CHAPTER 6

PANEL HEATING AND COOLING

PANEL heating and cooling uses controlled-temperature surfaces on the floor, walls, or ceiling; the temperature is maintained by circulating water, air, or electric current through a circuit embedded in the panel. A controlled-temperature surface is called a **radiant panel** if 50% or more of the heat transfer is by radiation to other surfaces seen by the panel. Radiant panel systems may be combined either with a central station air system of one-zone, constant temperature, constant volume design or with dual-duct, reheat, multizone or variable volume systems. These combined systems are called **hybrid HVAC systems**.

This chapter covers controlled-temperature surfaces that are the primary source of heating and cooling within the conditioned space. For snow-melting applications see Chapter 50 of the *ASHRAE Handbook—Applications*. Chapter 15 covers high-temperature surface radiant panels over 300°F energized by gas, electricity, or high-temperature water.

PRINCIPLES OF THERMAL RADIATION

Thermal radiation (1) is transmitted at the speed of light; (2) travels in straight lines and can be reflected; and (3) elevates the temperature of solid objects by absorption but does not noticeably heat the air through which it travels.

Thermal radiation is exchanged continuously between all bodies in a building environment. The rate at which radiant heat is transferred depends on the following factors:

- Temperature (of the emitting surface and receiver)
- Emittance (of the radiating surface)
- Reflectance, absorptance, and transmittance (of the receiver)
- View factor between the emitting surface and receiver (viewing angle of the occupant to the radiant source)

A critical factor is the structure of the body surface. In general, rough surfaces have low reflectance and high emittance/absorptance characteristics. Conversely, smooth or polished metal surfaces have high reflectance and low absorptance/emittance characteristics.

One example of radiant heating is the feeling of warmth when standing in the sun's rays on a cool, sunny day. Some of the rays come directly from the sun and include the entire electromagnetic spectrum. Other rays from the sun are absorbed by or reflected from surrounding objects. This generates secondary rays that are a combination of the wavelength produced by the temperature of the objects and the wavelength of the reflected rays. If a cloud passes in front of the sun, there is an instant sensation of cold. This sensation is caused by the decrease in radiant heat received from the sun, although there is little, if any, change in the ambient air temperature.

The preparation of this chapter is assigned to TC 6.5, Radiant Space Heating and Cooling.

Thermal comfort, as defined in ASHRAE *Standard* 55, is "that condition of mind which expresses satisfaction with the thermal environment." No system is completely satisfactory unless the three main factors controlling heat transfer from the human body (radiation, convection, and evaporation) result in thermal neutrality. Maintaining correct conditions for human comfort by radiant heat transfer is possible for even the most severe climatic conditions (Buckley 1989). Chapter 8 of the *ASHRAE Handbook—Fundamentals* has more information on thermal comfort.

Panel heating and cooling systems provide an acceptable thermal environment by controlling surface temperature in an occupied space, thus affecting the radiant heat transfer. With a properly designed system, a person should not be aware that the environment is being heated or cooled. The **mean radiant temperature (MRT)** has a strong influence on human comfort. When the temperature of the surfaces comprising the building (particularly outside walls with large amounts of glass) deviates excessively from the ambient temperature, convective systems sometimes have difficulty in counteracting the discomfort caused by cold or hot surfaces. Heating and cooling panels neutralize these deficiencies and minimize radiation losses or gains by the body.

Most building materials have surfaces with relatively high emittance factors and, therefore, absorb and reradiate radiant heat from active panels. Warm ceiling panels are effective because radiant heat is absorbed and reflected by the irradiated surfaces and not transmitted through the construction. Glass is opaque to the wavelengths emitted by active panels and, therefore, transmits little of the long-wave radiant heat to the outside. This is significant because all surfaces in the room tend to assume temperatures that result in an acceptable thermal comfort condition.

GENERAL EVALUATION

Principal **advantages** of radiant panel systems are the following:

- Comfort levels can be better than those of other conditioning systems because radiant loads are satisfied directly and air motion in the space is at normal ventilation levels.
- Space-conditioning equipment is not needed at the outside walls; this simplifies the wall, floor, and structural systems.
- Almost all mechanical equipment may be centrally located, simplifying maintenance and operation.
- No space within the conditioned room is required for mechanical equipment. This feature is especially valuable in hospital patient rooms and other applications where space is at a premium, where maximum cleanliness is essential, or where it is dictated by legal requirements.
- Draperies and curtains can be installed at the outside wall without interfering with the space-conditioning system.
- When four-pipe systems are used, cooling and heating can be simultaneous, without central zoning or seasonal changeover.
- Supply air quantities usually do not exceed those required for ventilation and dehumidification.

- The modular panel provides flexibility to meet changes in partitioning.
- A 100% outdoor air system may be installed with smaller penalties in terms of refrigeration load because of reduced air quantities.
- A common central air system can serve both the interior and perimeter zones.
- Wet surface cooling coils are eliminated from the occupied space, reducing the potential for septic contamination.
- The panel system can use the automatic sprinkler system piping (see NFPA *Standard* 13, Chapter 3, Section 3.6). The maximum water temperature must not fuse the heads.
- Radiant panel heating and cooling and minimum supply air quantities provide a draft-free environment.
- Noise associated with fan-coil or induction units is eliminated.
- Peak loads are reduced as a result of thermal energy storage in the panel structure, exposed walls, and partitions.
- Panels can be coupled with other conditioning systems for heat loss (gain) compensation for cold or hot floors, windows, etc.

Disadvantages are similar to those listed in Chapter 3 of the *ASHRAE Handbook—Fundamentals*. In addition:

- Response time can be slow if controls and/or heating elements are not selected or installed correctly
- Improper installation of pipe or element spacing and/or incorrect sizing of heat source can cause nonuniform surface temperatures or insufficient heating capacity

HEAT TRANSFER BY PANEL SURFACES

A heated or cooled panel transfers heat to or from a room by radiation and natural convection.

Radiation Transfer

The basic equation for a multisurface enclosure with gray, diffuse isothermal surfaces is derived by radiosity formulation methods (Chapter 3 of the *ASHRAE Handbook—Fundamentals*). This equation may be written as

$$q_r = J_p - \sum_{j=1}^{n} F_{pj} J_j \tag{1}$$

where

q_r = net radiation heat transferred by panel surface, Btu/h·ft²
J_p = total radiosity that leaves panel surface, Btu/h·ft²
J_j = radiosity from another surface in room, Btu/h·ft²
F_{pj} = radiation angle factor between panel surface and another surface in room (dimensionless)
n = number of surfaces in room other than panel

Equation (1) can be applied to simple and complex enclosures with varying surface temperatures and emittances. The net radiation transferred by the panels can be found by determining unknown J_j if the number of surfaces is small. More complex enclosures require computer calculations.

Radiation angle factors can be evaluated using Figure 6 in Chapter 3 of the *ASHRAE Handbook—Fundamentals*. Fanger (1972) shows room-related angle factors; they may also be developed from algorithms in ASHRAE's *Energy Calculations* 1 (1976).

Several methods have been developed to simplify Equation (1) by reducing a multisurface enclosure to a two-surface approximation. In the **MRT method**, the radiant interchange in a room is modeled by assuming that the surfaces radiate to a fictitious surface that has an area emittance and temperature giving about the same heat transfer as the real multisurface case (Walton 1980). In addition, angle factors do not need to be determined in the evaluation of a two-surface enclosure. The MRT equation may be written as

$$q_r = \sigma F_r [T_p^4 - T_r^4] \tag{2}$$

where

σ = Stefan-Boltzmann constant = 0.1713×10^{-8} Btu/h·ft²·°R⁴
F_r = radiation exchange factor (dimensionless)
T_p = effective temperature of heated (cooled) panel surface, °R
T_r = temperature of fictitious surface (unheated or uncooled), °R

The temperature of the fictitious surface is given by an area emittance weighted average of all surfaces other than the panel:

$$T_r = \frac{\sum_{j \neq p}^{n} A_j \varepsilon_j T_j}{\sum_{j \neq p}^{n} A_j \varepsilon_j} \tag{3}$$

where

A_j = area of surfaces other than panel
ε_j = thermal emittance other than panel (dimensionless)

When the emittances of an enclosure are nearly equal, and surfaces exposed to the panel are marginally unheated (uncooled), then Equation (3) becomes the area-weighted average temperature (AUST) of unheated (uncooled) surfaces exposed to the panels.

The radiation interchange factor for two-surface radiation heat exchange is given by the Hottel equation:

$$F_r = \frac{1}{\frac{1}{F_{p-r}} + \left(\frac{1}{\varepsilon_p} - 1\right) + \frac{A_p}{A_r}\left(\frac{1}{\varepsilon_r} - 1\right)} \tag{4}$$

where

F_{p-r} = radiation angle factor from panel to fictitious surface (1.0 for flat panel)
A_p, A_r = area of panel surface and fictitious surface, respectively
ε_p, ε_r = thermal emittance of panel surface and fictitious surface, respectively (dimensionless)

In practice, the thermal emittance ε_p of nonmetallic or painted metal nonreflecting surfaces is about 0.9. When this emittance is used in Equation (4), the radiation exchange factor F_r is about 0.87 for most rooms. Substituting this value in Equation (2), σF_r becomes about 0.15×10^{-8}. Min et al. (1956) showed that this constant was 0.152×10^{-8} in their test room. The radiation equation for heating or cooling becomes

$$q_r = 0.15 \times 10^{-8}[(t_p + 460)^4 - (\text{AUST} + 460)^4] \tag{5}$$

where

t_p = effective panel surface temperature, °F
AUST = area-weighted average temperature of uncontrolled surfaces in room, °F

Equation (5) establishes the general sign convention for this chapter, which states that heating by the panel is positive and cooling by the panel is negative.

Radiation exchange calculated from Equation (5) is given in Figure 1. The values apply to ceiling, floor, or wall panel output. Radiation removed by a cooling panel for a range of normally encountered temperatures is given in Figure 2.

In many specific instances where normal multistory commercial construction and fluorescent lighting are used, the room temperature at the 5 ft level closely approaches the average uncooled surface temperature (AUST). In structures where the main heat gain is through the walls or where incandescent lighting is used, the wall

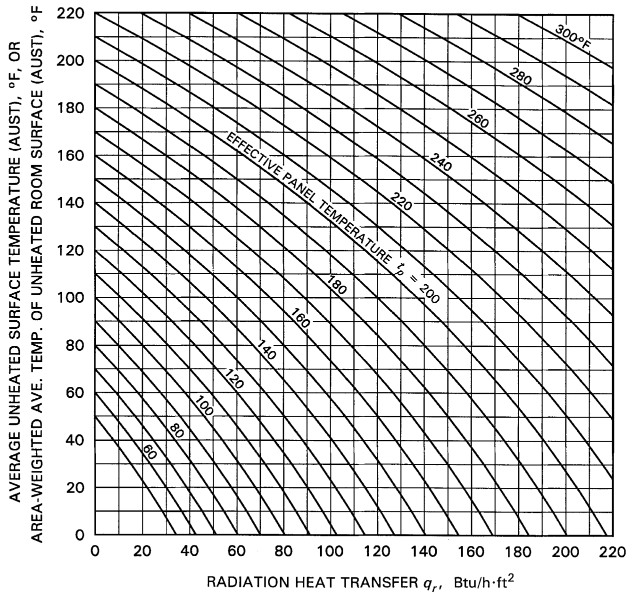


Fig. 1 Radiation Heat Transfer from Heated Ceiling, Floor, or Wall Panel

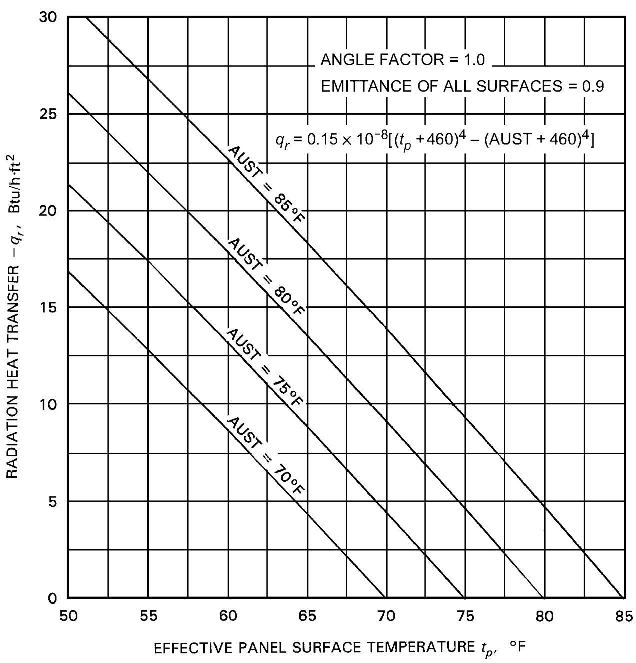


Fig. 2 Heat Removed by Radiation to Cooled Ceiling or Wall Panel

surface temperatures tend to rise considerably above the room air temperature.

Convection Transfer

The convection coefficient q_c is defined as the heat transferred by convection between the air and the panel. Heat transfer convection values are not easily established. Convection in panel systems is usually natural; that is, air motion is generated by the warming or cooling of the boundary layer of air. In practice, however, many factors, such as a room's configuration, interfere with or affect natural convection. Infiltration, the movement of persons, and mechanical ventilating systems can introduce some forced convection that disturbs the natural process.

Parmelee and Huebscher (1947) included the effect of forced convection on heat transfer from panels as an increment to be added to the natural convection coefficient. However, increased heat transfer from forced convection should not be used because the increments are unpredictable in pattern and performance, and forced convection does not significantly increase the total capacity of the panel system.

Convection in a panel system is a function of the panel surface temperature and the temperature of the airstream layer directly below the panel. The most consistent measurements are obtained when the air layer temperature is measured close to the region where the fully developed stream begins, usually 2 to 2.5 in. below the panels.

Min et al. (1956) determined natural convection coefficients 5 ft above the floor in the center of a 12 ft by 24.5 ft room (D_e = 16.1 ft). Equations (6) through (11), derived from this research, can be used to calculate heat transfer from panels by natural convection.

