Heat Transmission in Building Structures

Chapter 5

Basic Heat Transfer Modes

- Heat is transferred in buildings in the three known ways, which are conduction, convection and radiation

Thermal Conduction

It is a mechanism of heat transfer at the atomic level and it is given by the following equation:

$$\dot{q} = -kA \frac{dt}{dx} \tag{5-1}$$

where:

$\dot{q}$ = heat transfer rate, Btu/hr or W
k = thermal conductivity, Btu/(hr-ft-F) or W/(m-C)
A = area normal to heat flow, ft^2 or m^2
$\frac{dt}{dx}$ = temperature gradient, F/ft or C/m

Equation 5-1 incorporates a negative sign because $\dot{q}$ flows in the positive direction of x when $\frac{dt}{dx}$ is negative.

Flat wall case

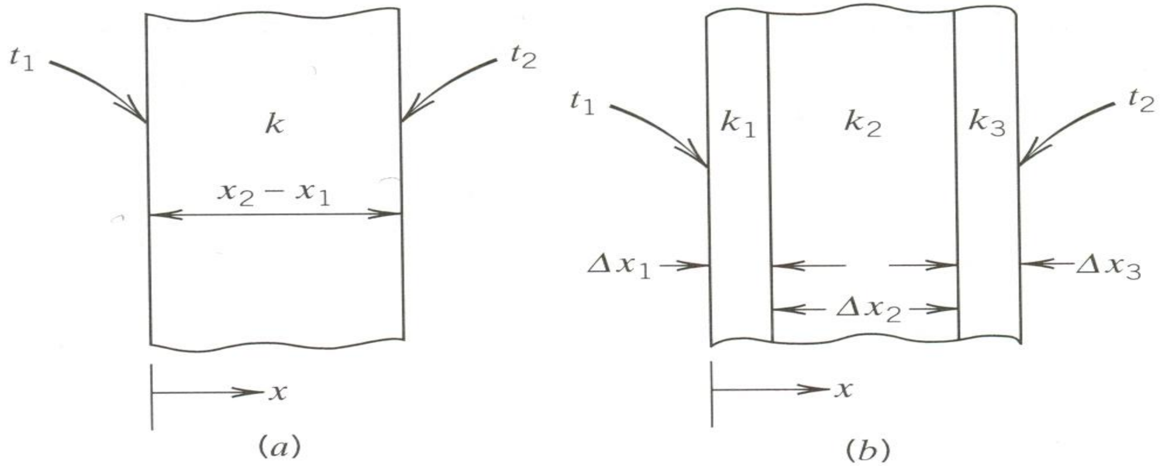


Figure 5-1 Nomenclature for conduction in plane walls.

$$\dot{q} = \frac{-kA(t_2 - t_1)}{x_2 - x_1} \tag{5-2a}$$

A very useful form of Eq. 5-2a is

$$\dot{q} = \frac{-(t_2 - t_1)}{R'} \tag{5-2b}$$

where R' is the thermal resistance defined by

$$R' = \frac{x_2 - x_1}{kA} = \frac{\Delta x}{kA} \tag{5-3a}$$

Thermal resistance R' is analogous to electrical resistance, and $\dot{q}$ and $(t_2 - t_1)$ are analogous to current and potential difference in Ohm's law. This analogy provides a very convenient method of analyzing a wall or slab made up of two or more layers of dissimilar material. Figure 5-1*b* shows a wall constructed of three different materials. The heat transferred by conduction is given by Eq. 5-2b, where the resistances are in series

$$R' = R_1' + R_2' + R_3' = \frac{\Delta x_1}{k_1 A} + \frac{\Delta x_2}{k_2 A} + \frac{\Delta x_3}{k_3 A} \tag{5-4}$$

Curved wall case

- The temperature gradient is assumed to be uniform and steady. The material is assumed to be homogeneous and have a constant value of thermal conductivity

