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OPTIMIZING RADIANT SYSTEMS FOR ENERGY EFFICIENCY AND COMFORT

EPC-14-009

CODES AND STANDARDS REPORT

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1. Introduction

One goal of this EPIC radiant project is to leverage the impact of this research through changes in relevant codes, handbooks, guidelines and standards. The primary frameworks for these changes are through the ASHRAE technical, standards and guidelines committees and the California Building Standards. These efforts are intended to support effective coverage of high thermal mass radiant systems for Title 24 code compliance and to document and support best practices as uncovered by the research activities associated with this EPIC project.

This overall report is divided into four major sections and combines four distinct reports relating to codes and standards: Codes and Standards Enhancement Reports, Title 24 Code Change Report, ASHRAE Standards and Handbooks Report, and Standard Addenda.

2. Codes and Standards Enhancement (CASE) Reports

The California Building Energy Efficiency Standards (Part 6 of the California Building Standards Code), colloquially and hereinafter referred to as Title 24, are designed to ensure that new and existing buildings meet minimum energy efficiency and indoor environmental quality requirements.

The standards are updated on a triennial basis by the California Energy Commission (CEC) to allow consideration and possible incorporation of new energy efficiency technologies and methods. New potential energy efficiency measures are evaluated through a Codes and Standards Enhancement (CASE) process that are managed by the investor-owned utilities (IOU) in California. The CASE studies require extensive research and evaluation of first cost impacts and life cycle cost effectiveness, as well as extensive stakeholder input and public comment.

The original expectation was that radiant systems would be a focus of a CASE study as part of the 2019 Title 24 update cycle, which was completed in 2018, but it was not prioritized by the IOUs for that cycle, which precluded the opportunity for the EPIC radiant research team to contribute to that effort. In lieu of that effort, the project resources were channeled instead into expanding the Radiant Cost Comparison effort to include energy savings analysis, and to expand the focus on the Title 24 Code Compliance Report.

3. Title 24 Code Change Report

The California Building Energy Efficiency Standards (Part 6 of the California Building Standards Code), colloquially and hereinafter referred to as Title 24, are designed to ensure that new and existing buildings meet minimum energy efficiency and indoor environmental quality requirements. The standards are updated on a triennial basis by the California Energy Commission (CEC) to allow consideration and possible incorporation of new energy efficiency technologies and methods. Title 24 contains building energy efficiency requirements applicable to most residential and nonresidential buildings throughout California.

The current version of Title 24 does not address factors specific to high thermal mass radiant systems within the body of the Standards, nor in the alternative compliance method and its associated compliance software. In addition, there are some modeling limitations for radiant systems in EnergyPlus, which is the simulation engine underlying the compliance software for the performance approach. Updates to Title 24 and the alternative compliance method are needed in order to ensure that minimum energy performance is maintained, to ensure that modeled performance accurately reflects proposed designs, and to properly allow buildings with radiant systems to take appropriate credit for their performance.

This report intends to provide a background and roadmap of the steps needed to provide effective coverage of radiant systems for Title 24 compliance.

3.1. Title 24 Overview

3.1.1. *Title 24 Compliance Approaches*

There are two methods for demonstrating compliance with Title 24:

- Prescriptive Method: This approach allows projects to comply by using methods known to be efficient. To show compliance, each individual component of the proposed building must meet specific prescribed requirements. The prescriptive approach is inflexible but provides a simple path for compliance.
- Performance Method: This approach provides more flexibility in building design by allowing projects to trade off different factors so long as the overall simulated performance meets or exceeds that of a standard reference building, which represents the equivalent “code-minimum” building. The Alternative Compliance Method establishes the modeling rules and assumptions for the proposed and standard models.

In addition to the two compliance paths above, there are mandatory measures that apply to all projects. The mandatory measures specify minimum requirements for the envelope, heating, ventilating and air conditioning (HVAC) and water heating equipment efficiency, and other components in buildings.

3.1.2. *Alternative Calculation Method*

CBECC-Com is the required software interface used to demonstrate compliance using the performance approach for non-residential buildings. The software allows for a user to define the proposed building and systems, and then generates a standard baseline model according to the rules defined in the ACM Manual. Annual simulation of the two models allows for comparison of the performance of the proposed design against a minimally-compliant reference model to demonstrate compliance. The CBECC-Com interface uses EnergyPlus as its simulation engine, which is a software tool developed and maintained by the Department of Energy (DOE).

The scope, features and capabilities of CBECC-Com are currently limited such that it can only simulate some traditional HVAC system types, and not all compliance modeling rules established in the ACM Manual have been implemented. The range of HVAC system capabilities in CBECC-Com can be improved by further development of the software interface itself but is also to some degree limited by the capabilities of the EnergyPlus simulation engine. For the improvements impacted by the latter case, changes would be required to the EnergyPlus source code (and to CBECC-Com) to expand the capabilities of the compliance software. Though EnergyPlus is open source, the Department of Energy, which is the agent that supports development of software, needs to be engaged to initiate these changes.

Though compliance simulations can be developed and run directly within the CBECC-Com program, there are currently two software tools developed by the private sector that are approved by the CEC as interfaces to CBECC-Com: IES Virtual Environment and EnergyPro. Both tools essentially provide a user interface to facilitate the generation of CBECC-Com input files for compliance simulation. If the modelers are using either of the tool, they are further limited by the input capability of the interface and the translation rules built into the tool as some of the modeling capabilities of CBECC-Com are not programmed to be used by IES VE or EnergyPro. Therefore, using these two programs essentially creates further limitations in the translation process.

3.1.3. *Title 24 Update Process*

To accommodate code compliance for new technologies, changes may be required to both the prescriptive and performance paths. Proposed changes to prescriptive requirements must be demonstrated to be life cycle cost effective and are subject to stakeholder review through the Codes and Standards Enhancement process in order to be approved by CEC. While the performance path allows more flexibility for projects to demonstrate compliance, updates to this compliance path require revisions to both the ACM Manual and the compliance software. In the following sections, we review the current applicability of code requirements for radiant systems and changes that could be made to mandatory, prescriptive, and performance requirements (both to the ACM Manual and the compliance software tools).

3.2. Title 24 for Radiant Systems

Title 24 measures covers various building components, such as envelope, HVAC, and lighting, and it regulates building and system design, material and equipment selection, and operation and verification. Since a radiant system is a specific type of HVAC cooling and heating system, this evaluation focuses on the HVAC requirements. Requirements for other building components would apply to a radiant building in the same manner as a building with a traditional VAV system. HVAC requirements related to ventilation, HVAC controls, HVAC primary systems and other HVAC applicable secondary systems, would also apply to buildings with radiant systems.

Radiant systems fundamentally use different approaches to meet ventilation and thermal comfort requirements than traditional all-air based systems. As a result, many of the Title 24 HVAC control and design requirements that establish minimum energy performance for a typical VAV system do not apply for a radiant system. The lack of requirements specifically addressing radiant systems also prevents projects from fully taking account for benefits and efficiency features of radiant systems. For example, radiant systems offer a different indoor environmental experience that provides acceptable thermal comfort across a wider range of drybulb temperatures, compared to traditional air systems. The current ACM modeling rules prescribe a fixed room air temperature, which does not allow for consideration of the wider room temperature ranges that may reduce energy use for radiant systems.