Natural convection from an all-heated ceiling

$$q_c = 0.041\frac{(t_p - t_a)^{1.25}}{D_e^{0.25}} \tag{6}$$

Natural convection from a heated floor or cooled ceiling

$$q_c = 0.39\frac{|t_p - t_a|^{0.31}(t_p - t_a)}{D_e^{0.08}} \tag{7}$$

Natural convection from a heated or cooled wall panel

$$q_c = 0.29\frac{|t_p - t_a|^{0.32}(t_p - t_a)}{H^{0.05}} \tag{8}$$

where

q_c = heat transfer by natural convection, Btu/h·ft²
t_p = effective temperature of panel surface, °F
t_a = temperature of air, °F
D_e = equivalent diameter of panel (4 × area/perimeter), ft
H = height of wall panel, ft

Schutrum and Humphreys (1954) measured panel performance in furnished test rooms that did not have uniform panel surface temperatures and found no variation in performance large enough to be significant in heating practice. Schutrum and Vouris (1954) established that the effect of room size was usually insignificant except for very large spaces like hangars and warehouses. In these cases Equations (6) and (7) should be used. Otherwise, Equations (6), (7), and (8) can be simplified to the following by D_e = 16.1 ft and H = 8.85 ft:

Natural convection from an all-heated ceiling

$$q_c = 0.020(t_p - t_a)^{0.25}(t_p - t_a) \tag{9a}$$

Natural convection from a heated ceiling may be enhanced by leaving cold strips (unheated ceiling sections) between ceiling panels. These strips help initiate the natural convection. In this case, Equation (9a) may be replaced by Equation (9b) (Kollmar and Liese 1957):

$$q_c = 0.13(t_p - t_a)^{0.25}(t_p - t_a) \tag{9b}$$

For large spaces such as aircraft hangars where panels are side by side, Equation (9b) should be adjusted with the multiplier $(16.1/D_e)^{0.25}$.

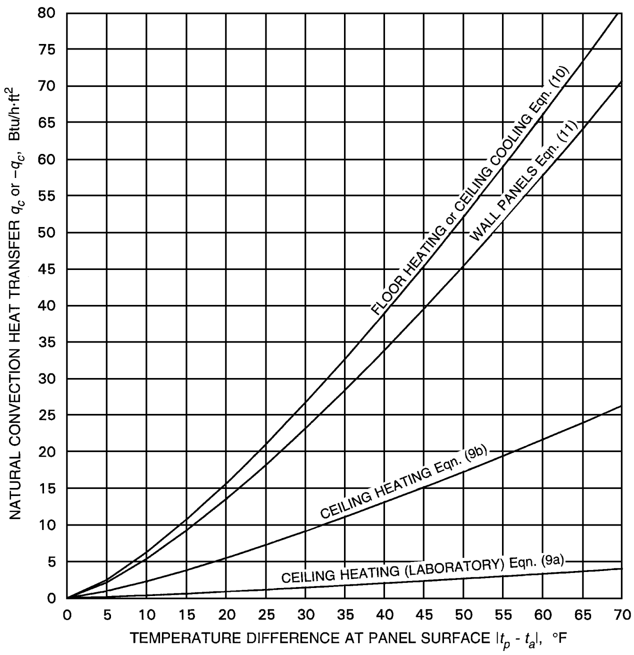


Fig. 3 Natural-Convection Heat Transfer at Floor, Ceiling, and Wall Panel Surfaces [Equations (9a), (9b), (10), and (11)]

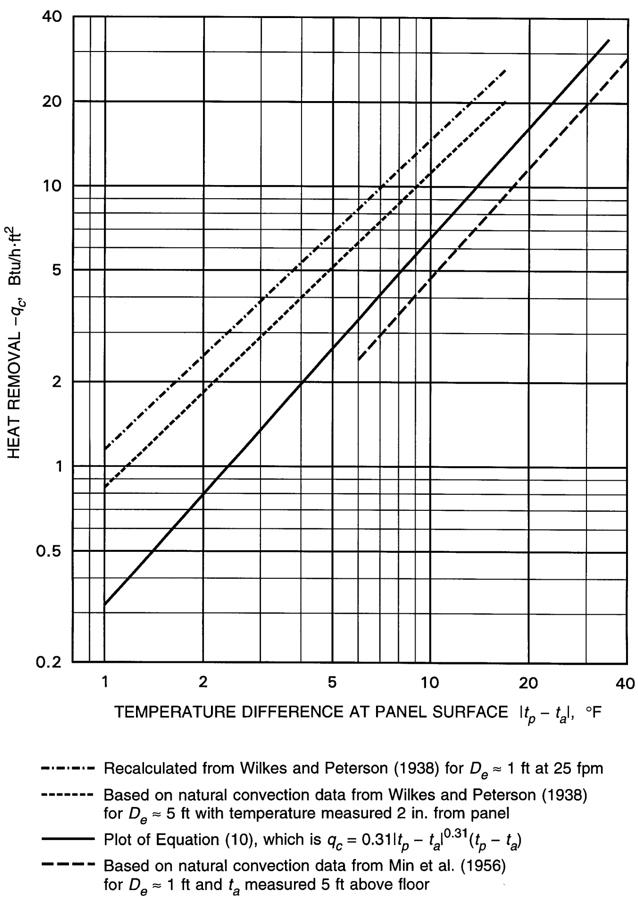


Fig. 4 Heat Removal by Ceiling Cooling Panels with Natural Convection [Equation (10)]

Natural convection from a heated floor or cooled ceiling

$$q_c = 0.31|t_p - t_a|^{0.31}(t_p - t_a) \quad (10)$$

Natural convection from a heated or cooled wall panel

$$q_c = 0.26|t_p - t_a|^{0.32}(t_p - t_a) \quad (11)$$

There are no confirmed data for floor cooling, but Equation (9b) may be used for approximate calculations. Under normal conditions t_a is the indoor air design temperature. In floor-heated or ceiling-cooled spaces with large proportions of exposed fenestration, t_a may be taken as equal to AUST.

In cooling, t_p is less than t_a, so q_c is negative. Figure 3 shows heat transfer by natural convection at floor, wall, and ceiling heating panels as calculated from Equations (10), (11), (9a), and (9b), respectively.

Figure 4 compares heat removal by natural convection at cooled ceiling panel surfaces, as calculated by Equation (10), with data from Wilkes and Peterson (1938) for specific panel sizes. An additional curve illustrates the effect of forced convection on the latter data. Similar adjustment of the data from Min et al. (1956) is inappropriate, but the effects would be much the same.

Combined Heat Transfer (Radiation and Convection)

The combined heat transfer from a panel surface can be determined by adding the radiant heat transfer q_r as calculated by Equation (5) (or from Figure 1 and Figure 2) to the convective heat transfer q_c as calculated from Equations (9a), (9b), (10), or (11) or from Figure 3 or Figure 4, as appropriate.

Equation (5) requires the AUST for the room. In calculating the AUST, the surface temperature of interior wall is assumed to be the same as the room air temperature. The inside surface temperature t_w of outside walls and exposed floors or ceilings can be calculated from the following heat transfer relationship:

$$h(t_a - t_u) = U(t_a - t_o) \quad (12)$$

or

$$t_u = t_a - \frac{U}{h}(t_a - t_o) \quad (13)$$

where

h = inside surface conductance of exposed wall or ceiling
U = overall wall heat transfer coefficient of wall, ceiling, or floor, Btu/h·ft²·°F
t_a = room air temperature, °F
t_u = inside surface temperature of outside wall, °F
t_o = outside air temperature, °F

From Table 1 in Chapter 25 of the *ASHRAE Handbook—Fundamentals*:

h = 1.63 Btu/h·ft²·°F for a horizontal surface with heat flow up
h = 1.46 Btu/h·ft²·°F for a vertical surface (wall)
h = 1.08 Btu/h·ft²·°F for a horizontal surface with heat flow down

Figure 5 is a plot of Equation (13) for a vertical outdoor wall with 70°F room air temperature and h = 1.46 Btu/h·ft²·°F. For rooms with temperatures above or below 70°F, the values in Figure 5 can be corrected by the factors plotted in Figure 6.

Tests by Schutrum et al. (1953a, 1953b) and simulations by Kalisperis (1985) based on a program developed by Kalisperis and Summers (1985) show that the AUST and room temperature are almost equal, if there is little or no outdoor exposure. Steinman et al. (1989) noted that this argument may not be appropriate for enclosures with large glass areas or a high percentage of outside wall and/or ceiling surface area. These cold surfaces have a lower AUST, which increases the radiant heat transfer.

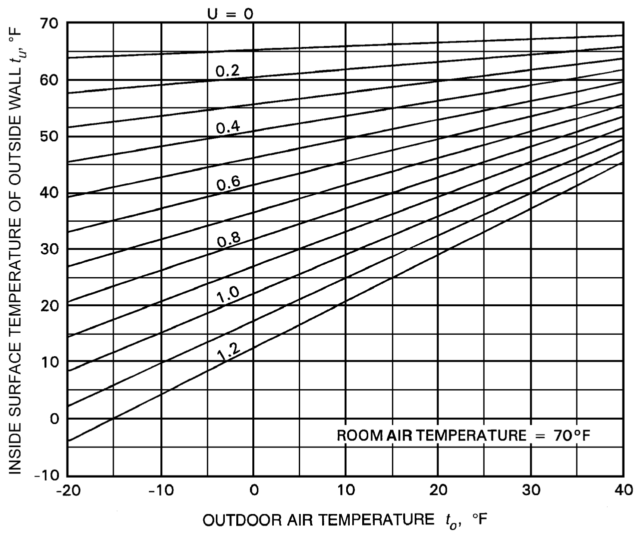


Fig. 5 Relation of Inside Surface Temperature to Overall Coefficient of Heat Transfer

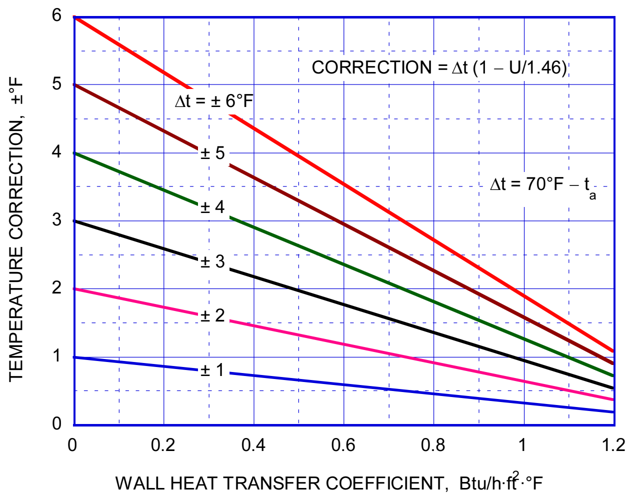


Fig. 6 Inside Surface Temperature Correction for Exposed Wall Air Temperatures Other than 70°F

Figure 7 shows the combined radiation and convection transfer for cooling, as given in Figure 2 and Figure 4. The data in Figure 7 do not include heat gains from sun, lights, people, or equipment; these data are available from manufacturers.

In suspended-ceiling panel systems, heat transfers from the back of the ceiling panel to the floor slab above (heating) and vice versa (cooling). The ceiling panel surface temperature is affected because of heat transfer to or from the panel and the slab by radiation and, to a much smaller extent, by convection. The radiation component can be approximated using Equation (5) or Figure 1. The convection component can be estimated from Equation (9b) or (10) or from Figure 3 or Figure 4. In this case, the temperature difference is that between the top of the ceiling panel and the midspace of the ceiling. The temperature of the ceiling space should be determined by testing, since it varies with different panel systems. However, much of this heat transfer is nullified when insulation is placed over the ceiling panel, which, for perforated metal panels, also provides acoustical control.

If lighting fixtures are recessed into the suspended ceiling space, radiation from the top of the fixtures raises the overhead slab temperature and transfers heat to the space by convection. This energy

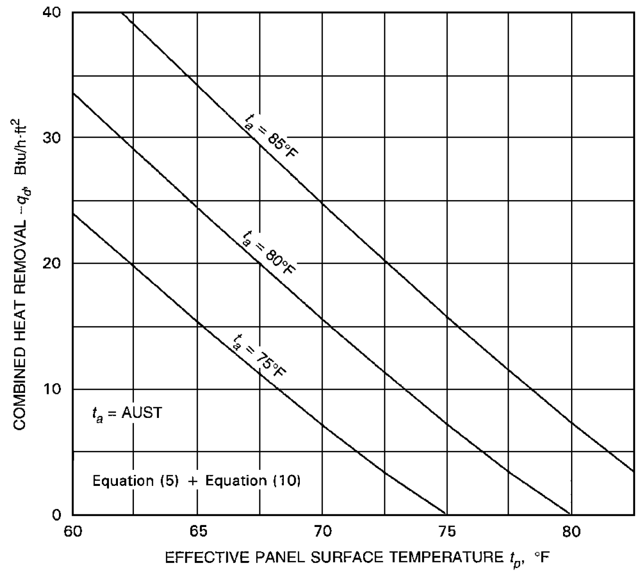


Fig. 7 Cooled Ceiling Panel Performance in Uniform Environment with No Infiltration and No Internal Heat Sources

is absorbed at the top of the cooled ceiling panels by radiation, in accordance with Equation (5) or Figure 2, and by convection, generally in accordance with Equation (9b). The amount the top of the panel absorbs depends on the system. Most manufacturers have information available. Similarly, panels installed under a roof absorb additional heat, depending on configuration and insulation.

GENERAL DESIGN CONSIDERATIONS

Radiant panel systems and hybrid HVAC systems are similar to other air-water systems in the arrangement of the system components. With radiant panel systems, room thermal conditions are maintained primarily by direct transfer of radiant energy, rather than by convection heating and cooling. The room heating and cooling loads are calculated in the conventional manner. Manufacturers' ratings generally are for total performance and can be applied directly to the calculated room load. With hybrid HVAC systems, the latent load is assigned to a convective system, and a large portion of the sensible load is assigned to a radiant panel system. In a hybrid system, the room air temperature and the MRT can be controlled independently (Kilkis et al. 1995).

