Applied Radiant Cooling and Displacement Ventilation

Geoff McDonell, P.Eng.[1]

RADIANT COOLING AND HEATING

Energy-efficient buildings do not need highly technical systems or solutions to be effective. We can look back in history and realize that the fundamental knowledge has always been with us, and we've just had trouble executing it. The Romans, with underfloor radiant heating and thermal mass heat storage (hypocausts), figured this out over 2000 years ago! The purpose of erecting a building of any kind is to provide controlled shelter from the environmental elements. Building issues such as thermal storage, glazing performance, light control, and building thermal loads must be considered together in a "team design" approach. Involvement by the entire building-design team, as early as possible in the building-design process, can lead to many more innovative and cost-effective solutions.

Traditionally, the architect has already conceptualized the building by the time the engineering consultants are handed the plans and then tasked with applying mechanical and electrical systems designs to it. This can lead to restrictions in terms of what might be the appropriate building systems for the project.

Radiant heating is a well-known and accepted method of heating a building. Whether a radiant floor or higher-intensity overhead heating panels, the technology and applications of heating systems are relatively well-known. Radiant cooling is far less understood, and misapplications in the past have led to a general suspicion of this type of mechanical cooling in residential and commercial buildings. Even radiant heating systems have had their share of horror stories, mainly due to incorrect application, poor materials, and fundamental installation problems.

The proper use and application of radiant cooling and heating systems can lead to a very energy-efficient mechanical system. The key is to reduce the building thermal loads to the point where these systems can be applied economically.

The building envelope is the most critical element of the building, and it affects every other component of the building. A poor envelope leads to energy-guzzling mechanical systems and poor comfort conditions at the perimeter, as well as excessive maintenance needs over the life of the building. A well-designed high-performance envelope will lead to a low-energy use mechanical system, lower energy consumption for lighting if daylighting concepts are incorporated, and much lower transient thermal loads around the perimeter zones inside the occupied space. The architectural and engineering challenge is to accomplish this at the same or lower cost than building a conventionally skinned building. Some key elements to consider are:

- exterior shading devices;
- high-performance glazing elements;
- thermal mass within the space or building;
- minimization of internal heat gains (e.g., lights and equipment).

Traditionally, North American HVAC engineers have tackled the control of indoor comfort conditions by using various types of air systems that typically move large volumes of conditioned air, particularly for cooling applications. These systems are flexible enough to be applied to "any building, any time, anywhere," and can handle high peak thermal loads with relatively short response times.

Reducing the building's peak loads by using a high-performance skin will allow for a smaller mechanical plant and the use of other types of heating and cooling systems rather than "all-air systems." The reduced mechanical and electrical infrastructure saves capital and operating costs, but the biggest impact is on the volume of the building: floor-to-floor heights can be reduced due to lower service plenum requirements, saving more money and resources. It has been proven in many cases that a highly energy-efficient building can be built at the same or lower capital costs than a standard office building, provided that the design team starts early enough in the process to refine the building structure, shape, envelope, and approach.

[1] Earth Tech Inc., 6th Floor, 1901 Rosser Ave., Burnaby, BC V5C 6S3, Canada; phone: 604-298-6181; fax: 604-294-8597; e-mail: geoff.mcdonell@earthtech.ca

With a tighter, more-efficient building skin, one of the other mechanical systems that can now be examined is radiant cooling, using the structural slabs or ceiling panels as the radiant surface. The "thermoactive slab" system uses the building mass as the main heating and cooling agent, replacing the traditional large air volumes used for air conditioning. In addition, it separates the heating and cooling function from the ventilation function of the HVAC system. This separation allows the designer to match equipment sizes to the individual functions. Thus, a minimalist approach can be used—a minimal amount of mechanical equipment and operating staff, and a system operating at minimal temperature differentials. This is the principle behind the European "BATISO" (*BAT*iment-*ISO*therm) constant-temperature building.

According to ASHRAE and European studies, the ideal human body comfort range is achieved through 50% radiation, 30% convection, and 20% evaporation. "All-air systems" typically deal with only the convection (air movement) and evaporation (humidity control) parts of this equation.