3.2.1. *Mandatory and Prescriptive Requirements*

Currently, there is very limited mandatory or prescriptive language that is specific to radiant system designs. The 2019 version of Title 24 effectively incorporates a prescriptive requirement for waterside economizers that would apply to radiant systems above a minimum capacity threshold. Given the wide range of radiant design and control approaches and the lack of industry consensus on best practice, it is difficult to identify mandatory and prescriptive requirements that would effectively and appropriately establish minimum energy performance for projects with radiant systems.

3.2.2. ***Performance requirements***

For a project to comply using the performance method, an energy model of the radiant design, including the radiant slab system, the ventilation system and the central plant, must be developed to compare to a baseline HVAC system. However, most energy simulation tools, including CBECC-Com, do not have the capability of explicitly modeling radiant slab systems, even though limited modeling rules for radiant slabs are available in the ACM Manual. The existing rules in the ACM Manual are insufficient to properly define the modeling inputs for radiant system.

3.2.2.1. Nonresidential Alternative Calculation Method (ACM) Reference Manual

The ACM Manual Section 5.7.5.7 provides modeling rules for floor-based radiant cooling systems and inputs required for Title 24 compliance evaluation. Some limitations are:

- The inputs prescribed in this section are limited to radiant slab zone models. There is no rule related to central plant control or the interaction with the DOAS system, which both have significant energy impacts (Feng and Cheng, 2018).
- The modeling rules prescribe a radiant slab system designed to use constant flow, variable supply temperature control with a recirculation pump at each zone. This radiant zone design and control approach may not be representative of the current industry practice.

In addition, there are no modeling rules for radiant heating application or radiant slab systems that use ceiling or wall as the active surfaces.

3.2.2.2. Software Functionality

Currently the two CEC-approved privately developed compliance software, IES Virtual Environment and EnergyPro, serve as an interface to CBECC-Com, which uses EnergyPlus as the simulation engine. Since CBECC-Com does not have the capability to explicitly model radiant slab systems, workarounds must be used to demonstrate compliance for a radiant system or designers must justify an exceptional calculation method. A common workaround employed is to model radiant slab systems as four-pipe fan coils with zero fan power. The DOAS system is modeled as a separate system that provides ventilation air into a space in parallel with the radiant slab system. The lack of capability to explicitly model radiant systems and lack of modeling rules for the associated ventilation system results in misrepresentations of the actual design, introduces the risk of gaming, and does not allow buildings with radiant systems to take appropriate credit for their performance.

3.3. Recommended Next Steps

Given the wide range of radiant design and control approaches and the lack of industry consensus on best practice, it is difficult to identify mandatory and prescriptive requirements that would effectively and appropriately establish minimum energy performance for projects with radiant systems. Further, radiant systems are generally installed in high performance buildings that aim to meet high energy efficiency targets. Projects with radiant systems thus typically follow the performance compliance approach in order to determine how much better the energy use is compared to the standard model. The lack of capability to explicitly model radiant systems and lack of modeling rules for the associated ventilation system results in misrepresentations of the actual design, introduces the risk of gaming, and does not allow buildings with radiant systems to take appropriate credit for their performance. Therefore, development of radiant systems requirements for the ACM Manual and the associated compliance software should be prioritized to address the current gap in the applicability of Title 24 to radiant systems. Recommended steps for prioritization:

1. Update the ACM Manual to establish keywords required to fully define the model inputs for radiant systems and the allowable ranges of inputs. This update should include new prescribed space temperature setpoints schedules that are to be used in proposed models with radiant systems to account for the impact of radiant surface temperatures, as described in Section 3.5.2. There are no barriers to implementing this step.
2. Update CBECC-Com to reflect the additions to the ACM Manual. CBECC-Com is continually being updated but is currently very limited in the range of HVAC system types that can be modeled. The private software companies that have developed interfaces to CBECC-Com would need to update their modeling tools to match the new CBECC-Com functionality in order for modelers to be able to take advantage of those simulation approaches.

Though not in the critical path, future efforts should evaluate opportunities for adding mandatory and prescriptive measures specific to radiant systems, as described below in Section 3.5. More study and simulation may be required to further these topics to the point where they would be ready for CASE initiatives.

Also, limitations in the ability of EnergyPlus to simulate certain aspects of radiant systems should be addressed through further program development. This additional development may require further study and discussion with stakeholders to prioritize required simulation capabilities based on the available understanding of current typical and best practices.

3.4. Radiant Technology Current State

High thermal mass radiant systems are fundamentally different from other HVAC systems, and therefore require very different design and control approaches from conventional HVAC systems. Many of the current standardized design practices were developed for all-air systems and may not apply for a radiant system. Designers are experimenting with different approaches and the industry is far away from reaching an agreement on best practices for almost every design and control aspect (Paliaga, Farahmand, Raftery, & Woolley, 2017).

Another barrier in the adoption of radiant technology is the lack of modeling tools to help designers understand the basic behavior of the systems. Most modeling software have been developed based on assumptions associated with the physics for all-air systems, and do not have the capability to capture radiation heat transfer effect explicitly. The tools are also programmed to separate the HVAC systems from the building mass instead of activating building mass to be part of the HVAC systems as is the case in the thermally massive radiant systems. Currently, the only commonly used tool that has a high thermal mass radiant module is EnergyPlus. IES Virtual Environment employs heat balance method to capture radiation heat transfer. However, it only has a module for light-weight radiant panel, which performs completely differently than high mass radiant slab system. Other commonly used software such as EnergyPro and eQuest use response factor based heat transfer modeling algorithms, which are fundamentally flawed for modeling radiant systems (Feng et al. 2013).

Modeling tools are also notoriously slow at catching up with design practices. As designers experiment with different design and control approaches, they do not have a tool that is easily available to perform the necessary evaluation. The table below summarizes the capabilities of EnergyPlus and CBECC-Com for some common radiant design and control strategies. For each approach, we also listed the ACM rules and suggested development priority.

Table 4.1: Title 24 modeling capability for common radiant design and control approaches

System	Attribute	EnergyPlus	CBECC-Com	ACM	Development Priority
Radiant Zone	Radiant heat transfer	Yes	No	No	High
	Evaluation of MRT	Yes	No	No	High
	Radiant panel	Yes	No	No	Low
	High mass radiant	Yes	No	No	High
	Slab setpoint control	Customized code	No	No	Low
	Bidirectional heat transfer	Yes	No	No	High
	Variable flow	Yes	No	No	High
	Variable temperature	Yes	No	Yes	High
	Pulsed flow	Customized code	No	No	Medium
	Heating/cooling switchover lockout	No	No	No	Low
	Multiple space types per radiant zone	No	No	No	Medium
	Precooling, load-shifting control	Yes	No	No	Medium
Radiant hydronic distribution	4-pipe to each zone	Yes	No	No	High
	Whole building 2-pipe	Yes	No	No	High