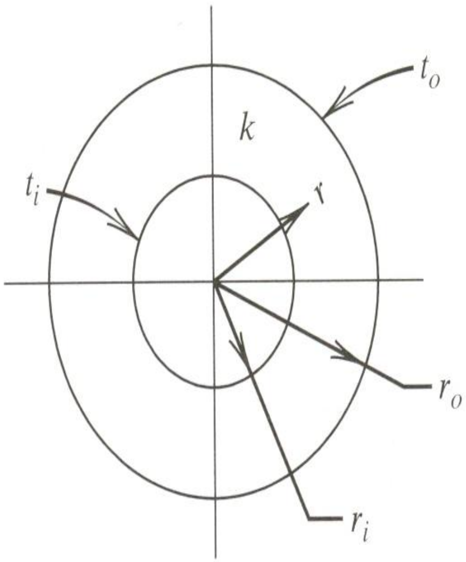


Figure 5-2 Radial heat flow in a hollow cylinde

$$\dot{q} = \frac{2\pi kL}{ln\left(\frac{r_0}{r_i}\right)}(t_i - t_0) \qquad (5\text{-}5)$$

where L is the length of the cylinder. Here the thermal resistance is

$$R' = \frac{ln\left(\frac{r_0}{r_i}\right)}{2\pi kL} \qquad (5\text{-}6)$$

- The thermal conductivity K, the density and the specific heat c_p are measured and given in tables for the sake of HVAC use. It is given in tables 5-1a and 5-1b.
- The thermal conductance C is also given in the tables

$$C = \frac{1}{R} = \frac{k}{\Delta x} \text{ Btu/(hr-ft}^2\text{-F) or W/(m}^2\text{-K)} \qquad (5\text{-}7)$$

Thermal Convection

- It is the transport of energy by mixing in addition to conduction and it is mainly happens in fluids through pips or ducts or a long surfaces.

$$\dot{q} = hA(t - t_w) \quad (5\text{-}8a)$$

where:

$\dot{q}$ = heat transfer rate from fluid to wall, Btu/hr or W
h = film coefficient, Btu/(hr-ft^2-F) or W/(m^2-C)
t = bulk temperature of the fluid, F or C
t_w = wall temperature, F or C

The film coefficient h is sometimes called the *unit surface conductance* or alternatively the *convective heat transfer coefficient*. Equation 5-8a may also be expressed in terms of thermal resistance:

$$\dot{q} = \frac{t - t_w}{R'} \tag{5-8b}$$

where

$$R' = \frac{1}{hA} \text{ (hr-ft)/Btu or C/W} \tag{5-9a}$$

so that

$$R = \frac{1}{h} = \frac{1}{C^*} \text{ (hr-ft}^2\text{-F)/Btu or (m}^2\text{-C)/W} \tag{5-9b}$$

- There are two types of convection:

Forced convection: when the bulk of the fluid is moving relative to the heat transfer surface. This motion is usually caused by blowers, fans or pumps. Most building structures have forced convection due to wind along outer walls or roofs.

Free convection: it happens when the flow is entirely due to buoyancy forces. It occurs inside narrow air spaces and on the inner walls.

Thermal Radiation

- it is the transfer of thermal energy by electromagnetic waves, and it can occur in a perfect vacuum.
- The direct net transfer of energy by radiation between two surfaces that see only each other and that are separated by a non-absorbing medium.

$$\dot{q}_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1}{A_1F_{12}} + \frac{1-\epsilon_2}{A_2\epsilon_2}} \qquad (5\text{-}10)$$

where:

σ = Boltzmann constant, 0.1713×10^{-8} Btu/(hr-ft^2-R^4) = 5.673×10^{-8} W/ (m^2-K^4)
T = absolute temperature, R or K
ϵ = emittance of surface 1 or surface 2
A = surface area, ft^2 or m^2
F = configuration factor, a function of geometry only (Chapter 6)

- It is assumed that both surfaces are gray, where the emittance € equals the absorptance α
- Figure 5-3 shows when the radiation is considered to be a significant factor