RADIANT COOLING TECHNOLOGIES

Current developments in radiant heating and cooling technologies have given rise to two basic methods of providing "BATISO" systems. In "cast-in-place" concrete buildings, one method is to cast tubing directly into the concrete slabs (see photo, p. 15). Warm or cool water is piped through the tubing to maintain a constant concrete slab temperature. This method works best if there is no dropped ceiling plenum, so the slab can act as an overhead cooling or heating source. Typically, a raised floor plenum is used to provide service space for electrical and utility systems.

Another common method is to use capillary tubing mats which can be cast in place, adhered to the underside of the slab or ceiling structure in a plaster ceiling (see photo, p. 15), or installed in suspended panels (e.g., drywall, acoustic tile, or metal). The capillary tubing mats offer more versatile installation schemes, and are also used for spot cooling or heating applications to supplement other building HVAC systems in many different building applications. This system is commonly used in Europe for older building retrofits where duct space is minimal, but small diameter piping can be easily run through the building to provide cooling and heating where required.

The capillary mats can be zoned and controlled on a room-by-room basis, but this adds capital cost for the piping and controls work. Larger-diameter tubing cast into the slab can also be zoned, but because of the slow temperature change rate of the concrete slab, room-by-room control is not an effective way of operating this type of system—it is best operated on a "major thermal zone" control basis, and on a seasonal basis.

The reason for this is clear—if the transient perimeter temperature fluctuations are virtually eliminated by the high-performance building skin, the entire inside of the occupied space becomes one "thermal zone." Since the entire zone is maintained at a constant temperature by the enormous thermal-storage effect of the concrete structure, there is no need for individual temperature control zones. Since the slab system is self-regulating, even transient thermal loads are compensated for automatically at the speed of light (infrared energy), without the need for additional controls or thermal zoning.

One of the major technical issues with plastic tubing systems is that the piping and capillary mats are normally fabricated from polypropylene plastic, which is *not* an oxygen barrier material. Thus, the piping system must be isolated from other metallic piping systems and components. The usual way to do this is to provide a central-station heat exchanger and circulation pump for the plastic piping systems to isolate them from the central boiler and chilled-water systems.

The in-slab tubing method, or the applied-to-slab capillary tubes, allows the building mass to work *with* the HVAC system as an energy storage reservoir (heating and cooling storage) in a "thermoactive slab" application. Once the building structure temperature has been stabilized, and the transient loads from the exterior (solar, heating, etc.) are minimized by the high-performance envelope, then the building HVAC systems do not need extreme operating temperatures or controllability to maintain a stable slab temperature, year round. The thermal storage of the concrete slab will easily handle local transient loads (e.g., meeting rooms and offices) while maintaining a steady cooling effect. Radiant heating and cooling is infrared energy which works at the speed of light and, since it represents 50% of the ideal human comfort equation (radiation component), it can provide superior indoor comfort compared to conventional "all-air systems." To visualize this, imagine walking into a large concrete parkade on a hot summer day. The cooler concrete creates a radiant cooling effect, and in spite of the

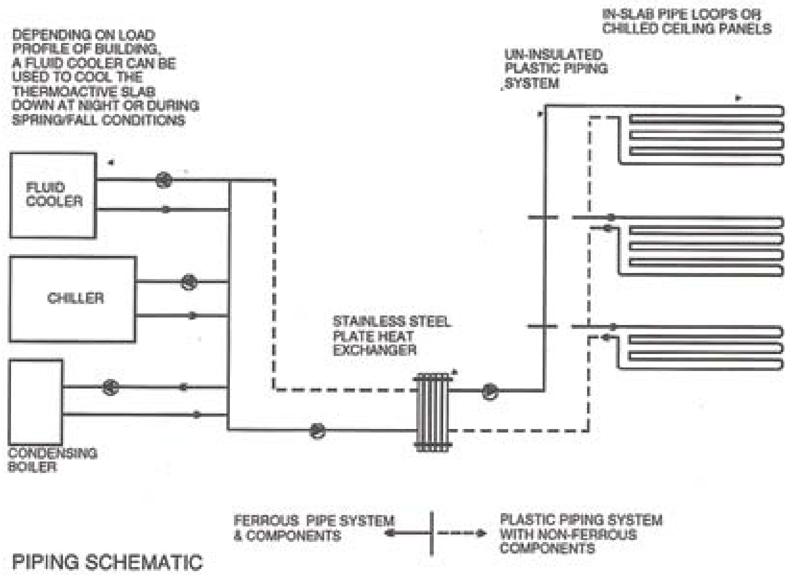


Figure 1.
A simple schematic showing the basic hydronic heating and cooling system

Source: Geoff McDonell, P.Eng.

warm air temperature, you feel cooler and more comfortable.

