CHAPTER 6

PANEL HEATING AND COOLING

PANEL heating and cooling systems use temperature-controlled indoor surfaces on the floor, walls, or ceiling; temperature is maintained by circulating water, air, or electric current through a circuit embedded in or attached to the panel. A temperature-controlled surface is called a **radiant panel** if 50% or more of the design heat transfer on the temperature-controlled surface takes place by thermal radiation. Panel systems are characterized by controlled surface temperatures below 150°C. Panel systems may be combined either with a central forced-air system of one-zone, constant-temperature, constant-volume design, or with dual-duct, reheat, multizone or variable-volume systems, decentralized convective systems, or in-space fan-coil units. These combined systems are called **hybrid (load-sharing) HVAC systems**.

This chapter covers temperature-controlled surfaces that are the primary source of sensible heating and cooling in the conditioned space. For snow-melting and freeze-protection applications, see Chapter 50 of the 2003 *ASHRAE Handbook—HVAC Applications*. Chapter 15 covers high-temperature panels over 150°C, which may be 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, (3) elevates the temperature of solid objects by absorption but does not noticeably heat the air through which it travels, and (4) is exchanged continuously between all bodies in a building environment. The rate at which thermal radiation occurs 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 and receiver surfaces (viewing angle of the occupant to the thermal radiation source)

ASHRAE research project RP-876 (Lindstrom et al. 1998) concluded that surface roughness and texture have insignificant effects on thermal convection and thermal radiation, respectively. Surface emittance (the ratio of the radiant heat flux emitted by a body to that emitted by a blackbody under the same conditions) for typical indoor surfaces, such as carpets, vinyl texture paint, and plastic, remained between 0.9 and 1.0 for panel surface temperatures of 30 to 55°C.

The structure of the radiation surface is critical. 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.

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

One example of heating by thermal radiation 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 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 the amount of heat received from solar radiation, although there is little, if any, change in the ambient air temperature.

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 thermal comfort by thermal radiation is possible for even the most severe climatic conditions (Buckley 1989). Chapter 8 of the 2001 *ASHRAE Handbook—Fundamentals* has more information on thermal comfort.

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

Most building materials have relatively high surface emittance and, therefore, absorb and reradiate heat from active panels. Warm ceiling panels are effective because 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 long-wave thermal radiation outside. This is significant because all surfaces in the conditioned space tend to assume temperatures that result in an acceptable thermal comfort condition.

GENERAL EVALUATION

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

- Because not only indoor air temperature but also mean radiant temperature can be controlled, total human thermal comfort may be better satisfied.
- Because the operative temperature for required human thermal comfort may be maintained by primarily controlling the mean radiant temperature of the conditioned indoor space, dry-bulb air temperature may be lower (in heating) or higher (in cooling),

which reduces sensible heating or cooling loads (see Chapter 15 for the definition and calculation of operative and mean radiant temperatures).

- Hydronic panel systems may be connected in series, following other hydronic heating or cooling systems (i.e., their return water may be used), increasing exergetic efficiency.
- Comfort levels can be better than those of other space-conditioning systems because thermal loads are satisfied directly and air motion in the space corresponds to required ventilation only.
- Waste and low-enthalpy energy sources and heat pumps may be directly coupled to panel systems without penalty on equipment sizing and operation. Being able to select from a wide range of moderate operation temperatures ensures optimum design for minimum cost and maximum thermal and exergetic efficiency.
- Seasonal thermal distribution efficiency in buildings may be higher than in other hydronic systems.
- In terms of simple payback period, ceiling cooling panels and chilled beams have the highest technical energy savings potential (DOE 2002).
- Part or all of the building structure may be thermally activated (Meierhans and Olesen 2002).
- Space-conditioning equipment is not required at outdoor exposed walls, simplifying wall, floor, and structural systems.
- Almost all mechanical equipment may be centrally located, simplifying maintenance and operation.
- No space within the conditioned space is required for mechanical equipment. This feature is especially valuable in hospital patient rooms, offices, and other applications where space is at a premium, if maximum cleanliness is essential or legally required.
- Draperies and curtains can be installed at outdoor exposed walls 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 requirements usually do not exceed those required for ventilation and humidity control.
- Reduced airflow requirements help mitigate bioterrorism risk, especially in large buildings.
- Modular panels provide flexibility to meet changes in partitioning.
- A 100% outdoor air system may be installed with smaller penalties in 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.
- Modular panel systems can use the automatic sprinkler system piping (see NFPA *Standard* 13, Section 3.6). The maximum water temperature must not fuse the heads.
- Panel heating and cooling with 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, as well as walls and partitions directly exposed to panels.
- Panels can be combined with other space-conditioning systems to decouple several indoor requirements (e.g., humidity control, indoor air quality, air velocity) and optimally satisfy them without compromises.
- In-floor heating creates inhospitable living conditions for house dust mites compared to other heating systems (Sugawara et al. 1996).

Disadvantages are similar to those listed in Chapter 3 of the 2001 *ASHRAE Handbook—Fundamentals*. In addition,

- Response time can be slow if controls and/or heating elements are not selected or installed correctly.
- Improper selection of panel heating or cooling tube or electrical heating element spacing and/or incorrect sizing of heating/cooling source can cause nonuniform surface temperatures or insufficient sensible heating or cooling capacity.
- Panels can satisfy only sensible heating and cooling loads unless hybrid panels are used [see the section on Hybrid (Load-Sharing) HVAC Systems]. In a stand-alone panel cooling system, dehumidification and panel surface condensation may be of prime concern. Unitary dehumidifiers should be used, or a latent air-handling system should be introduced to the indoor space.

HEAT TRANSFER BY PANEL SURFACES

Sensible heating or cooling panels transfer heat through temperature-controlled (active) surface(s) to or from an indoor space and its enclosure surfaces by thermal radiation and natural convection.

Heat Transfer by Thermal Radiation

The basic equation for a multisurface enclosure with gray, diffuse isothermal surfaces is derived by radiosity formulation methods (see Chapter 3 of the 2001 *ASHRAE Handbook—Fundamentals*). This equation may be written as

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

where

q_r = net heat flux because of thermal radiation on active (heated or cooled) panel surface, W/m²
J_p = total radiosity leaving or reaching panel surface, W/m²
J_j = radiosity from or to another surface in room, W/m²
F_{pj} = radiation angle factor between panel surface and another surface in room (dimensionless)
n = number of surfaces in room other than panel(s)

Equation (1) can be applied to simple and complex enclosures with varying surface temperatures and emittances. The net heat flux by thermal radiation at the panel surfaces can be determined by solving the 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 2001 *ASHRAE Handbook—Fundamentals*. Fanger (1972) shows room-related angle factors; they may also be developed from algorithms in ASHRAE's *Energy Calculations* I (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 thermal radiation interchange in an indoor space is modeled by assuming that the surfaces radiate to a fictitious, finite surface that has an emittance and surface temperature that gives about the same heat flux as the real multisurface case (Walton 1980). In addition, angle factors do not need to be determined in evaluating a two-surface enclosure. The MRT equation may be written as

$$q_r = \sigma F_r [T_p^4 - T_r^4] \qquad (2)$$

where

σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/(m²·K⁴)
F_r = radiation exchange factor (dimensionless)
T_p = effective temperature of heating (cooling) panel surface, °C
T_r = temperature of fictitious surface (unheated or uncooled), °C

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

$$T_r = \frac{\sum_{j=p}^{n} A_j \varepsilon_j T_j}{\sum_{j=p}^{n} A_j \varepsilon_j} \quad (3)$$

where

A_j = area of surfaces other than panels, m²
ε_j = thermal emittance of surfaces other than panel(s) (dimensionless)

When the surface emittances of an enclosure are nearly equal, and surfaces directly exposed to the panel are marginally unheated (uncooled), then Equation (3) becomes the area-weighted average unheated (uncooled) temperature (AUST) of such surfaces exposed to the panels. Therefore, any unheated (uncooled) surface in the same plane with the panel is not accounted for by AUST. For example, if only part of the floor is heated, the remainder of the floor is not included in the calculation of AUST, unless it is observed by other panels in the ceiling or wall.

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

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

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 indoor spaces. Substituting this value in Equation (2), σF_r becomes 4.93×10^{-8}. Min et al. (1956) showed that this constant was 5.03×10^{-8} in their test room. Then the equation for heat flux from thermal radiation for panel heating and cooling becomes approximately

$$q_r = 5 \times 10^{-8}[(t_p + 273.15)^4 - (\text{AUST} + 273.15)^4] \quad (5)$$

where

t_p = effective panel surface temperature, °C
AUST = area-weighted temperature of all indoor surfaces of walls, ceiling, floor, windows, doors, etc. (excluding active panel surfaces), °C

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 indoor air temperature at the 1.5 m level closely approaches the AUST. In structures where the main heat gain is through the walls or where incandescent lighting is used, wall surface temperatures tend to rise considerably above the indoor air temperature.

Heat Transfer by Natural Convection

Heat flux from natural convection q_c occurs between the indoor air and the temperature-controlled panel surface. Thermal convection coefficients are not easily established. In natural convection, warming or cooling the boundary layer of air at the panel surface generates air motion. In practice, however, many factors, such as the indoor space configuration, interfere with or affect natural convection. Infiltration/exfiltration, occupants' movement, and mechanical ventilating systems can introduce some forced convection that disturbs the natural convection.

Parmelee and Huebscher (1947) included the effect of forced convection on heat transfer occurring on heating or cooling panel surfaces as an increment to be added to the natural-convection coefficient. However, increased heat transfer from forced convection should not be factored into calculations because the increments are unpredictable in pattern and performance, and forced convection does not significantly increase the total heat flux on the active panel surface.

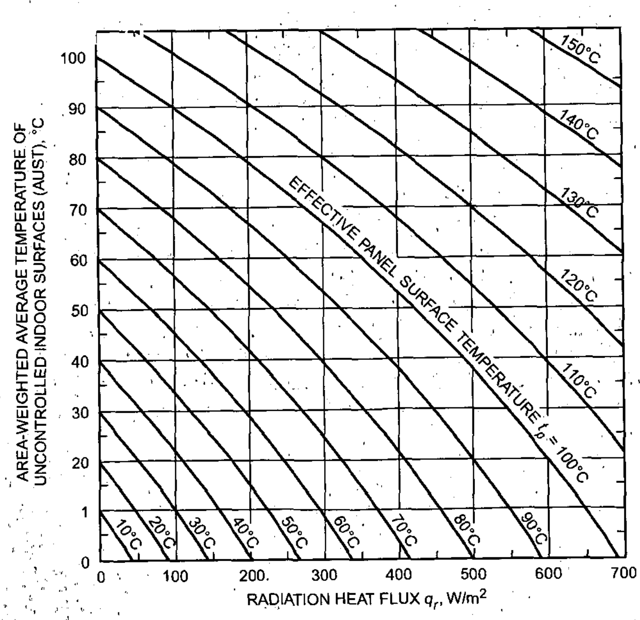


Fig. 1 Radiation Heat Flux at Heated Ceiling, Floor, or Wall Panel Surfaces

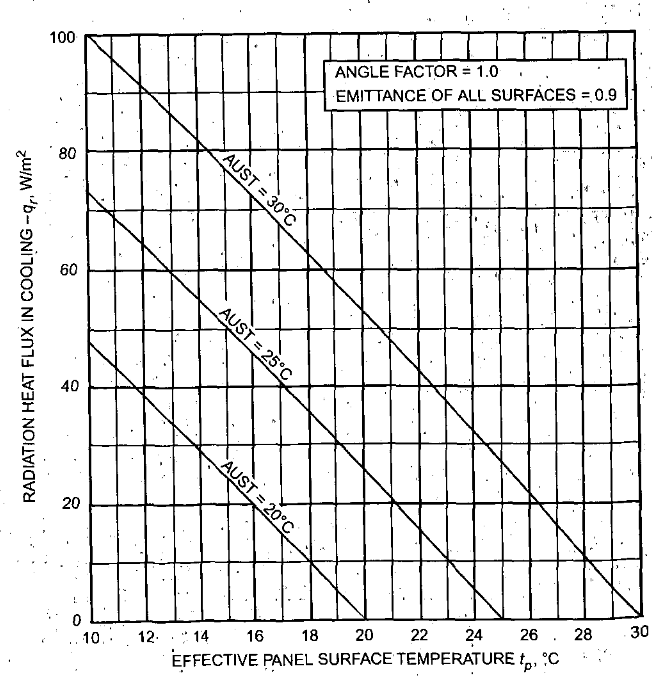


Fig. 2 Heat Removed by Radiation at Cooled Ceiling or Wall Panel Surface

Natural-convection heat flux in a panel system is a function of the effective panel surface temperature and the temperature of the air layer directly contacting the panel. The most consistent measurements are obtained when the dry-bulb air layer temperature is measured close to the region where the fully developed boundary layer begins, usually 50 to 65 mm from the panel surfaces.