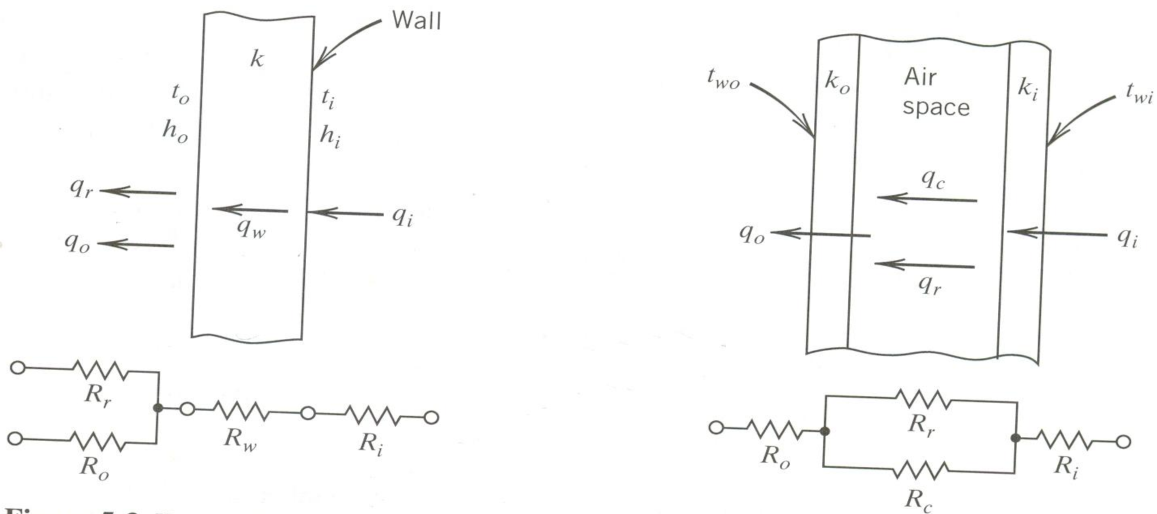


Figure 5-3 Wall and air space, illustrating thermal radiation effects.

the wall

$$\dot{q}_i = \dot{q}_w = \dot{q}_r = \dot{q}_o$$

and for the air space

$$\dot{q}_i = \dot{q}_r + \dot{q}_c = \dot{q}_o$$

The resistances can be combined to obtain an equivalent overall resistance R' with which the heat transfer rate can be computed using Eq. 5-2b:

$$\dot{q} = \frac{-(t_o - t_i)}{R'}$$

- Table 5-2a gives the surface film coefficient and unit thermal resistance as a function of wall position, direction of heat flow, air velocity and surface emittance for exposed surfaces such as outside walls.
- Table 5-2b gives representative values of emittance for some buildings and insulating materials
- Thermal radiation is a large factor when natural convection occurs.
- With higher air velocities the effect of radiation diminishes.
- Radiation is very important in the heat gains through ceiling spaces.
- Tables 5-3a and 5-3b give conductance and resistances for air spaces as a function of orientation

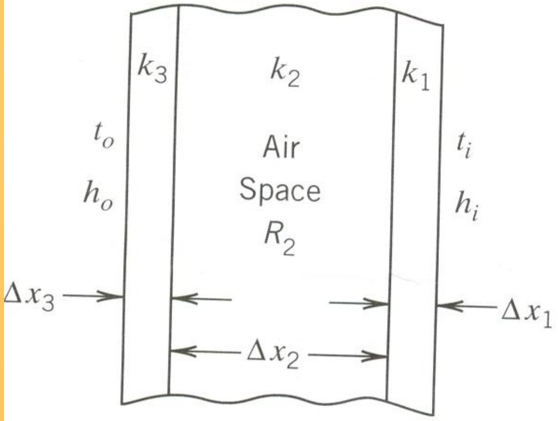


Figure 5-4 Wall with thermal resistances in series.

Each of the resistances may be expressed in terms of fundamental variables using Eqs. 5-3a and 5-9a:

$$R'_e = \frac{1}{h_i A_i} + \frac{\Delta x_1}{k_1 A_1} + \frac{R_2}{A_2} + \frac{\Delta x_3}{k_3 A_3} + \frac{1}{h_0 A_0} \tag{5-14}$$

The film coefficients may be read from Table 5-3*a*, the thermal conductivities from Tables 5-1*a* and 5-1*b*, and the thermal resistance for the air space from Tables 5-3*a* and 5-3*b*. For this case, a plane wall, the areas in Eq. 5-14 are all equal.

