EMBEDDED TUBE RADIANT COOLING SYSTEMS IN PRECAST PANELS

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ABSTRACT

As local jurisdictions and building owners continue to place increased emphasis on sustainable and responsible building strategies, design teams are looking beyond traditional HVAC solutions to maximize a system's energy efficiency while maintaining human comfort and safety. In-slab radiant heating systems have enjoyed popularity both here in the United States and abroad for years. Now, with the availability of improved control systems and better understanding within the design and construction community, the same concept can be applied to radiant cooling as an energy-efficient and cost-effective solution. This paper will cover the radiant cooling heat transfer fundamentals, system performance and capacity, construction methods and control strategies, with special considerations for systems embedded in precast concrete panels.

Keywords: Radiant Heating and Cooling, Creative/Innovative Solutions And Strategies, Sustainability

INTRODUCTION

Though scholars may point to ancient Rome as the birthplace of radiant heating, evidence by recent archeological digs in Asia and America shows that radiant floor heating systems have actually been used for over 3000 years[1]. Even before the Roman hypocausts, inhabitants in the northern hemisphere from the Neoglacial and Neolithic period heated their subterranean shelters by drafting smoke from fires through stone covered trenches excavated into the floor. The warmed stones would then radiate heat from the floor into the living spaces, creating relatively comfortable indoor environments in very harsh climates.

Fig.1 Hot smoke from ovens such as these at the Gyeongbokgung Royal Palace in Seoul, South Korea was drafted through under-floor trenches, creating warm living spaces.

Fig. 2 Under-floor heating systems were efficient and effective.

Water-based radiant heating systems have been used extensively in Europe for the past century. In these systems, warm water is circulated through a series of piping loops embedded in the concrete floor. The flow rate and temperature of the water is controlled to maintain the temperature of the thermal mass, thus providing superior comfort and energy efficiency.

Early references to the first radiant cooling systems date to the early 1930's, where domestic water was circulated through copper tubing.[2] Acceptance of these systems was slow, due to the capacity limitations of using domestic water, and concerns regarding potential condensation on the floor surface.

Fig. 3 Jemoli Department Store in Switzerland is reportedly the first large-scale commercial building to utilize radiant cooling.[3]

Over the past few decades, radiant cooling has demonstrated success as an engineered replacement for forced air-only systems. As jurisdictions and building owners adopt more stringent energy standards and require higher building performance ratings to meet ASHRAE's Building Energy Label program or Leadership in Energy and Environmental Design (LEED) certification, designers are turning to radiant cooling as a cost-effective, energy-efficient solution to help cool their buildings. Using the same principle as radiant heating, chilled water is circulated through the same series of piping loops embedded either in the floor, walls or ceilings. By controlling the slab temperature, a radiant cooling system can effectively manage all or a portion of the building's load, thereby reducing the total demand placed on the forced air system.

RADIANT COOLING BENEFITS

Each Over the past decade the number of radiant cooling systems designed, installed, and commissioned in North America has increased dramatically. Radiant cooling systems are gaining exposure and popularity for a variety of reasons. One of the main reasons is energy efficiency.

ENERGY EFFICIENCY

Because the heat transfer capacity of water is much higher than that of air, a radiant system that uses a circulator to move water (in lieu of a fan to move air) can achieve the same heat transfer using significantly less energy. Additionally, because of the way the human body reacts to its surrounding environment, comparable levels of comfort can be achieved at higher room temperatures (i.e. 78 degrees F/26.6 degrees C). Therefore a radiant cooling system that manages the bulk of the building's sensible loads (i.e. the loads that affect dry-bulb temperature), coupled with a smaller forced air system (for ventilation, latent loads, and supplemental sensible loads) can significantly reduce a building's total energy usage. Studies have shown total energy conservation for typical office buildings on the order of 17% - 53%[4]. Recently completed projects that have incorporated radiant cooling as part of an energy-efficient design solution include The David Brower Center (Berkeley, LEED Platinum), Cooper Union (New York City, LEED Platinum), NREL's Research Support Facility (Golden, Colorado; LEED Platinum) and Manitoba Hydro's Head Office Building (Winnipeg, MB; LEED Platinum).