Min et al. (1956) determined natural-convection coefficients 1.5 m above the floor in the center of a 3.66 by 7.47 m room (D_e = 4.91 m). Equations (6) through (11), derived from this research, can be used to calculate heat flux from panels by natural convection.

Natural-convection heat flux between **an all-heated ceiling surface and indoor air**

$$q_c = 0.20\frac{(t_p - t_a)^{1.25}}{D_e^{0.25}} \tag{6}$$

Natural-convection heat flux between **a heated floor or cooled ceiling surface and indoor air**

$$q_c = 2.42\frac{|t_p - t_a|^{0.31}(t_p - t_a)}{D_e^{0.08}} \tag{7}$$

Natural-convection heat flux between **a heated or cooled wall panel surface and indoor air**

$$q_c = 1.87\frac{|t_p - t_a|^{0.32}(t_p - t_a)}{H^{0.05}} \tag{8}$$

where

q_c = heat flux from natural convection, W/m^2
t_p = effective temperature of temperature-controlled panel surface, °C
t_a = indoor space dry-bulb air temperature, °C
D_e = equivalent diameter of panel (4 × area/perimeter), m
H = height of wall panel, m

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*, for which Equations (6) and (7) should be used. Otherwise, Equations (6), (7), and (8) can be simplified to the following by D_e = 4.91 m and H = 2.7 m:

Natural-convection heat flux between **an all-heated ceiling surface and indoor air**

$$q_c = 0.134(t_p - t_a)^{0.25}(t_p - t_a) \tag{9a}$$

Natural-convection heat flux from a heated ceiling may be augmented by leaving cold strips (unheated ceiling sections), which help initiate natural convection. In this case, Equation (9a) may be replaced by Equation (9b) (Kollmar and Liese 1957):

$$q_c = 0.87(t_p - t_a)^{0.25}(t_p - t_a) \tag{9b}$$

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

Natural-convection heat flux between **a heated floor or cooled ceiling surface and indoor air**

$$q_c = 2.13|t_p - t_a|^{0.31}(t_p - t_a) \tag{10}$$

Natural-convection heat flux between **a heated or cooled wall panel surface and indoor air**

$$q_c = 1.78|t_p - t_a|^{0.32}(t_p - t_a) \tag{11}$$

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

In cooling, t_p is less than t_a, so q_c is negative. Figure 3 shows heat flux 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.

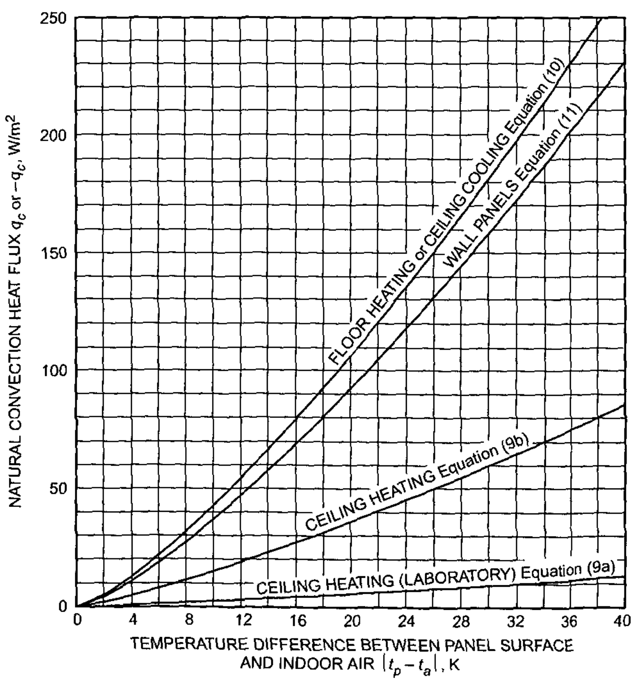


Fig. 3 Natural-Convection Heat Transfer at Floor, Ceiling, and Wall Panel Surfaces

Combined Heat Flux (Thermal Radiation and Natural Convection)

The combined heat flux on the active panel surface can be determined by adding the thermal-radiation heat flux q_r as calculated by Equation (5) (or from Figures 1 and 2) to the natural-convection heat flux 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 indoor space. In calculating the AUST, the surface temperature of interior walls may be assumed to be the same as the dry-bulb indoor air temperature. The inside surface temperature t_w of outdoor exposed walls and outdoor exposed floors or ceilings can be calculated from the following relationship:

$$h(t_a - t_u) = U(t_a - t_o) \tag{12}$$

or

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

where

h = natural-convection coefficient of the inside surface of an outdoor exposed wall or ceiling

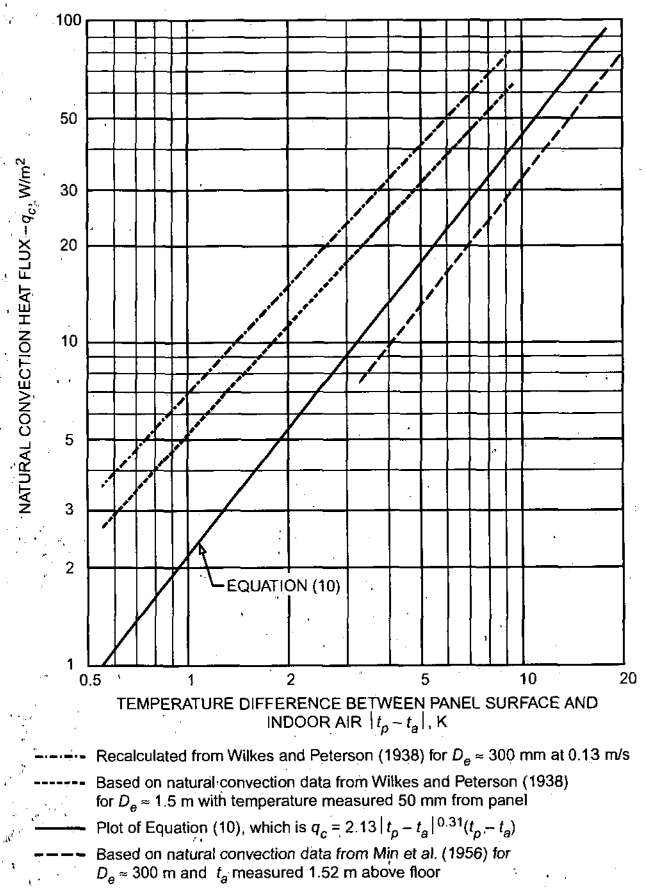


Fig. 4 Empirical Data for Heat Removal by Ceiling Cooling Panels from Natural Convection

U = overall heat transfer coefficient of wall, ceiling, or floor, W/(m²·K)
t_a = dry-bulb indoor space design air temperature, °C
t_u = inside surface temperature of outdoor exposed wall, °C
t_o = dry-bulb outdoor design air temperature, °C

From Table 1 in Chapter 25 of the 2001 *ASHRAE Handbook—Fundamentals*,

h = 9.26 W/(m²·K) for a horizontal surface with heat flow up
h = 9.09 W/(m²·K) for a vertical surface (wall)
h = 8.29 W/(m²·K) for a horizontal surface with heat flow down

Figure 5 is a plot of Equation (13) for a vertical outdoor wall with 21°C dry-bulb indoor air temperature and h = 9.09 W/(m²·K). For rooms with dry-bulb air temperatures above or below 21°C, 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 indoor air temperature are almost equal, if there is little or no outdoor exposure. Steinman et al. (1989) noted that this may not apply to enclosures with large fenestration or a high percentage of outdoor exposed wall and/or ceiling surface area. These surfaces may have a lower (in heating) or higher (in cooling) AUST, which increases the heat flux from thermal radiation.

Figure 7 shows the combined heat flux from thermal radiation and natural convection for cooling, as given in Figures 2 and 4. The data in Figure 7 do not include solar, lighting, occupant, or equipment heat gains.

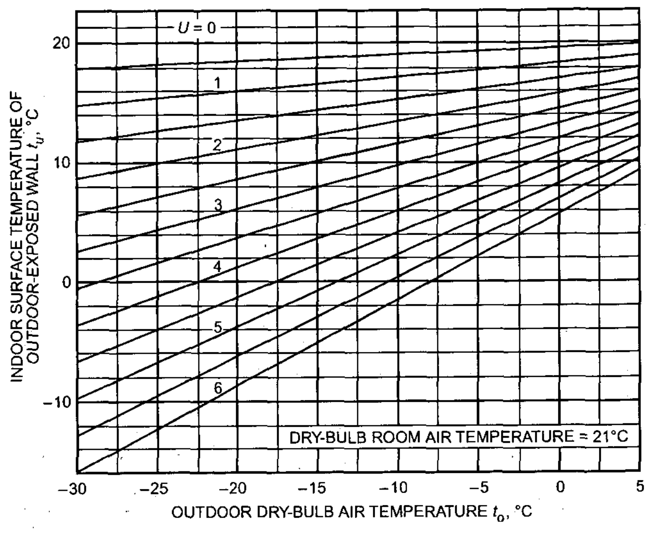


Fig. 5 Relation of Inside Surface Temperature to Overall Heat Transfer Coefficient

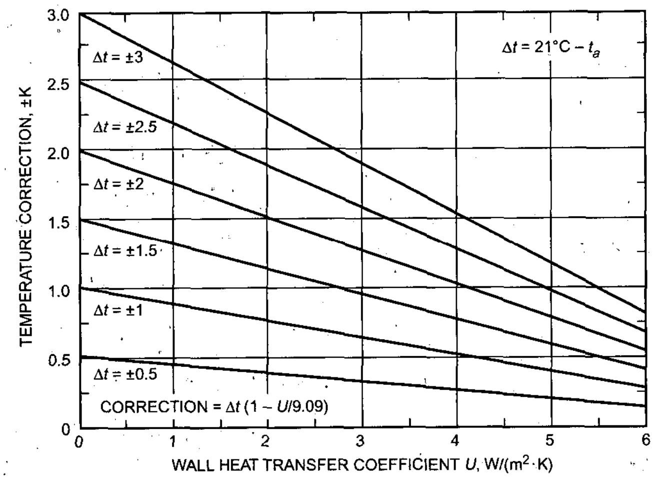


Fig. 6 Inside Surface Temperature Correction for Exposed Wall at Dry-Bulb Air Temperatures Other Than 21°C

In suspended-ceiling panels, heat is transferred from the back of the ceiling panel to the floor slab above (in heating) or vice versa (in cooling). The ceiling panel surface temperature is affected because of heat transfer to or from the panel and the slab by thermal radiation and, to a much smaller extent, by natural convection. The thermal-radiation component of the combined heat flux can be approximated using Equation (5) or Figure 1. The natural-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, because 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 artificial lighting fixtures are recessed into the suspended ceiling space, radiation from the top of the fixtures raises the overhead slab temperature and heat is transferred to the indoor air by natural convection. This heat is absorbed at the top of the cooled ceiling panels both by thermal radiation, in accordance with Equation (5) or Figure 2, and by thermal convection, generally in accordance with

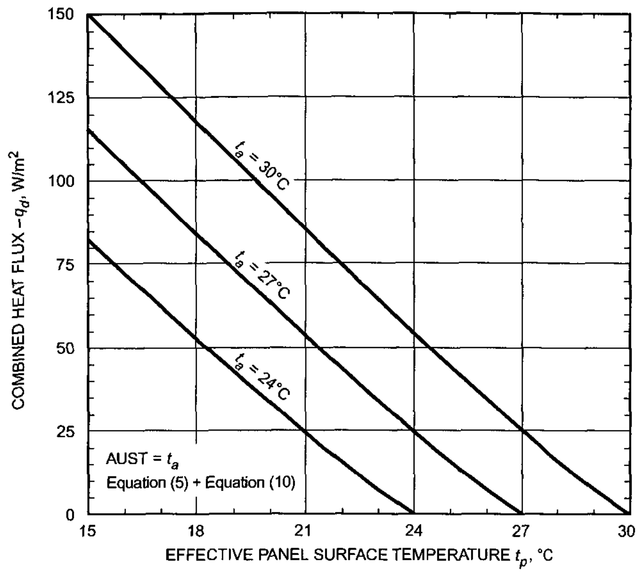


Fig. 7 Cooled Ceiling Panel Performance in Uniform Environment with No Infiltration and No Internal Heat Sources

Equation (9b). The amount the top of the panel absorbs depends on the system. Similarly, panels installed under a roof absorb additional heat, depending on configuration and insulation.