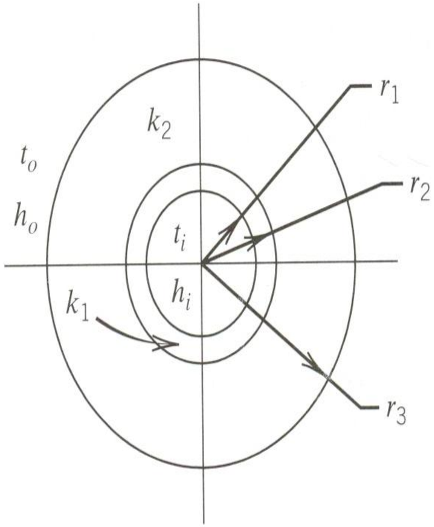


Figure 5-5 Insulated pipe in convective environment.

Unite resistance or conductance (equation 5-7) can be used
Only with appropriate area weighting factor when the area is not equal

Convection occurs on the inside and outside surfaces while heat is conducted through the pipe wall and insulation. The overall thermal resistance for the pipe of Fig. 5-5 is

$$R'_e = R'_o + R'_2 + R'_1 + R'_i \qquad (5\text{-}15)$$

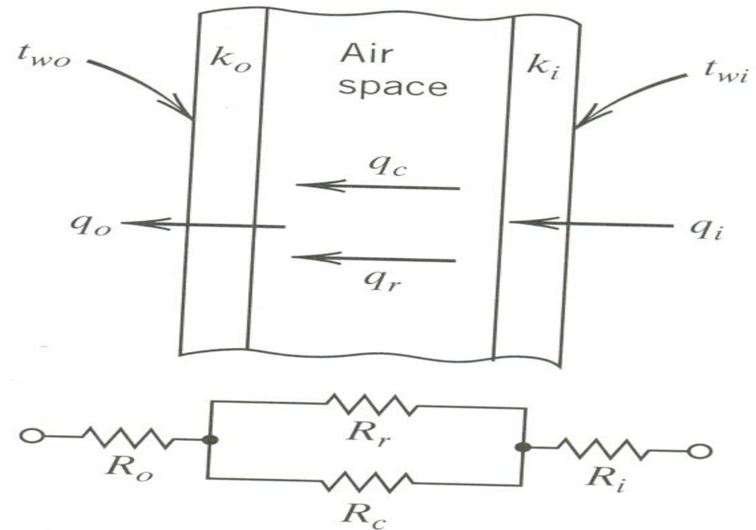
or, using Eqs. 5-6 and 5-9a,

$$R'_e = \frac{1}{h_o A_o} + \frac{In\left(\frac{r_3}{r_2}\right)}{2\pi k_2 L} + \frac{In\left(\frac{r_2}{r_1}\right)}{2\pi k_1 L} + \frac{1}{h_i A_i} \qquad (5\text{-}16)$$

Parallel thermal resistance

Thermal resistances may also occur in parallel. In theory the parallel resistances can be combined into an equivalent thermal resistance in the same way as electrical resistances:

$$\frac{1}{R'_e} = \frac{1}{R'_1} + \frac{1}{R'_2} + \frac{1}{R'_3} + \ldots + \frac{1}{R'_n} \qquad (5\text{-}17)$$



- When the ration of the larger to the smaller of the thermal resistance is less than about 5 equation 5-18 gives reasonable approximation of the equivalent thermal resistance.

$$U = \frac{1}{R'A} = \frac{1}{R} \text{ Btu/(hr-ft}^2\text{-F) or W/(m}^2\text{-C)} \tag{5-18}$$

The heat transfer rate in each component is then given by

$$\dot{q} = UA\Delta t \tag{5-19}$$

where:

UA = conductance, Btu/(hr-F) or W/C
A = surface area normal to flow, ft^2 or m^2
Δt = overall temperature difference, F or C

For a plane wall the area A is the same at any position through the wall. In dealing with nonplane or nonparallel walls, a particular area, such as the outside surface area, is selected for convenience of calculation. For example, in the problem of heat transfer through the ceiling–attic–roof combination, it is usually most convenient to use the ceiling area. The area selected is then used to determine the appropriate value of U for Eq. 5-19.

