

The physical significance of indicated quantities is illustrated further by the schematic diagram Fig. 2.

It should be emphasized that the thermal conductivity used should be expressed in consistent units; either using the inch or foot throughout.

Expressions of conductivity used in the heating field are usually inconsistent in this sense, in that it is customary to refer to the conductivity *per square foot* but for one inch of thickness. This custom has been adopted for the reason that wall thicknesses are usually expressed in inches, whereas if expressed in feet, decimal or fractional thicknesses would result. When dealing with flat walls no complication is involved in using the inconsistent expression of conductivity. However, when curved or spherical walls are considered, considerable complication is involved. Therefore, in this discussion the consistent units of conductivity expressed in *Btu per hour per square foot per degree Fahrenheit for one foot of thickness* are used throughout. Conductivity values obtained from Chapter 4 or Table 1 in this chapter, which are expressed in inconsistent units, must therefore be converted for use in the calculations of this

TABLE 1. APPROXIMATE UNIT THERMAL CONDUCTIVITIES OF MISCELLANEOUS MATERIALS<sup>a</sup>

| MATERIAL             | CONDUCTIVITY, $k$ BTU PER HOUR-PER SQ FT PER DEG F FOR ONE INCH THICKNESS |
|----------------------|---------------------------------------------------------------------------|
| Air.....             | 0.168                                                                     |
| Aluminum.....        | 1416.0                                                                    |
| Brass (70 - 30)..... | 720.0                                                                     |
| Cast-Iron.....       | 336.0                                                                     |
| Copper.....          | 2640.0                                                                    |
| Glass.....           | 3.6-7.32                                                                  |
| Lead.....            | 240.0                                                                     |
| Nickel.....          | 408.0                                                                     |
| Soil.....            | 2.4-12.0                                                                  |
| Steel, mild.....     | 312.0                                                                     |
| Water, liquid.....   | 4.08                                                                      |

<sup>a</sup>Thermal conductivities depend to some extent on temperature. The above magnitudes are approximate only. Refer to Heat Transmission, by W. H. McAdams (McGraw-Hill Co., 1942) for additional values.

chapter by dividing by 12. As an example, the conductivity of brick, expressed in inconsistent units as 5.0 in Table 3 of Chapter 4, becomes 0.42 when used in the calculations of this chapter. Also, it should be emphasized that in order to make the calculations and applications consistent in this chapter, *all dimensions of thickness must be expressed in feet.*

### Thermal Convection Equation

$$\frac{dq}{dA} = h_c (t_s - t_f) \quad (2)$$

This rate equation states that the thermal convection current per unit transfer area ( $dq/dA$ ), Btu per hour per square foot, is proportional to the temperature difference, ( $t_s - t_f$ ) which is the temperature of the surface less that of the fluid<sup>3</sup>. The proportionality factor is termed the *unit convection conductance* (sometimes called the film coefficient for convection),  $h_c$ , Btu per hour per square foot per degree Fahrenheit. These convection conditions are illustrated in Fig. 1.

<sup>3</sup>The particular fluid temperature to use for a given system will be noted under the discussion of that system.

The heat transmission by free or natural convection for objects surrounded by air can be conveniently expressed as in Equation 2a:

$$q_c = C \left( \frac{1}{D} \right)^{0.2} \left( \frac{1}{T_{av}} \right)^{0.181} (t_s - t_f)^{1.27} \quad (2a)$$

where

$q_c$  = heat transmission by convection, Btu per square foot per hour.

$C$  = a constant depending upon the surface shape.

$D$  = diameter of pipe or circular duct or height of vertical wall, inches. (Effect of diameter or height becomes constant at 24 in.)

$T_{av}$  = average of wall surface and surrounding air temperature, degrees Fahrenheit absolute.

$t_s - t_f$  = temperature excess between wall surface and surrounding air, degrees Fahrenheit.