GENERAL DESIGN CONSIDERATIONS

Panel systems and hybrid HVAC systems (typically a combination of panels and forced-convection systems) are similar to other air-water systems in the arrangement of system components. With panel systems, indoor thermal conditions are maintained primarily by thermal radiation, rather than by natural or forced-convection heat transfer. Sensible indoor space heating and cooling loads are calculated conventionally. In hybrid HVAC systems, the latent load is assigned to a forced-convection system, and a large part of the sensible load is assigned to the panel system. In a hybrid HVAC system, indoor air temperature and MRT can be controlled independently (Kilkis et al. 1995).

Because the mean radiant temperature (MRT) in a panel-heated or cooled indoor space increases or decreases as the sensible load increases, the indoor air temperature during this increase may be altered without affecting human thermal comfort. In ordinary structures with normal infiltration loads, the required reduction in air temperature is small, allowing a conventional room thermostat to be used.

In panel heating systems, lowered nighttime air and panel 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 nighttime air and panel 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 way to provide a higher-than-normal rate of heat input for rapid warm-up (e.g., fast-acting ceiling panels) is necessary.

Metal 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 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 also may be cut and fitted in the field; however, modification should be kept to a minimum to keep installation costs down. Hydronic panels can run continuously.

Panel Thermal Resistance

Any thermal resistance between the indoor space and the active panel surface, as well as between the active panel surface and the hydronic tubing or electric circuitry in the panel, reduces system performance. Thermal resistance to heat transfer may vary considerably among different panels, depending on the type of bond between the tubing (electric cabling) 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, (m·K)/W
r_s = thermal resistance between tube (electric cable) and panel body per unit spacing between adjacent tubes (electric cables), (m·K)/W
r_p = thermal resistance of panel body, (m^2·K)/W
r_c = thermal resistance of active panel surface covers, (m^2·K)/W
r_u = characteristic (combined) panel thermal resistance, (m^2·K)/W

For a given adjacent tube (electric cable) spacing M,

$$r_u = r_t M + r_s M + r_p + r_c \tag{14}$$

When the tubes (electric cables) are embedded in the slab, r_s may be neglected. However, if they are externally attached to the body of 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,

$$r_p = \frac{x_p - D_o/2}{k_p} \tag{15a}$$

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 (electric cable) are attached to the panel,

$$r_p = \frac{x_p}{k_p} \tag{15b}$$

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

Thermal resistance per unit on-center spacing (M = unity) of circular tubes with inside diameter D_i and thermal conductivity k_t is

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

For an elliptical tube with semimajor and semiminor axes of a and b, respectively, measured at both the outside and inside of the tube,

$$k_t = \ln\frac{(a_o + b_o)/(a_i + b_i)}{2\pi k_t} \tag{16b}$$

In an electric cable, $r_t = 0$.

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

$$r_t = \frac{1}{hD_i} \tag{16c}$$

If the tube has multiple layers, Equations (16a) or (16b) should be applied to each individual layer and then summed to calculate the tube's total thermal resistance. Thermal resistance of capillary tube mats can also be calculated from either Equation (16a) or (16b). Typically, capillary tubes are circular, 2 mm in internal diameter, and 12 mm apart.

Capillary tube mats can be easily applied to existing ceilings in a sand plaster cover layer. Capillary tubes operate under negative pressure, so they do not leak.

If the tube material is nonmetallic, oxygen ingress may be a problem, especially in panel heating. To avoid oxygen corrosion in the heating system, either (1) tubing with an oxygen barrier layer, (2) corrosion-inhibiting additives in the hydronic system, or (3) a heat exchanger separating the panel circuit from the rest of the system should be used.

Table 6 in Chapter 3 of the 2001 *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

Active panel surface coverings like carpets and pads on the floor can have a pronounced effect on a panel system's performance. The added thermal resistance r_c reduces the panel surface heat flux. To reestablish the required performance, the water temperature must be increased (decreased in cooling). Thermal resistance of a panel covering is

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

where

x_c = thickness of each panel covering, m
k_c = thermal conductivity of each panel cover, W/(m·K)

If the active panel surface has more than one cover, individual r_c values should be added. Table 3 gives typical r_c values for floor coverings.

If there are covered and bare floor panels in the same hydronic system, it may be possible to maintain a sufficiently high 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.

Table 1 Thermal Resistance of Ceiling Panels

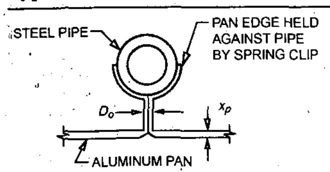
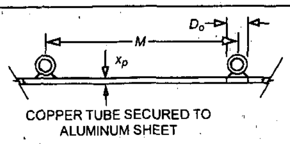
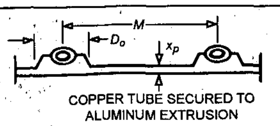
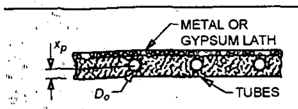
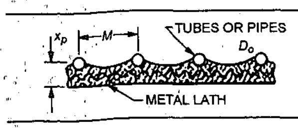
<table>
<tr><th rowspan="2">Type of Panel</th><th colspan="2">Thermal Resistance</th></tr>
<tr><th>r_p,</th><th>r_s,</th></tr>
<tr><td></td><td>$\frac{x_p}{k_p}$</td><td></td></tr>
<tr><td></td><td>$\frac{x_p}{k_p}$</td><td></td></tr>
<tr><td></td><td>$\frac{x_p}{k_p}$</td><td></td></tr>
<tr><td></td><td>$\frac{x_p - D_o/2}{k_p}$</td><td>≈ 0</td></tr>
<tr><td></td><td>$\frac{x_p - D_o/2}{k_p}$</td><td>$\le$</td></tr>
</table>

Table 2 Thermal Conductivity of Typical Tube Material

Material	Thermal Conductivity k_t, W/(m·K)
Carbon steel (AISI 1020)	52
Aluminum	237
Copper (drawn)	390
Red brass (85 Cu-15 Zn)	159
Stainless steel (AISI 202)	17
Low-density polyethylene (LDPE)	0.31
High-density polyethylene (HDPE)	0.42
Cross-linked polyethylene (VPE or PEX)	0.38
Textile-reinforced rubber hose (HTRH)	0.29
Polypropylene block copolymer (PP-C)	0.23
Polypropylene random copolymer (PP-RC)	0.24

Table 3 Thermal Resistance of Floor Coverings

Description	Thermal Resistance r_c, $(m^2 \cdot K)/W$
Bare concrete, no covering	0
Asphalt tile	0.009
Rubber tile	0.009
Light carpet	0.106
Light carpet with rubber pad	0.176
Light carpet with light pad	0.247
Light carpet with heavy pad	0.300
Heavy carpet	0.141
Heavy carpet with rubber pad	0.211
Heavy carpet with light pad	0.281
Heavy carpet with heavy pad	0.335
10 mm hardwood	0.095
16 mm wood floor (oak)	0.100
13 mm oak parquet and pad	0.120
Linoleum	0.021
Marble floor and mudset	0.031
Rubber pad	0.109
Prime urethane underlayment, 10 mm	0.284
1.5 kg/m^3 waffled sponge rubber	0.137
Bonded urethane, 13 mm	0.368

Notes:
1. Carpet pad thickness should not be more than 6 mm.
2. Total thermal resistance of carpet is more a function of thickness than of fiber type.
3. Generally, thermal resistance (R-value) is approximately 0.018 times the total carpet thickness in millimetres.
4. Before carpet is installed, verify that the backing is resistant to long periods of continuous heat up to 50°C.

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 (gain in cooling). Panel heat losses (gains) are part of the building heat loss (gain) if the heat transfer is between the panel and the outside of the building. If heat transfer is between the panel and another conditioned space, the panel heat loss (gain) is a positive conditioning contribution for that space instead. In either case, the magnitude of panel loss (gain) should be calculated.

Panel heat loss (gain) to (from) space outside the conditioned space 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 unless it is properly insulated.

The heat loss from most panels can be calculated by using the coefficients given in Table 4 in Chapter 25 of the 2001 *ASHRAE Handbook—Fundamentals*. These coefficients should not be used to determine downward heat loss from panels built on grade because heat flow from them is not uniform (ASHAE 1956, 1957; Sartain and Harris 1956). The heat loss from panels built on grade can be estimated from Figure 8 or from Equation (6) in Chapter 28 of the 2001 *ASHRAE Handbook—Fundamentals*.

Panel Performance

As with other electric or hydronic terminal units, panel performance can be described by the following equation:

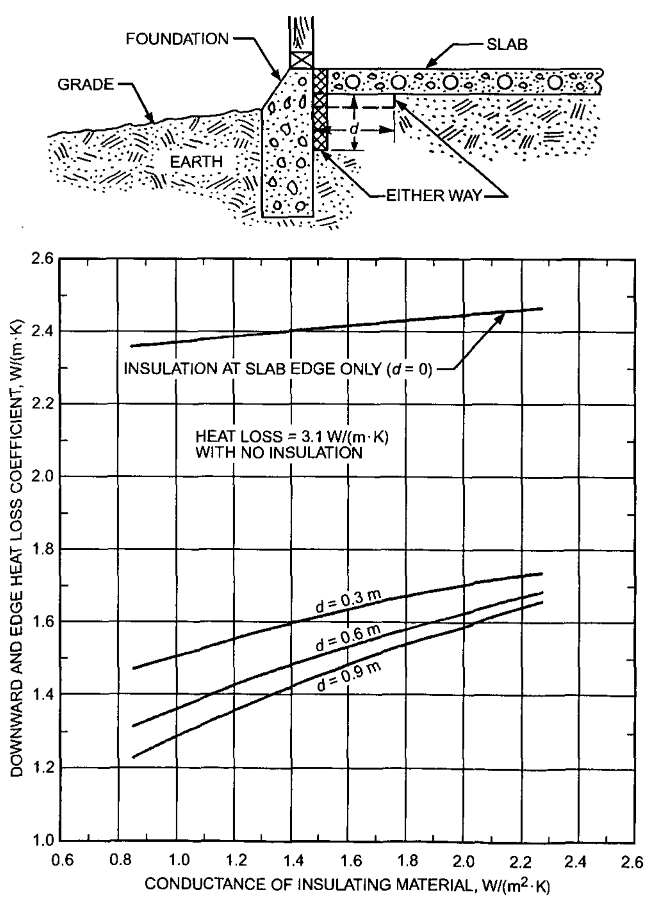


Fig. 8 Downward and Edgewise Heat Loss Coefficient for Concrete Floor Slabs on Grade

$$q = C\Delta T|\Delta T|^{m-1} \tag{18}$$

where

q = combined heat flux on panel surface, W/m²
C = characteristic performance coefficient, W/(m²·K^m)
ΔT = temperature difference, either $t_p - t_o$ in electric heating or $t_w - t_o$ in hydronic heating, K
t_o = operative temperature, °C
m = $2 + r_c/2r_p$

C and m for a particular panel may be either experimentally determined or calculated from the design material given in this chapter. In either case, sufficient data or calculation points must be gathered to cover the entire operational design range (ASHRAE Draft *Standard* 138P).