Thermal bridge

- A large variation in the thermal resistance of parallel conduction paths is called a thermal bridge
- A thermal bridge as in ASHREA is an envelope area with significantly higher rate of heat transfer than the contiguous enclosure.
- Example on that is a steel column in an insulated wall.
- Thermal bridges have two primary determintal effects: they increase heat gain or loss, and they cause condensation inside or on the envelope surface.
- These effects can be significant in the building's energy cost or damage done to the building structure by moisture.
- To overcome the effect of thermal bridging the following is suggested:

  a) use of lower-thermal-conductivity bridging material, b) changing the geometry or construction system, c) putting an insulating sheath around the bridge

Tabulated overall heat-transfer Coefficients Walls and Roofs

- Walls and roofs vary considerably in the materials from which they are constructed.

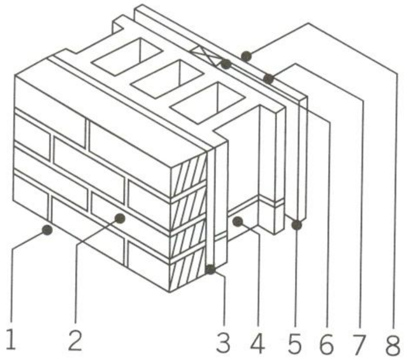
$$\dot{q} = UA\Delta t \quad (5\text{-}19)$$

where:

UA = conductance, Btu/(hr-F) or W/C
A = surface area normal to flow, ft^2 or m^2
Δt = overall temperature difference, F or C

$$R'_e = \frac{1}{h_i A_i} + \frac{\Delta x_1}{k_1 A_1} + \frac{R_2}{A_2} + \frac{\Delta x_3}{k_3 A_3} + \frac{1}{h_0 A_0} \quad (5\text{-}14)$$

Table 5-4a Coefficients of Transmission U of Masonry Cavity Walls, Btu/(hr-ft^2-F)[a]



Item	Resistance R (hr-ft^2-F)/Btu			
	Construction 1		Construction 2	
	Between Furring	At Furring	Between Furring	At Furring
1. Outside surface (15 mph wind)	0.17	0.17	0.17	0.17
2. Face brick, 4 in.	0.44	0.44	0.44	0.44
3. Cement mortar, 0.5 in.	0.10	0.10	0.10	0.10
4. Concrete block[b]	1.72	1.72	2.99	2.99
5. Reflective air space, 0.75 in. (50 F mean; 30 F temperature difference)	2.77	—	2.77	—
6. Nominal 1 × 3 in. vertical furring	—	0.94	—	0.94
7. Gypsum wallboard, 0.5 in., foil backed	0.45	0.45	0.45	0.45
8. Inside surface (still air)	0.68	0.68	0.68	0.68
Total thermal resistance R	$R_i = 6.33$	$R_s = 4.50$	$R_i = 7.60$	$R_s = 5.77$

Construction 1: $U_i = 1/6.33 = 0.158$; $U_s = 1/4.50 = 0.222$. With 20% framing (typical of 1 × 3 in. vertical furring on masonry @ 16 in. o.c.), $U_{av} = 0.8(0.158) + 0.2(0.222) = 0.171$

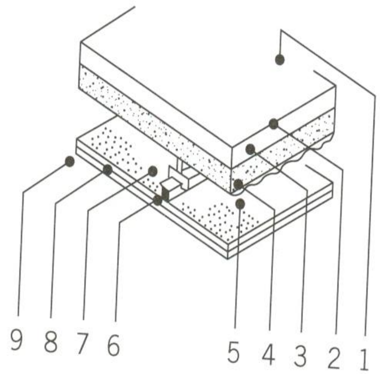
Construction 2: $U_i = 1/7.60 = 0.132 U_s = 1/5.77 = 0.173$.
With framing unchanged, $U_{av} = 0.8(0.132) + 0.2(0.173) = 0.140$

[a] U factor may be converted to W/(m^2-C) by multiplying by 5.68.

[b] 8 in. cinder aggregate in construction 1; 6 in. lightweight aggregate with cores filled in construction 2.

Source: Adapted by permission from *ASHRAE Handbook, Fundamentals Volume*, 1997.