Fig. 4 Radiant ceiling cooling systems helped the National Renewable Energy Lab's Research Support Facility reach their goal of LEED Platinum and Net Zero.

OTHER BENEFITS

Another key benefit of radiant systems is the greater architectural freedom afforded by a system that is hidden in the floor or ceiling slab. The visible components comprising the balance of the mechanical system (i.e. air handlers, ductwork, grilles, diffuser, etc.) can be much smaller, allowing greater flexibility in the aesthetic architectural design. The space requirements for the mechanical system (i.e. ceiling space for ductwork) can be compacted, potentially reducing building floor-to-floor heights. Additionally, because a radiant slab can much more effectively deal with direct solar loads, temperatures in areas with high fenestration (i.e. lobbies, etc.) can be more easily controlled with less noise and draft.

Radiant systems also provide improved human thermal comfort, by addressing radiant temperature. In typical settings, during low activity with light clothing and moderate air velocities, the human body transfers a majority of its sensible heat through radiation. Therefore, a thermal mass system that relies on radiation heat transfer can create a more comfortable environment compared to a system relying exclusively on convective heat transfer. By controlling floor temperatures and reducing surface temperature differentials resulting in reduced stratification and radiant asymmetry, a system that relies on radiant heat transfer is more conducive to human comfort.

The embedded tubes within the concrete slab require no maintenance. The radiant cooling system, including the chilled water source and distribution, requires no greater maintenance than typical fluid-based systems. However, the smaller forced air system translates to lower operating and capital costs (i.e. reduced fan horsepower, smaller filtration, smaller de(humidification) equipment, etc.) This, coupled with the system’s overall energy efficiency, leads to reductions in both operating and maintenance costs.

RADIANT COOLING FUNDAMENTALS

Heat transfer occurs whenever there is a temperature difference between two objects within a space, and continues until both objects are in thermal equilibrium. According to a formulation of the Second Law of Thermodynamics known as the Clausius statement, heat cannot naturally flow from a colder temperature to a hotter temperature. In other words, heat will always naturally flow from hot to cold. Heat is transferred in three different ways: Conduction, convection, and radiation. A radiant cooling system uses all three modes of heat transfer.

CONDUCTION

Conduction is heat transfer between two solids that are in direct contact with each other. Conduction occurs between the embedded tubing and the concrete slab. The heat transfer rate is based on the conductivity of materials, the tubing surface, and the temperature difference between the tubing and the slab. Conduction also occurs between the cooled slab and the objects in the space that are in contact with the slab, including air film, furnishings, and occupants. If a person is standing on a cooled slab, then a quantity of body heat will naturally flow via conduction to the slab. The heat transfer rate is based on the cumulative R-values from clothing (i.e. socks, shoes), the floor conductivity, and temperature difference between the occupant and the floor surface. To prevent discomfort due to temperature differentials, ASHRAE Standard 55 recommend that floor slab temperatures should be above 66 degrees F (19 degrees C) for occupants wearing normal foot wear in occupied spaces. One advantage of using embedded cooling pipes in radiant ceilings is that conduction will never occur between the cooled surface and the occupant, thereby allowing lower surface temperatures resulting in increased radiant absorption. It should be noted that in temperature ranges typical of radiant floor cooling systems, and in consideration of footwear R-values, the amount of conductive heat transfer from foot to slab is relatively low and therefore typically considered negligible.

CONVECTION

Convection is heat transferred through a moving fluid or gas. In the case of radiant based HVAC systems natural or “free” air convection occurs due to differences in air densities influenced through contact with warmed or cooled surfaces. This is a design consideration with ceilings as the layer of air in contact with the cool ceiling will drop due to its higher density, increasing air movement, and thus heat transfer, in the space. Forced convection occurs in the air handler, where fans are used to force the cooled air into the space. Because convection deals with heat transfer through the movement of air, the air temperature is directly affected.

