperature than lower temperature.

Fill a vessel with cold water and heat it to the boiling point. Note that boiling causes it to overflow due to expansion. Now let the water cool. You will note that when the water is cold, the vessel will not be as full because the water will have contracted.

The point of maximum density of water is 39.1°F. The most remarkable characteristic of water is its expansion below *and* above its point of maximum density. Imagine 1 lb of water at 39.1°F placed in a cylinder having a cross-sectional area of 1 in^2 (Figure 2-13). The water having a volume of 27.68 in^3 will fill the cylinder to a height of 27.68 in. If the water is cooled, it will expand, and at, say, 32°F (the freezing point) will rise in the tube to a height of 27.7 in before freezing. If the water is heated, it will also expand and rise in the tube; and at the boiling point (for atmospheric pressure 212°F) it will occupy the tube to a height of 28.88 in.

The elementary hot-water heating system in Figure 2-14 illustrates the principle of thermal circulation. The weight of the hot

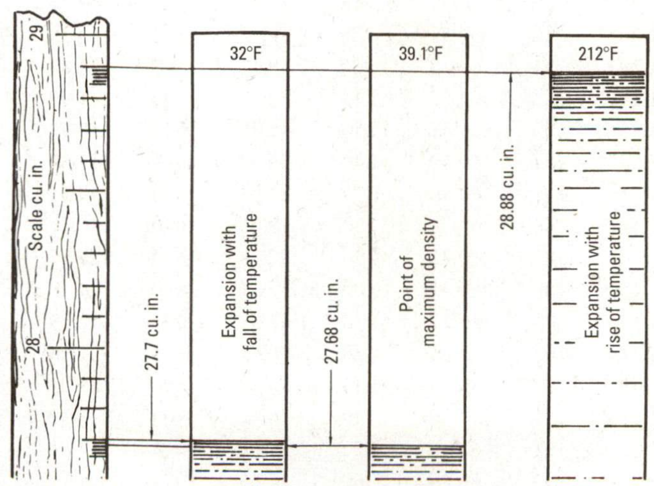

Figure 2-13 The point of maximum density.

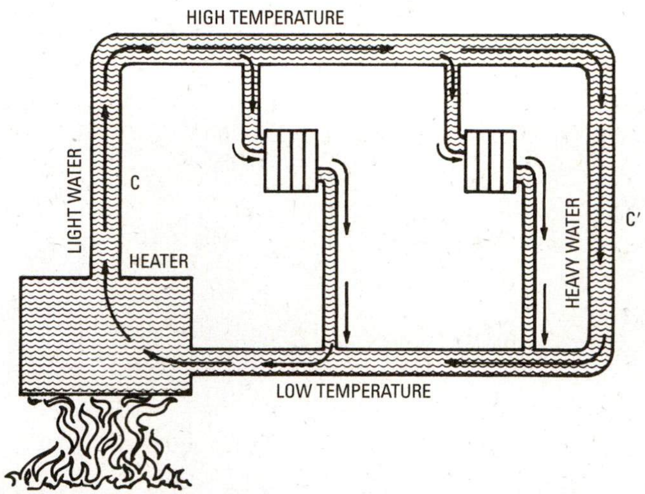

Figure 2-14 The principle of thermal circulation.

and expanded water in the upflow column C, being less than that of the cold and contracted water in the downflow column C′, upsets the equilibrium of the system and results in a continuous circulation of water as indicated by the arrows. In other words, the heavy, low-temperature water sinks to the lowest point in the boiler (or system) and displaces the light, high-temperature water, thus causing continuous circulation as long as there is a temperature difference in different parts of the boiler (or system). This is referred to as *thermal circulation.*

Electricity

Electricity differs from air, steam, or water in that it does not actually convey heat from one point to another; therefore, including it in a list of heat-conveying mediums can be misleading at first glance.

Electricity can best be defined as a quantity of electrons either in motion or in a state of rest. When these electrons are at rest, they are referred to as being *static* (hence the term *static electricity*). Electrons in *motion* move from one atom to another, creating an electrical current and thereby a medium for conveying *energy* from one point to another. Many different devices have been created to change the energy conveyed by an electric current into heat, light, and other forms of energy. Electric-fired furnaces and boilers are examples of devices used to produce heat.