Table 5-4*b* Coefficients of Transmission *U* of Flat Built-up Roofs[a]



Item	Resistance *R*: Construction 1	Resistance *R*: Construction 2
1. Outside surface (15 mph wind)	0.17	0.17
2. Built-up roofing, 0.375 in.	0.33	0.33
3. Rigid roof deck insulation[b]	—	4.17
4. Concrete slab, lightweight aggregate, 2 in.	2.22	2.22
5. Corrugated metal deck	0	0
6. Metal ceiling suspension system with metal hanger rods	0[c]	0[c]
7. Nonreflective air space, greater than 3.5 in. (50 F mean; 10 F temperature difference)	0.93[d]	0.93[d]
8. Metal lath and lightweight aggregate plaster, 0.75 in.	0.47	0.47
9. Inside surface (still air)	0.61	0.61
Total thermal resistance R	4.73	8.90

Construction 1: $U_{avg} = 1/4.73 = 0.211$ Btu/(hr-ft^2-F)[e]
Construction 2: $U_{avg} = 1/8.90 = 0.112$ Btu/(hr-ft^2-F)[e]

[a]Heat flowup. Use largest air space (3.5 in.) value shown in Table 5-3*a*.
[b]In construction 2 only.
[c]Area of hanger rods is negligible in relation to ceiling area.
[d]Use largest air space (3.5 in.) shown in Table 5-3*a*.
[e]*U*-factor may be converted to W/(m^2-C) by multiplying by 5.68.

The data given in Tables 5-4*a* and 5-4*b* and Examples 5-1 and 5-2 are based on

1. Steady-state heat transfer
2. Ideal construction methods
3. Surrounding surfaces at ambient air temperature
4. Variation of thermal conductivity with temperature negligible

Some caution should be exercised in applying calculated overall heat transfer coefficients such as those of Tables 5-4*a* and 5-4*b*, because the effects of poor workmanship and materials are not included. Although a safety factor is not usually applied, a moderate increase in U may be justified in some cases.

The overall heat-transfer coefficients obtained for walls and roofs should always be adjusted for thermal bridging, as shown in Tables 5-4*a* and 5-4*b*, using Eq. 5-18. This adjustment will normally be 5 to 15 percent of the unadjusted coefficient.

The coefficients of Tables 5-4*a* and 5-4*b* have all been computed for a 15 mph wind velocity on outside surfaces and should be adjusted for other velocities. The data of Table 5-2*a* may be used for this purpose.

The following example illustrates the calculation of an overall heat-transfer coefficient for an unvented roof–ceiling system.

Windows and Doors

- Tables 5-5a and 5-5b give the overall heat transfer coefficient. The values are for winter design conditions, but can be used in summer when corrected according to wind velocity using table 5-7.

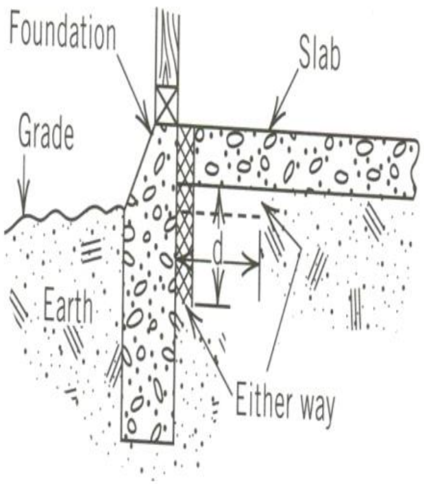
Concrete Floors and Walls below Grade

- The heat transfer through basement walls and floors depends on the temperature difference between the inside air and the ground, the wall or floor material (mainly concrete) and the conductivity of the ground.
- Tables 5-9 and 5-10 give reasonable results for load calculations but should not be used for annual or seasonal load estimates.
- Judgment must be used in selecting data for basement floors less than 5 ft (1.5 m) below grad.
- For slabs, it is reasonable to use slab on grad data, down to about 3 ft (90 cm).
- Heat losses from below grade walls and floors are dependent on the ground temperature near surface than on the deep ground temperature.
- Ground surface temperature vary about a mean value by an amplitude (Amp), which is a function of geographic location.
- The heat loss is given by equation 5-20

Floor Slabs at Grade Level

Analysis has shown that most of the heat loss is from the edge of a concrete floor slab. When compared with the total heat losses of the structure, this loss may not be significant; however, from the viewpoint of comfort the heat loss that lowers the floor temperature is important. Proper insulation around the perimenter of the slab is essential in severe climates to ensure a reasonably warm floor.

