Current Practice for Design and Control of High Thermal Mass Radiant Cooling Systems, and Opportunities for Future Improvements

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ABSTRACT

Radiant cooling and heating have the potential for improved energy efficiency, demand response, comfort, indoor environmental quality, and architectural design. Many radiant buildings have demonstrated outstanding performance in these regards. However, there are no well-established best practices for design of radiant buildings and their control systems, and most industry professionals are unfamiliar with radiant systems.

This study summarizes interviews with eleven professionals with substantial experience with design and operation of radiant buildings in North America. Interviews focused specifically on high thermal mass radiant buildings, referred to as thermally active building systems (TABS). Interviews revealed a diverse range of approaches for design and control of TABS buildings. While interviewees expressed many similar approaches, they also have many unique preferences.

Examples of consistent themes include the use of dedicated outdoor air systems for ventilation and for supplemental cooling, and the use of a relatively simple control schemes that target a constant slab temperature for all times of the day and night. However, interviewees described unique preferences for space types where TABS should be applied, design and types of valves or pumps used for radiant zone control, the control of changeover between slab heating to slab cooling, and many other design considerations.

Preferences appear to be driven by project constraints and by personal experience. Interviewees report that their design preferences are effective, but there is no industry consensus about how alternatives compare for energy performance. This paper outlines opportunities for further research, improvement radiant design and control, and the development of best practices.

Introduction

Radiant cooling and heating have the potential for improved energy efficiency, demand response, comfort, indoor environmental quality, and architectural design. Many radiant buildings have demonstrated outstanding performance in these regards, and the technology's application in commercial buildings appears to be expanding, especially among high performance buildings and zero net energy buildings (Maor 2016, NBI 2016, Higgins 2017). However, most buildings industry professionals are unfamiliar with radiant systems.

The design and control of high thermal mass radiant cooling – Thermally Active Building Systems (TABS) – are especially unfamiliar to industry professionals. These systems cool building masses from the inside out, which uniquely decouples the time of cooling plant operation from the time that heat is extracted from the occupied space. Consequently, air

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temperature thermostat cannot directly control the space cooling rate the way a typical forced air system operates. Control strategy choices for TABS systems can be expected to impact comfort and energy use, yet there are not well-established guidelines for design of radiant buildings and their control systems.

Therefore, this study's objective was to document current TABS radiant buildings' design and control practices by interviewing professionals with subject expertise. In this paper, we review the project scope and methodology, and then present information about current practices related to: systems configuration design, sequences of operation (SOO), and system commissioning. In view of these findings, we identify ways that TABS radiant building design could be improved, and discuss needs for future research.

Methodology

As part of the California Energy Commission (CEC) Electric Program Investment Charge (EPIC) project **Optimizing Radiant Systems for Energy Efficiency and Comfort**, and in conjunction with the Center for the Built Environment (CBE) at University of California at Berkeley, TRC Energy Services conducted research to investigate best practices for design and control of TABS radiant cooling systems for commercial buildings. The goal of this portion of the EPIC project was to summarize current best practices as reported by experts. Research consisted primarily of interviews with radiant cooling design experts, with related exploration into previous literature and designer SOO. Radiant cooling was the focus of the research, but findings related to radiant heating are included when pertinent to radiant cooling design and control.

We conducted eleven interviews with radiant cooling experts in 2016. These interviewees were individuals within our industry networks, with practical experience in design, construction, and operation of TABS radiant buildings. We used a structured interview method to obtain responses to the same topic areas, and asked interviewees to share their typical and/or preferred design approaches, including motivations for each design approach, design tradeoffs, and challenges associated with implementation. We asked that responses focus on design and control of TABS (rather than radiant panels or embedded surface systems) for projects in North America. Interviews lasted one hour and included questions in each of the following topic areas:

- Interviewee background
- System configuration
- Controls and sequence of operation
- System commissioning

We analyzed and summarized interviewee responses for each question, paraphrased quotes that help capture key ideas, categorized the variety of responses to each question, and tabulated the count of responses in each category. The categorization of responses was developed after the interviews to group common themes – the categories were not a pre-determined set of options. Response categorizations were emailed to the designers for review, and many provided both confirmations and corrections to our original categorizations.