System	Attribute	EnergyPlus	CBECC-Com	ACM	Development Priority
	mixed 4-pipe and 2-pipe system	No	No	No	Low
System	Dedicated outdoor air system (DOAS)	Yes	Yes	No	High
	Distinct thermal vs radiant zones	No	No	No	Low
	Heat recovery at DOAS	Yes	Yes	No	Medium
	Demand controlled ventilation	Yes	Yes	No	High
	Demand-based temperature reset	Yes	Yes	No	Medium
	Supply air temperature control with space humidity feedback	Customized code	No	No	Low
	Supplemental cooling and heating through DOAS	Yes	Yes	No	Low
	Supplemental cooling and heating (not thru DOAS)	Yes	Yes	No	Low
	Natural ventilation	Yes	No	Yes	Low
Plant	Air source heat pump with heat recovery	No	No	No	Low
	Integrated waterside economizer	Yes	Yes	Yes	n/a
	Demand based chilled water supply temperature reset	Customized code	No	Yes	Medium
	Demand based hot water supply temperature reset	Customized code	No	No	Medium

3.5. Potential Change Topics

This section documents the potential change topics that are required to enable radiant system for Title 24 compliance. The intends are to facilitate a holistic design approach to improve the overall radiant design efficiency and encourage the designers to consider the synthesis of the radiant slab system design, the DOAS system and the plant design approach. Here is a summary of the types of change needed:

- Changes needed to ensure actual radiant design and control practices can be captured. For example, allowing flexible temperature setpoint schedule for the proposed design if radiant systems are used.
- Changes to prevent or effectively penalize energy inefficient design or control practices. This involves using mandatory measures to prevent practices that are proved to be energy inefficient and enabling CBECC-Com to have the capability to catch the bad performance. Examples include preventing supplying neutral air from DOAS, particularly for cases without heat recovery.
- Changes needed to ensure potential good practices can be modeled and captured. Findings from the EPIC Radiant project have suggested some design and control features that should be considered to improve energy efficiency. One example is to allow pre-conditioning for load shifting. Changes in the modeling rules and code languages would be required to allow designers to capture the benefits or penalties.

3.5.1. *Provide Definition of Different Radiant System Types*

- Scope of Change: Title 24 definition section
- Priority Level: High
- Background and justification: There are many radiant system types and each can have different dynamic thermal behaviors to control signals and thus different design and control measures could be used to improve energy efficiency. Currently ASHRAE and ISO standards and guidelines have classified radiant systems based on their structural and geometrical characteristics. One of the limitations in this approach is that it cannot capture the differences in the dynamic response behavior between system types, which are important for design solutions and control strategies development. To address this issue, Ning et al. 2017 investigated an approach that characterizes radiant system types based on their response time or time constant. However, there are still controversies in the industry in terms the terminology and the categorization approach,
- Recommendation: The code should provide a definition for each type of radiant system and specify the applicability of code measures explicitly when needed.

3.5.2. *Space Temperature Setpoints Change in Proposed Design*

- Compliance Approach: Performance Approach
- Scope of Change: ACM modeling rule for proposed design, CBECC-Com modeling capability change
- Priority Level: High
- Background and Justification: Modeling rules provides prescribed drybulb space temperature schedules for each occupancy type where the same schedule is used for both

standard and proposed models. Radiant systems can generally provide similar thermal comfort over a wider range of drybulb temperatures, compared to all-air systems, due to a reduced impact of mean radiant temperature on the operative temperature. Since the space temperature schedules are prescribed, the modeling rules do not allow designs to account for this advantage of radiant systems. To address this, Addendum r to 90.1 2013 has language that allows proposed systems to use different schedules if the systems provide occupant thermal comfort via means other than directly controlling air dry bulb and wetbulb temperature directly regulate.

- Recommendation: A possible approach to implement this change would be to develop new prescribed space cooling and heating schedules that have a fixed drybulb temperature offset compared to the current schedules, Alternatively, demonstration of equivalent comfort between the baseline and proposed designs that meet ASHRAE 55 comfort requirements shall be required for compliance purpose.

3.5.3. *System Operation and Space Temperature Setpoint Schedules for Allowing Pre-conditioning in Proposed Design*

- Compliance Approach: Performance
- Scope of Change: Title 24 modeling rule change for proposed design, CBECC-Com modeling capability change
- Priority: medium
- Background and Justification: Modeling rules provide prescribed operation and dry-bulb space temperature schedules for each occupancy type where the same schedule is used for both standard and proposed models. High thermal mass radiant system allows great opportunity for load shifting which contributes to the reduction of Time Dependent Valuation of Energy. Allowing flexibility in HVAC system operation schedule and different dry-bulb space temperature schedule for the proposed design during pre-conditioning operation can capture the impact this strategy.
- Recommendation: CBECC-Com should provide an option for designers to indicate if any space load-shifting (as opposed to storage tank for HVAC load shifting) strategy is to be implemented. If this option is selected, it should allow user specified operation schedule for certain HVAC systems and allow users to specify dry-bulb temperature setpoint schedules during unoccupied hours. To prevent potential discomfort caused by preconditioning the space, proposed design must demonstrate that ASHRAE 55 Standard comfort requirements can be satisfied

3.5.4. *Prevent Dedicated Outdoor Air System from Reheating Ventilation to Neutral Temperature*

- Compliance Approach: Mandatory measures
- Scope of Change: Title 24 Mandatory Rule
- Priority: High
- Background and Justification: Many practitioners have been providing neutral or near neutral supply air temperature from dedicated ventilation air system by reheating dehumidified air. The Cost Comparison of Radiant and VAV System study, which is one of the Task 5 deliverables of this EPIC project, demonstrated that this approach causes significant cooling and heating energy waste in the California Bay Area climate and should

not be allowed without heat recovery. ASHRAE Standard 90.1 Section 6.5.2.6 provide rules to prevent reheating ventilation air when the majority of zones require cooling.

- Recommendation: Modify the 90.1 requirement for Title 24 implementation. The 90.1 requirement is vague and difficult to enforce. More research are required to assist in code language development, including climate justifications and exceptions.

3.5.5. *DOAS Supply Air Temperature Control Approach*

- Compliance Approach: Prescriptive and performance approach
- Scope of Change: Title 24 modeling rule change for proposed design, CBECC-Com modeling capability change
- Priority: Medium
- Background and Justification: DOAS supply air temperature is a critical control parameter that has significant energy impacts. The Cost and Energy Comparison study has demonstrated that the radiant design site energy use ranged from 2.7 kBtu/ft^2 to 4.4 kBtu/ft^2 for the case building simply by varying the DOAS supply air temperature control approach (Feng and Cheng, 2018). Currently, there is no code regulation or modeling rules on DOAS supply air temperature control. As CBECC-Com now allows users users to specify separate cooling and heating setpoints from DOAS, no modeling rules leaves space for faulty control during the performance modeling. For example, modelers sometimes provide unconditioned or partially conditioned outside air directly into the space, and the room terminal units (radiant system, VRV, etc.) only need to pick up the remaining sensible load. This modeling approach is fundamentally different from actual operation in terms of the psychrometric functionality of each system, and may present a significant performance discrepancy between the actual system and the modeled system. In reality, during certain times of the year, the DOAS system needs to dehumidify the ventilation air to avoid high space humidity levels. Therefore, due to load diversity in different spaces, the DOAS subcools the ventilation air, and will result in cooling and heating energy waste if space-by-space humidity monitoring is not available and inevitably reheat energy by some terminal units. However, by supplying unconditioned ventilation air into the space, the model unrealistically extends the free-cooling hour of the DOAS system and eliminates reheat at the terminal units. In the model, there is no need to maintain space humidity. This modeling approach shows false benefits of DOAS system.