RADIATION

Not surprisingly, the bulk of sensible heat transfer that occurs in a radiant cooling system is through radiation. Radiation is heat transfer through electromagnetic waves travelling through space. When the incident waves from a warmer surface come into contact with a cooler surface, the energy is absorbed, reradiated, reflected or transmitted. Because radiation is heat transfer through electromagnetic energy, it does not rely on nor affect the air it travels through. An example of radiation is the sun, whose waves travel through the vacuum of space as short-wave radiation to warm the Earth’s surface. The heat transfer rate is influenced by a number of factors, including the absorptivity, reflectivity and emissivity of the surfaces, wavelength(temperature), and the spatial relationship between the cooled surface and the occupant (defined as the view and angle factors). In radiant cooling, the electromagnetic waves from the occupant are drawn towards the cooled slab, resulting in the occupant experiencing a cooling effect.

SENSIBLE VS. LATENT LOADS

One important consideration to keep in mind is that embedded tube radiant cooling systems can only address sensible load, or the loads that affect dry-bulb temperature. In typical applications, the radiant cooling system will have a capacity on the order of 12-14 Btu/ft^2. For loads exceeding the radiant capacity, a secondary system would then be needed to satisfy the balance of the sensible load, along with the latent and ventilation load.

SYSTEM COMPONENTS

A radiant heating and cooling system is comprised of the following primary components:

- Chilled Water / Warm Water Source
- Circulation/ Mixing System
- Manifold(s)
- Conditioned Slab / Tubing
- Control System

CHILLED WATER SOURCE / WARM WATER SOURCE

A radiant heating/cooling system requires a source of chilled water and heating hot water. In typical commercial applications, this can come from the same chilled water and heating hot water mains that serve the building's air handlers or fan coil units. It is important that the building's hydronic distribution system is designed to provide adequate flow and head to the radiant system manifolds when there is a demand. The typically higher operating cooling temperatures of 55 degrees F (13 degrees C), in lieu of 42 degrees F (6 degrees C) for coil applications) allow greater flexibility in potential chilled water sources. Other sources for chilled water could be stand-alone chillers, fluid coolers, geothermal with or without ground source heat pumps (GSHPs) or lake/bay water. The same is true for heating, where typical operating temperatures are on the order of 86-100 degrees F(30-38 degrees C). Alternative sources for heating hot water could be stand-alone boiler systems, geothermal systems with or without GSHPs, process waste heat, or solar hot water/ storage systems.

CIRCULATION/MIXING SYSTEM

Circulators are used to flow water through the embedded tubing system; and can be centrally located in the mechanical room where water temperature mixing takes place, and/or throughout the building in localized areas. Depending on the specific design requirements, a radiant heating/cooling system can have one or more operating temperatures or "mixed water temperatures." For each mixed water temperature, valves will be needed to reach the target supply water temperature dependent on the main chilled water and heating hot water supply temperatures.

MANIFOLD(S)

Supply and return distribution water is piped to manifolds, where the radiant loops are connected. Manifolds can typically have between 2 to 12 loops connected to them and are offered with a variety of options. Manifolds are commonly located within recessed wall cabinets or in mechanical rooms. Because of limitations in loop length, manifold locations must be carefully coordinated with the architect.

CONDITIONED SLAB / TUBING

The slab is warmed or cooled by water flowing through tubing embedded in the slab. There are a variety of tubing materials, including copper and cross-linked polyethylene (PEX).

CONTROL SYSTEM

The radiant control system is a critical component of any high-efficiency building system. The control system continuously monitors indoor space temperature and relative humidity to determine the optimal target supply water temperature for maximizing the system's performance while ensuring that condensation never occurs on the slab. Inadequate control strategies often lead to sub-par performance, poor response times, energy inefficiencies, inconsistent operation with respect to the airside system, and condensation.

Temperature and humidity sensors are required to effectively manage the slab temperature and to ensure that condensation does not occur on the cooled slab while the system is in cooling mode. Temperature sensors are used to monitor room temperature, outside air temperature, slab temperature, and operating water temperatures. Humidity sensors are used to monitor indoor relative humidity.