Because the mean radiant temperature (MRT) in a panel-heated space increases as the heating load increases, the controlled air temperature during this increase may be lowered without affecting comfort. In ordinary structures with normal infiltration loads, the required reduction in air temperature is small, enabling a conventional room thermostat to be used.

In panel heating systems, lowered night temperature can produce less satisfactory results with heavy panels such as concrete floors. These panels cannot respond to a quick increase or decrease in heating demand within the relatively short time required, resulting in a very slow reduction of the space temperature at night and a correspondingly slow pickup in the morning. Light panels, such as plaster or metal ceilings and walls, may respond to changes in demand quickly enough for satisfactory results from lowered night temperatures. Berglund et al. (1982) demonstrated the speed of response on a metal ceiling panel to be comparable to that of convection systems. However, very little fuel savings can be expected even with light panels unless the lowered temperature is maintained for long periods. If temperatures are lowered when the area is unoccupied, a means of providing a higher-than-normal rate of heat input for rapid warm-up (e.g., fast-acting radiant ceiling panels) is necessary.

Metal radiant heating panels, hydronic and electric, are applied to building perimeter spaces for heating in much the same way as finned-tube convectors. Metal panels are usually installed in the ceiling and are integrated into the ceiling design. They provide a fast response system (Watson et al. 1998).

Partitions may be erected to the face of hydronic panels but not to the active heating portion of electric panels because of possible element overheating and burnout. Electric panels are often sized to fit the building module with a small removable filler or dummy panel at the window mullion to accommodate future partitions. Hydronic panels can run continuously. Hydronic panels also may be cut and fitted in the field; however, modification should be kept to a minimum to keep installation costs down.

Panel Thermal Resistance

Any hindrance in the panel to heat transfer from or to its surface will reduce the performance of the system. Thermal resistance to the flow of heat may vary considerably among different panels, depending on the type of bond between the tubing (wiring) and the panel material. Factors such as corrosion or adhesion defects between lightly touching surfaces and the method of maintaining contact may change the bond with time. The actual thermal resistance of any proposed system should be verified by testing. Specific resistance and performance data, when available, should be obtained from the manufacturer. Panel thermal resistances include

r_t = thermal resistance of tube wall per unit tube spacing in a hydronic system, $ft^2 \cdot h \cdot °F/Btu \cdot ft$
r_s = thermal resistance between tube (electric cable) and panel per unit spacing, $ft^2 \cdot h \cdot °F/Btu \cdot ft$
r_p = thermal resistance of panel, $ft^2 \cdot h \cdot °F/Btu$
r_c = thermal resistance of panel covers, $ft^2 \cdot h \cdot °F/Btu$
r_u = characteristic panel thermal resistance, $ft^2 \cdot h \cdot °F/Btu$

For tube spacing M,

$$r_u = r_t M + r_s M + r_p + r_c \qquad (14)$$

When the tubes (electric cables) are embedded in the slab, r_s may be neglected. However, if they are attached to the panel, r_s may be significant, depending on the quality of bonding. Table 1 gives typical r_s values for various ceiling panels.

The value of r_p may be calculated if the characteristic panel thickness x_p and the thermal conductivity k_p of the panel material are known.

If the tubes (electric cables) are embedded in the panel,

$$r_p = \frac{x_p - D_o/2}{k_p} \qquad (15a)$$

where D_o = outside diameter of the tube (electric cable). Hydronic floor heating by a heated slab and gypsum-plaster ceiling heating are typical examples.

If the tubes are attached to the panel,

$$r_p = x_p/k_p \qquad (15b)$$

Metal ceiling panels (see Table 1) and tubes under subfloor (see Figure 23) are typical examples.

Thermal resistance per unit spacing of a circular tube with an inside diameter D_i and thermal conductivity k_t is

$$r_t = \frac{\ln(D_o/D_i)}{2\pi k_t} \qquad (16)$$

Table 1 Thermal Resistance of Ceiling Panels

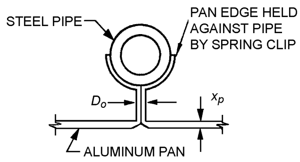
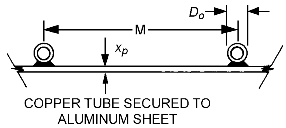
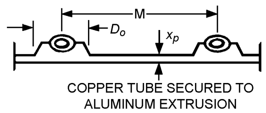
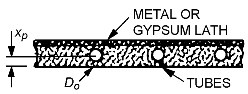
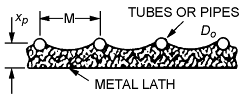
Type of Panel	Thermal Resistance r_p, $ft^2 \cdot h \cdot °F/Btu$	Thermal Resistance r_s, $ft^2 \cdot h \cdot °F/Btu \cdot ft$
	$\frac{x_p}{k_p}$	0.55
	$\frac{x_p}{k_p}$	0.22
	$\frac{x_p}{k_p}$	0.17
	$\frac{x_p - D_o/2}{k_p}$	≈ 0
	$\frac{x_p - D_o/2}{k_p}$	≤ 0.20

Table 2 Thermal Conductivity of Typical Tube Material

Material	Thermal Conductivity k_t, Btu/h·ft·°F
Carbon steel (AISI 1020)	30
Copper (drawn)	225
Red brass (85 Cu-15 Zn)	92
Stainless steel (AISI 202)	10
Low-density polyethylene (LDPE)	0.18
High-density polyethylene (HDPE)	0.24
Cross-linked polyethylene (VPE or PEX)	0.22
Textile-reinforced rubber heat transfer hose (HTRH)	0.17
Polypropylene block copolymer (PP-C)	0.13
Polypropylene random copolymer (PP-RC)	0.14
Polybutylene (PB)	0.13

In an electric cable, $r_t = 0$.

In metal pipes, r_t is virtually the fluid-side thermal resistance:

$$r_t = 1/hD_i \qquad (16a)$$

Table 6 in Chapter 3 of the *ASHRAE Handbook—Fundamentals* may be used to calculate the forced-convection heat transfer coefficient h. Table 2 gives values of k_t for different tube and pipe materials.

Effect of Floor Coverings

Panel coverings like carpets and pads on the floor can have a pronounced effect on the performance of a panel system. The added thermal resistance r_c reduces the panel surface heat transfer. In order to reestablish the required performance, the temperature of the

Table 3 Thermal Resistance of Floor Coverings

Description	Thermal Resistance r_c, $ft^2 \cdot h \cdot °F/Btu$
Bare concrete, no covering	0
Asphalt tile	0.05
Rubber tile	0.05
Light carpet	0.60
Light carpet with rubber pad	1.00
Light carpet with light pad	1.40
Light carpet with heavy pad	1.70
Heavy carpet	0.80
Heavy carpet with rubber pad	1.20
Heavy carpet with light pad	1.60
Heavy carpet with heavy pad	1.90
3/8 in. hardwood	0.54
5/8 in. wood floor (oak)	0.57
1/2 in. oak parquet and pad	0.68
Linoleum	0.12
Marble floor and mudset	0.18
Rubber pad	0.62
Prime urethane underlayment, 3/8 in.	1.61
48 oz. waffled sponge rubber	0.78
Bonded urethane, 1/2 in.	2.09

Notes:
1. Carpet pad should be no more than 1/4 in. thick.
2. Total resistance of the carpet is more a function of thickness than of fiber type.
3. A general rule for approximating the R-value is 2.6 times the total carpet thickness in inches.
4. Before carpet is installed, it should be established that the backing is resistant to long periods of continuous heat up to 120°F.

water must be increased (decreased in cooling). Thermal resistance of a panel covering is

$$r_c = x_c / k_c \tag{17}$$

where

x_c = thickness of each panel covering, ft
k_c = thermal conductivity of each panel covering, Btu/h·ft·°F

If the panel is covered by more than one cover, individual r_c values should be added. Table 3 gives typical r_c values for floor coverings.

Where covered and bare floor panels exist in the same system, it may be possible to maintain a high enough water temperature to satisfy the covered panels and balance the system by throttling the flow to the bare slabs. In some instances, however, the increased water temperature required when carpeting is applied over floor panels makes it impossible to balance floor panel systems in which only some rooms have carpeting unless the piping is arranged to permit zoning using more than one water temperature.

Panel Heat Losses or Gains

Heat transferred from the upper surface of ceiling panels, the back surface of wall panels, the underside of floor panels, or the exposed perimeter of any panel is considered a panel heat loss. Panel heat losses are part of the building heat loss if the heat is transferred outside of the building. If the heat is transferred to another heated space, the panel loss is a source of heat for that space instead. In either case, the magnitude of panel loss should be determined.

Panel heat loss to space outside the room should be kept to a reasonable amount by insulation. For example, a floor panel may overheat the basement below, and a ceiling panel may cause the temperature of a floor surface above it to be too high for comfort

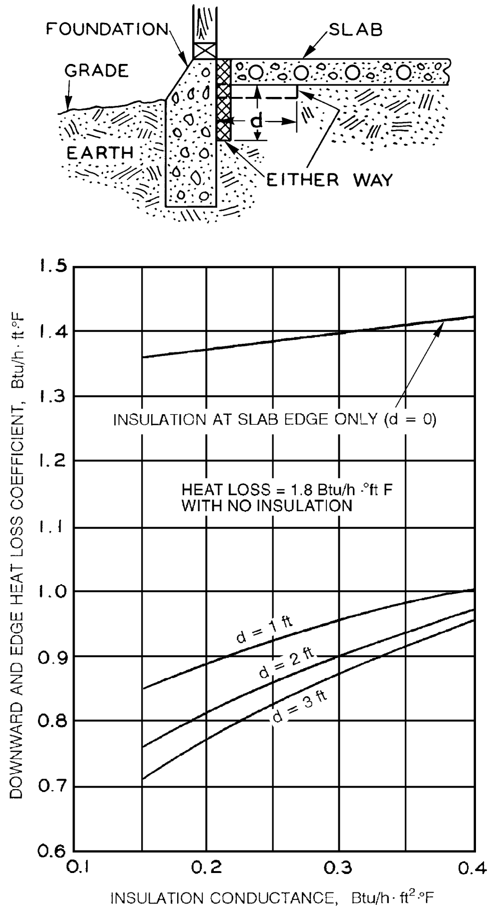


Fig. 8 Downward and Edgewise Heat Loss Coefficient for Concrete Floor Slabs on Grade

The heat loss from most panels can be calculated by using the coefficients given in Table 4 in Chapter 25 of the *ASHRAE Handbook—Fundamentals*. These coefficients should not be used to determine the downward heat loss from panels built on grade because the heat flow from them is not uniform (Sartain and Harris 1956; ASHAE 1956, 1957). The heat loss from panels built on grade can be estimated from Figure 8 or Equation (6) in Chapter 28 of the *ASHRAE Handbook—Fundamentals*.

DESIGN OF PANELS

Panel surface temperature is controlled by either hydronic or electric circuits. The required effective surface temperature t_p for a combined heat transfer q (where $q = q_r + q_c$) can be calculated by using applicable heat transfer equations for q_r and q_c depending on the position of the panel. At a given t_a, AUST must be predicted first. Figure 9 and Figure 10 can also be used to find t_p when q and AUST are known. The next step is to determine the required mean water (brine) temperature t_w in a hydronic system. It depends primarily on t_p, tube spacing M, and the characteristic panel thermal resistance r_u. Figure 9 provides design information for ceiling and cooling panels, positioned either at the ceiling or on the floor.

The combined heat transfer for ceiling and floor panels used to heat or cool rooms can be read directly from Figure 9. Here q_u is the combined heat transfer on the floor panel and q_d is the combined heat transfer on the ceiling panel. For an electric resistance heating system, t_w scales correspond to the skin temperature of the cable.