- Recommendation: It would require more research to develop an optimal DOAS supply air temperature control sequence. We are approved by ASHRAE Research Committee to develop a research project work statement on this topic. The objectives of the research project would be to provide designers with guidance on climate and application dependent supply air temperature control sequence design, and to provide them with detailed control sequences that are ready for implementation.

3.5.6. *Ensure Accurate Modeling of the hybrid DOAS Terminal Units and the Local Terminal Units*

- Compliance Approach: Performance
- Scope of Change: CBECC-Com modeling capability
- Priority: High

- Background and Justification: DOASs typically serve local (zonal) space temperature control systems such as variable refrigerant flow (VRF) fan-coils, 4-pipe fan-coils, water-source heat pumps, chilled beams, radiant systems. The terminal units of the DOAS could be configured to directly supply air into the space (i.e. in parallel with the zonal systems) or to connect to the inlet of the zonal systems (i.e. in series with the zonal systems). There is a significant difference between the two configurations in terms of energy consumption and control of the systems.
- Recommendation: CBECC-Com should be configured to give users option to indicate the connection configuration of the DOAS terminal system and the zonal system such that the proposed model can accurately reflect the design intent.

3.5.7. ***Prevent generating high temperature cooling water and low temperature heating water by blending***

- Compliance Approach: Prescriptive measures
- Scope of Change: Title 24 prescriptive rule change
- Priority: medium
- Background and Justification: Radiant systems can only remove space sensible load, and they require the design to decouple latent and sensible load. One advantage of this is they can use high temperature cooling water for cooling and low temperature heating water for heating, and thus allow the central plant efficiency to be significantly improved. However, many designs generate the water serving the radiant systems by blending cold supply water (e.g. generated by a typically operated chilled water plant) with return water and thus wipe out the energy efficiency opportunity. The opportunity to improve plant side efficiency is one of the major advantages a radiant system has over a traditional VAV system. If a radiant project is to use prescriptive approach for compliance, this benefit must be included by design.
- Recommendation: For systems that decouple latent and sensible load, if the terminal units are designed to use high temperature cooling water and low temperature heating water, Title 24 should include prescriptive requirement to generate the cold and hot water without blending. There could be exception for small systems that use district cooling or heating water

3.5.8. ***Prevent High Thermal Mass Radiant System from Switchover between Heating and Cooling Mode Frequently***

- Compliance Approach: Prescriptive approach
- Scope of Change: Title 24 prescriptive requirement
- Priority: Medium
- Background and Justification: Air temperature in spaces conditioned by high thermal mass radiant slab system are slow to response to change in hydronic system control. The thermal mass activated in the radiant slabs act as a thermal storage mechanism such that it is very inefficient to switch between heating and cooling mode frequently. Frequent switch between heating and cooling will cause significant energy waste for little thermal comfort improvement. The compliance approach should avoid this practice to ensure energy efficiency.

- Recommendation: Add prescriptive requirement that prevent heating/cooling switchover within prescribed time limit. The time limits could be different depending on radiant slab types (or thickness of activated mass), though typically preventing switchover within the same 24-hour period is sufficient.

3.5.9. *Radiant Ceiling Slab Capacity Adjustment Based on Suspended Ceiling Coverage*

- Compliance Approach: Performance
- Scope of Change: CBECC-Com modeling capability
- Priority: Low
- Background and Justification: Radiant ceiling slab capacity will decrease as a function of increasing coverage (blockage) by a suspended ceiling. However, recent laboratory testing shows that the amount of capacity reduction is relatively minor for ceiling coverage of up to 50% (11% reduction for 47% coverage; Karmann et al. 2017). Overall HVAC energy consumption could be different as supplemental cooling or heating may be required.

  Designers should model the capacity reduction when there is a suspended ceiling in the space to ensure that the system is capable of maintaining acceptable comfort conditions, The current model cannot accurately capture the impacts of a suspended ceiling on thermal comfort and energy performance.
- Recommendation: CBECC-Com to include features to adjust radiant slab capacity based on ceiling coverage percentage

3.5.10. *Enable Modeling Capability to Allow Ventilation Zones to be Distinct from Thermal Zones*

- Compliance Approach: Performance
- Scope of Change: CBECC-Com and EnergyPlus modeling capability
- Priority: Low
- Background and Justification: Radiant designs usually use different ventilation and radiant thermal zoning approaches. This design feature is an important difference between a radiant design and most other HVAC designs. It is mostly driven by radiant slab constructability and cost as large radiant zone means lowered costs. When the ventilation and radiant thermal zones are different, the two systems may fight if not controlled properly and thus caused unique challenges in control strategies. However, most simulation software cannot capture this because they don’t have the capability to model separate thermal and ventilation zones.
- Recommendation: The simulation engine needs to be modified to allowed radiant slab zoning to be different from ventilation zones. This would require conversation with stakeholder beyond Title 24 players (EnergyPlus Development by DOE)

3.5.11. *Enable Direct Control of Radiant Slab Temperature*

- Compliance Approach: Performance
- Scope of Change: EnergyPlus simulation engine and CBECC-Com modeling capability
- Priority: Low
- Background and Justification: High thermal mass radiant systems usually are designed to control slab temperature instead of directly control space temperature. The simulation

engine should be modified to include this feature in order to capture the impact of this design practice.

- Recommendation: EnergyPlus simulation engine and CBECC-Com should be modified to allow direct control of radiant slab temperature. This would require conversation with stakeholder beyond Title 24 players (EnergyPlus Development by DOE)

4. ASHRAE Standards and Handbooks Report

The overall radiant research project covered a range of topics with findings reported in formal EPIC deliverables and academic publications. The impact of many of these findings can be broadened by incorporating the new findings into the ASHRAE standards and handbooks.

This report provides a summary of topics that are recommended to be added to the ASHRAE Standards and Handbooks.

4.1. Provide Consistent Definitions for Different Radiant System Types

4.1.1. *Standard and Handbook Section Affected*

ASHRAE Handbook System and Equipment, Chapter 6

4.1.2. *Proposed Change Description*

Revisions of ASHRAE Handbook System and Equipment, Chapter 6 to provide a response time-based definitions for different types of radiant systems, describe why different design and control approaches need to be used.

- Currently in the handbook, there are terminology and definition of radiant system types based on their structure and geometry, a new definition based on the thermal behavior of radiant systems should be added
- Add different design and control approaches depending on system types

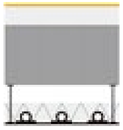
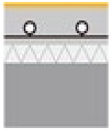
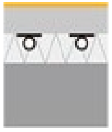
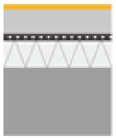
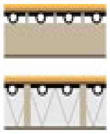
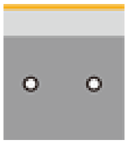
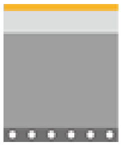
4.1.3. *Discussion*

Radiant system design and control standards (ISO and ASHRAE) and guidebooks currently classify radiant systems as a function of their structure and geometry. We assume that design solutions, testing methods, and control strategies of radiant systems can be more clearly described and classified based on their thermal parameters. Various radiant system types can have different dynamic thermal behaviors to control signals. In general, light radiant panels, such as plaster or metal ceilings and walls, may respond to changes in demand quickly enough for satisfactory results from lowered (higher) air and panel temperatures in winter (summer), while heavy radiant panels such as concrete floor can produce less satisfactory results. Design and control methods should be different for different radiant systems. For quick response systems, the 24 h peak cooling load is enough in their design and sizing, while accumulated cooling load is needed in designing slow response systems which utilize peak load shifting strategy. In system control, conventional control methods can be applied to quick response systems, while different control strategies are needed for slow response systems.