Interview Findings

We interviewed eleven prominent professionals who have designed a combined total of approximately 330 radiant cooling projects. Most often, interviewees were the lead design engineer, but occasionally served as the overseeing principal or consultant to the architect. We focused on experts working in North America, and therefore most of the radiant cooling projects discussed in these interviews were in the United States and Canada.

Interviewees consistently described the following key characteristics of radiant cooled buildings that underpin design approaches and how they control radiant systems:

- The upper limit of cooling capacity from TABS is lower than conventional air systems. It is important to reduce building envelope and internal loads, and supplemental cooling may be required too.
- TABS' high thermal inertia results in very slow changes in radiant surface temperature. This is both an advantage and a challenge.
- The cooling capacity from TABS is somewhat self-regulating because heat transfer to the cooled slab surface naturally and instantaneously responds to changes in air and other surface temperatures.

In addition to these broad takeaways, the following sections summarize findings related to system configuration, control sequences, and commissioning. In each topic area, we highlight the common practices and then discuss the variety of practices.

System Configuration

The study team asked interviewees about several different aspects of system configuration focused on:

- Slab configuration
- Supplemental cooling
- DOAS design
- Zoning

Common practices and variation in practices are discussed below.

Common Practices

Most TABS designers prefer to embed radiant tubing within the structural slab. This approach is less costly than pouring a topping slab, and activates the entire thermal mass. However, sometimes tubing is located in a topping slab for various reasons; usually this is installed without insulation between the structural and topping slabs to maximize thermal mass.

Almost all radiant cooled buildings also use radiant systems for heating. Rarely, heating is provided with an alternate method, such as perimeter radiant panels. Not all radiant heated buildings use the radiant systems for cooling.

Interviewees consistently said that radiant systems have smaller cooling capacity than air systems and that indoor conditions respond slowly to changes in chilled water temperature or flow rate. Furthermore, many designers prefer large radiant zones – some even aim to control the entire floor plate as a single zone. For these reasons, interviewees emphasized a need for high-performance envelopes to minimize the magnitude and variation in heat gain, particularly to ensure that perimeter areas are not subjected to excessive variation in heat gain as compared to interior areas. At the same time, many interviewees noted that radiant cooling can remove direct solar radiation that strikes radiant surfaces much more rapidly than other types of heat gain; and for this reason, radiant floor cooling is sometimes specified in spaces with larger than normal solar gains.

Most radiant system designers include supplemental cooling – sometimes in select zones and sometimes in all zones. Supplemental cooling maintains comfort when gains exceed radiant system capacity, enables tighter temperature control in specific areas, and provides short term cooling capacity in spaces with highly variable gains (such as conference rooms). Designers use dedicated outside air systems (DOAS) ubiquitously to provide fresh air ventilation in radiant buildings and often also use the DOAS to provide supplemental cooling by adjusting volume flow, supply air temperature, or both together. Two general methods for supplemental cooling that most interviewees have used include:

1. In zones where radiant is expected to provide most of the needed cooling capacity, interviewees provided supplemental cooling with the DOAS ventilation system, either by increasing the delivered flow rate, or by decreasing the supply air temperature below space temperature. To enable supplemental cooling, the DOAS maximum airflow rate is typically sized above code minimum ventilation requirements by 20 to 30%, and cooling capacity is sized accordingly to achieve desired supply air conditions.
2. In zones where heat gains are expected to greatly exceed TABS cooling capacity, most interviewees include fan coils, radiant ceiling panels, or variable air volume (VAV) air supply for supplemental cooling.

Variation in Practices

Significant differences between interviewees related to system configuration design included:

- **Appropriate space types for radiant cooling**. Interviewees were divided between those that have only included radiant cooling in specific space types (lobbies, atrium, open plan spaces, etc.) and those who have had success with radiant cooling in a wide variety of space types – including private offices and high-density spaces with variable gains such as classrooms and art galleries.
    - A few designers noted that offices pose difficulties for TABS, including acoustics, management of small individual thermal zones, and the need to accommodate flexibility for future tenant reconfiguration.
    - Designers who feel that radiant systems are appropriate for most occupancy types, state that supplementary systems can be used to fine-tune conditions in individual

    spaces or when reconfigurations occur, even when radiant floor zoning has large zones by orientation and interior/perimeter.