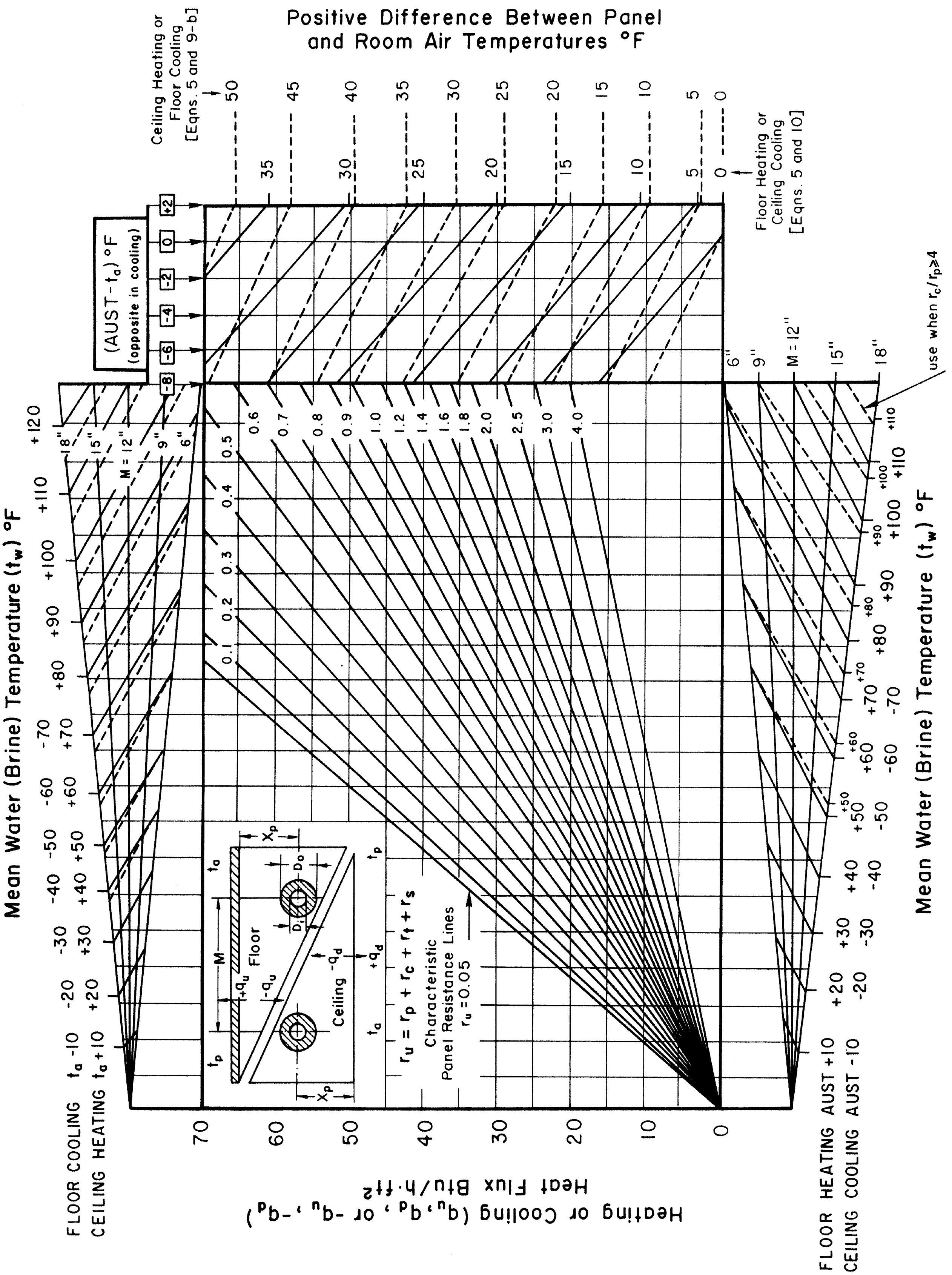


Fig. 9 Design Graph for Heating and Cooling with Floor and Ceiling Panels

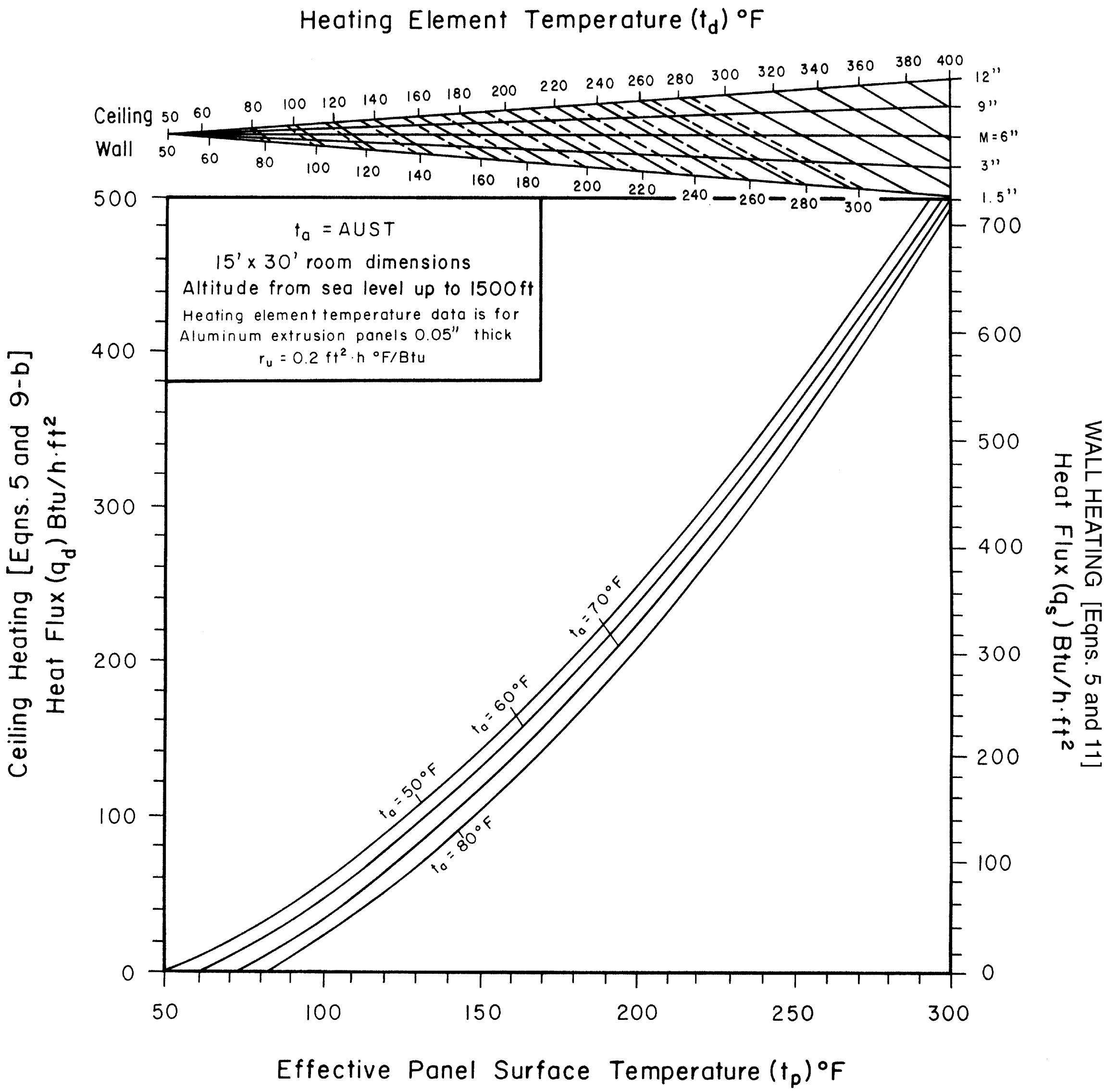


Fig. 10 Design Graph for Heating with Aluminum Ceilings and Wall Panels

The following algorithm (TSI 1994) may also be used to design and analyze panels:

$$t_d \approx t_a + \frac{(t_p - t_a)M}{2W\eta + D_o} + q(r_p + r_c + r_s M) \tag{18}$$

where

t_d = mean skin temperature of tubing (electric cable), °F
q = combined heat transfer flux on panel surface, Btu/h·ft²
t_a = design indoor air temperature, °F
In floor-heated or ceiling-cooled spaces with large exposed fenestration, t_a may be replaced with AUST.
D_o = outside diameter of tube or characteristic contact width of the tube with the panel (see Table 1), ft
M = on-center spacing of circuit, ft
$2W$ = net spacing between tubing (electric cables), $M - D_o$, ft
η = fin efficiency, dimensionless

$$\eta = \frac{\tanh(fW)}{fW} \tag{19a}$$

$$\eta \approx 1/fW \qquad \text{for } fW > 2 \tag{19b}$$

The following equation, which includes transverse heat diffusion in the panel and surface covers, may be used to calculate the fin coefficient:

$$f \approx \left[\frac{q}{m(t_p - t_a)\sum_{i=1}^{n} k_i x_i}\right]^{1/2} \qquad \text{for } t_p \neq t_a \tag{20}$$

where

$m = 2 + r_c/2r_p$
n = number of layers with different materials, including panel and surface covers
x_i = characteristic thickness of each layer i, ft
k_i = thermal conductivity of each layer i, Btu/h·ft·°F

For a hydronic system, the required mean water (brine) temperature is

$$t_w = (q + q_b)Mr_t + t_d \quad (21)$$

where q_b is the flux of back and perimeter heat losses (positive) in a heated panel or gains (negative) in a cooled panel.

PANEL HEATING AND COOLING SYSTEMS

The following are the most common forms of panels applied in panel heating systems:

- Metal ceiling panels
- Embedded piping in ceilings, walls, or floors
- Electric ceiling panels
- Electrically heated ceilings or floors
- Air-heated floors

Residential heating applications usually consist of pipe coils or electric elements embedded in masonry floors or plaster ceilings. This construction is suitable where loads are stable and solar effects are minimized by building design. However, in buildings where glass areas are large and load changes occur faster, the slow response, lag, and override effect of masonry panels are unsatisfactory. Light metal panel ceiling systems respond quickly to load changes (Berglund et al. 1982).

Radiant panels are often located in the ceiling because it is exposed to all other surfaces and objects in the room. It is not likely to be covered as are the floors, and higher surface temperatures can be used. Also, its smaller mass enables it to respond more quickly to load changes. Figure 10 gives design data for radiant ceiling and wall panels up to 300°F.

Example 1. An in-slab, on-grade panel (see Figure 20) will be used for both heating and cooling. M = 1 ft (12 in.), r_u = 0.5 ft²·h·°F/Btu, and r_c/r_p is less than 4. t_a is 68°F in winter and 76°F in summer.

AUST is expected to be 2°F less than t_a in winter heating and 1°F higher than t_a in summer cooling.

What is the mean water temperature and effective floor temperature (1) for winter heating when q_u = 40 Btu/h·ft², and (2) for summer cooling when $-q_u$ = 15 Btu/h·ft²?

Solution:

Winter heating

To obtain the mean water temperature using Figure 9, start on the left axis where q_u = 40 Btu/h·ft². Proceed right to the intersect r_u = 0.5 and then down to the M = 12 in. line. The reading is AUST + 56, which is the solid line value because $r_c/r_p < 4$. As stated in the initial problem statement, AUST = t_a − 2 or AUST = 68 − 2 = 66°F. Therefore the mean water would be t_w = 66 + 56 = 122°F.

To obtain the effective floor temperature, start at q_u = 40 Btu/h·ft² in Figure 9 and proceed right to AUST = t_a − 2°F. The solid line establishes 21°F as the difference between the panel and the room air temperatures. Therefore, the effective floor temperature $t_p = t_a + 21$ or t_p = 68 + 21 = 89°F.

Summer cooling

Using Figure 9, start at the left axis at $-q_u$ = 15 Btu/h·ft². Proceed to r_u = 0.5, and then up (for cooling) to M = 12 in., which reads t_a − 23 or 76 − 23 = 53°F mean water temperature for cooling.

To obtain the effective floor temperature at $-q_u$ = 15 Btu/h·ft², proceed to AUST − t_a = +1°F, which reads −11°F. Therefore, the effective floor temperature is 76 − 11 = 65°F.

Example 2. An aluminum extrusion panel 0.05 in. thick with pipe spacing of M = 0.5 ft (6 in.) is used in the ceiling for winter heating. If a ceiling heat flux q_d of 400 Btu/h·ft² is required to maintain room temperature t_a at 70°F, what is the required heating element temperature t_d and effective panel surface temperature t_p?

Solution:

Using Figure 10, enter the left axis heat flux q_d at 400 Btu/h·ft². Proceed to the t_a = 70°F line and then up to the M = 6 in. line. The ceiling heating element temperature t_d is 320°F. From the bottom axis of Figure 10, the effective panel surface temperature t_p is 265°F.

Special Cases

Figure 9 may also be used for panels with tubing not embedded in the panel:

- x_p is 0 if tubes are externally attached.
- In spring-clipped external tubing, D_i is 0 and D_o is the thickness of the clip.

Warm air and electric heating elements are two design concepts used in systems influenced by local factors. The warm air system has a special cavity construction where air is supplied to a cavity behind or under the panel surface. The air leaves the cavity through a normal diffuser arrangement and is supplied to the room. Generally, these systems are used as floor radiant panels in schools and in floors subject to extreme cold, such as in an overhang. Cold outdoor temperatures and heating medium temperatures must be analyzed with regard to potential damage to the building construction. Electric heating elements embedded in the floor or ceiling construction and unitized electric ceiling panels are used in various applications to provide both full heating and spot heating of the space.

HYDRONIC PANEL SYSTEMS

Design Considerations

Hydronic radiant panels can be used with two- and four-pipe distribution systems. Figure 11 shows the arrangement of a typical system. It is common to design for a 20°F temperature drop for heating across a given grid and a 5°F rise for cooling, but larger temperature differentials may be used, if applicable.

Panel design requires determining panel area, panel type, supply water temperature, water flow rate, and panel arrangement. Panel performance is directly related to room conditions. Air-side design also must be established. Heating and cooling loads may be calculated by

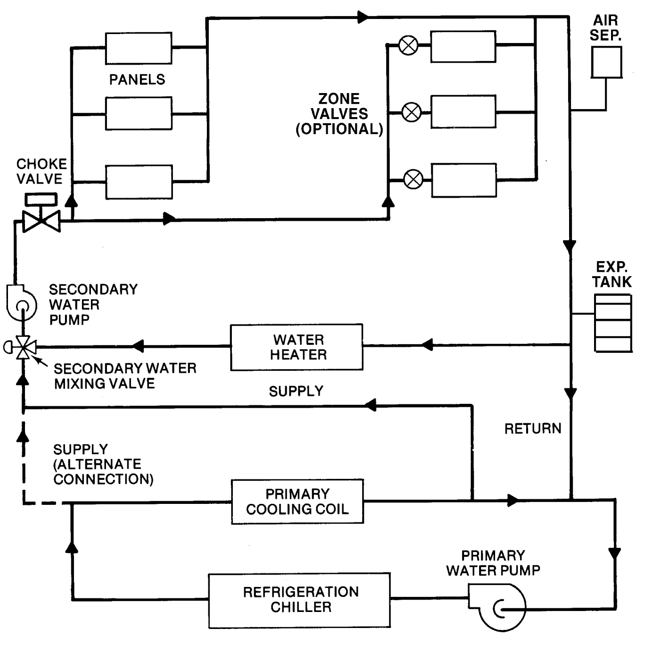


Fig. 11 Primary/Secondary Water Distribution System with Mixing Control

procedures covered in Chapters 25 through 30 of the *ASHRAE Handbook—Fundamentals*. The procedure is as follows:

A. **Cooling**

1. Determine room design dry-bulb temperature, relative humidity, and dew point.
2. Calculate room sensible and latent heat gains.
3. Select mean water temperature for cooling.
4. Establish minimum supply air quantity.
5. Calculate latent cooling available from air.
6. Calculate sensible cooling available from air.
7. Determine panel cooling load.
8. Determine panel area for cooling.

B. **Heating**

1. Designate room design dry-bulb temperature for heating.
2. Calculate room heat loss.
3. Select mean water temperature for heating.
4. Determine surface temperatures of unheated surfaces. Use Equation (13) to find surface temperatures of exterior walls and exposed floors and ceilings. Interior walls are assumed to have surface temperatures equal to the room air temperature.
5. Determine AUST of surfaces in room.
6. Determine surface temperature of heated radiant surface. Refer to Figure 9 and Figure 10 if AUST does not greatly differ from room air temperature. Use Equations (5), (9a), (9b), (10), and (11) or refer to Figure 1 and Figure 3 otherwise.
7. Determine panel area for heating. Refer to Figure 9 and Figure 10 if AUST does not vary greatly from room air temperature. Refer to manufacturers' data for panel surface temperatures higher than those given in Figure 9 and Figure 10.
8. Design the panel arrangement.