Response time or times constant are two widely used expressions to describe the dynamic behaviors of radiant systems. Time constant has a rigorous definition common to many scientific and technological fields. Physically, for linear time-invariant system, or lumped system whose characteristic can be described by a one-node parameter, the time constant represents the time it takes the system's step response to reach 63.2% (36.8%) of its final value for systems that increase in value from a step increase (decrease)[1]. Response time is a less rigorous expression; multiple response time can be defined to describe the dynamic behavior of a system. Time constant can be referred to as one specific response time for lumped system. For radiant systems, the response time (τ_{30}, τ_{50}, $\tau_{63.2}$ or τ_{95}) can be defined as the time it takes for its surface temperature or capacity to reach 30%, 50%, 63.2%, or 95% of the final and initial value difference when a step change of in control of the system is applied as input. In practice, $\tau_{63.2}$ and τ_{95} are widely used because $\tau_{63.2}$ is similar to the commonly known time constant; while τ_{95} can represent the time it takes for a system to change from one condition to another stable condition. When using response time, attention should be paid to: a) the definition refers to the time to activate a radiant system itself, it does not mean the time to bring room condition from one to other, the later one also depends on the thermal inertia of a room; b) the relationship τ_{95}=$\tau_{63.2}$ don't work for radiant systems; c) the response time for other parameters (e.g. pipe level temperature) can be defined as needed in design and control of radiant system.

The response time for radiant systems can be obtained via various ways, verified finite difference method (FDM), finite element method (FEM), building simulation software can be used, and testing and commissioning are needed for slow response systems. Based on a number of simulations for different radiant systems, the response time τ_{95} < 10 min for radiant ceiling panels, 1 < τ_{95} < 9 h for embedded surface systems, 9 < τ_{95} < 19 h for thermally activated building systems, the average $\tau_{63.2}$ or τ_{95} for different radiant systems are shown in Table 4.1.

Table 4. 1 The response time ($\tau_{63.2}$ and τ_{95}) for different radiant system types

Radiant system types	Quick response	Medium response				Slow response	
Structure type	RCP	Type A	Type B	Type D	Type G	Type E	Type F
Sketch drawing							
Unit	min	h	h	h	h	h	h
Average $\tau_{63.2}$	1.4	1.7	1.2	0.9	0.7	5.1	0.4
Average τ_{95}	4.0	4.9	3.3	2.5	1.5	13.8	12.4

Note: Type A, B, C, D are G embedded surface systems (ESS) with piped embedded in the surface layer of floor, ceiling or wall; Type E and F are thermally activated building systems (TABS) [2].

[1] B.G. Liptak, Instrument Engineers' Handbook, Fourth Edition, Volume Two: Process Control and Optimization, CRC Press, 2005

[2] ISO 11855: Building Environment Design - Design, Dimensioning, Installation and Control of Embedded Radiant Heating and Cooling Systems, 2012

4.2. Provide Comfort Data in Real Radiant Buildings

4.2.1. *Codes Section Affected*

ASHRAE Handbook System and Equipment, Chapter 6

4.2.2. *Proposed Handbook Change Description*

Revisions of ASHRAE Handbook System and Equipment, Chapter 6 to provide thermal comfort data in real radiant buildings and the comparison to VAV buildings.

4.2.3. *Discussion*

We performed a literature review in 2015 to assess if radiant systems provide better, equal or lower thermal comfort than all-air systems. We found that a limited number of studies are available and therefore a solid answer could not be given at the time of publication. Nevertheless, there was suggestive evidence that radiant systems may provide equal or better comfort than all-air systems, as was determined in our subsequent more detailed study below. Given that there was not sufficient information in the literature, we implemented the CBE occupant survey in 26 buildings. By combining the radiant surveys with previously completed surveys in all-air buildings, we were able to assemble the largest dataset, to our knowledge, used in a comparison of occupant satisfaction in radiant buildings. We analyzed the indoor environmental quality survey results from 3,892 respondents in 60 office buildings located in North America; 34 of which used all-air systems and 26 of which used radiant systems as the primary conditioning system. The results indicate that radiant and all-air spaces have equal indoor environmental quality, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings.

4.3. Cooling Load Definitions and Calculations

4.3.1. *Standard and Handbook Section Affected*

ASHRAE Handbook Fundamentals, Chapter 18 Nonresidential Cooling and Heating Load Calculations

ASHRAE Handbook Fundamentals, Chapter 19 Energy estimating and modeling methods

4.3.2. *Proposed Change Description*

Revision of ASHRAE Handbook Fundamentals Chapter 18 to provide accurate definition of cooling load and calculation method that is appropriate for both radiant systems and all-air systems; changes include:

- Revise the explanation of the fundamentals so as to be inclusive of systems that invoke radiant heat transfer for conditioning the space
- Revise the definition of load so as to allow dynamic design temperature setpoint profiles, and describe the allowable operative temperature behavior to align with ASHRAE 55.
- Add discussion about the relationship between operative temperature and air temperature with design day conditions.

Revision of ASHRAE Handbook Fundamentals Chapter 19 to provide accurate definition of cooling and heat gain, as well as a modeling method that is appropriate for both radiant systems and all-air systems.

- Current chapter erroneously assumes that all convective heat gain translates to sensible cooling load, when in fact (except for cases with adiabatic surfaces) non-active surfaces may be cooler than indoor air, in which case they extract heat by convection and reduce the cooling load.

4.3.3. *Discussion*

ASHRAE Handbook Fundamentals Chapter 18 is written with the presumption that only forced-air HVAC systems can extract heat gains entering or generated inside a space. This assumption dictates terminology definitions, descriptions of heat transfer mechanisms, and calculation methodologies that do not generalize to other types of HVAC systems e.g. radiant cooling and heating systems. For example, the chapter describes that radiant energy must first be absorbed by the space's internal surfaces and objects and then after a time-delay, the radiant energy is converted to convection energy in which the HVAC system can extract from the space. Implying that only convection heat gains can be directly accounted as cooling loads as shown in Figure 4.1. However, in a radiant system, the active surface(s) (the temperature-controlled surface(s) of the radiant system) can remove both convection and radiant heat gains directly. Thus, a fraction of the total convection and a fraction of the total radiant heat gains can be accounted as direct cooling loads. The remaining heat gains go through the thermal storage effect where they get absorbed by the space's internal non-active surface(s) and objects and then after a certain time-delay become a cooling load through either convection or radiation. A generalized heat gain to cooling load process can be described with a proposed revised diagram shown in Figure 4.2 where each symbol describes a function that depends on heat gain type, HVAC system type, and/or thermal response of the space.