- **Zone valves or pumps**. Some designers prefer achieving zone control with valves, while others strongly prefer circulator pumps.
    - Interviewees that preferred valves were divided in their preference for radiant floor control valve type. Most preferred 2-position on/off valves that effectively pulse water into the radiant zone with on/off control, while others prefer modulating valves that continually modulate flow.
    - Interviewees that preferred pumps indicated that in buildings with a small number of zones that are fairly close to each other, valves can be used, but in instances where there are many zones (or large zones) circulator pumps are used.
- **Two-pipe versus four-pipe distribution systems.** Approximately half of interviewees use two-pipe distribution for the entire building, meaning all radiant zones must be in the same mode, either heating or cooling. The other half of interviewees are evenly split between: (a) providing four-pipe distribution to the zone level, or (b) providing four-pipe distribution to sections of the building with two-pipe distribution continuing to groups of zones. Solution (b) is a way to balance first costs with level of control – by limiting four-pipe distribution to sections of the building that may need to be in different modes (heating or cooling) such as each floor, by orientation, or by floor and orientation. Interviewees who use two-pipe distribution explained that with a well-designed envelope, the need for heating and cooling should change slowly over the year, and that the slab setpoint will be essentially neutral during swing seasons.
- **Supplemental cooling design**. Interviewees had a wide variety of approaches for zoning and controlling DOAS systems to provide supplemental cooling, and these were often designed in response to the unique needs of each building.
    - On one extreme the DOAS system has VAV boxes at every zone, although most interviewees try to avoid this design because of the high initial cost.
    - More commonly, the DOAS can vary flow or temperature at the air-handling unit (AHU) without any zone control, to provide supplemental cooling to all zones.
    - The DOAS system may have a limited number of zone dampers that are either pressure independent (VAV boxes) or pressure dependent (simple zone dampers).

Controls and Sequences of Operation

The study team asked interviewees about several different aspects of design of controls and SOO:

- Slab temperature control
- Zone air temperature control
- Interaction with supplemental cooling and mode changeover
- Condensation control
- DOAS control

Common practices and variation in practices are discussed below.

Common Practices

Interviewees explained that the cooling capacity of TABS systems naturally adjusts to temporal and spatial variations in heat gains. This self-regulation occurs because heat transfer to the slab surface instantaneously responds to changes in the surrounding air temperature and changes in the temperature of other surfaces in the space. Interviewees noted that this characteristic is a critical design consideration. Self-regulation is the reason that radiant systems can maintain comfort throughout large zones even though slab surface temperatures respond slowly to changes in chilled water temperature or flow. The temporal and spatial granularity of zone control for radiant systems is typically much coarser than for typical VAV air systems.

Indoor conditions in TABS buildings do not respond quickly to changes in supply water temperature or flow rate; therefore, the type of reactive control strategies traditionally used for conventional VAV systems are not especially useful for high mass radiant systems. Instead, controls for TABS radiant buildings are configured to target a slab temperature setpoint – measured with an embedded slab temperature sensor – by adjusting chilled water supply temperature or flow rate. Almost all interviewees shared that TABS buildings are controlled to maintain relatively constant slab temperature setpoint round-the-clock, instead of a zone air temperature set point. Each zone may have a unique slab temperature set point that is selected to result in comfort within the space throughout the day. These set points are usually programmed to change slowly over the course of the seasons, or as a function of recent outside temperatures. Only a few interviewees allow setback during vacant periods, and typically they are small setbacks. Choosing the appropriate relationship between slab temperature set point and outside air temperature typically requires tuning during the first few seasons of operation.