PANEL DESIGN

Either hydronic or electric circuits control the active panel surface temperature. The required effective surface temperature t_p necessary to maintain a combined heat flux q (where $q = q_r + q_c$) at steady-state design conditions can be calculated by using applicable heat flux equations for q_r and q_c, depending on the position of the panel. At a given t_a, AUST must be predicted first. Figures 9 and 10 can also be used to find t_p when q and AUST are known. The next step is to determine the required average 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 heating and cooling panels, positioned either at the ceiling or on the floor.

The combined heat flux for ceiling and floor panels can be read directly from Figure 9. Here q_u is the combined heat flux on the floor panel and q_d is the combined heat flux on the ceiling panel. For an electric heating system, t_w scales correspond to the skin temperature of the cable. The following algorithm (TSI 1994) may also be used to design and analyze panels under steady-state conditions:

$$t_d \approx t_a + \frac{(t_p - t_a)M}{2W\eta + D_o} + q(r_p + r_c + r_s M) \tag{19}$$

where

t_d = average skin temperature of tubing (electric cable), °C
q = combined heat flux on panel surface, W/m²
t_a = dry-bulb indoor air design temperature, °C. In floor-heated or ceiling-cooled indoor spaces that have large fenestration, t_a may be replaced with AUST.
D_o = outside diameter of embedded tube or characteristic contact width of attached heating or cooling element with panel (see Table 1), m
M = on-center spacing of adjacent tubes (electric cables), m
$2W$ = net spacing between tubing (electric cables), $M - D_o$, m
η = fin efficiency, dimensionless

The first two terms in Equation (19) give the maximum (minimum in cooling) value of the panel surface temperature profile; consequently, if tube spacing M is too large, hot strips along the panel surface may occur, or local condensation occur on these strips in sensible cooling mode.

$$\eta = \frac{\tanh(fW)}{fW} \tag{20a}$$

$$\eta \approx 1/fW \qquad \text{for } fW > 2 \tag{20b}$$

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

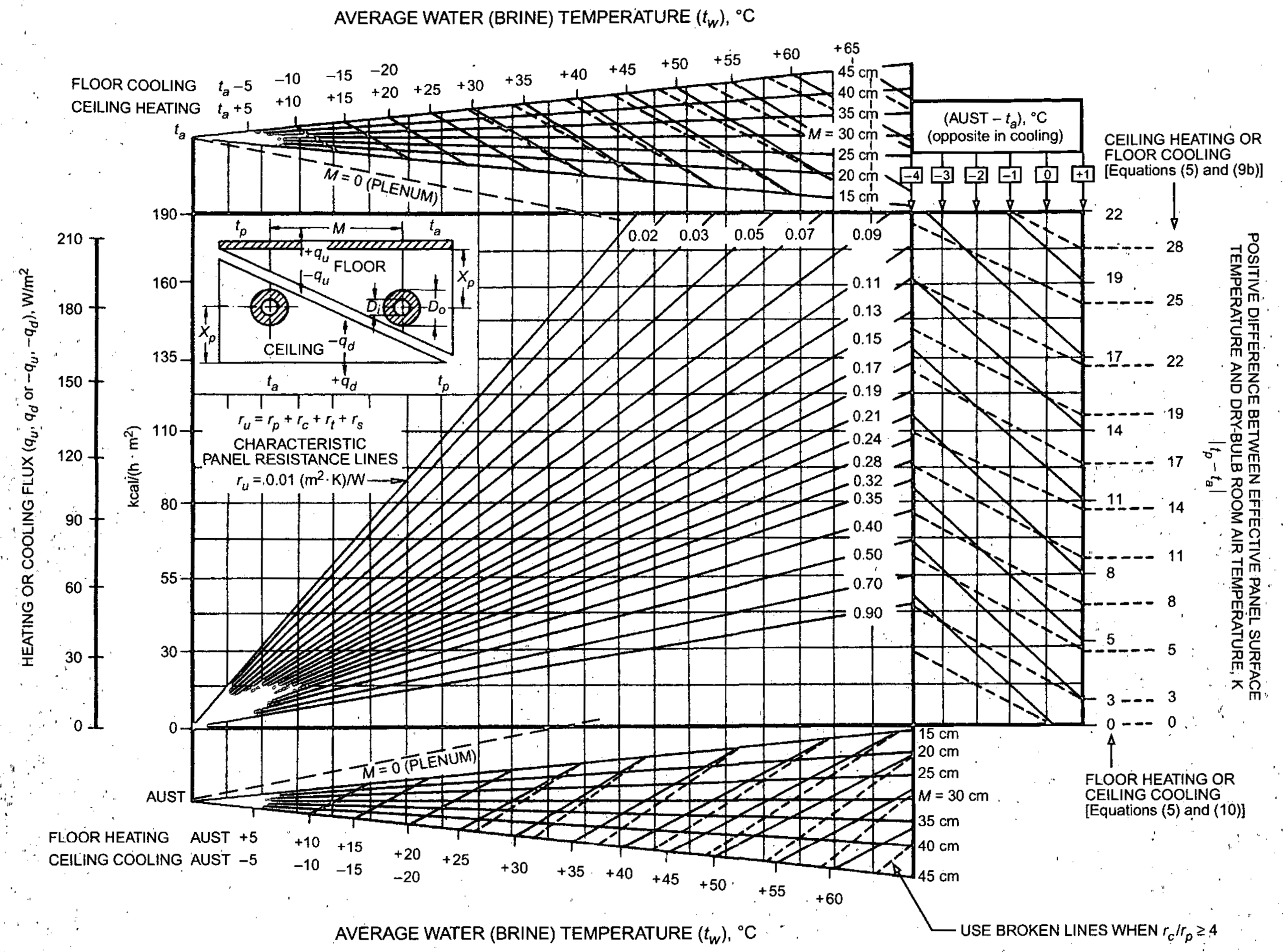


Fig. 9 Design Graph for Sensible Heating and Cooling with Floor and Ceiling Panels

$$f \approx \left[\frac{q}{m(t_p - t_a)\sum_{i=1}^{n} k_i x_i} \right]^{1/2} \quad \text{for } t_p \neq t_a \tag{21}$$

where

f = fin coefficient
m = $2 + r_c/2r_p$
n = total number of different material layers, including panel and surface covers
x_i = characteristic thickness of each material layer i, m
k_i = thermal conductivity of each layer i, W/(m·K)

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

$$t_w = (q + q_b)Mr_t + t_d \tag{22}$$

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

This algorithm may be applied to outdoor slab heating systems, provided that the combined heat flux q is calculated according to Chapter 50 in the 2003 *ASHRAE Handbook—HVAC Applications*, with the following conditions: no snow, no evaporation, q (in panel heating) = q_h (radiation and convection heat flux in snow-melting calculations). With a careful approach, outdoor slab cooling systems may be analyzed by incorporating the solar radiation gain, thermal radiation, and forced convection from the sky and ambient air.

HEATING AND COOLING PANEL SYSTEMS

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

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

Residential heating applications usually consist of tubes or electric elements embedded in masonry floors or plaster ceilings. This construction is suitable where loads are stable and building design minimizes solar effects. However, in buildings where fenestration is large and thermal loads change abruptly, the slow response, thermal lag, and override effect of masonry panels are unsatisfactory. Metal ceiling panels with low thermal mass respond quickly to load changes (Berglund et al. 1982).

Panels are preferably located in the ceiling because it is exposed to all other indoor surfaces, occupants, and objects in the conditioned indoor space. It is not likely to be covered, as floors are, and higher surface temperatures can be maintained. Figure 10 gives design data for ceiling and wall panels with effective surface temperatures up to 140°C.

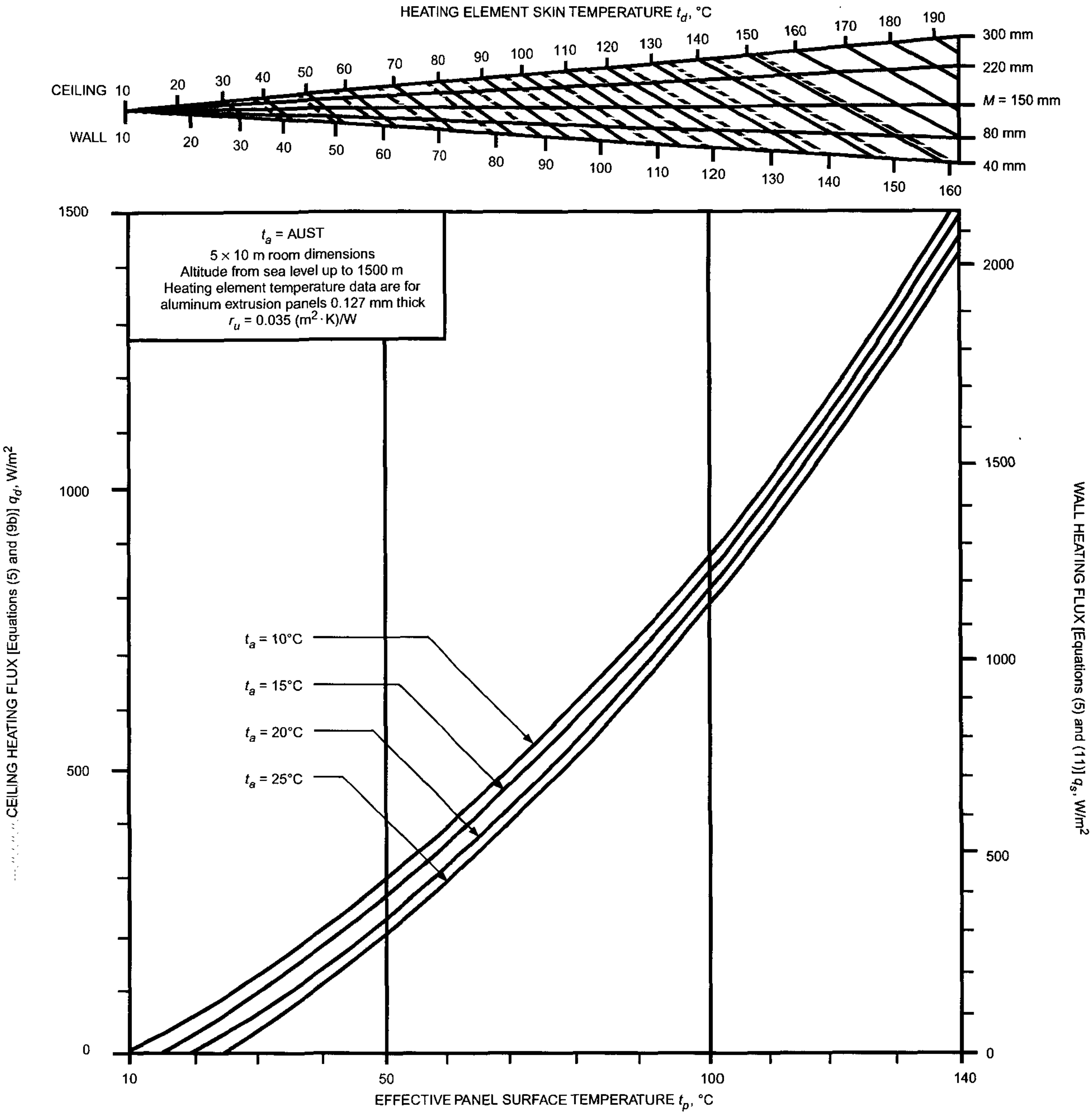


Fig. 10 Design Graph for Heating with Aluminum Ceiling and Wall Panels

Example 1. An in-slab, on-grade panel (see Figure 20) will be used for both heating and cooling. M = 300 mm, r_u = 0.09 (m²·K)/W, and r_c/r_p is less than 4. t_a is 20°C in winter and 24.5°C in summer.

AUST is expected to be 1 K less than t_a in winter heating and 0.5 K higher than t_a in summer cooling.