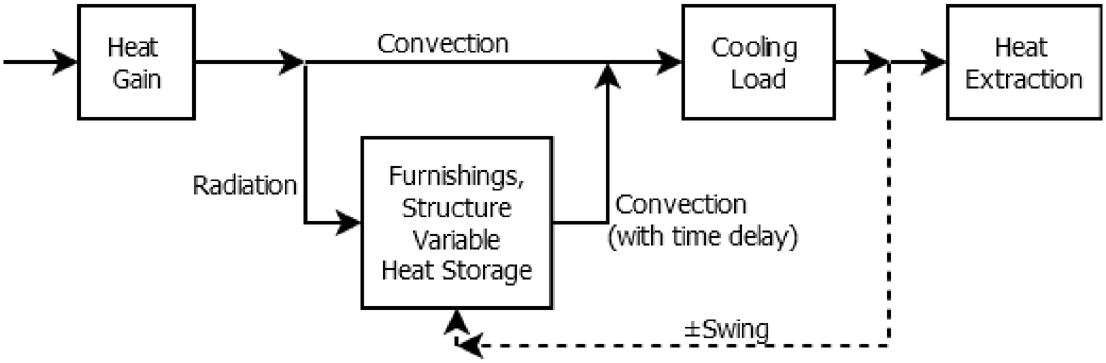


Figure 4.1: Current heat gain to cooling load flow diagram presented in ASHRAE Handbook Fundamentals Chapter 18. The diagram illustrates how radiant energy is first absorbed by the space's internal surfaces and furnishing before becoming a cooling load.

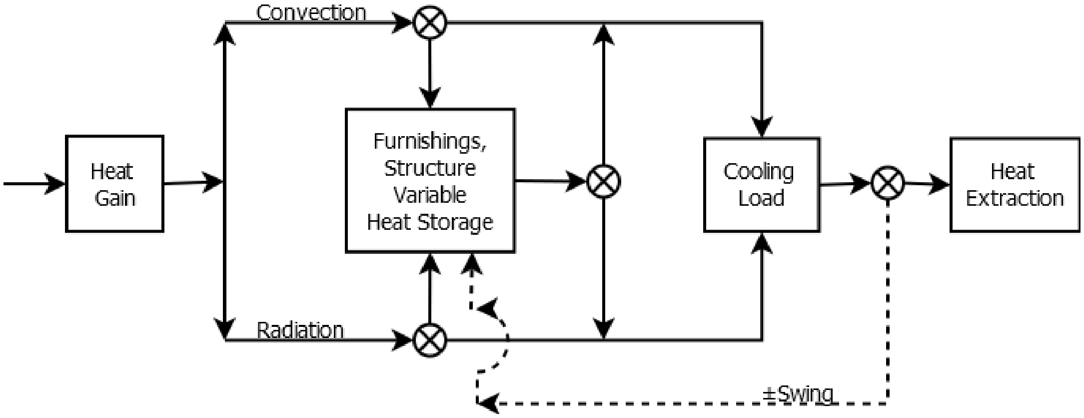


Figure 4.2: Proposed heat gain to cooling load flow diagram that generalizes to any type of HVAC system. The symbol describes a function that depends on heat gain type, HVAC system type, and/or thermal response of the space.

In another example where Chapter 18 does not generalize to different types of HVAC systems is in the definition of the space cooling load. The current definition is the following: *the rate at which sensible and latent heat must be removed from the space to maintain a constant space air temperature and humidity.* The current definition has three important limitations:

1. Assumes that the same cooling load will result in the space regardless of the type of HVAC system and control installed for the space.
2. Requires the controlled temperature of the space to be constant.
3. The controlled temperature of the space is the dry-bulb air temperature.

Different HVAC systems will affect the thermal storage effect differently. An underfloor air distribution (UFAD) system will generally have a higher peak cooling load than a traditional overhead system since the presence of the raised floor will convert solar heat gains into convection heat gains at a faster rate than a floor concrete slab would. Radiant systems affect the thermal storage effect by removing radiant heat gains directly and minimizing the quantity of heat gains that can be stored in the space's internal non-active surfaces and objects.

The second limitation arises because it is not feasible or practical for some types of HVAC systems to maintain a constant temperature in the space. Forced air systems can maintain constant zone temperatures because these systems directly change the air temperature in the zone and air does not take a lot of energy to change its temperature. Hence, having a quick response to change the space's thermal environment. In a radiant system, the air is not directly controlled. Instead a surface temperature is controlled and indirectly influencing the space air temperature. Thus, there will be a challenge to maintain a constant air temperature with the radiant system's weaker thermal coupling with the space's air volume. In addition, a radiant system with embedded tubing in the floor/ceiling concrete slab will have an increased response time in changing the active surface(s) temperature since it needs to cool down a substantial amount of mass further impeding direct control of the space air temperature.

Moreover, there exists a range of temperatures where people feel thermally comfortable as described in ASHRAE Standard 55. It is unnecessary to maintain a constant temperature and Chapter 18 can be explicit in allowing different space temperature profiles as long as they are within ASHRAE Standard 55 comfort criteria. ASHRAE Standard 55 also describes six parameters that affect people's thermal comfort: dry-bulb temperature, mean radiant temperature, relative humidity, air movement, and the person's metabolism and clothing level. In theory, the four space environment parameters can be actively controlled as part of the HVAC system. As such, these four parameters should be included in the space cooling load definition and not just dry-bulb air temperature. The parameters can be used to calculate upper and lower thermal comfort limits with a new type of temperature called operative temperature. Operative temperature accounts for occupant's heat transfer to and from the space through convection and radiation. An operative temperature that is not required to stay constant allows flexibility in calculating the space cooling load for different HVAC systems.

In summary, ASHRAE Handbook Fundamentals Chapter 18 needs to remove the assumption that only forced-air systems remove heat gains from the space. In doing so, terminology definitions, descriptions of heat transfer mechanisms, and calculation methodologies can be revised in order to generalize cooling load calculations for many types of HVAC systems.

4.4. Effect of Night Cooling for Buildings Conditioned by Radiant System

4.4.1. ***Standard and Handbook Section Affected***

ASHRAE Handbook Fundamentals, Chapter 18 Nonresidential Cooling and Heating Load Calculations

ASHRAE Handbook Fundamentals, Chapter 19 Energy estimating and modeling methods

ASHRAE Guideline 36-2018, High-Performance Sequences of Operation for HVAC Systems,

ASHRAE Handbook Systems & Equipment Chapter 6 Radiant Heating and Cooling

4.4.2. ***Proposed Change Description***

- Revise ASHRAE Handbook Fundamentals Chapter 18 Nonresidential Cooling and Heating Load Calculations to properly account for the space heat extraction by radiant cooling, to allow load calculation based on dynamic operative temperature profile, and to consider pre-cooling and natural ventilation night flush cooling.
- Revise ASHRAE Handbook Fundamental Chapter 19 Energy estimating and modeling methods to properly define heat gains and cooling loads for cases with radiant cooling, and to allow load calculation based on dynamic operative temperature profile, and consider pre-cooling and natural ventilation night flush cooling.
- Develop a sequence of operations to coordinate natural ventilation cooling with radiant cooling systems so that radiant cooling will be less likely to preempt the thermal benefits of natural ventilation cooling.
- ASHRAE Handbook Systems & Equipment Chapter 6 Radiant Heating and Cooling should be revised to properly describe the impact that radiant cooling has on (1) envelope heat transfer, and thermal energy storage in non-active masses.