CONVENTIONAL SYSTEM DESIGN

There are a variety of conventional options for installing a radiant heating/cooling system, depending on the building construction. The most common configurations for commercial construction are: Slab on Grade, Suspended Slab, and Topping Slab.

SLAB ON GRADE

The most common installation method for commercial construction is slab on grade, where the PEX-a tubing is embedded directly in the structural slab. A vapor barrier, such as high density polyethylene sheeting, is recommended between the radiant slab and compacted base material. Insulation can be critical for proper and efficient operation of the radiant floor system. Heat energy flows in the line of least resistance. Proper use of insulation directs the flow of heat toward the intended space. This is especially important with areas with high water tables/ moist soil conditions. Good insulation practice also increases the response time of the system.

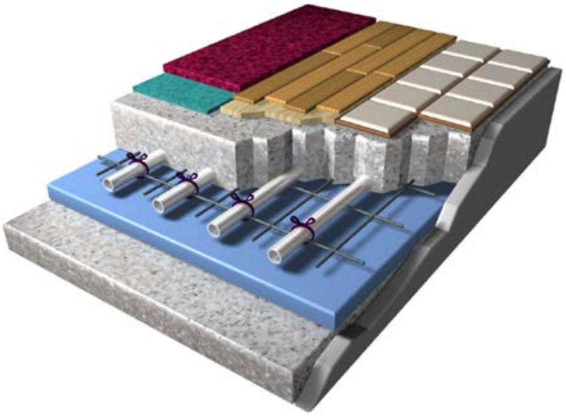

Fig. 5 Conventional Slab on Grade Construction

SUSPENDED SLAB

Structural slab on metal deck installations are common for the upper levels of multi-story buildings. The installation of radiant tubing is very similar to slab on grade installation. The main difference is the insulation, which is typically polyurethane spray foam applied to the underside of the deck. In some cases, the contractor may wish to lay rigid foam board insulation on top of the metal deck under the structural slab. Coordination with the structural engineer is critical to ensure that such an installation does not affect the integrity of the slab.

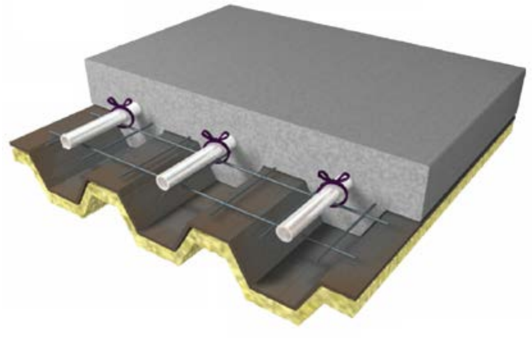

Fig. 6 Suspended Slab Installation

TOPPING SLAB

For installations on existing slabs, or where the structural engineer or local jurisdiction prohibits the installation of tubing within the structural slab, the tubing can be installed in a non-structural topping slab. This installation method is very similar to a slab on grade installation. Since the topping slab does not provide any structural support, it is typically thinner (approximately 3”) and is therefore considered a “low-mass” system. It will have shorter response times, but will have less thermal mass, due to the thermal break of the insulation layer. Design of this topping slab should be done by the project structural engineer.

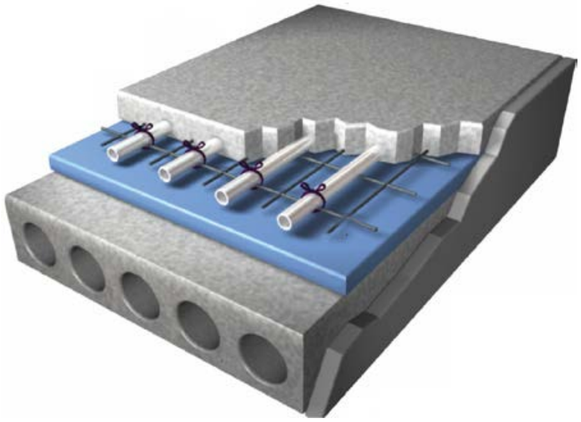

Fig. 7 Topping Slab Installation

PRECAST SLAB

The placement of the tubing in the precast slab or panel would have to be determined by the slab designer. As with the methods outlined above, the tubing can be attached using a variety of approaches. Wire ties to the rebar or a non-structural welded wire mesh is common. The benefit of embedding the tubing in the precast slab or panel is that its placement and coordination with other items in the slab, such as conduit, can be easily done in a controlled environment.