What is the average water temperature and effective floor temperature (1) for winter heating when q_u = 130 W/m², and (2) for summer cooling when $-q_u$ = 50 W/m²?

Solution:

Winter heating

To obtain the average water temperature using Figure 9, start on the left axis where q_u = 130 W/m². Proceed right to the intersect r_u = 0.09 and then down to the M = 300 mm line. The reading is AUST + 31, which is the solid line value because r_c/r_p < 4. As stated in the initial problem, AUST = t_a – 1 or AUST = 20 – 1 = 19°C. Therefore, the average water temperature would be t_w = 31 + 19 = 50°C.

To find the effective floor temperature, start at q_u = 130 W/m² in Figure 9 and proceed right to AUST = t_a – 1 K. The solid line establishes 12 K as the temperature difference between the panel and the indoor air. Therefore, the effective floor temperature t_p = t_a + 12 or t_p = 20 + 12 = 32°C.

Summer cooling

Using Figure 9, start at the left axis at $-q_u$ = 50 W/m². Proceed to r_u = 0.09, and then up (for cooling) to M = 300 mm, which reads t_a – 11 or 24.5 – 11 = 13.5°C average water temperature for cooling.

To obtain the effective floor temperature at $-q_u$ = 50 W/m², proceed to AUST – t_a = +0.5 K, which reads –5°C. Therefore, the effective floor temperature is 24.5 – 5 = 19.5°C.

Example 2. An aluminum extrusion panel, which is 0.127 mm thick with heat element spacing of M = 150 mm, is used in the ceiling for heating. If a ceiling heat flux q_d of 1260 W/m² is required to maintain room temperature t_a at 20°C, what is the required heating element skin temperature t_d and effective panel surface temperature t_p?

Solution:

Using Figure 10, enter the left axis heat flux q_d at 1260 W/m^2. Proceed to the line corresponding to t_a = 20°C and then move up to the M = 150 mm line. The ceiling heating element temperature t_d at the intersection point is 160°C. From the bottom axis of Figure 10, the effective panel surface temperature t_p is 129°C.

Special Cases

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

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

Warm air and electric heating elements are two design concepts 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 indoor space. Generally, these systems are used as floor 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 panels can be used with two- and four-pipe distribution systems. Figure 11 shows a typical system arrangement. It is common to design for a 10 K temperature drop for heating across a given grid and a 3 K rise for cooling, but larger temperature differentials may be used, if applicable.

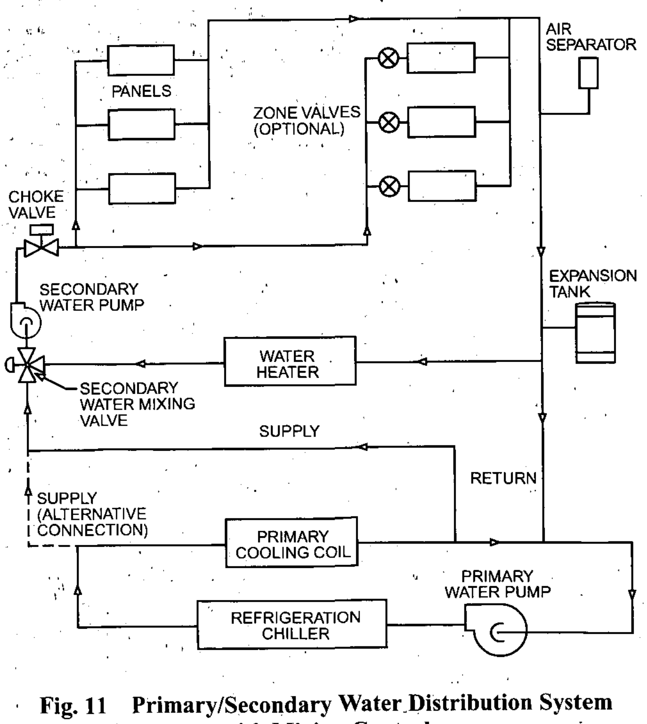


Fig. 11 Primary/Secondary Water Distribution System with Mixing Control

Panel design requires determining panel area, panel type, supply water temperature, water flow rate, and panel arrangement. Panel performance is directly related to indoor space conditions. Air-side design also must be established. Heating and cooling loads may be calculated by procedures covered in Chapters 25 through 30 of the 2001 *ASHRAE Handbook—Fundamentals*. The procedure is as follows:

Sensible Cooling

1. Determine indoor design dry-bulb temperature, relative humidity, and dew point.
2. Calculate sensible and latent heat gains.
3. Establish minimum supply air quantity for ventilation.
4. Calculate latent cooling available from supply air.
5. Calculate sensible cooling available from supply air.
6. Determine remaining sensible cooling load to be satisfied by panel system.
7. Determine minimum permissible effective cooling panel surface temperature that will not lead to surface condensation at design conditions.
8. Determine AUST.
9. Determine necessary panel area for remaining sensible cooling.
10. Determine average panel cooling water (brine) temperature for given tube spacing, or determine necessary tube spacing if average panel cooling water (brine) temperature is known.

Sensible Heating

1. Designate indoor design dry-bulb temperature for panel heating.
2. Calculate room heat loss.
3. Determine AUST. 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 indoor air temperature.
4. Calculate required effective surface temperature of panel. Refer to Figures 9 and 10 if AUST does not greatly differ from indoor air temperature. Otherwise, use Equations (5), (9a), (9b), (10), and (11) or refer to Figures 1 and 3.
5. Determine panel area. Refer to Figures 9 and 10 if AUST does not vary greatly from indoor air temperature.
6. Refer to manufacturers' data for panel surface temperatures higher than those given in Figures 9 and 10. For panels with several covers, average temperature of each cover and effective panel surface temperature must be calculated and compared to temperature-withstanding capacity for continuous operation of every cover material. For this purpose, Equation (18) may be used: add thermal resistances of all cover layers between panel surface and cover layer in question, then multiply by q and add to first two terms in Equation (18). This is t_{ha}, approximated temperature of the particular layer at design.
7. Determine tube spacing for a given average water temperature or select electric cable properties or electric mat size.
8. In a hydronic panel system, if tube spacing is known, determine required average water temperature.
9. Design panel arrangement.

Other Steps Common for Sensible Heating and Cooling

1. Check thermal comfort requirements in the following steps [see Chapter 8 of the 2001 *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 2001 *ASHRAE Handbook—Fundamentals*).
   (b) Determine optimum operative temperature at coldest point in conditioned space (see the Comfort Equations for Radiant Heating section in Chapter 8 of the 2001 *ASHRAE Handbook—Fundamentals*. Note that the same equations may be adopted for panel cooling).

(c) Determine MRT at the coldest point in the conditioned space [see Chapter 15 and Fanger (1972)].
Note: If indoor air velocity is less than 0.4 m/s and MRT is less than 50°C, operative temperature may be approximated as the average of MRT and t_a.
(d) From the definition of operative temperature, establish optimum indoor design air temperature at coldest point in the room. If optimum indoor design air temperature varies greatly from designated design temperature, designate a new temperature.
(e) Determine MRT at hottest point in conditioned space.
(f) Calculate operative temperature at hottest point in conditioned space.
(g) Compare operative temperatures at hottest and coldest points. For light activity and normal clothing, the acceptable operative temperature range is 20 to 24°C [see NRB (1981) and ANSI/ASHRAE *Standard* 55-1992R]. If the range is not acceptable, the panel system must be modified.
(h) Calculate radiant temperature asymmetry (NRB 1981). Acceptable ranges are less than 5 K for warm ceilings, 15 K for cool ceilings, 10 K for cool walls, and 27 K for warm walls at 10% local discomfort dissatisfaction (ANSI/ASHRAE *Standard* 55-1992).

2. Determine water flow rate and pressure drop. Refer to manufacturers' guides for specific products, or use the guidelines in Chapter 35 of the 2001 *ASHRAE Handbook—Fundamentals*. Chapter 12 of this volume also has information on hydronic heating and cooling systems.
3. 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:

$$Q_i = (L_{eq}/L_i)^{1/r} Q_{tot} \tag{23}$$

where

$L_{eq} = \left[\sum_{i=1}^{n} L_i^{-1/r} \right]^{-r}$, m
Q_i = flow rate in circuit *i*, L/s
Q_{tot} = total flow rate in supply manifold, L/s
L_i = coil length of hydronic circuit *i*, m
r = 1.75 for hydronic panels (Siegenthaler 1995)

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

- 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.
- Individual panels can be connected for parallel flow using headers, or for sinuous or serpentine flow. To avoid flow irregularities in 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, using a combination series-parallel arrangement can solve this problem. Serpentine flow ensures a more even panel surface temperature throughout the heating or cooling zone.
- 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.
- Design piping systems to accept thermal expansion adequately. Do not allow forces from piping expansion to be transmitted to panels. Thermal expansion of ceiling panels must be considered.
- In hydronic systems, thermoplastic, rubber tubes, steel, or copper pipes 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 a soft-drawn coil. Fittings and connections should be minimized. Bending should be used to change direction. 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.
- Placing the thermostat on a wall where it can observe both the outdoor exposed wall and the warm panel should be considered. The normal thermostat cover reacts to the warm panel, and thermal radiation from the panel to the cover tends to alter the control point so that the thermostat controls 1 to 2 K lower when the outdoor temperature is a minimum and the panel temperature is a maximum. Experience indicates that panel-heated spaces are more comfortable under these conditions than when the thermostat is located on a back wall.
- 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.
- When selecting heating design temperatures for a ceiling panel surface, the design parameters are as follows:
  - Excessively high temperatures over the occupied zone cause the occupant to experience a "hot head effect."
  - Temperatures that are too low can result in an oversized, uneconomical panel and a feeling of coolness at the outside wall.
  - Locate ceiling panels adjacent to perimeter walls and/or areas of maximum load.
  - With normal ceiling heights of 2.4 to 2.8 m, panels less than 1 m wide at the outside wall can be designed for 113°C surface temperature. If panels extend beyond 1 m into the indoor space, the panel surface temperature should be limited to the values given in Figure 16. The surface temperature of concrete or plaster panels is limited by construction.
- Floor panels are limited to surface temperatures of less than 29°C in occupied spaces for comfort reasons. Subfloor temperature may be limited to the maximum exposure temperature specified by the floor cover manufacturer.
- When the panel chilled-water system is started, the circulating water temperature should be maintained at indoor air temperature until the air system is completely balanced, the dehumidification equipment is operating properly, and building relative humidity is at design value.
- 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 activate panel CO (cooling only) mode, and both panels are used for cooling.
- To prevent condensation on the cooling panels, the panel water supply temperature should be maintained at least 0.5 K above the indoor design dew-point temperature. This minimum difference is recommended to allow for the normal drift of temperature controls for water and air systems, and also to provide a factor of safety for temporary increase in indoor relative humidity.
- Selection of summer design indoor dew point below 10°C generally is not economical.

- The most frequently applied method of dehumidification uses cooling coils. If the main cooling coil is six rows or more, the dew point of leaving air will approach the leaving water temperature. The cooling water leaving the dehumidifier can then be used for the panel water circuit.
- 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.
- When chemical dehumidification is used, hygroscopic chemical dew-point controllers are required at the central apparatus and at various zones to monitor dehumidification.
- When cooled ceiling panels are used with a variable air volume (VAV) system, the air supply rate should be near maximum volume to ensure adequate dehumidification before the cooling ceiling panels are activated.

Other factors to consider when using panel systems are .