For horizontal cylinders, the value of  $C = 1.016$  has been well established by various investigations. For vertical plates, the value of  $C = 1.394$  has been fairly well established. A value of  $C = 1.79$  for horizontal plates warmer than the surrounding air facing upward and 0.89 for

TABLE 2. HEAT TRANSMISSION BY FREE CONVECTION FOR LARGE VERTICAL SURFACES Expressed in Btu per square foot per hour

| TEMP<br>DEG<br>F | TEMPERATURE DIFFERENCE BETWEEN BODY AND SURROUNDING STILL AIR AT 80 F |     |      |      |      |      |      |      |      |      |      |      |       |       |
|------------------|-----------------------------------------------------------------------|-----|------|------|------|------|------|------|------|------|------|------|-------|-------|
|                  | 0                                                                     | 10  | 20   | 30   | 40   | 50   | 60   | 70   | 80   | 90   | 100  | 110  | 120   | 130   |
| 0                | 0                                                                     | 4.4 | 10.4 | 17.4 | 25.0 | 33.2 | 41.8 | 50.6 | 59.9 | 69.4 | 79.4 | 89.2 | 99.4  | 109.8 |
| 1                | 0.3                                                                   | 4.9 | 11.1 | 18.1 | 25.8 | 34.1 | 42.6 | 51.5 | 60.8 | 70.3 | 80.4 | 90.2 | 100.4 | 110.9 |
| 2                | 0.6                                                                   | 5.5 | 11.8 | 18.9 | 26.7 | 34.9 | 43.5 | 52.4 | 61.8 | 71.3 | 81.4 | 91.2 | 101.5 | 112.0 |
| 3                | 1.0                                                                   | 6.0 | 12.5 | 19.7 | 27.5 | 35.7 | 44.3 | 53.4 | 62.7 | 72.3 | 82.4 | 92.2 | 102.6 | 113.0 |
| 4                | 1.4                                                                   | 6.6 | 13.2 | 20.5 | 28.3 | 36.6 | 45.2 | 54.3 | 63.7 | 73.3 | 83.3 | 93.3 | 103.6 | 114.1 |
| 5                | 1.8                                                                   | 7.3 | 13.9 | 21.2 | 29.2 | 37.4 | 46.1 | 55.2 | 64.6 | 74.3 | 84.2 | 94.3 | 104.7 | 115.2 |
| 6                | 2.3                                                                   | 7.9 | 14.6 | 22.0 | 30.0 | 38.3 | 47.0 | 56.1 | 65.6 | 75.3 | 85.2 | 95.3 | 105.7 | 116.3 |
| 7                | 2.8                                                                   | 8.5 | 15.3 | 22.7 | 30.8 | 39.1 | 47.8 | 57.1 | 66.5 | 76.3 | 86.2 | 96.3 | 106.7 | 117.3 |
| 8                | 3.3                                                                   | 9.1 | 16.0 | 23.5 | 31.6 | 40.0 | 48.7 | 58.0 | 67.5 | 77.4 | 87.2 | 97.4 | 107.8 | 118.4 |
| 9                | 3.8                                                                   | 9.7 | 16.7 | 24.3 | 32.4 | 40.9 | 49.7 | 59.0 | 68.4 | 78.4 | 88.2 | 98.4 | 108.8 | 119.5 |

horizontal plates warmer than air facing downward is indicated by recent investigations<sup>4</sup>.

The heat transmission by free convection from vertical walls 24 in. or more in height is given in Table 2 as calculated from Equation 2a for ambient air temperature of 80 F. The values in Table 2 will not be changed appreciably by a considerable change in air temperature for a given temperature excess. For instance, a change in air temperature from 80 to 40 F will increase the heat transmission given in Table 2 by only 1.3 per cent.

Table 2 can also be used for calculating the free convection rate of transmission for various commercial shapes such as pipes and ducts. These calculations are simplified by the use of the factors in Tables 3 and 4. Table 3 gives factors by which the values in Table 2 must be multiplied to obtain the free convective transfer from various shapes whose characteristic dimensions are 24 in. or over, and Table 4 gives the factors to be used in conjunction with the factors in Table 3 for obtaining the free convection from Table 2 for pipes and ducts whose characteristic dimensions are less than 24 in.

<sup>4</sup>The Transmission of Heat by Radiation and Convection, by Griffith and Davis (Special Report No. 9, 1922, Department of Scientific and Industrial Research, His Majesty's Stationery Office, London, England).