C. **Both Heating and Cooling**

1. Check thermal comfort requirements in the following steps [see Chapter 8 of the *ASHRAE Handbook—Fundamentals* and NRB (1981)].

   (a) Determine occupant's clothing insulation value and metabolic rate (see Tables 4, 7, and 8 in Chapter 8 of the *ASHRAE Handbook—Fundamentals*).
   (b) Determine the optimum operative temperature at the coldest point in the room (see Figure 15 in Chapter 8 of the *ASHRAE Handbook—Fundamentals* for other values).
   (c) Determine the MRT at the coldest point in the room [see Fanger (1972)].
   (d) From the definition of operative temperature, establish the optimum room design temperature at the coldest point in the room. If the optimum room design temperature varies greatly from the designated room design temperature, designate a new temperature.
   (e) Determine the MRT at the hottest point in the room.
   (f) Calculate the operative temperature at the hottest point in the room.
   (g) Compare the operative temperatures at the hottest and coldest points in the room. For light activity and normal clothing, the acceptable operative temperature range is 68 to 75°F [see NRB (1981) for other ranges]. If the range is not acceptable, the heating system must be modified.
   (h) Calculate radiant temperature asymmetry (NRB 1981). Acceptable ranges are less than 18°F for windows and less than 9°F for warm ceilings.

2. Determine water flow rate and pressure drop. Refer to manufacturers' guides for specific products, or use the guidelines in pages 35.1 through 35.7 of the *ASHRAE Handbook—Fundamentals*. Chapter 12 of this volume also has information on hydronic heating and cooling systems.

The supply and return manifolds need to be carefully designed. If there are circuits of unequal coil lengths, the following equations may be used (Hansen 1985; Kilkis 1998) for a circuit *i* connected to a manifold with *n* circuits:

$$Q_i = (L_{eq}/L_i)^{1/r} Q_{tot} \tag{22}$$

where

$L_{eq} = \left[\sum_{i=1}^{n} L_i^{-1/r} \right]^{-r}$, ft

Q_i = flow rate in circuit *i*, gpm

Q_{tot} = total flow rate in supply manifold, gpm

L_i = coil length of circuit *i*, ft

r = 1.75 for hydronic panels (Siegenthaler 1995)

The application, design, and installation of panel systems have certain requirements and techniques:

1. As with any hydronic system, look closely at the piping system design. Piping should be designed to ensure that water of the proper temperature and in sufficient quantity is available to every grid or coil at all times. Proper piping and system design should minimize the detrimental effects of oxygen on the system. Reverse-return systems should be considered to minimize balancing problems.
2. Individual panels can be connected for parallel flow using headers, or for sinuous or serpentine flow. To avoid flow irregularities within a header-type grid, the water channel or lateral length should be greater than the header length. If the laterals in a header grid are forced to run in a short direction, this problem can be solved by using a combination series-parallel arrangement. Serpentine flow will ensure a more even panel surface temperature throughout the heating or cooling zone.
3. Noise from entrained air, high-velocity or high-pressure-drop devices, or pump and pipe vibrations must be avoided. Water velocities should be high enough to prevent separated air from accumulating and causing air binding. Where possible, avoid automatic air venting devices over ceilings of occupied spaces.
4. Design piping systems to accept thermal expansion adequately. Do not allow forces from piping expansion to be transmitted to panels. Thermal expansion of the ceiling panels must be considered.
5. In circulating water systems, plastic, rubber, steel, and copper pipe or tube are used widely in ceiling, wall, or floor panel construction. Where coils are embedded in concrete or plaster, no threaded joints should be used for either pipe coils or mains. Steel pipe should be the all-welded type. Copper tubing should be soft-drawn coils. Fittings and connections should be minimized. Changes in direction should be made by bending. Solder-joint fittings for copper tube should be used with a medium-temperature solder of 95% tin, 5% antimony, or capillary brazing alloys. All piping should be subjected to a hydrostatic test of at least three times the working pressure. Maintain adequate pressure in embedded piping while pouring concrete.
6. Placing the thermostat on a side wall where it can see the outside wall and the warm panel should be considered. The normal thermostat cover reacts to the warm panel, and the radiant effect of the panel on the cover tends to alter the control point so that the thermostat controls 2 to 3°F lower when the outdoor temperature is a minimum and the panel temperature is a maximum. Experience indicates that radiantly heated rooms are more comfortable under these conditions than when the thermostat is located on a back wall.
7. If throttling valve control is used, either the end of the main should have a fixed bypass, or the last one or two rooms on the mains should have a bypass valve to maintain water flow in the

main. Thus, when a throttling valve modulates, there will be a rapid response.

8. When selecting heating design temperatures for a ceiling panel surface, the design parameters are as follows:

   (a) Excessively high temperatures over the occupied zone cause the occupant to experience a "hot head effect."
   (b) Temperatures that are too low can result in an oversized, uneconomical panel and a feeling of coolness at the outside wall.
   (c) Locate ceiling panels adjacent to perimeter walls and/or areas of maximum load.
   (d) With normal ceiling heights of 8 to 9 ft, panels less than 3 ft wide at the outside wall can be designed for 235°F surface temperature. If panels extend beyond 3 ft into the room, the panel surface temperature should be limited to the values as given in Figure 16. The surface temperature of concrete or plaster panels is limited by construction.

9. Floor panels are limited to surface temperatures of less than 84°F in occupied spaces for comfort reasons. Subfloor temperature may be limited to the maximum exposure temperature specified by the floor covering manufacturer.
10. When the panel chilled water system is started, the circulating water temperature should be maintained at room temperature until the air system is completely balanced, the dehumidification equipment is operating properly, and building humidity is at design value.
11. When the panel area for cooling is greater than the area required for heating, a two-panel arrangement (Figure 12) can be used. Panel HC (heating and cooling) is supplied with hot or chilled water year-round. When chilled water is used, the controls function activate panel CO (cooling only), and both panels are used for cooling.

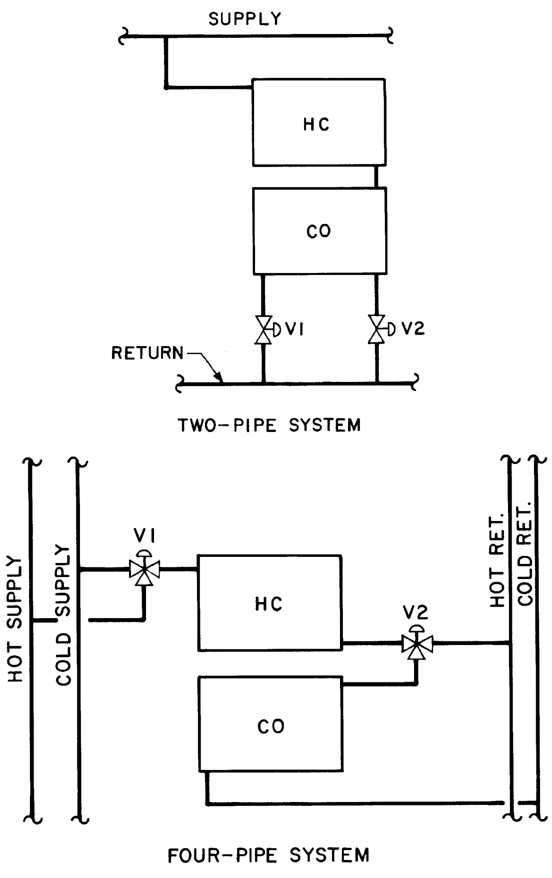


Fig. 12 Split Panel Piping Arrangement for Two-Pipe and Four-Pipe Systems

12. To prevent condensation on the room side of cooling panels, the panel water supply temperature should be maintained at least 1°F above the room design dew-point temperature. This minimum difference is recommended to allow for the normal drift of temperature controls for the water and air systems, and also to provide a factor of safety for temporary increase in space humidity.
13. Selection of summer design room dew point below 50°F generally is not economical.
14. The most frequently applied method of dehumidification uses cooling coils. If the main cooling coil is six rows or more, the dew point of the leaving air will approach the temperature of the leaving water. The cooling water leaving the dehumidifier can then be used for the panel water circuit.
15. Several chemical dehumidification methods are available to control latent and sensible loads separately. In one application, cooling tower water is used to remove heat from the chemical drying process, and additional sensible cooling is necessary to cool the dehumidified air to the required system supply air temperature.
16. When chemical dehumidification is used, hygroscopic chemical-type dew-point controllers are required at the central apparatus and at various zones to monitor dehumidification.
17. When cooled ceiling panels are used with a variable air volume (VAV) system, the air supply rate should be near maximum volume to assure adequate dehumidification before the cooling ceiling panels are activated.

Other factors to consider when using panel systems are

1. Evaluate the panel system to take full advantage in optimizing the physical building design.
2. Select recessed lighting fixtures, air diffusers, hung ceilings, and other ceiling devices to provide the maximum ceiling area possible for use as radiant panels.
3. The air-side design must be able to maintain humidity levels at or below design conditions at all times to eliminate any possibility of condensation on the panels. This becomes more critical if space dry- and wet-bulb temperatures are allowed to drift as an energy conservation measure, or if duty cycling of the fans is used.
4. Do not place cooling panels in or adjacent to high-humidity areas.
5. Anticipate thermal expansion of the ceiling and other devices in or adjacent to the ceiling.
6. Design operable windows to discourage unauthorized opening.

HYDRONIC METAL CEILING PANELS

Metal ceiling panels can be integrated into a system that heats and cools. In such a system, a source of dehumidified ventilation air is required in summer, so the system is classed as an air-and-water system. Also, various amounts of forced air are supplied year-round. When metal panels are applied for heating only, a ventilation system may be required, depending on local codes.

Ceiling panel systems are an outgrowth of the perforated metal, suspended acoustical ceilings. These radiant ceiling systems are usually designed into buildings where the suspended acoustical ceiling can be combined with panel heating and cooling. The panels can be designed as small units to fit the building module, which provides extensive flexibility for zoning and control; or the panels can be arranged as large continuous areas for maximum economy. Some ceiling installations require active panels to cover only a portion of the room and compatible matching acoustical panels for the remaining ceiling area.

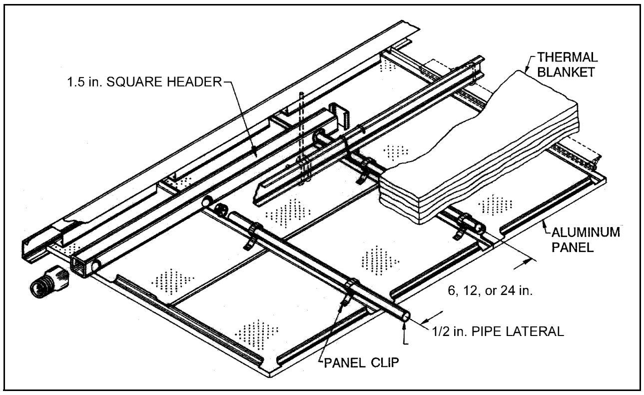


Fig. 13 Metal Ceiling Panels Attached to Pipe Laterals

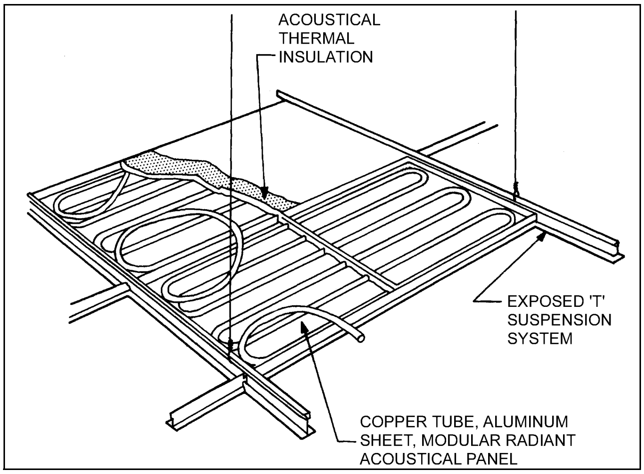


Fig. 14 Metal Ceiling Panels Bonded to Copper Tubing

Three types of metal ceiling systems are available. The first consists of light aluminum panels, usually 12 in. by 24 in., attached in the field to 0.5 in. galvanized pipe coils. Figure 13 illustrates a metal ceiling panel system that uses 0.5 in. pipe laterals on 6, 12, or 24 in. centers, hydraulically connected in a sinuous or parallel flow welded system. Aluminum ceiling panels are clipped to these pipe laterals and act as a heating panel when warm water is flowing or as a cooling panel when chilled water is flowing.

The second type of panel consists of a copper coil secured to the aluminum face sheet to form a modular panel. Modular panels are available in sizes up to about 36 in. by 60 in. and are held in position by various types of ceiling suspension systems, most typically a standard suspended T-bar 24 in. by 48 in. exposed grid system. Figure 14 illustrates metal panels using a copper tube pressed into an aluminum extrusion, although other methods of securing the copper tube have proven equally effective.

Metal ceiling panels can be perforated so that the ceiling becomes sound absorbent when acoustical material is installed on the back of the panels. The acoustical blanket is also required for thermal reasons, so that the reverse loss or upward flow of heat from the metal ceiling panels is minimized.