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

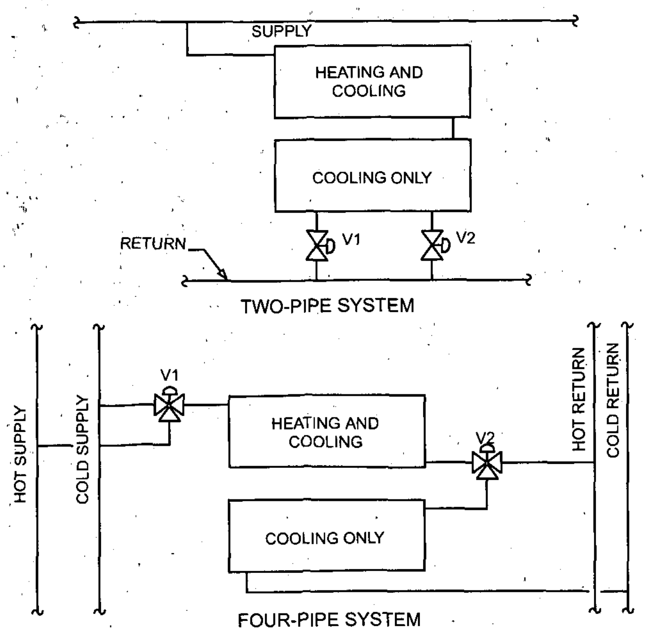


Fig. 12 Split Panel Piping Arrangement for Two-Pipe and Four-Pipe Systems

Ceiling panel systems are an outgrowth of perforated metal, suspended acoustical ceilings. These ceiling panel 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 part of the indoor space and compatible matching acoustical panels for the remaining ceiling area.

Three types of metal ceiling systems are available. The first consists of light aluminum panels, usually 300 by 600 mm, attached in the field to 15 mm galvanized pipe coils. Figure 13 illustrates a metal ceiling panel system that uses 15 mm pipe laterals on 150, 300, or 600 mm 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 910 by 1520 mm and are held in position by various types of ceiling suspension systems, most typically a standard suspended T-bar 600 by 1200 mm 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.

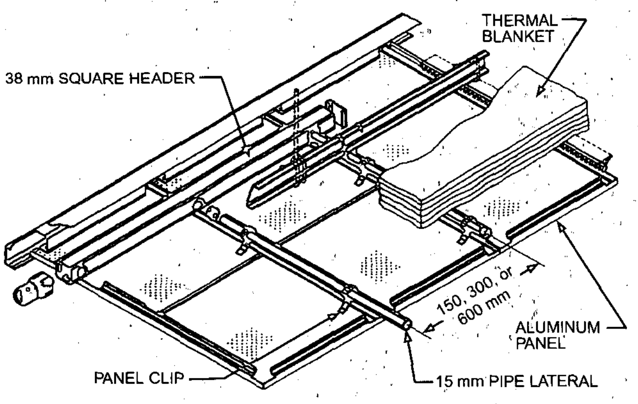


Fig. 13 Metal Ceiling Panels Attached to Pipe Laterals

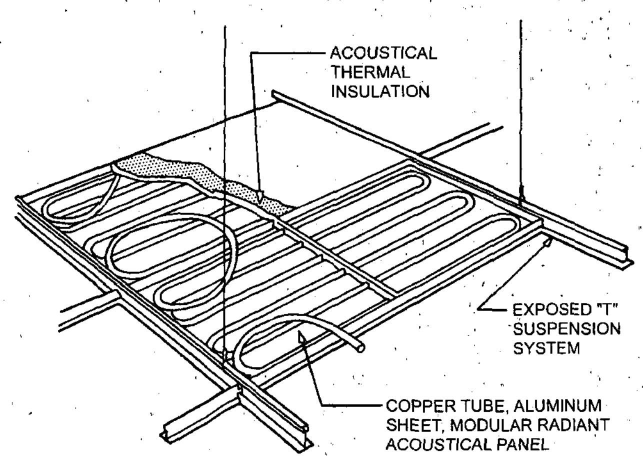


Fig. 14 Metal Ceiling Panels Bonded to Copper Tubing

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 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 380 or 510 mm wide usually satisfy a typical office building's heating requirements. Lengths up to 6 m 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.

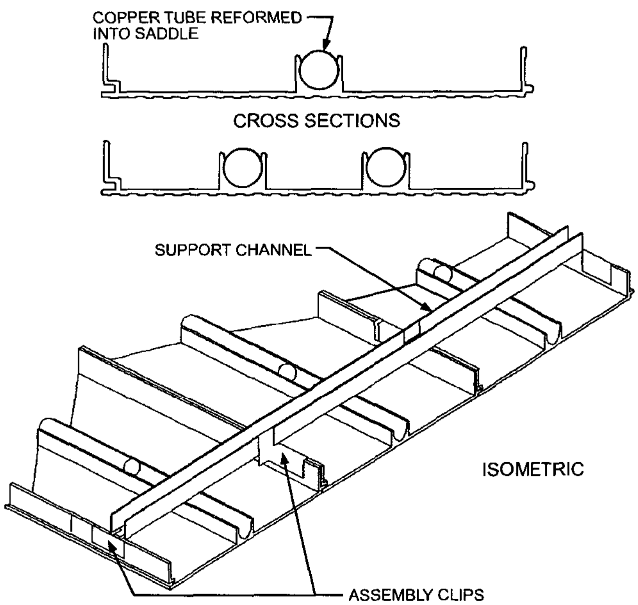


Fig. 15 Extruded Aluminum Panels with Integral Copper Tube

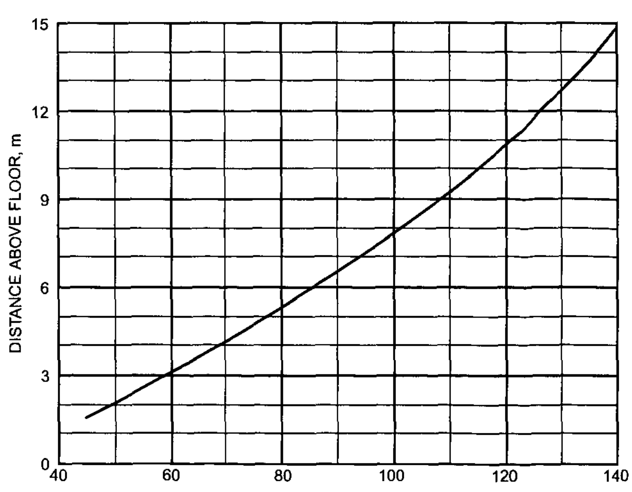


Fig. 16 Permitted Design Ceiling Surface Temperatures at Various Ceiling Heights

Metal ceiling panels can be used with any of the all-air cooling systems described in Chapter 2. Chapters 26 to 29 of the 2001 *ASHRAE Handbook—Fundamentals* describe how to calculate heating loads. Double-glazing and heavy insulation in outside walls reduce transmission heat losses. As a result, infiltration and reheat have become of greater concern. Additional design considerations include the following:

- Perimeter radiant heating panels extending not more than 1 m into the indoor space may operate at higher temperatures, as described in the section on Hydronic Panel Systems.
- Hydronic panels operate efficiently at low temperature and are suitable for condenser water heat reclaim systems.
- Locate ceiling panels adjacent to the outside wall and as close as possible to the areas of maximum load. The panel area within 1 m of the outside wall should have a heating capacity equal to or greater than 50% of the wall transmission load.
- 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 this heat is lost to the return air system in heating mode.
- When selecting heating design temperatures for a ceiling panel surface or average water temperature, the design parameters are as follows:
    - Excessively high temperatures over the occupied zone will cause the occupant to experience a "hot head effect."
    - Temperatures that are too low can result in an oversized, uneconomical panel and a feeling of coolness at the outside wall.
    - Give ceiling panel location priority.
    - With normal ceiling heights of 2.4 to 2.8 m, panels less than 1 m wide at the outside wall can be designed for 113°C surface temperature. If panels extend beyond 1 m into the indoor space, the panel surface temperature should be limited to the values as given in Figure 16.
- Allow sufficient space above the ceiling for installation and connection of the piping that forms the panel ceiling.

Metal 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, easy to control, and responsive. The system is a basic air-and-water system. First costs are competitive with other systems, and 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 panels can also be integrated into the ceiling design to provide a narrow band of panel heating around the perimeter of the building. The panel system offers advantages over baseboard or overhead air in appearance, comfort, operating efficiency and cost, maintenance, and product life.

ASHRAE/ANSI *Standard* 138P, Method of Testing for Rating Hydronic Ceiling Panels, discusses testing and rating of ceiling panels.

DISTRIBUTION AND LAYOUT

Chapters 3 and 12 apply to panels. Layout and design of metal ceiling panels for heating and cooling begin early in the job. The type of ceiling chosen influences the panel 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 70°C 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:

- Pipe or tube is embedded in the lower portion of a concrete slab, generally within 25 mm of its lower surface (Figure 17). 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 20 mm above the undersurface of the slab. The minimum coverage must comply with local building code requirements.
- 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.
- Smaller-diameter copper or thermoplastic tube is attached to the underside of wire or gypsum lath. Plaster is then applied to the lath to embed the tube, as shown in Figure 19.
- 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 laid in a sinusoidal pattern, although some header or grid-type coils have been used in ceilings. Coils may be thermoplastic, ferrous, or nonferrous pipe or tube, with coil pipes spaced from 110 to 230 mm on centers, depending on the required heat flux, pipe or tube size, and other factors.

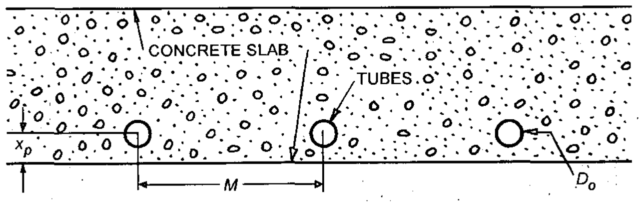


Fig. 17 Coils in Structural Concrete Slab

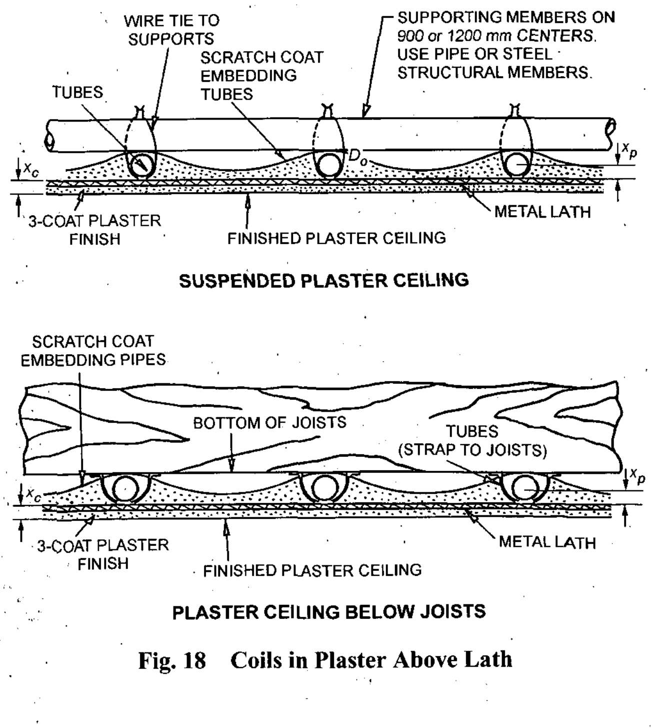


Fig. 18 Coils in Plaster Above Lath

Where plastering is applied to pipe coils, a standard three-coat gypsum plastering specification is followed, with a minimum of 10 mm of cover below the tubes when they are installed below the lath. Generally, the surface temperature of plaster panels should not exceed 50°C, which may be satisfied by limiting the average water temperature to a maximum temperature of 60°C.

Insulation should be placed above the coils to reduce back loss, which is the difference between heat supplied to the coil and net useful heat output to the heated indoor space.

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, water supplied to the panels should not be more than 10 K above the prevailing indoor air temperature and not in excess of 32°C.

Water should be circulated at this temperature for about two days, and then increased at a rate of about 3 K per day to 60°C.

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)]. Equations (5) and (11) give the heat flux at the surface of wall panels.

Hydronic Floor Panels

Interest has increased in 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 heat be evenly distributed over the floor. Spacing is generally 100 to 300 mm on centers for the coils. Wide spacing under tile or bare floors can cause uneven surface temperatures.