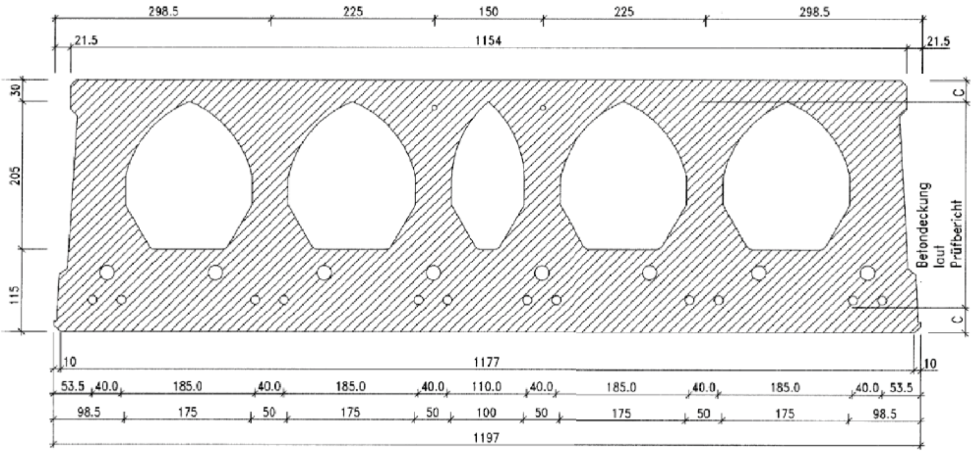

Fig.8 A section of a hollowcore slab showing the location of embedded tubing.

TUBING PARAMETERS

There are a number of different options for arranging the tubing in the slab. The method used will depend on a number of factors, including the size/shape of the room, obstructions, and the heat gain in the space. The most common tubing sizes for commercial heating and cooling applications are ½”, 5/8” and ¾”. The tubing size is based on the flow rate required to meet the heating or cooling load, with the larger diameters serving greater flows with lower pressure drops. On-center spacing ranges between 6” and 9”. The wider spacing would require lower supply water temperatures for cooling and may result in hot and cold spots across the floor surface. The closer spacing allows higher supply water temperatures for cooling and a more even surface temperature, but requires more tubing. The maximum tubing length is normally selected between 350’ – 450’ per loop to limit pressure drop and return water temperature. This includes the active length serving the space and the distance between the manifold and the space being served. The combined total length of tubing (sum of all loops) needed for a space is a function of the area (in square feet) and the on-center spacing.

SYSTEM DESIGN STRATEGIES

RADIANT FLOOR SLABS VS. RADIANT CEILING SLABS

While radiant floor cooling systems are more prevalent (as they are commonly an extension of a radiant floor heating system), there are several reasons why a radiant ceiling may provide improved performance. Assuming that the space design includes exposed concrete ceilings, radiant ceilings can provide up 31 BTU/SF of sensible capacity [5.] This is due to the convective component of heat transfer and the ability to operate the ceiling slab at lower temperatures.

CONTROL STRATEGIES

There are a variety of options available when it comes to managing the radiant floor system. A common, simplified approach is to use cooling and heating setpoints to control supply water temperature. This method will require trial and error adjustments to fine tune the system and at times may provide sub-par performance and surface condensation. A combination radiant heating/cooling system can be effectively controlled using an indoor adaptive reset strategy. This strategy determines the ideal target water temperature by assessing the space conditions (temperature, operative temperature, relative humidity), the water temperature (supply and return), and the slab temperature, and continuously adjusts the target water temperature based on the rate at which the space temperature changes to maximize the effectiveness of the slab while ensuring that the surface temperature never reaches dew point.