The third type of panel is an aluminum extrusion face sheet with a copper tube mechanically fastened into a channel housing on the back. Extruded panels can be manufactured in almost any shape and size. Extruded aluminum panels are often used as long, narrow panels at the outside wall and are independent of the ceiling system. Panels 15 or 20 in. wide usually satisfy the heating requirements of a typical office

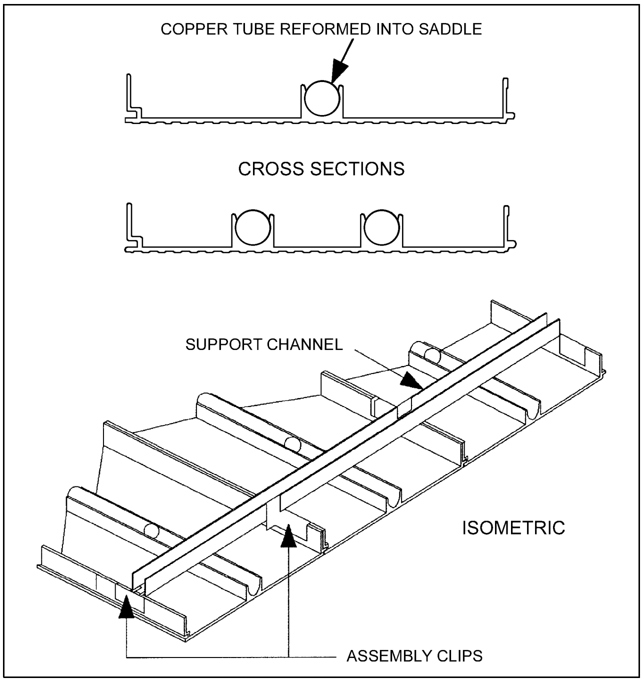


Fig. 15 Extruded Aluminum Panels with Integral Copper Tube

building. Lengths up to 20 ft are available. Figure 15 illustrates metal panels using a copper tube pressed into an aluminum extrusion.

Performance data for extruded aluminum panels vary with the copper tube/aluminum contact and test procedures used. Hydronic ceiling panels have a low thermal resistance and respond quickly to changes in space conditions. Table 1 shows thermal resistance values for various ceiling constructions.

Metal radiant ceiling panels can be used with any of the all-air cooling systems described in Chapter 2. Chapters 26 through 29 of the *ASHRAE Handbook—Fundamentals* describe how to calculate heating loads. Double glazing and heavy insulation in outside walls have reduced transmission heat losses. As a result, infiltration and reheat have become of greater concern. Additional design considerations are as follows:

1. Perimeter radiant heating panels not extending more than 3 ft into the room may operate at higher temperatures, as described under item 8d in the section on Hydronic Panel Systems.
2. Hydronic panels operate efficiently at low temperature and are suitable for condenser water heat reclaim systems.
3. Locate ceiling panels adjacent to the outside wall and as close as possible to the areas of maximum load. The panel area within 3 ft of the outside wall should have a heating capacity equal to or greater than 50% of the wall transmission load.
4. Ceiling system designs based on passing return air through perforated modular panels into the plenum space above the ceiling are not recommended because much of the panel heat transfer is lost to the return air system.
5. When selecting heating design temperatures for a ceiling panel surface or mean water temperature, the design parameters are as follows:

   (a) Excessively high temperatures over the occupied zone will cause the occupant to experience a "hot head effect."
   (b) Temperatures that are too low can result in an oversized, uneconomical panel and a feeling of coolness at the outside wall.
   (c) Give the technique in item 3 priority.

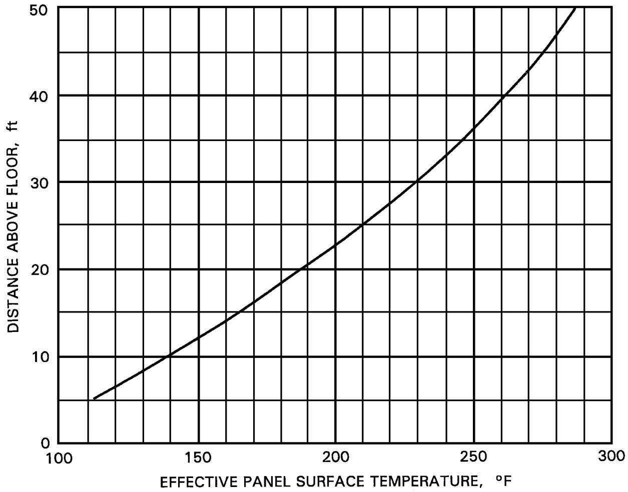


Fig. 16 Permitted Design Ceiling Surface Temperatures at Various Ceiling Heights

(d) With normal ceiling heights of 8 to 9 ft, panels less than 3 ft wide at the outside wall can be designed for 235°F surface temperature. If panels extend beyond 3 ft into the room, the panel surface temperature should be limited to the values as given in Figure 16.

6. Allow sufficient space above the ceiling for installation and connection of the piping that forms the radiant panel ceiling.

Metal radiant acoustic panels provide heating, cooling, sound absorption, insulation, and unrestricted access to the plenum space. They are easily maintained, can be repainted to look new, and have a life expectancy in excess of 30 years. The system is quiet, comfortable, draft-free, and easy to control, and it responds quickly. The system is a basic air-and-water system. First costs are competitive with other systems, and a life-cycle cost analysis often shows that the long life of the equipment makes it the least expensive in the long run. The system has been used in hospitals, schools, office buildings, colleges, airports, and exposition facilities.

Metal radiant panels can also be integrated into the ceiling design to provide a narrow band of radiant heating around the perimeter of the building. The radiant system offers advantages over baseboard or overhead air in appearance, comfort, operating efficiency and cost, maintenance, and product life.

DISTRIBUTION AND LAYOUT

Chapter 3 and Chapter 12 apply to radiant panels. Layout and design of metal radiant ceiling panels for heating and cooling begin early in the job. The type of ceiling chosen influences the radiant design, and conversely, thermal considerations may dictate what ceiling type to use. Heating panels should be located adjacent to the outside wall. Cooling panels may be positioned to suit other elements in the ceiling. In applications with normal ceiling heights, heating panels that exceed 160°F should not be located over the occupied area. In hospital applications, valves should be located in the corridor outside patient rooms.

One of the following types of construction is generally used:

1. Pipe or tube is embedded in the lower portion of a concrete slab, generally within 1 in. of its lower surface. If plaster is to be applied to the concrete, the piping may be placed directly on the wood forms. If the slab is to be used without plaster finish, the piping should be installed not less than 0.75 in. above the undersurface of the slab. Figure 17 shows this method of construction.

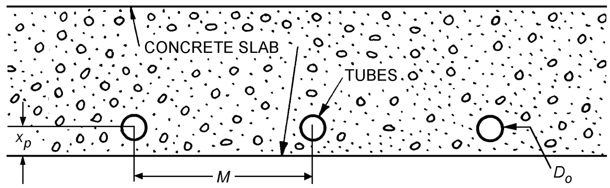


Fig. 17 Coils in Structural Concrete Slab

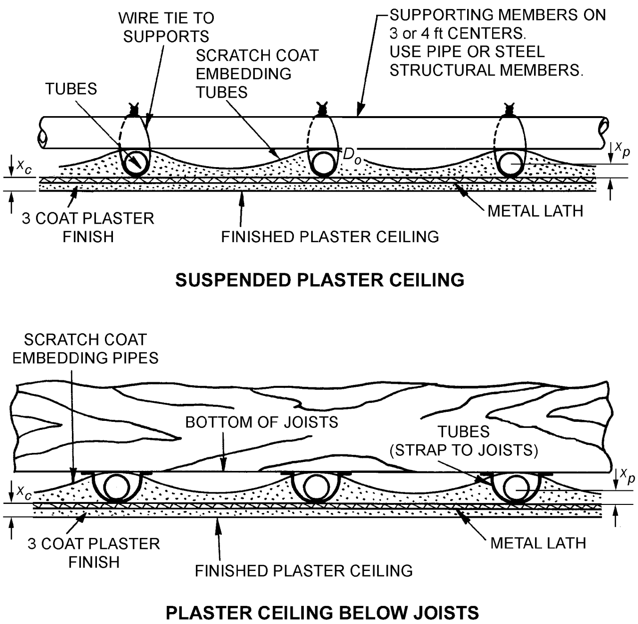


Fig. 18 Coils in Plaster above Lath

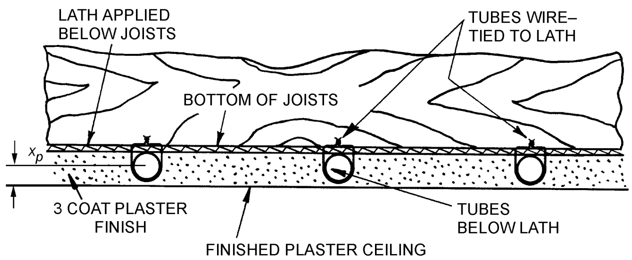


Fig. 19 Coils in Plaster below Lath

The minimum coverage must comply with local building code requirements.

2. Pipe or tube is embedded in a metal lath and plaster ceiling. If the lath is suspended to form a hung ceiling, the lath and heating coils are securely wired to the supporting members so that the lath is below, but in good contact with, the coils. Plaster is then applied to the metal lath, carefully embedding the coil as shown in Figure 18.
3. Smaller diameter copper or plastic tube is attached to the underside of wire lath or gypsum lath. Plaster is then applied to the lath to embed the tube, as shown in Figure 19.
4. Other forms of ceiling construction are composition board, wood paneling, etc., with warm water piping, tube, or channels built into the panel sections.

Coils are usually the sinuous type, although some header or grid-type coils have been used in ceilings. Coils may be plastic, ferrous, or nonferrous pipe or tube, with coil pipes spaced from 4.5 to 9 in. on centers, depending on the required output, pipe or tube size, and other factors.

Where plastering is applied to pipe coils, a standard three-coat gypsum plastering specification is followed, with a minimum of 3/8 in. of cover below the tubes when they are installed below the lath. Generally, the surface temperature of plaster panels should not exceed 120°F. This can be accomplished by limiting the water temperature in the pipes or tubes in contact with the plaster to a maximum temperature of 140°F. Insulation should be placed above the coils to reduce back loss, the difference between heat supplied to the coil and net useful output to the heated room.

To protect the plaster installation and to ensure proper air drying, heat must not be applied to the panels for two weeks after all plastering work has been completed. When the system is started for the first time, the water supplied to the panels should not be higher than 20°F above the prevailing room temperature at that time and not in excess of 90°F. Water should be circulated at this temperature for about two days, then increased at a rate of about 5°F per day to 140°F.

During the air-drying and preliminary warm-up periods, there should be adequate ventilation to carry moisture from the panels. No paint or paper should be applied to the panels before these periods have been completed or while the panels are being operated. After paint and paper have been applied, an additional shorter warm-up period, similar to first-time starting, is also recommended.

Hydronic Wall Panels

Although piping embedded in walls is not as widely used as floor and ceiling panels, it can be constructed by any of the methods outlined for ceilings or floors. Its design is similar to other hydronic panels [see Equations (18) to (21)]. Heat transfer at the surface of wall panels is given by Equations (5) and (11).

Hydronic Floor Panels

Interest has increased in radiant floor heating with the introduction of nonmetallic tubing and new design, application, and control techniques. Whichever method is used for optimum floor output and comfort, it is important that the heat be evenly distributed over the floor. Spacing is generally 4 to 12 in on centers for the coils. Wide spacing under tile or bare floors can cause uneven surface temperatures.

Embedded Piping in Concrete Slab. Plastic, rubber, ferrous, and nonferrous pipe and tube are used in floor slabs that rest on grade. The coils are constructed as sinuous-continuous pipe coils or arranged as header coils with the pipes spaced from 6 to 18 in. on centers. The coils are generally installed with 1.5 to 4 in. of cover above them. Insulation is recommended to reduce the perimeter and back losses. Figure 20 shows the application of pipe coils in slabs resting on grade. Coils should be embedded completely and should not rest on an interface. Any supports used for positioning the heating coils should be nonabsorbent and inorganic. Reinforcing steel, angle iron, pieces of pipe or stone, or concrete mounds can be used. No wood, brick, concrete block, or similar materials should support coils. A waterproofing layer is desirable to protect insulation and piping.

Where coils are embedded in structural load-supporting slabs above grade, construction codes may affect their position. Otherwise, the coil piping is installed as described for slabs resting on grade.

The warm-up and start-up period for concrete panels are similar to those outlined for plaster panels.

Embedded systems may fail sometime during their life. Adequate valves and properly labeled drawings will help isolate the point of failure.

Suspended Floor Piping. Piping may be applied on or under suspended wood floors using several methods of construction. Piping may be attached to the surface of the floor and embedded in a layer of concrete or gypsum, mounted in or below the subfloor, or attached directly to the underside of the subfloor using metal panels to improve heat transfer from the piping. An alternate method is to install insulation with a reflective surface and leave an air gap of 2 to 4 in. to the subfloor. Whichever method is used for optimum floor output and comfort, it is important that the heat be evenly distributed throughout the floor. Pipes are generally spaced 4 to 12 in. apart. Wide spacing under tile or bare floors can cause uneven surface temperatures.

Figure 21 illustrates construction with piping embedded in concrete or gypsum. The thickness of the embedding material is generally 1 to 2 in. when applied to a wood subfloor. Gypsum products specifically designed for floor heating can generally be installed 1 to 1.5 in. thick because they are more flexible and crack-resistant than concrete. When concrete is used, it should be of structural quality to reduce cracking due to movement of the wood frame or shrinkage. The embedding material must provide a hard, flat, smooth surface that can accommodate a variety of floor coverings.