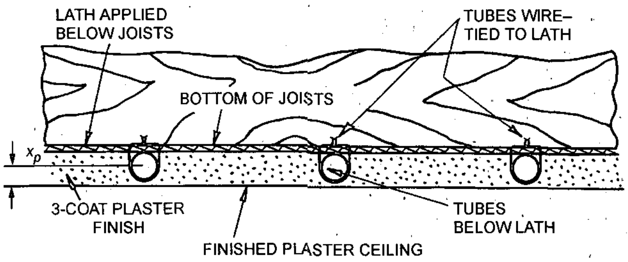


Fig. 19 Coils in Plaster Below Lath

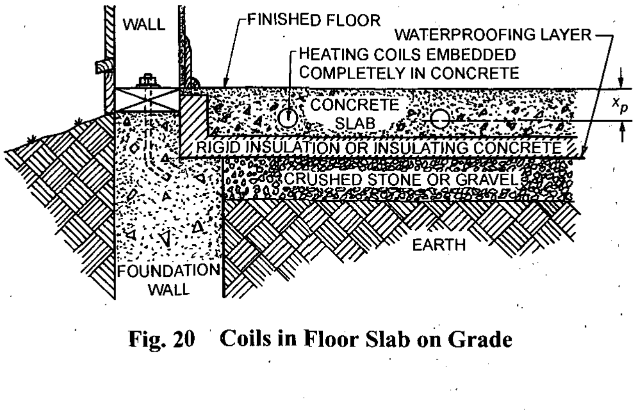


Fig. 20 Coils in Floor Slab on Grade

Embedded Tubes or Pipes in Concrete Slab. Thermoplastic, rubber, ferrous, and nonferrous pipes, or composite tubes (e.g., thermoplastic tubes with aluminum sleeves) are used in floor slabs that rest on grade. Hydronic coils are constructed as sinusoidal-continuous coils or arranged as header coils with a spacing of 150 to 450 mm on centers. The coils are generally installed with 40 to 100 mm of cover above them. Insulation is recommended to reduce perimeter and back losses. Figure 20 shows application of hydronic coils in slabs resting on grade. Coils should be embedded completely and should not rest on an interface. Any supports used for positioning 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 help isolate the point of failure.

Suspended Floor Tubing or Piping. Piping may be applied on or under suspended wood floors using several construction methods. 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 alternative method is to install insulation with a reflective surface and leave an air gap of 50 to 100 mm to the subfloor. Whichever method is used for optimum floor output and comfort, it is important that heat be evenly distributed throughout the floor. Tubing generally has a spacing of 100 to 300 mm on centers. 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 25 to 50 mm when applied to a wood subfloor. Gypsum products specifically designed for floor heating can generally be installed 25 to 40 mm thick because they are more flexible and crack-resistant than concrete. When concrete is used, it should be of structural quality to reduce cracking caused by movement of the wood frame or shrinkage. The embedding material must provide a hard, flat, smooth surface that can accommodate a variety of floor covers.

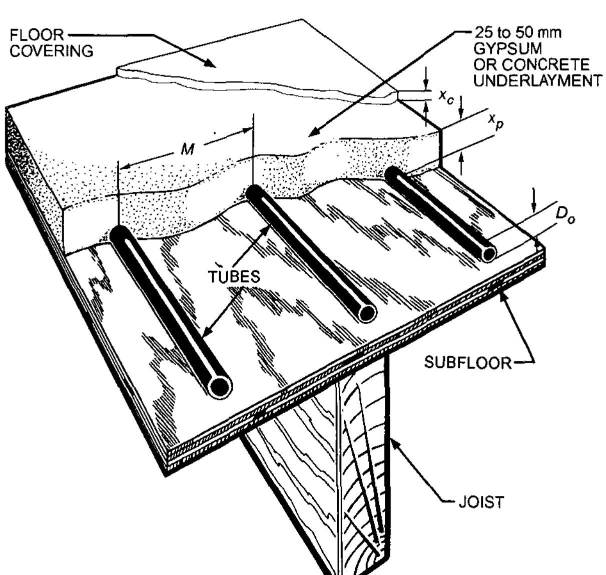


Fig. 21 Embedded Tube in Thin Slab

As shown 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 adding metal heat transfer plates, which spread heat beneath the finished flooring.

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 system effectiveness. The method that transfers and spreads heat evenly through the subfloor with the least resistance produces the best results.

ELECTRICALLY HEATED PANEL SYSTEMS

Several panel systems convert electrical energy to heat, raising the temperature of conditioned indoor surfaces and the indoor air. 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 floor panels is limited to what is comfortable to occupants' feet.

Electric Ceiling Panels

Prefabricated Electric Ceiling Panels. These panels are available in sizes 300 to 1800 mm wide by 600 to 3600 mm long by 13 to

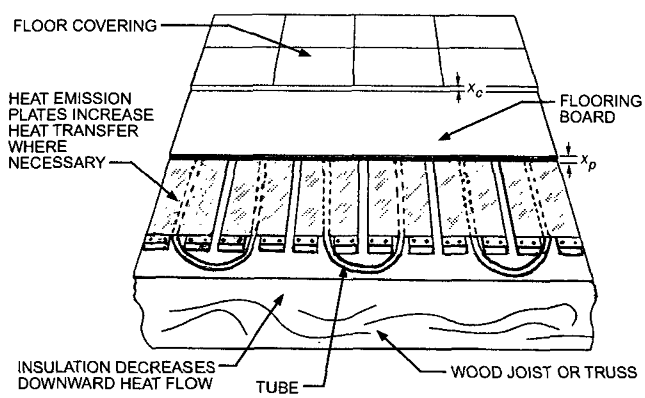


Fig. 22 Tube in Subfloor

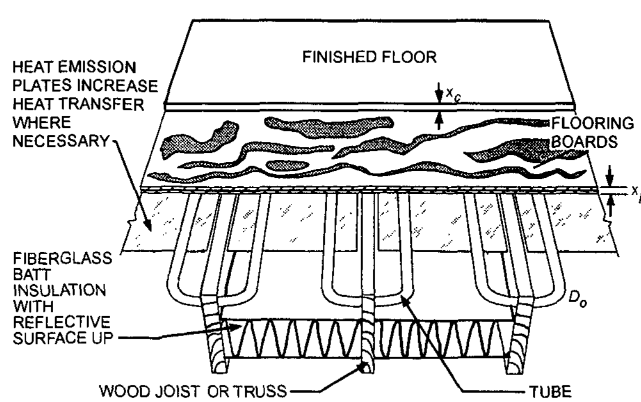


Fig. 23 Tube Under Subfloor

50 mm thick. They are constructed with metal, glass, or semirigid fiberglass board or vinyl. Heated surface temperatures range from 40 to 150°C, with corresponding heat fluxes ranging from 270 to 1100 W/m^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. Heat flux is limited to 240 W/m to maintain the board's integrity by keeping the heated surface temperature below 40°C. 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 600 by 1200 mm panels for lay-in ceilings (Figure 24) are about 25 mm thick and have a mass of 2.6 to 11 kg. Typical characteristics of an electric 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 1200 mm wide to 2400 mm long. Their maximum power output is 1000 W/m^2.

Table 4 Characteristics of Typical Electric Panels

Resistor material	Graphite or nichrome wire
Relative heat intensity	Low, 540 to 1350 W/m^2
Resistor temperature	80 to 180°C
Envelope temperature (in use)	70 to 150°C
Thermal 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 heat flux, length, and voltage practical
Life expectancy	Over 10 000 h

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

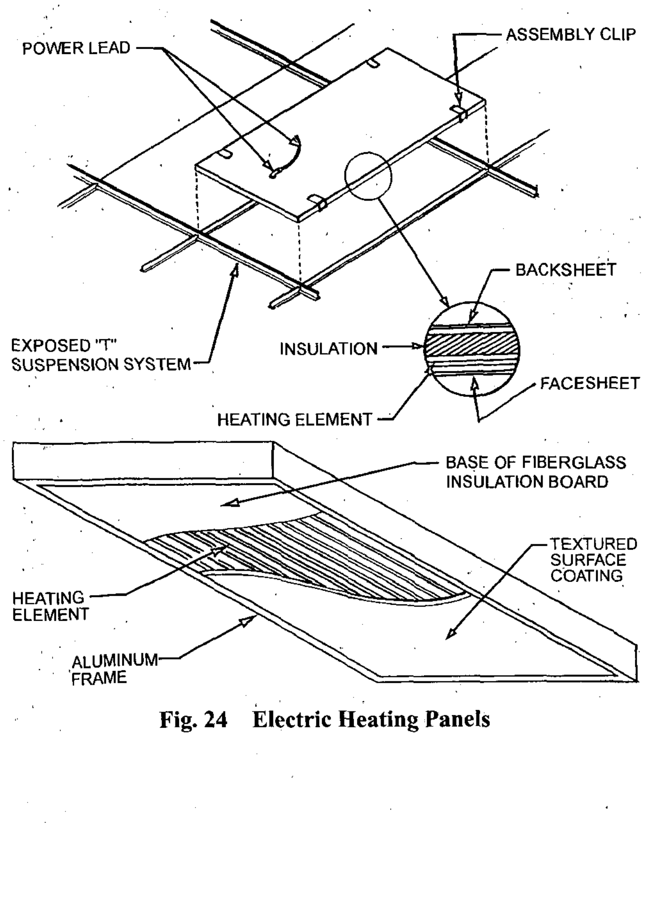


Fig. 24 Electric Heating Panels

Electric Ceiling Panel Systems. These systems are laminated conductive coatings, printed circuits, or etched elements nailed to the bottom of ceiling joists and covered by 13 mm gypsum board. Heat flux is limited to 190 W/m^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.

Electric Cables Embedded in Ceilings. Electric heating cables for embedded or laminated ceiling panels are factory-assembled units furnished in standard lengths of 25 to 550 m. These cable lengths cannot be altered in the field. The cable assemblies are normally rated at 9 W/m 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 2 m nonheating leads for connection at the thermostat or junction box.

Electric cables for panel heating have electrically insulated sleeves resistant to medium temperature, water absorption, aging effects, and chemical action with plaster, cement, or ceiling lath material. This insulation is normally made of polyvinyl chloride (PVC), which may have a nylon jacket. The thickness of the insulation layer is usually about 3 mm.

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 cover layer of thermally noninsulating sand plaster about 13 to 19 mm 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 150 mm nonheating border around the periphery of the ceiling. A 200 mm clearance must be provided between heating cables and the edges of the outlet or junction boxes used for surface-mounted lighting fixtures. A 50 mm 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 electrical power and lighting wiring be run above the