Because the radiant cooling system will typically only manage a portion of the sensible load, with a secondary system used to handle the balance of the loads, a common control strategy is to base load with the radiant floor, operating it as an offset to room setpoint, while allowing the secondary system to manage the trim loads. In doing so, the faster-reacting airside system can accommodate rapid shifts in load, while the radiant system is used to effectively provide continuous base capacity. This two-stage cooling approach can be very effective in maintaining comfortable spaces regardless of fluctuations in internal and envelope loads. This is important because in most cases, the temperature of the thermal mass cannot be changed quickly. Depending on the thickness of the slab and the operating room conditions, it may take hours for a slab to change from one setpoint temperature to another. While this may be perceived as a limitation in system controllability, it provides constant and steady capacity despite load fluctuations.

PRECAST SYSTEM DESIGN

A precast system design differs from the conventional installation methods outlined above in two specific ways. First of all, the tubing layouts for a precast slab or panel will be designed for each modular panel, not for the entire zone. Secondly, the connections to the manifold for supply and return chilled water must be handled in a different manner.

TUBING LAYOUTS

In a conventional installation, tubing is routed in serpentine fashion to cover an entire radiant zone. The tubing loops are then brought back to a manifold, typically located in a wall cabinet. In the example loop layout below, there are eleven radiant loops, with average loop lengths of approximately 350 feet each. All loops connect to a wall manifold located on the side of the building.

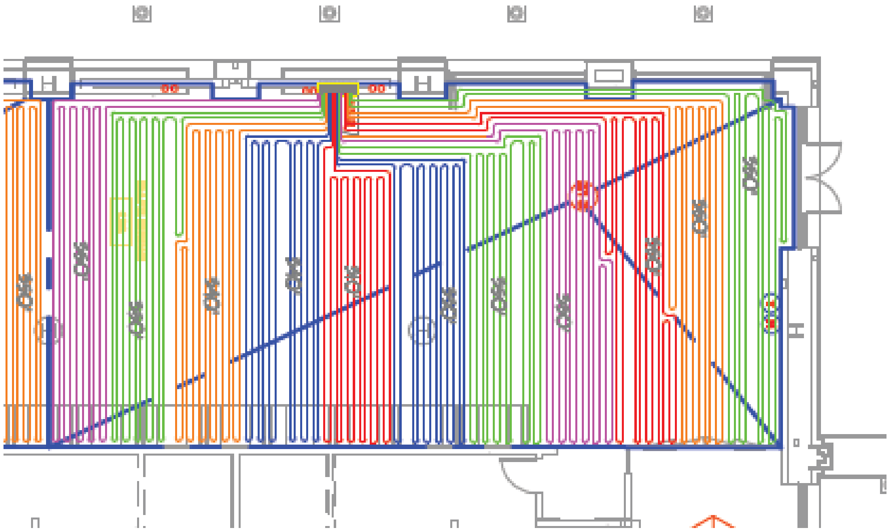

Fig.9 Conventional loop layout makes efficient use of the space.

The tubing would be installed on site and laid out for the entire zone, which measures approximately 60’ x 30’. If this building were to be constructed using precast concrete panels, the radiant approach would have to be defined at the panel level. In this case, the 60’ x 30’ zone may be installed as four (4) 15’ x 30 ‘panels, side by side.

This layout would call for three loops, which supply and return water connections at each end. Each loop is approximately 300 feet long. In total, this approach would require twelve loops for the four panels. Depending on the layout of the panels, the tubing may exit the slab at the top or at the ends. Either way, a means of connecting the loops to a main header will be needed. Care must be taken in securing and protecting the tubing as it is transported from the factory to the jobsite. Since PEX tubing is not UV resistant, this typically involves wrapping the tubing in a non-opaque bag.