The key technical issue is to get the interior cooling load of the building down to below 6.5–7.0 watts per square foot (70–75 w/m^2). In climates like the Pacific Northwest, the heating takes care of itself, as the winter heat losses are easily met by the building interior heat gains when high-performance glazing is used. Similarly, the high-performance buildings in many areas of Switzerland and Germany do not require auxiliary perimeter heat at all, where their winter design temperature is 5°F to 14°F (-10°C to -15°C). In more severe winter climates, supplemental perimeter heating may be needed, depending on the extent and type of glazing and how cold it gets in winter.

Another issue to consider is ambient relative humidity. The performance of chilled ceilings and chilled slabs are limited by the dewpoint of the air in the building. The lower temperature limit for radiant-cooling systems is approximately 61°F (16°C), which prevents any condensation problems in most climates. It may be possible to use lower chilled ceiling temperatures in drier climates, or if dehumidification equipment is used in the supply-air system (but this adds cost and equipment, which is what we want to avoid). The rule of thumb is: If the building cooling load exceeds 7.4 watts per square foot (80 w/m^2), a chilled ceiling or thermoactive slab is not going to be able to handle the load effectively, and alternate or supplemental systems must be examined. This cooling load is actually quite generous when compared to a typical office building today. Excluding perimeter solar load and heat gains due to transmission, typical internal heat generation rates are:

Lights	= 1.4 w/ft^2 (15 w/m^2)
People @ 1/150 ft^2	= 0.67 w/ft^2 (7.2 w/m^2)
Equipment (computers, etc.)	= 2.53 w/ft^2 (27.2 w/m^2)
Total Interior Average Load	= 4.6 w/ft^2 (49.4 w/m^2)

As these figures show, there is still a relatively generous allowance for some degree of perimeter heat gain. Note that the thermal load for the ventilation system is not included in the internal load of the building. Properly executed, the minimal ventilation air (generally 20 cubic feet per minute per person [10 l/s per person]) is "energy neutral" with respect to the central plant loading and space temperature.

The main mechanical plant (chillers and boilers) now does not need to be sized for the high peak loads of a "normal" building, which uses an all-air system as the temperature-control system. In the European low-energy (BATISO-style) buildings, the mechanical-plant is generally 40% the size of that of a standard building. The premium cost of the high-performance building envelope is easily offset by the savings in mechanical plant size, now that all the heating and cooling is done by a hydronic system rather than masses of air. The energy-savings track record of BATISO-type buildings dating back over 12 years indicates that energy savings of 70% over conventional systems are common. An air system is still

Photo: Vladimir Mikler, P.Eng.

All this, and opening windows too!

A "through-the-floor" air-supply system used in Germany

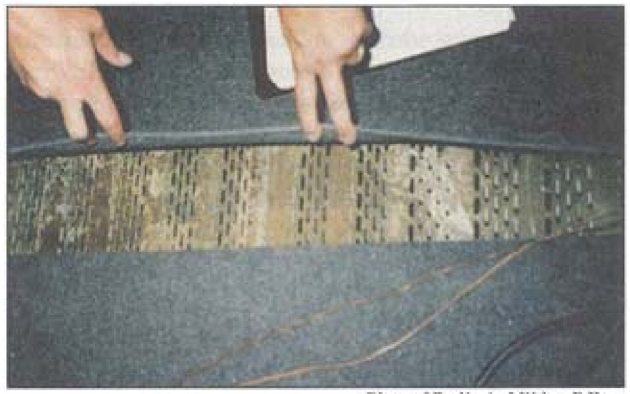


Photo: Vladimir Mikler, P.Eng.