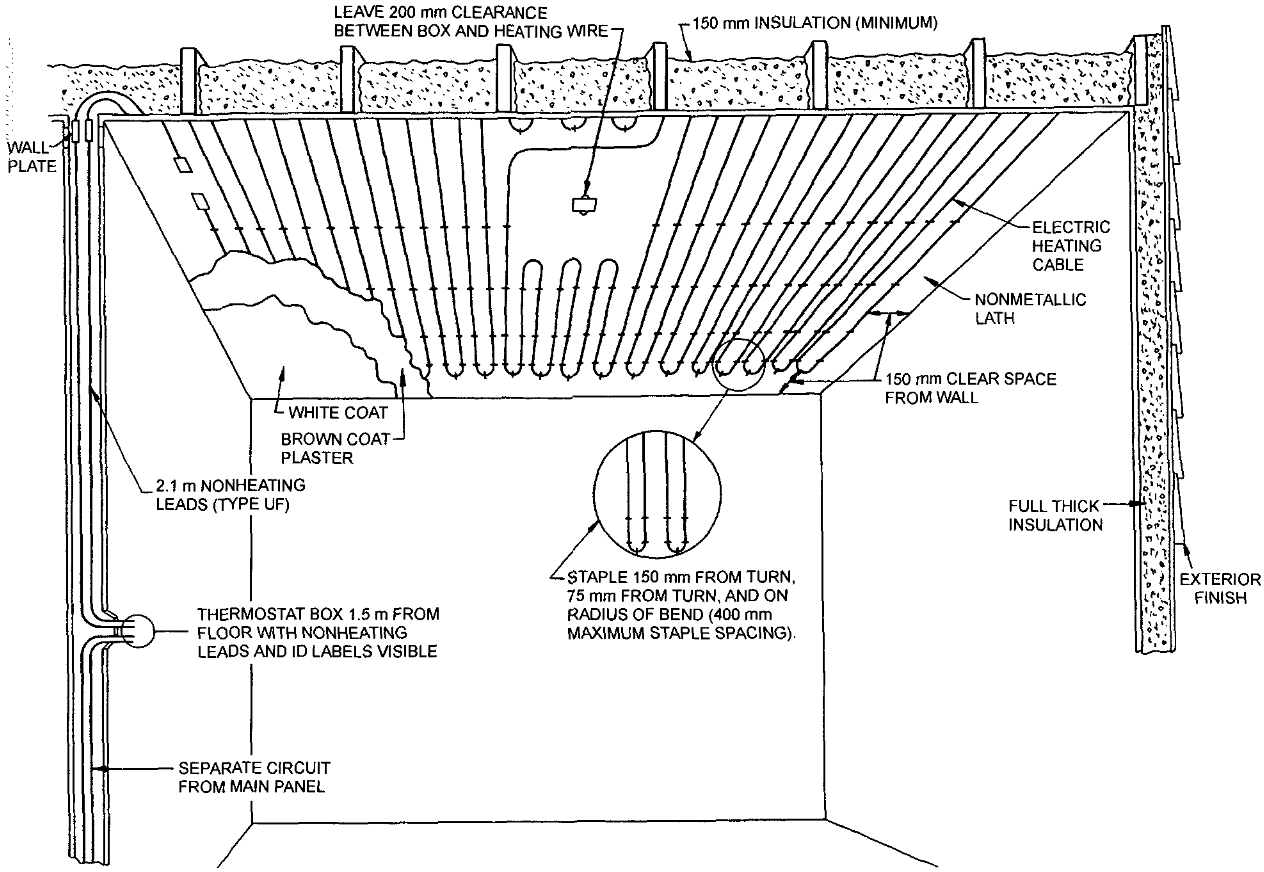


Fig. 25 Electric Heating Panel for Wet Plaster Ceiling

thermal insulation or at least 50 mm above the heated ceiling surface, or that the wiring be derated.

In drywall ceilings, the heating cable is always installed with the cable runs parallel to the joist. A 65 mm 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 indoor space

For cable having a heat flux of 9 W/m, the minimum permissible spacing is 40 mm between adjacent runs. Some manufacturers recommend a minimum spacing of 50 mm for drywall construction.

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

$$M = 1000A_n/C \tag{24}$$

where

M = cable spacing, mm
A_n = net panel heated area, m²
C = length of cable, m

Net panel area A_n in Equation (24) 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 (24) contains a slight safety factor, and small lighting fixtures are usually ignored in determining net ceiling area.

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

$$R' = R\frac{[1 + \alpha_e(t_d - 20)]}{[1 + \alpha_o(t_d - 20)]} \tag{25}$$

where

R = electrical resistance of electric cable at standard temperature (20°C), Ω/m
α_e = thermal coefficient for material resistivity, °C^{-1}
α_o = thermal expansion coefficient, °C^{-1}
t_d = surface temperature of electric cable at operating conditions [see Equation (18)], °C

The 65 mm clearance required under each joist for nailing in drywall applications occupies one-fourth of the ceiling area if the joists are 400 mm on centers. Therefore, for drywall construction, the net area A_n must be multiplied by 0.75. Many installations have a spacing of 40 mm for the first 600 mm from the cold wall. Remaining cable is then spread over the balance of the ceiling.

Electric 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 U.S. codes prohibit such panels. Some of the prefabricated panels described in the preceding section are also used for wall panel heating.

Electric Floor Panels

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 layer has been placed and hardened.

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 0.2 to 9 m^2 and with heat fluxes from 160 to 270 W/m^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, heat fluxes (power densities), and lengths. A cable assembly consists of the specified length of heating cable, waterproof hot-cold junctions, 2 m 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-sleeve 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 (24). In general, cable heat flux and spacing should be such that floor panel heat flux is not greater than 160 W/m. Check the latest edition of the *National Electrical Code®* (NFPA *Standard* 70) and other applicable codes to obtain information on maximum panel heat flux 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 pours. The first pour should be at least 75 mm 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 between 40 and 50 mm thick. This top layer must not be insulating concrete. At least 25 mm 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 50 mm from adjoining walls and partitions. Methods of fastening the cable to the concrete include the following:

- Staple the cable to wood nailing strips fixed in the surface of the rough slab. Daubs of cement, plaster of paris, or tape maintain the predetermined cable spacing.
- In light or uncured concrete, staple the cable directly to the slab using hand-operated or powered stapling machines.
- 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 40 to 50 mm of the finished level. The surface is rough-screeded and the mats placed in position. The final cap is 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 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 part of the air is passed through the indoor space 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 Panel Design 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 (19) gives the required surface temperature t_d of the plenum. The design of the air side of the system can be carried out by following the principles given in Chapters 26 and 34 of the 2001 *ASHRAE Handbook—Fundamentals*.

If the floor surface is porous, air-heated or air-cooled panels may also be used to satisfy at least part of the latent loads. In this case, the heating or cooling air is conditioned in a central plant. Part of this air diffuses into the indoor conditioned space, as shown in Figure 28. Additional hydronic tubing or electric heating elements may also be attached to the back side of the floor panel to enable independent control of sensible and latent load handling (Kilkis 2002).

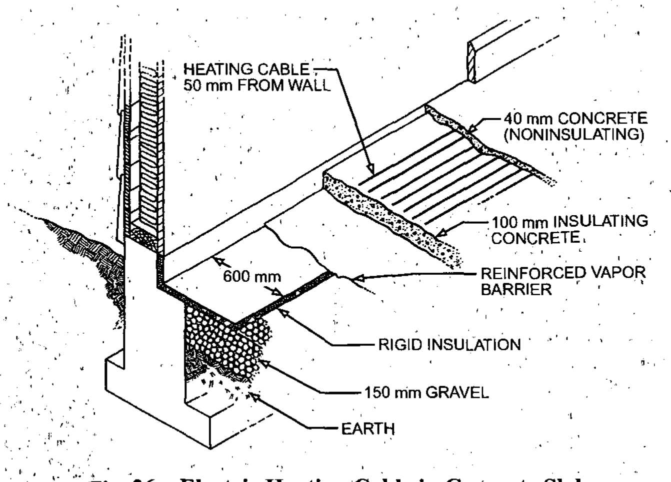


Fig. 26 Electric Heating Cable in Concrete Slab

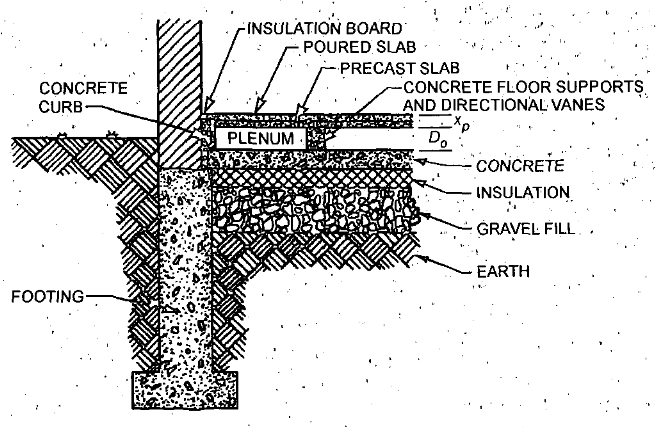


Fig. 27 Warm Air Floor Panel Construction

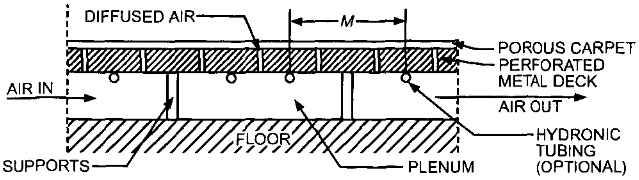


Fig. 28 Typical Hybrid Panel Construction

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 mean radiant temperature in 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 Chapters 12 and 14 also apply to panel heating. Because 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-thermal-mass panels such as concrete 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 during the delay, then possibly periods of uncomfortable and wasteful overshoot. Careful economic analysis may reveal that nighttime setback 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 rates, this means modulating the temperature difference between the outgoing and returning water; this is accomplished with mixing valves, fuel modulation, or, for constant thermal power sources, pulse-width modulation (on-off control). Slabs with embedded electric cables can be controlled by pulse-width modulators such as the common round thermostat with anticipator or its solid-state equivalent.

Outdoor reset control, another widely accepted approach, 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 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 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.

Sensible Cooling Panel Controls

The average water (brine) temperature in the hydronic circuit of panels can be controlled either 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 artificial lighting load or for indoor spaces at a corner with large fenestration on both walls.

Temperature control of the indoor air and panel water supply should not be a function of the outdoor weather. Normal thermostat drift is usually adequate compensation for the slightly lower temperatures desirable during winter weather. This drift should result in an indoor air temperature change of no more than 0.8 K. Control of 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 year-round 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.

Heating Slab Controls

In comfort heating, the effective surface temperature of a heated floor slab is held to a maximum of 27 to 29°C. As a result, when the heated slab is the primary heating system, thermostatic controls sensing air temperature should not be used to control the heated slab 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 building heat loss is calculated for an outdoor temperature between 21 to −19°C, and the effective floor temperature range is maintained between 21 to 29°C with a remote sensing thermostat, the ratio of change in outdoor temperature to change in the heated slab temperature is 40:8, or 5:1. This means that a 5 K drop in outdoor temperature requires a 1 K 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.

HYBRID (LOAD-SHARING) HVAC SYSTEMS

In general, any HVAC system relies on a single heat transfer mode as its major heat transfer mechanism. For example, central air conditioning is a forced-convection system, and a high-intensity radiant system operates almost purely with thermal radiation. Additionally, every system has a typical range for satisfactory and economical operation, with its own advantages, limitations, and disadvantages. A single system may not be sufficient to encompass all requirements of a given building in the most efficient and economical way. Under these circumstances, it may be more desirable to decouple several components of indoor space conditioning, and satisfy them by several dedicated systems. A hybrid heating and cooling system is an optimum partnership of multiple, collocated, simultaneously operating heating and cooling systems, each of which is based on one of the primary heat transfer modes (i.e., radiation and convection). In its most practical form, hybrid heating and cooling may consist of a panel and a

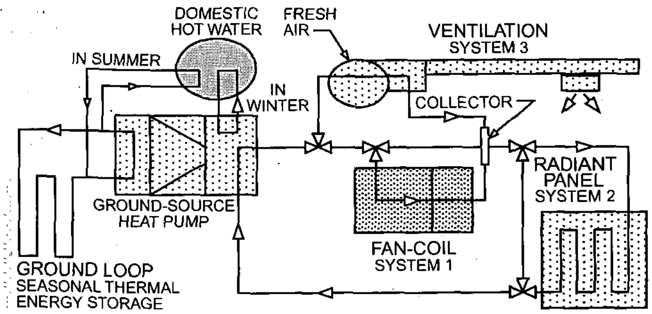


Fig. 29 Typical Residential Hybrid HVAC System

forced-air system. The forced-air component may be a central HVAC system or a hydronic system such as fan-coils, as shown in Figure 29. Here, a panel system is added downstream of the condensing fan-coils, and ventilation is provided by a separate system with substantially reduced duct size. Space heating and cooling is achieved by a ground-source heat pump. A hybrid HVAC system is more responsive to control and maintains required operative temperatures for human thermal comfort, because both the operative air and mean radiant temperature can be independently controlled and zoned. Dehumidification and ventilation problems that may be associated with standalone panel cooling systems may be eliminated by hybrid HVAC systems.

ASHRAE research project RP-1140 (Scheatzle 2003) successfully demonstrated the use of panel systems for both heating and cooling, in conjunction with a forced-convection system, to economically achieve year-round thermal comfort in a residence using both active and passive performance of the building and a ground-source heat pump. Skylighting, an energy recovery ventilator, and packaged dehumidifiers were also used. Twenty-four-month-long tests indicated that a radiant/convective system can offer substantial cost savings, given proper design and control.

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