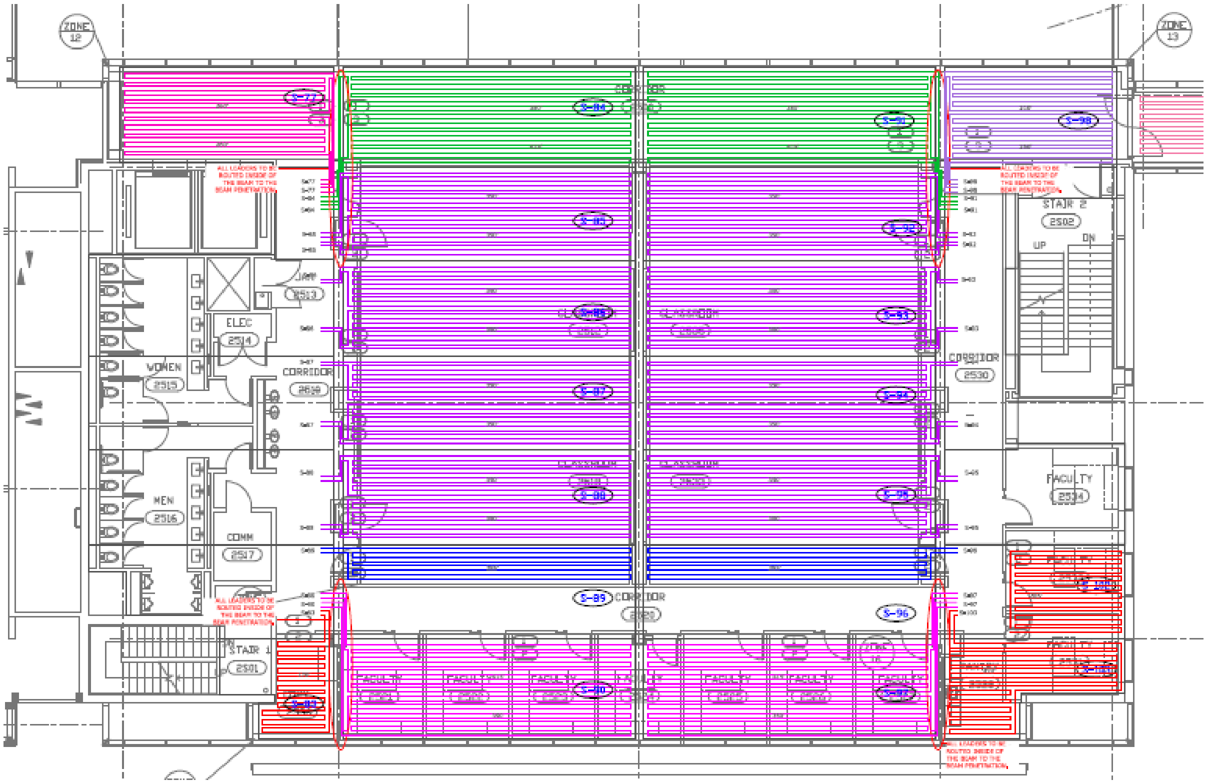

Fig 10. A sample radiant system layout utilizing precast floor slabs.

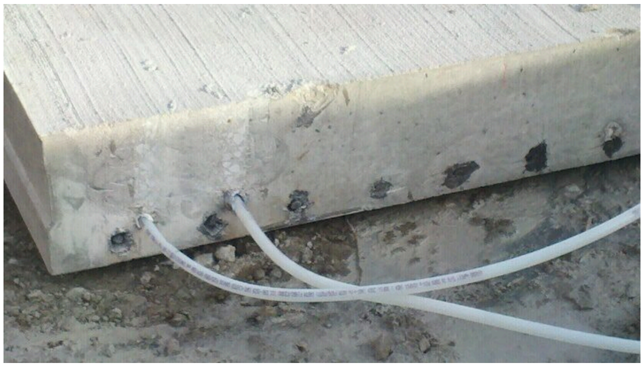

Fig 11. A precast slab with tubing exiting on the end.