An example of capillary tube "mat" installation, just prior to the application of a plaster ceiling

Photo: Vladimir Mikler, P.Eng.

Photo: Geoff McDonell, P.Eng.

Baseboard air distribution integrated with a communication/ power chase –Sarinaport Building, Fribourg, Switzerland

A view of the in-slab tubing placed just before the concrete is poured. ICT Building, Calgary, Alberta (Sept 2000)

Photo: Michel Vachon

Photo: Vladimir Mikler, P.Eng.

A graphic example of passive displacement airflow across the floor in a test lab required to provide the outdoor air for ventilation, typically 20% of the air normally circulated by an all-air type system, but it only needs to be supplied at room temperature, so the fan power, and the heating and cooling requirements for moving and conditioning this air, are much reduced. Such a system addresses *all* of the human comfort components: radiation, convection and evaporation.

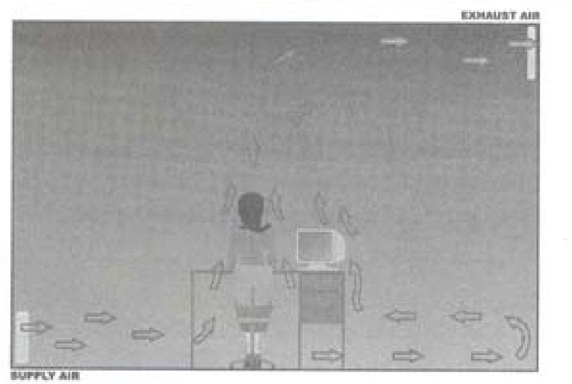
AIR DISTRIBUTION SYSTEMS

In Part I of this article, radiant heating and cooling systems were outlined and explained, with the key element being control of the building envelope to reduce the building heating and cooling loads. Once the heating and cooling requirements are reduced, it is possible to de-couple the heating and cooling function from the ventilation function. If the heating and cooling of the interior of the building are taken care of by a hydronic system, the only requirement for an air system is to supply outdoor air for ventilation. Thus, the building air system can become only 20% of the size one normally expects for an "all-air" type temperature control system.

The entire air distribution infrastructure becomes smaller, requiring less mechanical space and plenum space. This can assist in reducing floor-to-floor heights in the building, thus allowing further economies to be made to the capital cost of the building. The effective distribution of the ventilation air can be accomplished in a number of traditional ways, via overhead ductwork or through raised floor plenums.

The European, and especially German, building codes are such that the interior air movement velocities are defined and mandated; so air distribution is a very highly engineered aspect of the mechanical systems. "Displacement ventilation" systems are commonly used, in order to keep air velocities in the occupied spaces to less than 50 feet per minute (0.25 m/s). Raised-floor systems and perimeter baseboard-style air diffusers are generally used, for effective room air diffusion and ventilation at low velocities (see photo, p. 15). Most displacement air distribution systems are designed for a *maximum* outlet air velocity of 40 feet per minute (0.20 m/s) at a *minimum* supply air temperature of 63°F (17°C). While some supplemental cooling capacity can be provided by a displacement ventilation system, it is normally not considered if the primary cooling is being performed by a hydronic radiant-cooling system.

Positive-displacement air-supply systems rely on low-velocity air being distributed at a low level and allowing stratified warm air to be returned or exhausted at high level. It is intended to work with "medium temperature" air at not less than 63°F (17°C) to a nominal maximum of 75°F (24°C). The principle is to reduce the "vertical gradient" of the temperature difference of the supply-air temperature to room-air temperature, as well as to reduce the energy required to cool the supply air down to the 54°F (12°C) temperatures normally used for "all-air" systems. Due to the higher supply air temperatures used for positive-displacement air systems, the air quantities being supplied need to be carefully considered if high cooling loads exist in the space.



Source: Enrico Dagostino

Figure 2. Displacement ventilation pattern diagram

The best applications for displacement ventilation systems are:

- areas with high ceilings where routing for low level air supply is available;
- spaces in which cooling loads have been minimized, so heating and cooling can be handled using hydronic systems and the air system is *not* the primary source of heating or cooling; and
- theaters or auditoriums where there is an opportunity to supply air at a low level in the seating area and allow stratification to high ceilings (an example where large ventilation air quantities are required due to the high population load, but ultra-quiet air supply is also needed).