As illustrated in Figure 22, tubing may also be installed in the subfloor. The tubing is installed on top of the rafters between the subflooring members. Heat diffusion and surface temperature can be improved uniformly by the addition of metal heat transfer plates,

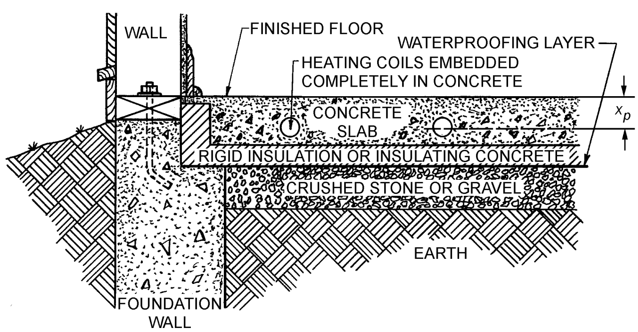


Fig. 20 Coils in Floor Slab on Grade

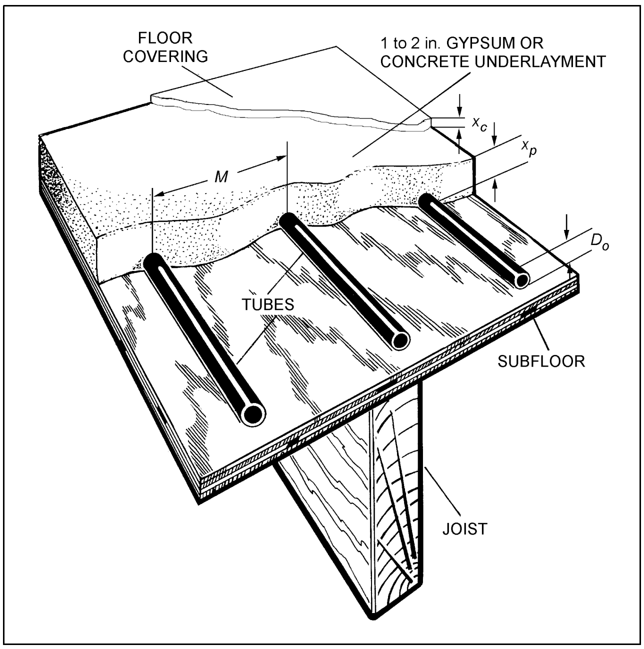


Fig. 21 Embedded Tube in Thin Slab

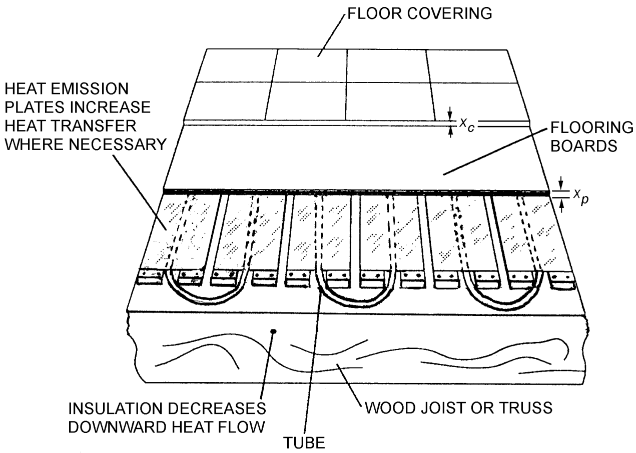


Fig. 22 Tube in Subfloor

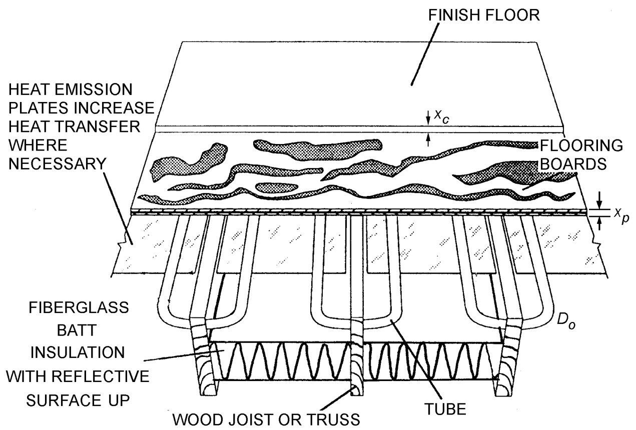


Fig. 23 Tube under Subfloor

which spread the heat beneath the finished flooring. This construction is illustrated in Figure 22.

A third construction option is to attach the tube to the underside of the subfloor with or without metal heat transfer plates. The construction is illustrated in Figure 23.

Transfer from the hot water tube to the surface of the floor is the important consideration in all cases. The floor surface temperature affects the actual heat transfer to the space. Any hindrance between the heated water tube and the floor surface reduces the effectiveness of the system. The method that transfers and spreads heat evenly through the subfloor with the least resistance produces the best results.

ELECTRICALLY HEATED SYSTEMS

Several heating systems convert electrical energy to heat, which raises the temperature of interior room surfaces. These systems are classified by the temperature of the heated system. Higher temperature surfaces require less area to maintain occupant comfort. Surface temperatures are limited by the ability of the materials to maintain their integrity at elevated temperatures. The maximum effective surface temperature of radiant floor panels is limited to what is comfortable to the feet of occupants.

Ceiling Systems

Prefabricated Electric Ceiling Panels. These panels are available in sizes 1 to 6 ft wide by 2 to 12 ft long by 0.5 to 2 in. thick. They are constructed with metal, glass, or semirigid fiberglass board or vinyl. Heated surface temperatures range from 100 to 300°F, with

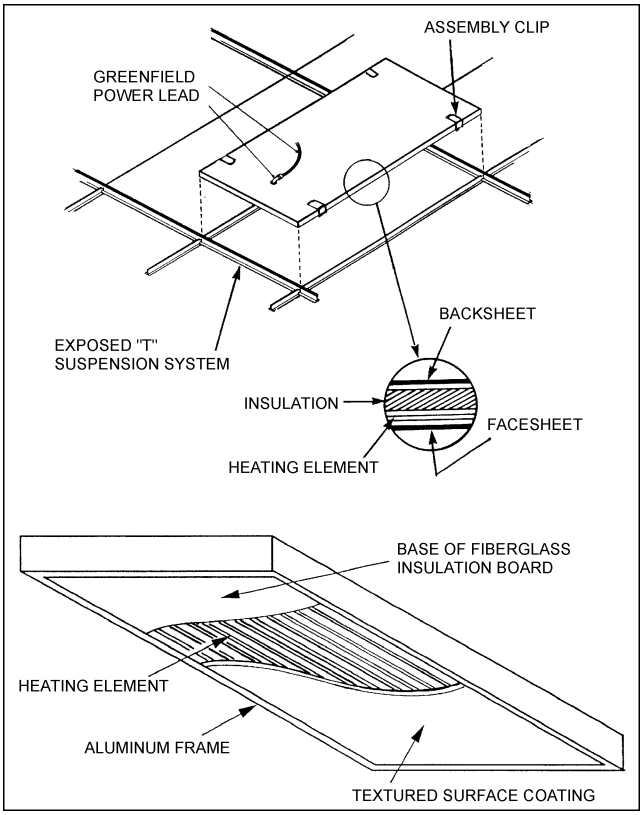


Fig. 24 Electric Heating Panels

corresponding power densities ranging from 25 to 100 W/ft^2 for 120 to 480 V services.

A panel of gypsum board embedded with insulated resistance wire is also available. It is installed as part of the ceiling or between joists in contact with a ceiling. Power density is limited to 22 W/ft^2 to maintain the integrity of the board by keeping the heated surface temperature below 100°F. Nonheating leads are furnished as part of the panel.

Some panels can be cut to fit; others must be installed as received. Panels may be either flush or surface mounted, and in some cases, they are finished as part of the ceiling. Rigid 2 ft by 4 ft panels for lay-in ceilings (Figure 24) are about 1 in. thick and weigh from 6 to 25 lb. Typical characteristics of an electrical radiant panel are listed in Table 4. Panels may also be (1) surface mounted on gypsum board and wood ceilings or (2) recessed between ceiling joists. Panels range in size from 4 ft wide to 8 ft long. Their maximum power output is 95 W/ft^2.

Electric Ceiling Systems. These systems are laminated conductive coatings, printed circuits, or etched elements nailed to the bottom of ceiling joists and covered by 1/2 in. gypsum board. Power density is limited to 18 W/ft^2. In some cases, the heating element can be cut to fit available space. Manufacturers' instructions specify how to connect the system to the electric supply. Appropriate codes should be followed when placing partitions, lights, and air grilles adjacent to or near electric panels.

Electrical Cables Embedded in Ceilings. Electric heating cables for embedded or laminated ceiling panels are factory-assembled units furnished in standard lengths of 75 to 1800 ft. These cable lengths cannot be altered in the field. The cable assemblies are normally rated at 2.75 W per linear foot and are supplied in capacities from 200 to 5000 W in roughly 200 W increments. Standard cable assemblies are available for 120, 208, and 240 V. Each cable unit is supplied with 7 ft nonheating leads for connection at the thermostat or junction box.

Table 4 Characteristics of Typical Electric Panel Heater

Resistor material	Graphite or nichrome wire
Relative heat intensity	Low, 50 to 125 W/ft^2
Resistor temperature	180 to 350°F
Envelope temperature (in use)	160 to 300°F
Radiation-generating ratio[a]	0.7 to 0.8
Response time (heat-up)	240 to 600 s
Luminosity (visible light)	None
Thermal shock resistance	Excellent
Vibration resistance	Excellent
Impact resistance	Excellent
Resistance to drafts or wind[b]	Poor
Mounting position	Any
Envelope material	Steel alloy or aluminum
Color blindness	Very good
Flexibility	Good—wide range of power density, length, and voltage practical
Life expectancy	Over 10,000 h

[a]Ratio of radiant output to power input (elements only).
[b]May be shielded from wind effects by louvers, deep-drawn fixtures, or both.

Electric cables for panel heating have electrically insulated coverings resistant to medium temperature, water absorption, aging effects, and chemical action with plaster, cement, or ceiling lath material. This insulation is normally a polyvinyl chloride (PVC) covering, which may have a nylon jacket. The outside diameter of the insulation covering is usually about 0.12 in.

For plastered ceiling panels, the heating cable may be stapled to gypsum board, plaster lath, or similar fire-resistant materials with rust-resistant staples (Figure 25). With metal lath or other conducting surfaces, a coat of plaster (brown or scratch coat) is applied to completely cover the metal lath or conducting surface before the cable is attached. After the lath is fastened on and the first plaster coat is applied, each cable is tested for continuity of circuit and for insulation resistance of at least 100 kΩ measured to ground.

The entire ceiling surface is finished with a covering of thermally noninsulating sand plaster about 0.50 to 0.75 in. thick or other approved noninsulating material applied according to manufacturer's specifications. The plaster is applied parallel to the heating cable rather than across the runs. While new plaster is drying, the system should not be energized, and the range and rate of temperature change should be kept low by other heat sources or by ventilation until the plaster is thoroughly cured. Vermiculite or other insulating plaster causes cables to overheat and is contrary to code provisions.

For laminated drywall ceiling panels, the heating cable is placed between two layers of gypsum board, plasterboard, or other thermally noninsulating fire-resistant ceiling lath. The cable is stapled directly to the first (or upper) lath, and the two layers are held apart by the thickness of the heating cable. It is essential that the space between the two layers of lath be completely filled with a noninsulating plaster or similar material. This fill holds the cable firmly in place and improves heat transfer between the cable and the finished ceiling. Failure to fill the space between the two layers of plasterboard completely may allow the cable to overheat in the resulting voids and may cause cable failure. The plaster fill should be applied according to manufacturer's specifications.

Electric heating cables are ordinarily installed with a 6 in. nonheating border around the periphery of the ceiling. An 8 in. clearance must be provided between heating cables and the edges of the outlet or junction boxes used for surface-mounted lighting fixtures. A 2 in. clearance must be provided from recessed lighting fixtures, trim, and ventilating or other openings in the ceiling.

Heating cables or panels must be installed only in ceiling areas that are not covered by partitions, cabinets, or other obstructions. However, it is permissible for a single run of isolated embedded cable to pass over a partition.

The *National Electrical Code* (NFPA *Standard* 70) requires that all general power and light wiring be run above the thermal insulation or at least 2 in. above the heated ceiling surface, or that the wiring be derated.

In drywall ceiling construction, the heating cable is always installed with the cable runs parallel to the joist. A 2.5 in. clearance between adjacent cable runs must be left centered under each joist for nailing. Cable runs that cross over the joist must be kept to a minimum. Where possible, these crossings should be in a straight line at one end of the room.

For cable having a power density of 2.75 W/ft, the minimum permissible spacing is 1.5 in. between adjacent runs. Some manufacturers recommend a minimum spacing of 2 in. for drywall construction.

The spacing between adjacent runs of heating cable can be determined using the following equation:

$$M = 12A_n/C \tag{23}$$

where

M = cable spacing, in.
A_n = net panel heated area, ft^2
C = length of cable, ft

Net panel area A_n in Equation (23) is the net ceiling area available after deducting the area covered by the nonheating border, lighting fixtures, cabinets, and other ceiling obstructions. For simplicity, Equation (23) contains a slight safety factor, and small lighting fixtures are usually ignored in determining net ceiling area.

Resistance of the electric cable must be adjusted according to its temperature at design conditions (Ritter and Kilkis 1998):

$$R' = R\frac{[1 + \alpha_e(t_d - 68)]}{[1 + \alpha_o(t_d - 68)]} \tag{24}$$

where

R = electrical resistance of electric cable at standard temperature (68°F), Ω/ft
α_e = thermal coefficient for material resistivity, °F^{-1}
α_o = thermal expansion coefficient, °F^{-1}
t_d = surface temperature of electric cable at operating conditions [see Equation (18)], °F

The 2.5 in. clearance required under each joist for nailing in drywall applications occupies one-fourth of the ceiling area if the joists are 16 in. on centers. Therefore, for drywall construction, the net area A_n must be multiplied by 0.75. Many installations have a spacing of 1.5 in. for the first 2 ft from the cold wall. Remaining cable is then spread over the balance of the ceiling.

Electrically Heated Wall Panels

Cable embedded in walls similar to ceiling construction is used in Europe. Because of possible damage from nails driven for hanging pictures or from building alterations, most codes in the United States prohibit such panels. Some of the prefabricated panels described in the preceding section are also used for wall panel heating.

Electrically Heated Floors

Electric heating cable assemblies such as those used for ceiling panels are sometimes used for concrete floor heating systems. Because the possibility of cable damage during installation is greater for concrete floor slabs than for ceiling panels, these assemblies must be carefully installed. After the cable has been placed, all unnecessary traffic should be eliminated until the concrete covering has been placed and hardened.