Several interviewees indicated that alternate plant designs could avoid the need to generate low temperature chilled water throughout the year, including use of night sky cooling, ground source or water source heat pumps, and water side economizing. While these were indicated as desirable strategies, most radiant buildings use conventional chillers that operate a typical low chilled water temperature. Further, most interviewees do not attempt active load shifting to reduce mechanical equipment operation during peak demand hours or take advantage of improved equipment efficiency overnight. One designer that had attempted load shifting explained that the strategy was ultimately abandoned to avoid the risk of morning discomfort, and instead adopted an approach that always maintains a constant slab temperature.

Usually, the control of radiant systems and supplemental cooling systems are not explicitly coordinated: radiant systems are controlled to maintain slab temperature and supplemental systems are controlled to maintain air temperature. None of our interviewees had controlled DOAS equipment to provide economizer cooling when outdoor conditions are appropriate. However, about half of our interviewees have used natural ventilation for thermal regulation in radiant buildings.

Avoiding condensation on radiant surfaces is important, but not difficult, and can be addressed through design and appropriate set points for the radiant surfaces and DOAS systems. Most avoid condensation on radiant surfaces by dehumidifying ventilation air to a dew point temperature or relative humidity target, then by maintaining chilled water temperature supplied to the slab above the dew point. Almost no interviewees had encountered condensation in practice. Those few that had encountered condensation problems attributed the issues to unusual situations (often during commissioning) or improper operation. The issues were resolved through operator training and control sequence revisions. In the collective experience of our interviewees, nobody had experienced ongoing issues with condensation.

Variation in Practices

Significant differences in design of controls and SOO between interviewees include:

- **Space temperature set points**. Some designers recommend space air temperature set points that are like those used in conventional HVAC systems, while others advocate for radiant systems to operate with a wider dead band between heating and cooling.
- **Condensation risk.** Interviewees differed on whether or not to include active controls to reduce condensation risk. Condensation control is climate dependent, which may explain some of the variation in approaches, although some of these contrasting approaches were used in the same climate:
    - Some interviewees emphasized that active control of slab supply water temperature and/or DOAS dewpoint are critical to prevent condensation. A few interviewees explained that as a fail-safe, they include simple moisture switches located on the CHW supply pipe near the zone manifold that disable CHW supply when condensation is detected.
    - Other interviewees emphasized that they do not need active control when a system is engineered to never reach a condensation condition during normal operating conditions. Indoor humidity is used only for monitoring and alarming.
    - Some designers ensure that chilled water temperature stays at least 2°F above the dew point, while others allow the chilled water temperature to drop below dew point as long as the slab surface temperature does not.
- **Slab temperature sensor location.** All interviewees measure slab temperature, but were divided in their preference for slab temperature sensors located at the depth of radiant tubing versus near (or at) the surface of the slab. Most locate a sensor in-between the tubes, and at same level as the tubes. Three interviewees locate the sensor near the slab surface, at a depth of 1-2 inches. For large zones some interviewees averaged multiple slab temperature sensors.
- **Chilled water plant size**. About half of our interviewees shared that TABS buildings influence the sizing of a chilled water plant, while the other half specify a plant that is the same size as it would be for an equivalent building with conventional VAV cooling. One interviewee explained that chiller equipment could be smaller if a TABS building were controlled to store thermal energy like a flywheel, but that it is difficult to control such a system without risking discomfort occasionally, and that customer and operator expectations do not usually allow for such a control strategy.
- **Chilled water plant supply temperature**. Without exception, radiant cooling systems operate with higher chilled water temperature (at the zone) than typical air handling systems to help reduce the likelihood for condensation and discomfort. However, about half of interviewees design to generate chilled water at low temperatures typical of conventional buildings (mid-40°F), then blend with return water from radiant systems to achieve an appropriate radiant supply water temperature. This control decision is driven by a need for low temperature chilled water used for dehumidification, or for