Figure 5-8 shows typical placement of edge insulation and heat loss factors for a floor slab. Location of the insulation in either the vertical or horizontal position has



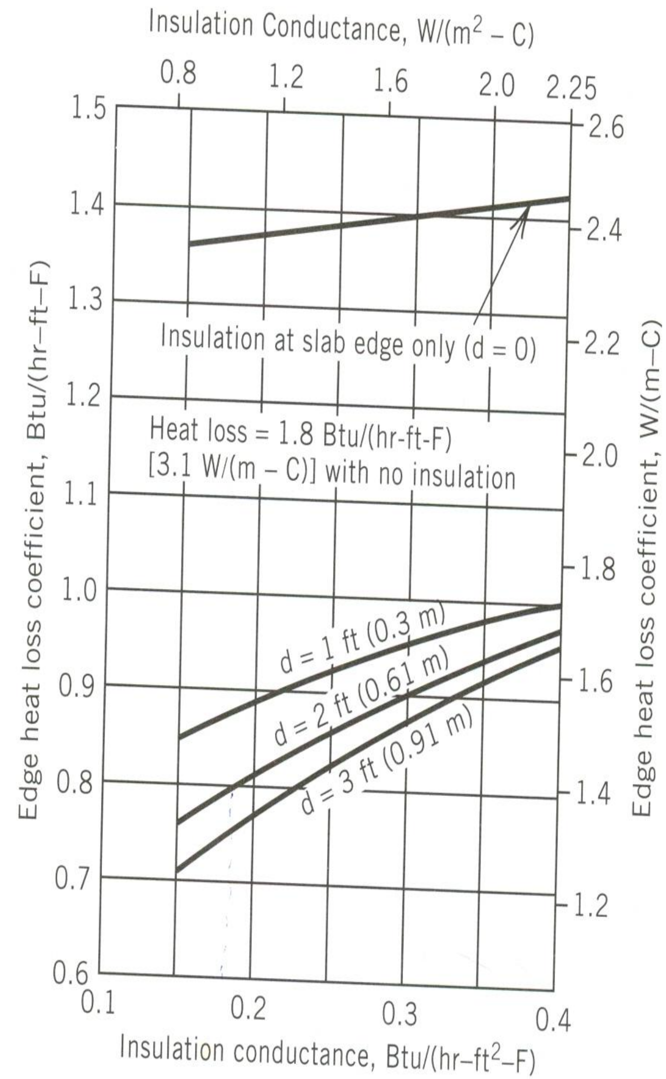


Figure 5-8 Heat loss factors for slab floors on grade. (Reprin *Handbook, Systems and Equipment Volume,* 2000.)

The heat loss from the slab is expressed as

$$\dot{q} = U'P(t_i - t_o) \tag{5-23}$$

where:

U' = heat loss coefficient, Btu/(hr-ft-F) or W/(m-C)
P = Perimeter of slab, ft or m
t_i = inside air temperature, F or C
t_o = outdoor design temperature, F or C

Moisture Transmission

- The moisture moves from a location where the concentration is high to lower concentration.
- Moisture transmission occurs in the form of vapor that condenses when comes in contact with a surface with temperature lower than its dew point.
- The movement and condensation of moisture can cause sever damage to the structure and may lead to mold formation, which can be toxic to residents.
- During winter the moisture is the greatest in the interior space.
- The moisture reduces the thermal resistance of the insulation. Freeze ups may occur and cause damage to the structure.
- During summer months, the moisture transfer process is from inside to outside.
- The transfer of moisture can be controlled through the use of barriers or retardants such as aluminum foil, thin plastic film and ventilation
- The moisture retarder should be near the warmest surface to prevent moisture from entering the insulation.
- The barrier is usually installed between the inside finish layer and the insulation.
- In summer the moisture can be controlled by natural ventilation.