4.4.3. ***Discussion***

Experimental results from our side-by-side comparison of space heat extraction rates for radiant and all air cooling systems revealed that for the two systems to maintain equal operative temperature conditions, radiant cooling must remove more heat overall. The difference is attributed to the fact that radiant cooling extracts heat from all surfaces in a building, which reduces all indoor surface temperatures. This increases envelope heat transfer (because the temperature difference across the envelope is larger), and reduces the amount of heat that is stored in non-active masses, which reduces the amount of heat that non-active masses can release passively to the environment. The magnitude of the difference between the cumulative thermal energy requirements for radiant and all-air systems depends on many factors, and is sharply impacted by the availability of passive cooling. In buildings with natural ventilation cooling, the continuous operation of radiant systems will preempt some of the benefit of natural ventilation cooling. Our experiments indicated that in such cases, radiant cooling may have to process 40% more thermal energy each day. On the other hand, in climates with little or no opportunity for passive heat rejection, the differences would be much smaller. The benefits of natural ventilation cooling are substantial, even in buildings with radiant cooling, but in buildings that use both strategies radiant cooling will have to extract more heat than all-air cooling. The additional thermal burden is partly attributed to the control sequence typically used to coordinate these systems. It is likely that a more sophisticated control sequence could help to increase the benefit of natural ventilation in buildings with radiant cooling. However, achieving this will require a control strategy that allows air temperature (and operative temperature) to drift over the course of each day, but this type of dynamic approach is not currently recognized by ASHRAE fundamentals. Moreover, ASHRAE Guideline 36-2018, High-Performance Sequences of Operation for HVAC Systems does not yet include any sequences for radiant cooling systems. Future additions ought to develop strategies to strategically coordinate natural ventilation and radiant cooling

4.5. Impacts of Direct Solar

4.5.1. ***Standard and Handbook Section Affected***

ASHRAE Handbook Applications, Chapter 54

ASHRAE Handbook System and Equipment, Chapter 6

4.5.2. ***Proposed Change Description***

We propose the inclusion of model developed by Feng et al. 2016 into ASHRAE calculation method.

4.5.3. ***Discussion***

Work of Feng et al. 2016 and Pantelic et al. 2018 showed that radiant floor exposed to direct Solar could have a cooling capacity significantly higher compared to the capacity calculated by the current method. Our work showed that capacity increase is a function of on the amount of incident solar that exposes the floor.

Feng et al. 2016 proposed the change to the current capacity calculation to include the impact of the direct solar. Results showed that the actual cooling capacities are in average 1.44 times higher than the values calculated with the ISO 11855 method, and 1.2 times higher than the ASHRAE method. Pantelic et al. in the lab experiment demonstrated that regions of the floor have capacity 4 times higher than ISO and ASHRAE capacity calculation suggest.

4.6. Impacts of Ceiling Acoustic Panels on Cooling Capacity

4.6.1. *Standard and Handbook Section Affected*

ASHRAE Handbook System and Equipment, Chapter 6

4.6.2. *Proposed Change Description*

ASHRAE Handbook Systems & Equipment Chapter 6 Radiant Heating and Cooling should be revised to provide guidance on design of radiant ceiling slabs with suspended acoustic ceiling panels.

4.6.3. *Discussion*

Radiant slab systems when applied in the ceiling (e.g., TABS) are characterized by large areas of exposed concrete, which may create acoustical challenges due to the high reflectivity of the hard surface. Recent full-scale laboratory experiments have investigated the impact on radiant cooling capacity of adding free-hanging acoustical panels to address the acoustic quality problem. Karmann et al. (2017) found that by covering only 47% of the ceiling area with horizontal free-hanging acoustical clouds below a radiant chilled ceiling, only an 11% reduction in cooling capacity was measured while achieving acceptable sound absorption performance. Lacarte et al. (2017) found similar results as follows: (1) 11% reduction in cooling capacity for 43% coverage by horizontal free-hanging acoustical panels, and (2) 12% reduction in cooling capacity for 60% coverage ratio by vertical free-hanging acoustical panels. Both results indicate that good acoustic quality can be achieved with only a relatively minor reduction of cooling capacity. These reliable research results will allow designers to install acoustical panel solutions with minimal impact on TABS cooling performance.

4.7. Impacts of Air Movement on Cooling Capacity

4.7.1. *Standard and Handbook Section Affected*

ASHRAE Handbook System and Equipment, Chapter 6

4.7.2. *Proposed Change Description*

ASHRAE Handbook Systems & Equipment Chapter 6 Radiant Heating and Cooling should be revised to provide guidance on design of radiant systems (ceiling and floor) when ceiling fans are used to increase air movement along the active radiant surface.

4.7.3. *Discussion*

Recent full-scale laboratory experiments have investigated the impact of fans on radiant cooling capacity. Karmann et al. (2018) studied the combined effect of fans and acoustical clouds on the cooling capacity for an office room. The test conditions consisted of a ceiling fan between the clouds (blowing in the upward or downward direction) and small fans above the clouds (blowing horizontally) at the ceiling level to increase the convective heat transfer along the cooled ceiling. The tests conducted without fans showed that cooling capacity decreased, but only by 11%, when acoustical cloud coverage was increased to 47%, representing acceptable sound absorption. The ceiling fan increased cooling capacity by up to 22% when blowing upward and up to 12% when blowing downward compared to the reference case over the different cloud coverage ratios. For the small fan tests, cooling capacity increases with coverage by the acoustical clouds up to a maximum increase of 26%.

Pantelic et al. (2018) conducted laboratory experiments to study the impact of ceiling fans on the cooling performance of a radiant floor system. Higher air speeds along the floor increased the radiant slab cooling capacity by ~12% (from 32 to 36 W/m^2) when the operative temperature was 24°C and, up to ~19% (40 W/m^2) when it is increased to 26°C.

The above results indicate that fan-induced air movement can be used to enhance the cooling performance of radiant systems, both at the ceiling and floor levels.

4.8. Design Considerations and Practices

4.8.1. *Standard and Handbook Section Affected*

ASHRAE Handbook System and Equipment, Chapter 6

4.8.2. *Proposed Change Description*

ASHRAE Handbook Systems & Equipment Chapter 6 Radiant Heating and Cooling should be revised to provide designers with feedback on cost-sensitive aspects of radiant system design, and to suggest control and design measures to reduce cost while maintain or improve energy efficiency.

4.8.3. *Discussion*

Survey of most experienced radiant designers shows there is a diverse range of approaches for design and control of the systems and there is limited information on the cost effectiveness of these different design practices (Paliaga, Farahmand, Raftery, & Woolley, 2017),

The study that compares construction cost of alternative radiant and variable air volume (VAV) HVAC designs for an office building in California shows higher cost for radiant systems mainly due to high premium of labor for piping (Feng and Cheng, 2018). There some aspects of the radiant system design have more significant impact on costs and warrant careful attention. These considerations include:

- Consider the use of radiant mats, instead of traditional radiant loops, to reduce cost through reduced labor. However, radiant mat designs may not be practical or as cost effective for buildings with smaller or oddly-shaped zones.
- Increase radiant tube spacing if possible to reduce material and labor costs, in particular for conventional loop designs. With extended operation, radiant slabs with wider spacing may achieve similar thermal performance as slabs with smaller spacing.
- Strategically design hydronic distribution systems to minimize total pipe length. We compared the installed cost differences for two different approaches: a single set of pipe risers vs. multiple pipe-risers. The former relies on a single set of larger risers and long horizontal distribution runs on each floor, whereas the latter employs multiple sets of smaller risers strategically located to minimize the overall amount of pipe length and overall piping costs by $2.5/ft^2 for the case study building. This strategy may reduce construction cost for any system with distributed piping but is particularly critical for high thermal mass radiant since there are both chilled and hot water pipe distribution systems.