conventional systems (e.g., VAV, fan coils) in areas of the building where radiant cooling was not included. Interviewees that had designed central plants that supplied warmer chilled water for the radiant floor described the following strategies:
    - Two chilled water plants that supply different temperatures,
    - Chiller in series with the lead chiller generating warmer temperature water for radiant cooling, or
    - Chilled water plant supplying warmer water to the radiant system and DX used for dehumidification in DOAS air handlers and/or conventional VAV systems.
- **Heating and cooling mode changeover**. Interviewees had a wide variety of approaches to control changeover between radiant slab cooling and heating modes, and emphasized the need for tuning changeover during the first year of occupancy. Interviewees stated several different ways to control changeover:
    - Slab temperature and/or fluid temperature setpoints are reset based on season or trailing mean outside air temperature, resulting in slab temperatures often near space temperature when changeover occurs. This is usually combined with other strategies listed below.
    - Delay changeover for multi-hour periods where the radiant slab is off. Interviewees and SOO we reviewed noted a slab lockout time in the range of 2 to 24 hours and that this parameter often needs to be adjusted in the field.
    - Measure slab temperature to ensure it has reached space temperature (fully discharged) before changeover is allowed.
    - Adhere to ASHRAE 90.1 requirements for two-pipe system changeover time delay requirements.
    - Limit slab heating mode and cooling mode to operate within a certain range of outside air conditions (e.g., both modes may be disabled between 65°F and 75°F).
    - Rely on natural ventilation to condition the space for the period in between active heating and cooling.

  Although many interviewees mentioned that there are long periods (weeks or months) between the need for slab heating and the need for slab cooling, many designers allow the slab to changeover in a matter of days or hours depending on recent weather conditions and real-time demand. Interviewees were also divided in their concern that changes in mode can lead to energy waste when a slab changes mode too quickly, with some saying the situation should be avoided but is occasionally needed to maintain comfort. Other interviewees noted that a change in mode for the slab is only a difference of a few degrees, so that changeover in the same day is not of extreme consequence if there are appropriate delays that avoid shocking the central plant.

System Commissioning

Interviewees told us that it is usually necessary to tune up radiant buildings during the first year of occupancy and to educate controls contractors and operations staff about proper system setup and management. Typically, buildings require unique settings based on building characteristics as well as climate zone that must be determined during occupancy and often require expert designer input to fine tune. Adjustments that typically occur include:

- Slab temperature set point for each zone
- Seasonal slab temperature set point reset
- Supplemental cooling quantity (usually determined by DOAS supply air temperature)
- Flow in individual radiant loops with manual balancing valves at the manifold.

All designers said that building operators need education to understand and operate a radiant cooled building properly, as radiant buildings are controlled very differently than buildings with other types of HVAC systems. Designers often stay engaged for the first year of occupancy to ensure project success even when they were not retained for ongoing commissioning services.

Opportunities for Further Research and Improvement in Common Practices

Interviewees often explained their different engineering solutions as being responsive to the varying needs of each application – including unique solutions for each building, owner, and climate. However, many interviewees seemed flexible in their approach, which yields opportunities for improving common practice. Where differences in design approach exist, there may be opportunities for refinement and improvement of design solutions. We provide commentary to identify opportunities to improve common practice and opportunities for further research. Note that this is a partial list suggested by the authors and not representative of the interviewees' opinions.

- **Self-regulation.** The self-regulating nature of radiant TABS is a critical design consideration and key to the success of radiant buildings. Despite the importance of self-regulation, interviewees did not have quantitative information on the magnitude of the effect, response time, or specific approaches to design decision making (e.g., when self-regulation is acceptable versus when zonal supplemental cooling is required). Assumptions about self-regulation have a large impact on zoning and supplemental systems design, and it is likely that many radiant buildings rely too much on supplemental cooling when they could rely on self-regulation. Fully accounting for self-regulation could reduce system cost by avoiding unnecessary supplemental systems and control system complexity. Primary research and a literature review of published research on the self-regulation of radiant cooling should be used to develop quantitative design tools accessible to designers.
- **Heating and cooling mode changeover**. Given the variety of methods used, a simple and standardized approach to heating/cooling changeover control would be helpful. Controls could address seasonal or weather based resets, lockouts between heating and cooling modes, and prevention of overshoot and energy waste when modes change too quickly.