For example, technology has been developed for the Reichstag Building in Berlin, where perforated raised-floor panels and a porous carpet are used to create supply air up through the carpet (see photo, p. 15).

The maximum air velocity is around 3–5 feet per minute (0.9–1.5 m/min), which is not high enough to lift dust or dirt out of the carpet; the carpet actually acts as an air filter to keep contaminants from the floor plenum from being blown up into the occupied space (a common problem in most raised-floor air-distribution systems using the higher velocity bucket-type individual floor diffusers without terminal filters in them). Normal housekeeping will remove the trapped dust and keep this "final filter" clean.

Based on laboratory tests, the average human body, whether sitting or standing, generates approximately 58 cubic feet per minute (100 m^3/h) of air movement due to the buoyant / convective effect of the body temperature relative to 70°F (21°C) ambient air. Cool air at low level is drawn up and past a heat source (e.g., a human body) to return / exhaust grilles at or near the ceiling level of the room, creating an ideal air-movement path for superior indoor-air quality.

In one test lab situation, a room was simulated based on a chilled ceiling system and floor-plenum air-distribution system, with a space-cooling load of approximately 7.4 watts per square foot (80 w/m^2). The ceiling surface temperature was maintained at 63°F (17°C) by capillary mats in suspended ceiling panels, the supply air temperature was approximately 68°F (20°C), and the room air temperature remained at 68°F–70°F (20°C–21°C) in the occupied zone throughout the test. Cold smoke sticks were used to track air movement and, using passive displacement air through the floor, it was clear that air movement resulted in clean primary air being attracted to, and rising up at the heat sources. The rising air effectively carried air contaminants and body heat to upper levels of the room (see photo, p. 15).

The principle for BATISO-concept buildings is to decouple the ventilation system from the heating and cooling systems and maintain a uniform, constant interior temperature. All you really need for air supply in the building is the ventilation air (outdoor air) for health and the corresponding makeup air to replace exhaust air out of washrooms and other ventilation-loads areas. The heating and cooling systems could consist of a radiant system of water loops operating at moderate temperatures—typically 60°F–62°F (16°C–17°C) for cooling and 75°F–79°F (24°C–26°C) for heating. The ventilation air would normally be supplied at 64°F–68°F (18°C–20°C) and an air-to-air heat exchanger on the building exhaust system recovers any heating or cooling energy available before the exhaust air is dumped out of the building. Small water pipes with no insulation, and small ducts with no insulation lead to minimized mechanical space and low energy consumption, at a low capital cost for the mechanical system.

CONCLUSION

This combined approach, using high-performance glazing, thermoactive slabs, chilled ceilings, and displacement ventilation systems, has been used successfully in Western Europe for the last 15 years, with increasing use in the last 5 years due to rising energy costs. Both applied chilled ceiling systems (capillary tube mats or ceiling panels) as well as thermoactive slab systems are well known in Switzerland and Germany and have been shown to save up to 60% of the energy use compared to conventionally designed and constructed buildings. The track record of the "BATISO" buildings has also shown that they can be constructed at the same, or lower cost than conventional buildings, and can provide superior indoor comfort conditions, compared to traditional "all-air systems." While systems like these are quite common now in Europe, radiant-cooling systems have not yet been accepted in North America for a number of reasons. However, many radiant-cooling systems are functioning successfully in North America, some of which have been in operation for over 35 years.

ADDITIONAL RESOURCES

Web Sites

www.bim.kth.se/fbf/papers/paper9/hydronic_thermal_conditioning.htm

www-twapanels.ca/cooling/faq.html

www.epb.lbl.gov/EPB/thermal/hydronic.html

www.tga-feustel.de/ies/kaiser.html

www-epb.lbl.gov/thermal/dissertation.html

www.advancedbuildings.org/main_t_heat_radiant_heating.htm

www.buildinggreen.com/features/mr/cooling.html

http://eande.lbl.gov/CBS/NEWSLETTER/NL4/RadiantCooling.html

Literature

Systems and Equipment Handbook. 1996. Chapter 6: "Panel Heating and Cooling." ASHRAE.