- The study building utilizes a four-pipe system to each radiant zone in the baseline radiant system. Many designers employ a 2-pipe distribution approach or a combination of 2-pipe and 4-pipe approach. If the latter approaches were used, designers may need to consider the potential thermal comfort impacts. More research and design guidance are needed to help designers decide which approach works best for their buildings.
- Utilize large radiant zones to minimize the number of changeover assemblies to reduce the cost of the radiant design but may potentially sacrifice comfort depending on the layout. This is another area that needs more research and guidance.
- The middle floors of a thermally active multi-story building will generally have both the floor and ceiling as active radiant surfaces, whereas the ground floor may only have the ceiling activated if radiant tubing is not installed in the slab-on-grade (or similarly the top floor may only have the floor activated if radiant tubing is not installed in the roof). The N+1 slab, i.e. radiant in slab-on-grade floor or in-roof layer, adds significant cost. For the case study building, adding radiant in the slab-on-grade would increase the total cost by about \$3.2/ft^2.
- For high thermal mass radiant system designs, there may be an opportunity to reduce the capacities of central plant equipment if load shifting control strategies are to be implemented. Though theoretically possible, this does not appear to be common design approach today, likely due to perceived risk of capacity shortfalls. If this is proven to be acceptable in the future, there would be some savings in central plant equipment costs.

5. Standard Addenda

This report provides a summary of potential addenda for ASHRAE Standards and Guidelines based on research activities performed and identified as part of this EPIC project.

5.1. Radiant Slab Control

5.1.1. *Codes and Standards Affected*

ASHRAE Guideline 36P: High performance sequences of operation for HVAC systems.

5.1.2. *Description of Proposed Codes and Standards Change*

ASHRAE Guideline 36 should include sections to provide high performance control sequences to radiant slab systems. The control sequences should have the following features:

- Capable of maintaining thermal comfort level to meet ASHRAE 55 Standard Requirements
- Allow designers to lock out heating and cooling switchover for a specified period of time
- Allow designers to lock out radiant slab operation for load shifting strategy

5.1.3. *Discussion*

Raftery et al. (Raftery, Duarte, Schiavon, & Bauman, 2017) presents a new controller for high thermal mass radiant systems that can be implemented within a typical Building Automation System. Figure 5.1 shows a schematic diagram of the controller in cooling mode. The controller responds to both zone and slab temperature conditions and allows a user to specify periods during the day in which the radiant system cannot operate. The primary control loop is an on/off controller that controls the radiant zone valve in response to the error between the temperature sensor in the slab, placed close to the surface, and the slab setpoint.

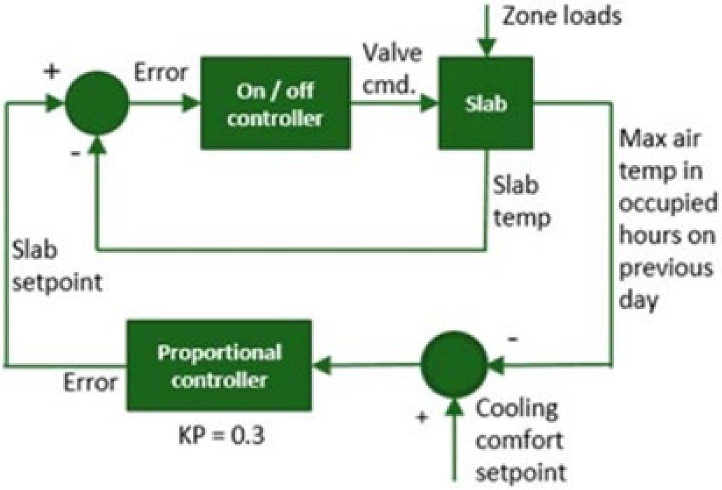


Figure 5.1 Schematic diagram of the controller in cooling mode. The same approach applies in heating mode, but using the minimum instead of maximum air temperature on the previous day, and heating instead of cooling comfort setpoint (Raftery, Duarte, Schiavon, & Bauman, 2017)

The slab setpoint control loop then uses a proportional controller that operates using the error between the maximum/minimum zone air temperature during occupied hours on the previous day relative to the comfort setpoint for cooling/heating. This secondary controller activates once at the end of the occupied period each day, and makes the change to the slab setpoint. The comfort setpoint is 1°F (adjustable) above or below the heating and cooling limits (respectively) of the comfort bounds defined for the zone. In this way, the controller gradually responds to changes in the zone loads over the course of several days.

In addition, the controller can only operate in one mode each day – either intermittent cooling, off for the entire day, or intermittent heating. This ensures a 24-hour period between mode changes to avoid wasted energy use from heating and cooling during the same day.

Lastly, the designer selects a period in which the radiant system does not operate- e.g. shut-off from 12pm to 2am. This feature allows building owners to minimize utility charges at peak periods.

In addition, the controller can only operate in one mode each day – either intermittent cooling, off for the entire day, or intermittent heating. This ensures a 24-hour period between mode changes to avoid wasted energy use from heating and cooling during the same day.

5.2. DOAS Supply Air Temperature Control

5.2.1. *Codes and Standards Affected*

ASHRAE Guideline 36P: High performance sequences of operation for HVAC systems.

5.2.2. *Description of Proposed Codes and Standards Change*

ASHRAE Guideline 36 should include a section to regulate control sequences for Dedicated Outside Air Systems, in particular for the supply air temperature control strategy.

5.2.3. *Discussion*

Dedicated outdoor air systems (DOAS) usually have heating, cooling, and dehumidification capability, and often have outdoor air energy recovery and possibly run-around heat recovery systems. While DOASs need to achieve their primary functions of cooling, heating, and dehumidification, conservatively conditioning the outdoor air to achieve those functions may result in significant energy waste. In the design industry, one simple and common approach is to supply neutral air temperature from the DOAS, which involves cooling the air and then heated to back neutral (Paliaga, Farahmand, Raftery, & Woolley, 2017). Though commonly employed, this strategy may result in a significant increase in HVAC energy use. The Cost and Energy Comparison study, one of the Task 5 deliverables, has demonstrated that the radiant design site energy use ranged from 2.7 kBtu/ft^2 to 4.4 kBtu/ft^2 for the case study building simply by varying the DOAS supply air temperature control approach (Feng and Cheng, 2018).

While there are design guides that offer general considerations and principles to control DOAS supply air dry bulb and dew point temperature, it is difficult for designers to translate principles into concrete control sequences that will function in practice. We are not aware of any literature that offers detailed annual operational sequences aiming to achieve both energy efficiency and the basic psychometric functions. We are approved by ASHRAE Research Committee to develop a research project work statement on this topic. The objectives of the research project would be to provide designers with guidance on climate and application-dependent supply air temperature control for DOAS, and to develop detailed control sequences that are ready for implementation. The results of research will be used to improve ASHRAE's Advanced Energy Design Guides Series (ASHRAE) and potentially to be included in the ASHRAE Guideline 36 (ASHRAE 2018).

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