- **Pre-cooling**. The thermal mass and large response time for TABS can allow control sequences that strategically shift cooling plant operation to times when electricity is less expensive, or when outside temperature is better for cooling plant efficiency. However, we learned that very few TABS buildings actively employ these strategies. Many interviewees recognize this opportunity but have concerns such as risk of thermal discomfort, or limited energy savings potential because the slab temperature can only be reduced a small amount when considering the large thermal time lag of the mass. One of the challenges is lack of algorithms to predict pre-cooling response. A few interviewees said that weather based predictive control would be useful for radiant cooling but also noted that there are no proven algorithms that they could rely on.
- **Chilled water plant supply temperature**. Radiant cooling can reduce energy use by operating at a relatively warm chilled water temperature; this can improve chiller efficiency, and enable the use of chiller-less water-cooling strategies. Many TABS buildings do not take advantage of this opportunity. Our interviews revealed that chilled water is often generated at a low temperature to provide dehumidification, or to serve forced air cooling in portions of the building that do not include radiant, and then mixed with return water to supply higher temperature chilled water to the radiant systems. Some radiant designers use separate chillers for the separate purposes, but cost concerns often result in a single low temperature chiller plant for the whole building. Life-cycle cost analysis of various cooling plant solutions, including the variety of solutions used by interviewees, would reveal the most cost-effective solutions and help justify the investment in a more efficient cooling based on energy cost savings.
- **Chilled water temperature and condensation risk.** Most designers are careful to keep chilled water temperature well above the dew point. However, since the slab surface temperature is always warmer than the chilled water supply temperature, at least one designer allows supply water temperature to drop below dew point, while remaining careful to keep the slab temperature above dew point. Operating at lower chilled water temperatures and associated lower slab surface temperature increases the cooling capacity of a radiant floor while increasing the risk of condensation. Condensation on chilled water piping is prevented by standard insulation and vapor barrier details, but it is unclear if there is risk of condensation on radiant manifolds and piping between the manifold and slab. Designer decisions for chilled water temperature have impacts on both the energy used to cool the slab and dehumidify ventilation air.
- **Two-pipe versus four-pipe distribution**. Some interviewees used two-pipe hydronic distribution systems to reduce piping costs. They suggested that a high-performance envelope reduces the need for different zones to be in different modes, as well as rapid mode changeover in the same zone, thus eliminating the need for a four-pipe system. Interviewees that used four-pipe distribution systems either to the zone or groups of similar zones sought improved control and comfort at each zone level. Analysis of cost tradeoffs between four-pipe distribution and building heat gain management (improved envelope, reduced internal loads, etc.) may reveal the most cost-effective balance for specific types of buildings in specific climates. In addition, quantification of radiant self-regulation (discussed in the first bullet point) is required to determine when a two-pipe system is insufficient to maintain comfort.

- **Radiant and supplemental cooling interlocks**. Regardless of how the radiant and supplemental control loops are interlocked, the control loop for supplemental cooling systems always responds more rapidly to changes in space temperature than does the control of massive radiant systems. In the end, it is not clear if the SOO typically used to interlock radiant and supplemental systems minimizes energy use for the two systems combined. Interviewees did not comment on the relative cooling energy cost between supplemental cooling versus radiant cooling and how to minimize it. In addition, many interviewees specify controls without any interaction or lockout between DOAS air systems controls and radiant slab controls – which we believe could lead to "fighting" between the DOAS and radiant floor. Interviewees were not concerned about potential fighting, often citing the very small temperature differences. None of the interviewees modulate DOAS supplemental cooling based on availability of free cooling (economizer operation) even though the energy cost of supplemental cooling in this situation may be less than radiant cooling energy cost. In all cases there appears to be an opportunity to reduce energy use with control sequences that consider the benefits and tradeoffs of both supplemental cooling and slab cooling.
- **Supplemental cooling control.** Supplemental cooling design and control is usually a critical piece of the overall radiant system solution and interviewees had a wide variety of approaches. Many used novel solutions to reduce cost and avoid a fully VAV DOAS air system. Interviews did not have sufficient time to delve into the nuance and variety of DOAS system design and how the DOAS is controlled to provide supplemental cooling (also see the previous item). Further investigation into this topic would be useful.
- **Supplemental heating.** Only a few projects used supplemental heating in addition to radiant slab heating. We suspect that the need for supplemental heating only occurs in very cold climates, but we did not have time to determine if this design decision occurs only in cold climates, nor what the outdoor design condition threshold might be that triggers it.
- **Ceiling fans**. Although many interviewees recognized that ceiling fans could extend the comfort envelope, reduce stratification, and increase the convective cooling capacity for radiant surfaces, few had ever utilized the strategy. Several interviewees mentioned that many architects generally do not consider ceiling fans a viable design option, and others explained that better information is needed about the specific benefits to advance the design strategy. A couple interviewees mentioned that ceiling fans would disrupt stratification from radiant floor cooling and displacement ventilation. Those who have utilized ceiling fans said that they consider air movement as a factor that impacts thermal comfort, but that they have not specifically considered the increase in convection from radiant surfaces when designing the radiant system. Others were hopeful about including the strategy in the appropriate circumstances. Further investigation into the energy impacts of ceiling fans in radiant applications would be useful.
- **Use of mean radiant temperature.** Interviewees explained that zone air temperature tends to vary more in radiant buildings but we did not get quantitative data on the magnitude, nor how the air temperature variation compared to mean radiant temperature