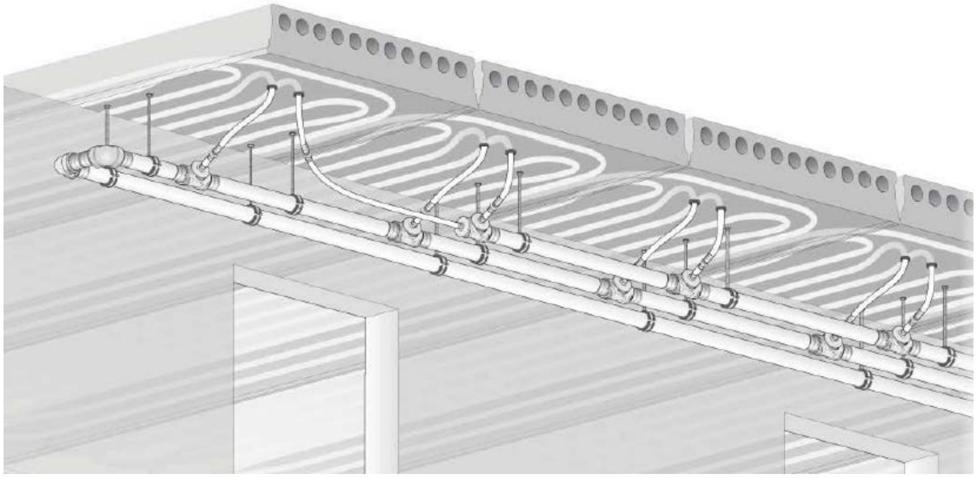

Fig. 12 A header system is used to connect the tubing exiting the precast panel.

RADIANT COOLING CHALLENGES

While radiant cooling systems are gaining in popularity due to the increased demand for energy efficient building systems, there remain several obstacles. One of the key obstacles is the general lack of understanding among many in the design and construction industry. The HVAC industry is comfortable with and accustomed to maintaining the temperature of indoor environments by circulating conditioned air. Mechanical contractors understand how to install, control and maintain traditional HVAC systems. The fundamental concepts of heat transfer and thermal mass are often forgotten by system designers who are used to using industry-standard “rules of thumbs” or conventions when selecting and designing systems. Because thermal mass systems do not react the same way that forced air systems act, engineers and building owners need to adjust their expectations and understanding of how the system is intended to operate. Also, most of the common analysis tools used to model building energy performance do not include a module to accurately model a radiant cooling slab. In these cases, higher-level modeling tools are required or general approximations are used.

This is even more of a challenge with precast slabs or panels, as very few precast manufacturers have incorporated embedding tubing into their process. The systems must be carefully designed and coordinated, as these systems are very difficult to modify in the field.

In addition to this, other obstacles exist, such as performance limitations and increased system complexity.

PERFORMANCE LIMITATIONS

A typical radiant floor cooling system will be able to handle between 12-14 BTU/SF of sensible load. A radiant ceiling can handle up to 31 BTU/SF. In buildings with poor envelopes and/or high internal loads, this may only represent a small percentage of the total sensible load. The capacity of the system may also be lessened due to high indoor relative humidity, which would limit the operating water temperature to avoid surface condensation. Additionally, floor coverings such as carpet may decrease the system's effectiveness.

Under ideal conditions, where the bare concrete radiant floor slab is used in a well-designed envelope with nominal internal loads and humidity control, the radiant cooling system can be very effective. In order cases, however, the projected performance of the system must be evaluated in light of budget limitations.

CONCLUSION

As building owners and jurisdictions continue to demand high-performance buildings, system designers are looking for solutions to reduce energy usage. By taking advantage of a building's thermal mass, an embedded tube radiant cooling system can be an effective and energy efficient alternative to a conventional forced-air-only system. When installed as part of a precast panel assembly, the process can be more closely controlled. While there are certain considerations that must be taken into account when incorporating radiant systems in a precast panel, these systems can be used not only to reduce energy, but to provide improved comfort and ventilation while increasing architectural flexibility. Improved understanding and controls, along with increased familiarity with installation methods will greatly help radiant cooling become more accepted in the design and construction community. When considering radiant cooling as a system option, the design team must evaluate the system's projected capacity, the building's total cooling loads, construction type and budget so that a thorough analysis can be done.

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