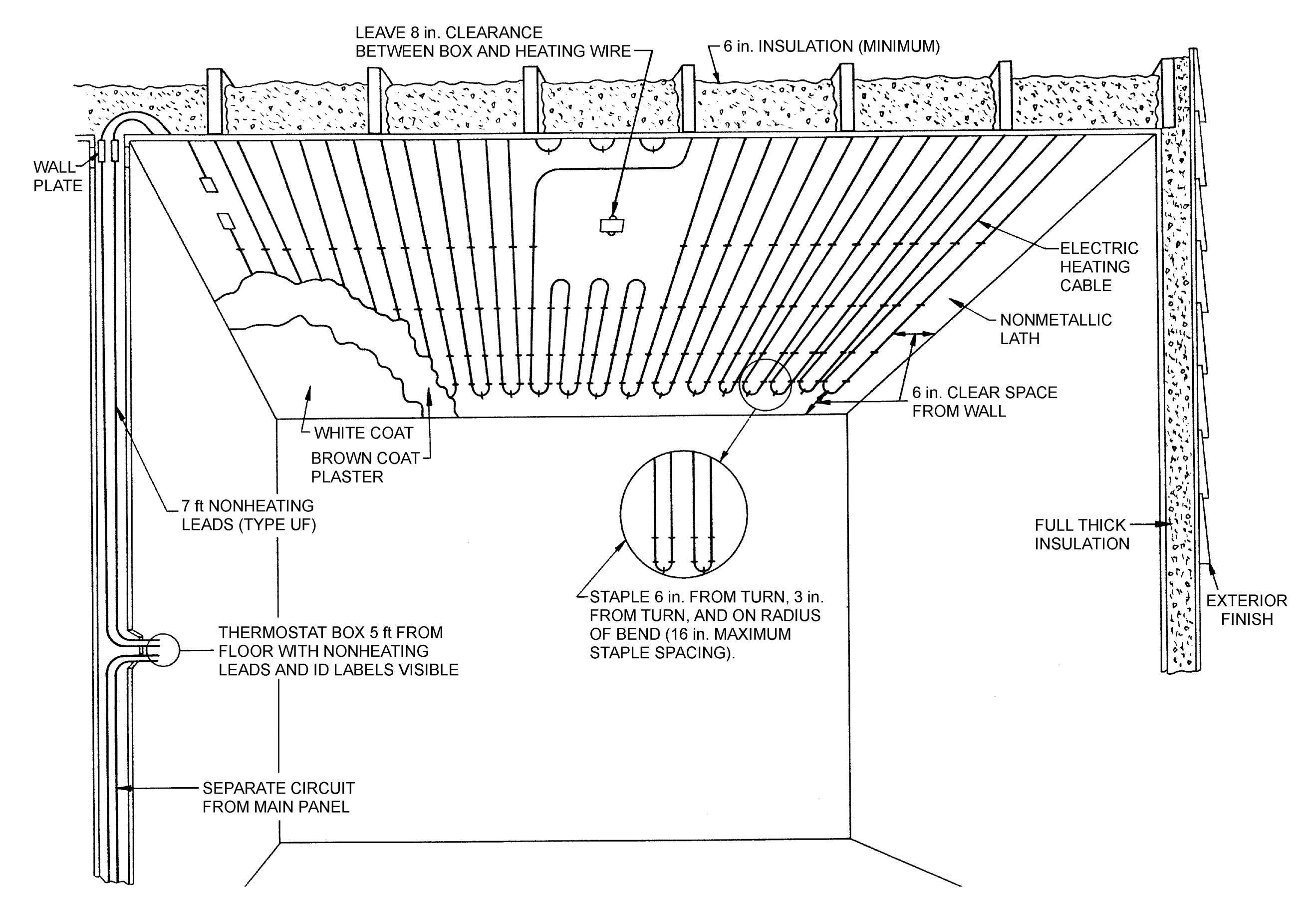


Fig. 25 Electric Heating Panel for Wet Plaster Ceiling

Preformed mats are sometimes used for electric floor slab heating systems. These mats usually consist of PVC-insulated heating cable woven into or attached to metallic or glass fiber mesh. Such mats are available as prefabricated assemblies in many sizes from 2 to 100 ft^2 and with power densities ranging from 15 to 25 W/ft^2. When mats are used with a thermally treated cavity beneath the floor, a heat storage system is provided, which may be controlled for off-peak heating.

Mineral-insulated (MI) heating cable is another effective method of slab heating. MI cable is a small-diameter, highly durable, flexible heating cable composed of solid electric-resistance heating wire or wires surrounded by tightly compressed magnesium oxide electrical insulation and enclosed by a metal sheath. MI cable is available in stock assemblies in a variety of standard voltages, power densities, and lengths. A cable assembly consists of the specified length of heating cable, waterproof hot-cold junctions, 7 ft cold sections, UL-approved end fittings, and connection leads. Several standard MI cable constructions are available, such as single conductor, twin conductor, and double cable. Custom-designed MI heating cable assemblies can be ordered for specific installations.

Other outer-covering materials that are sometimes specified for electric floor heating cable include (1) silicone rubber, (2) lead, and (3) tetrafluoroethylene (Teflon).

For a given floor heating cable assembly, the required cable spacing is determined from Equation (23). In general, cable power density and spacing should be such that floor panel power density is not greater than 15 W/ft^2. Check the latest edition of the *National Electrical Code* (NFPA *Standard* 70) and other applicable codes to obtain information on maximum panel power density and other required criteria and parameters.

Floor Heating Cable Installation. When PVC-jacketed electric heating cable is used for floor heating, the concrete slab is laid in two pourings. The first pour should be at least 3 in. thick and, where practical, should be insulating concrete to reduce downward heat loss. For a proper bond between the layers, the finish slab should be placed within 24 h of the first pour, with a bonding grout applied. The finish layer should be at least 1.5 in. and no more than 2 in. thick. This top layer must not be insulating concrete. At least 1 in. of perimeter insulation should be installed as shown in Figure 26.

The cable is installed on top of the first pour of concrete no closer than 2 in. from adjoining walls and partitions. Methods of fastening the cable to the concrete include the following:

1. Staple the cable to wood nailing strips fixed in the surface of the rough slab. The predetermined cable spacing is maintained by daubs of cement, plaster of paris, or tape.
2. In light or uncured concrete, staple the cable directly to the slab using hand-operated or powered stapling machines.
3. Nail special anchor devices to the first slab to hold the cable in position while the top layer is being poured.

Preformed mats can be embedded in the concrete in a continuous pour. The mats are positioned in the area between expansion and/or construction joints and electrically connected to a junction box. The slab is poured to within 1.5 to 2 in. of the finished level. The surface is rough-screeded and the mats placed in position. The final cap is

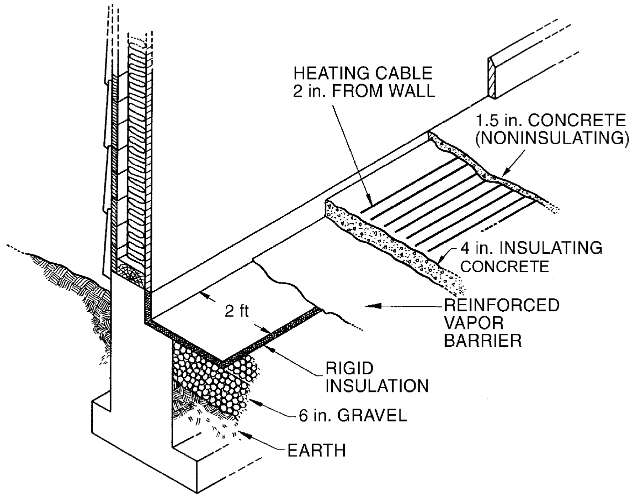


Fig. 26 Electric Heating Cable in Concrete Slab

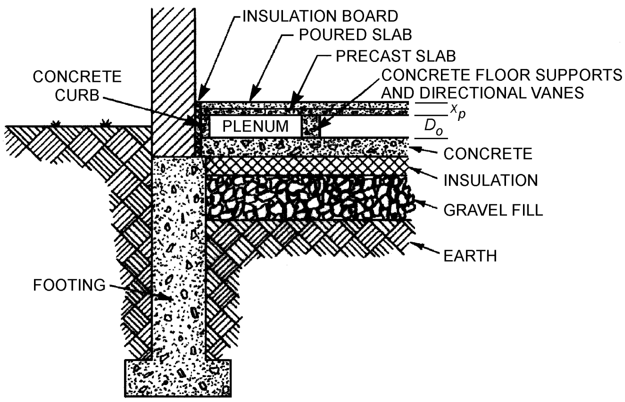


Fig. 27 Warm Air Floor Panel Construction

applied immediately. Because the first pour has not set, there is no adhesion problem between the first and second pours, and a monolithic slab results. A variety of contours can be developed by using heater wire attached to glass fiber mats. Allow for circumvention of obstructions in the slab.

MI electric heating cable can be installed in concrete slab using either one or two pours. For single-pour applications, the cable is fastened to the top of the reinforcing steel before the pour is started. For two-layer applications, the cable is laid on top of the bottom structural slab and embedded in the finish layer. Proper spacing between adjacent cable runs is maintained by using prepunched copper spacer strips nailed to the lower slab.

AIR-HEATED OR AIR-COOLED PANELS

Several methods have been devised to warm interior room surfaces by circulating heated air through passages in the floor. In some cases, the heated air is recirculated in a closed system. In others, all or a part of the air is passed through the room on its way back to the furnace to provide supplementary heating and ventilation. Figure 27 indicates one common type of construction. Compliance with applicable building codes is important.

In principle, the heat transfer equations for the panel surface and the design algorithm explained in the section on Design of Panels apply. In these systems, however, the fluid (air) moving in the duct has a virtually continuous contact with the panel. Therefore, $\eta \approx 1$, $D_o = 0$, and $M = 1$. Equation (18) gives the required surface temperature t_d of the plenum. The design of the air side can be carried out by following the principles given in Chapters 26 and 34 of the *ASHRAE Handbook—Fundamentals*.

CONTROLS

Automatic controls for panel heating may differ from those for convective heating because of the thermal inertial characteristics of the panel and the increase in the mean radiant temperature within the space under increasing loads. However, low-mass systems using thin metal panels or thin underlay with low thermal heat capacity may be successfully controlled with conventional control technology using indoor sensors. Many of the control principles for hot water heating systems described in Chapter 12 and Chapter 14 also apply to panel heating. Because radiant panels do not depend on air-side equipment to distribute energy, many control methods have been used successfully; however, a control interface between heating and cooling should be installed to prevent simultaneous heating and cooling.

High-mass panels such as concrete radiant slabs require a control approach different from that for low-mass panels. Because of thermal inertia, significant time is required to bring such massive panels from one operating point to another, say from vacation setback to standard operating conditions. This will result in long periods of discomfort from low temperature, then possibly periods of uncomfortable and wasteful overshoot. Careful economic analysis may reveal that a nighttime setback strategy is not warranted.

Once a slab is at operating conditions, the control strategy should be to supply the slab with heat at the rate that heat is being lost from the space (MacCluer et al. 1989). For hydronic slabs with constant circulator flow rate, this means modulating the temperature difference between the outgoing water and the returning water; this is accomplished via mixing valves, via fuel modulation, or, for constant thermal power sources, via pulse-width modulation (on-off control). Slabs with embedded electric resistance cable can be controlled by pulse-width modulators such as the common round thermostat with anticipator or its solid-state equivalent.

A related approach, outdoor reset control, has enjoyed wide acceptance. An outdoor reset control measures the outdoor air temperature, calculates the supply water temperature required for steady operation, and operates a mixing valve or boiler to achieve that supply water temperature. If the heating load of the controlled space is primarily a function of the outdoor air temperature, or indoor temperature measurement of the controlled space is impractical, then outdoor reset control alone is an acceptable control strategy. When other factors such as solar or internal gains are also significant, indoor temperature feedback should be added to the outdoor reset.

In all radiant panel applications, precautions must be taken to prevent excessive temperatures. A manual boiler bypass or other means of reducing the water temperature may be necessary to prevent new panels from drying out too rapidly.

Cooling Controls

The panel water circuit temperature is typically controlled by mixing, by heat exchange, or by using the water leaving the dehumidifier. Other considerations are listed in the section on General Design Considerations. It is imperative to dry out the building space before starting the panel water system, particularly after extended down periods such as weekends. Such delayed starting action can be controlled manually or by a device.

Panel cooling systems require the following basic areas of temperature control: (1) exterior zones, (2) areas under exposed roofs, to compensate for transmission and solar loads, and (3) each typical interior zone, to compensate for internal loads. For optimum results, each exterior corner zone and similarly loaded face zone should be treated as a separate subzone. Panel cooling systems may also be zoned to control temperature in individual exterior offices, particularly in applications where there is a high lighting load or for corner rooms with large glass areas on both walls.

The temperature control of the interior air and panel water supply should not be a function of the outdoor weather. The normal thermostat drift is usually adequate compensation for the slightly lower temperatures desirable during winter weather. This drift should be limited to result in a room temperature change of no more than 1.5°F. Control of the interior zones is best accomplished by devices that reflect the actual presence of the internal load elements. Frequently, time clocks and current-sensing devices are used on lighting feeders.

Because air quantities are generally small, constant volume supply air systems should be used. With the apparatus arranged to supply air at an appropriate dew point at all times, comfortable indoor conditions can be maintained throughout the year with a panel cooling system. As with all systems, to prevent condensation on window surfaces, the supply air dew point should be reduced during extremely cold weather according to the type of glazing installed.

Electric Heating Slab Controls

For comfort heating applications, the surface temperature of a floor slab is held to a maximum of 80 to 84°F. Therefore, when the slab is the primary heating system, thermostatic controls sensing air temperature should not be used to control temperature; instead, the heating system should be wired in series with a slab-sensing thermostat. The remote sensing thermostat in the slab acts as a limit switch to control maximum surface temperatures allowed on the slab. The ambient sensing thermostat controls the comfort level. For supplementary slab heating, as in kindergarten floors, a remote sensing thermostat in the slab is commonly used to tune in the desired comfort level. Indoor-outdoor thermostats are used to vary the floor temperature inversely with the outdoor temperature. If the heat loss of the building is calculated for an outdoor temperature of 70 to 0°F, and the floor temperature range is held from 70 to 84°F with a remote sensing thermostat, the ratio of the change in outdoor temperature to the change in slab temperature is 70:14, or 5:1. This means that a 5°F drop in outdoor temperature requires a 1°F increase in the slab temperature. An ambient sensing thermostat is used to vary the ratio between outdoor and slab temperatures. A time clock is used to control each heating zone if off-peak slab heating is desirable.

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For additional references on radiant heating, see the section on Bibliography in Chapter 15.