(MRT) variation.[2] Further investigation into the actual temperature variation that occurs (separating air temperature from mean radiant temperature) would be useful for designers, controls contractors, and building operators. Data collection methods could include more simulation or measured in the field in operating radiant cooled buildings.

- **System commissioning**. Typically, radiant buildings require unique settings that need to be determined during occupancy and often require expert designer input to fine tune. Designers noted that these improved industry education, or development of self-tuning control sequences could help to address these challenges.
- **Terminology.** There is a wide range of different terminology and understanding among experienced designers in the same field. For example, designers indicate that different design that apply to TABS versus embedded surface systems (which have lower 'activated' mass because they are isolated from a structural slab by insulation). Variations in terminology and system design approach presented challenges during interviews and analysis of interview results. There is an opportunity to create a topology of radiant cooling that is more inclusive of the various aspects of radiant systems, and rigorously defined.

Conclusions

Radiant cooling can reduce energy use and electrical demand for heating, cooling and ventilation, but most design professionals are not familiar with the technology. We interviewed experts in the field to document the current practices for design and control of radiant cooling systems. This paper documents the landscape of current practice for design and control of TABS buildings in North America. We have presented the results for public consideration and to enable the refinement and standardization of best practices.

We found that in some aspects there are common themes for how radiant cooling is normally employed, but in other aspects there are a wide variety of strategies and opinions among experts. There are significant differences between the various design and control strategies currently employed in radiant buildings which have clear implications for energy performance and comfort. Some of these differences are driven by project constraints, while others appear to be driven by designer preference, or by individual understanding about the behavior and capabilities of radiant systems. Radiant cooled buildings are often not designed or controlled to consummate some of the well-recognized efficiency opportunities conferred by the technology. For example, more than half of radiant cooled buildings use conventional chillers and operate them at typical low chilled water temperatures. Furthermore, all of our interviewees designed radiant buildings that were controlled to maintain a slab temperature setpoint continuously, and none had proactively controlled radiant cooling systems for nighttime operation to avoid peak electrical demand periods, to improve cooling plant efficiency, or to reduce the required size for a cooling plant.

[2] Our observation based on current and past research is that over the course of a typical day the mean radiant temperature is typically more stable and cooler (in cooling)/warmer (in heating) in a radiant building than in a forced air building, but the zone air temperature changes more than in a forced air building. Moreover, MRT and air temperature in radiant buildings are closer to each other than in a forced air building, therefore an air temperature sensor is closer to operative temperature in a radiant than in a forced air building.

To support broader adoption of radiant cooling, we see a need for standardized SOO and rigorous iterative improvement of these sequences based on feedback from completed projects. Our findings can inform development of industry standards, design guidelines, resources for education and training, and best practices for design and control of radiant systems. Our interviews also revealed gaps in research where the most efficiency strategies have not yet been evaluated, such as an assessment of the coordination between radiant systems and supplemental cooling systems.

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