Energy Research and Development Division

FINAL PROJECT REPORT

Optimizing Radiant Systems for Energy Efficiency and Comfort

Appendix H: Cooling Load and Design Sizing Report

California Energy Commission

Edmund G. Brown Jr., Governor

April 2019

Cooling Load and Design Sizing Report

Jonathan Woolley, Fred Bauman, Carlos Duarte, Paul Raftery, and Jovan Pantelic

Optimizing Radiant Systems for Energy Efficiency and Comfort (EPC-14-009) Task 3.1
UC Berkeley
December 2018

ABSTRACT

The current standard procedure for design sizing of cooling systems is not well suited for design of buildings with radiant cooling. There are several reasons that the standard design procedure for radiant cooling systems (*ASHRAE Systems & Equipment 2016 Chapter 6: Radiant Heating and Cooling*) is flawed, including that the current standard definition of space cooling load (*ASHRAE Fundamentals 2017 Chapter 18: Nonresidential Cooling and Heating Load Calculations*) omits fundamental principles that are essential to the operation of radiant cooling. This report identifies several specific shortcomings with the current standard cooling load definition and with the standard cooling system design sizing procedure. We explain the fundamental flaws with each, discuss why addressing these shortcomings is especially important to the optimal design and operation of radiant cooling systems, and provide general recommendations for how the procedures ought to be improved. The issues and recommendations presented in this report have been informed by several research projects conducted as part of the CEC EPIC research program *Optimizing Radiant Systems for Energy and Comfort (EPC-14-009)*. In addition to identifying specific flaws with standard cooling load and design sizing procedures, we also discuss how each aspect of our research has provided evidence about or potential solutions to each issue.

1. OVERVIEW OF "COOLING LOAD" AND ITS USE IN SYSTEM DESIGN

To design a cooling system and properly size all of its subcomponents, an engineer must begin by calculating the "space heat extraction rate" that would be required to achieve intended indoor thermal conditions for each space in a building. The rate at which heat must be extracted from a space is dynamic; it changes in time mainly because the balance of heat gains to – and losses from – a space changes in time, and because surfaces within and enclosing a space absorb and store a portion of the heat gains. As a consequence of this thermal storage, the space heat extraction rate required by a cooling system is generally smaller than the heat gain rate, yet it can persist after heat gains subside if heat stored in surfaces is released back to the space. Moreover, the heat gains to a space change from day-to-day, so engineers typically size a cooling system based on the conditions in a hypothetical "design day". This process is referred to as a "cooling load calculation", and the product of the calculation is a time series estimate of the "space cooling load" – the space heat extraction rate that would be required to maintain comfort in the hypothetical design day scenario.

Following a cooling load calculation, engineers select and size terminal cooling devices that are capable of satisfying the maximum space cooling load, then design and size distribution systems and cooling plants that are capable of satisfying the maximum sum of coincident heat transfer rates from all terminal cooling devices. The "cooling capacity" of a terminal heat transfer device, a distribution system, or a cooling plant, is the steady state heat extraction rate that could be produced by continuous operation. The cooling capacity for a system is not a constant value; rather, it depends on coincident environmental conditions and system states. For example, the cooling capacity of an air cooled chiller depends on the outdoor air temperature, the chiller entering water temperature, and the water flow rate.

In most circumstances the time required for the heat extraction rate to reach steady state following a change to the inputs – the "response time" – is small relative to the time required for either the space cooling load or environmental conditions to change. Since this response time is relatively quick designers typically assume that the steady state cooling capacity is a reasonable estimate of what a system can produce at a particular point in time, and therefore sizing a cooling system generally entails specifying a cooling plant, distribution system, and terminal heat transfer devices each with the cooling capacity to match the maximum space cooling load at coincident conditions plus additional heat transfer rates attributed sources such as duct leakage, or heat gain from ventilation introduced at the air handler.

However, as the remainder of this document discusses, the current standard definition of "cooling load" is unclear, and incomplete. It omits fundamental heat transfer pathways and so cannot properly represent all types of cooling systems. Similarly, the standard design sizing procedure – which directs engineers to match the steady state "space cooling capacity" to the peak "space cooling load" – is not appropriate for all types of cooling systems. Our research has revealed that these fundamental shortcomings are especially problematic for radiant cooling systems. Section 2 explores the reasons that the formal definition of "cooling load" is unsatisfactory, and why it matters to the design of radiant cooling systems. Then, Section 3 explains why the current standard design sizing procedure is not appropriate for the design of radiant cooling systems.

2. THE FORMAL DEFINITION OF "COOLING LOAD" IS UNSATISFACTORY

Designers use a variety of different computer programs to conduct cooling load calculations, but the procedure is formally defined by *ASHRAE Fundamentals 2017 Chapter 18: Nonresidential Cooling and Heating Load Calculations*. In addition to a conceptual definition, the chapter describes two different mathematical methods by which the cooling load can be calculated: a Heat Balance (HB) method, and the Radiant Time Series (RTS) method. As discussed at length in Section 2.2, there are different implementations of the so-called "Heat Balance method". Henceforth we refer to the implementation presented in *ASHRAE Fundamentals 2017 Chapter 18* as "ASHRAE's Heat Balance method". Although the ASHRAE definition of cooling load and the recommended calculation methods have been applied successfully for the design of many buildings, our research has revealed that they impose several assumptions and constraints that limit them from accurately representing all cooling systems types and applications. In particular, the existing formal conception of cooling load:

1. Does not reflect prevailing standards that characterize acceptable thermal environmental conditions for human occupancy
2. Does not reflect the methods used by modern building energy simulation software for calculation of space heat extraction rates by different cooling system types
3. Does not account for the impact of system control strategies
4. Does not provide unambiguous explanation of the "cooling load" and related concepts within the context of whole system design

These shortcomings are especially troublesome for radiant cooling systems. Subsections 2.1–2.4 describe each of the fundamental issues listed above in greater detail, and explain why they are problematic for the design and control of radiant cooling systems.

2.1. The formal definition of "cooling load" does not reflect prevailing standards that address acceptable thermal environmental conditions for human occupancy

2.1.1. Explanation of the shortcoming

ASHRAE 2017 Chapter 18 defines "cooling load" as the space heat extraction rate that would be required "to maintain a constant space air temperature and humidity". This requirement overlooks the best understanding of human thermal comfort in indoor environments – as standardized by ASHRAE 55 – which acknowledges that multiple factors influence comfort, and that it is acceptable for thermal conditions in a space to change somewhat over the course of a day. By constraining "cooling load" to a constant air temperature, instead of referencing a more comprehensive metric for comfort, the current definition excludes many systems and control strategies that do not maintain a constant air temperature, yet can provide acceptable thermal comfort. In fact, it's not as if constant air temperature provides constant thermal comfort; for a typical forced air system, the temperature of surfaces within and enclosing a space changes as they absorb heat, which causes operative temperature to change throughout the day. This disconnect would be especially apparent in a space with substantial solar gains, in which a constant air temperature may not adequately counteract the comfort impacts of increased surface temperatures and direct insolation.

Whereas controls for forced air systems typically measure indoor air temperature and adjust system states to maintain an indoor air temperature setpoint, controls for high thermal mass radiant systems typically measure mass temperature and adjust system states to maintain a mass temperature setpoint. With this strategy, indoor thermal conditions are only controlled in an open loop fashion. Through commissioning, building operators can select a mass temperature setpoint that will consistently result in comfortable indoor conditions, but indoor air temperature cannot be expected to remain constant, as is currently prescribed by the ASHRAE definition of "cooling load". Compared to a space with forced air cooling, the surface temperatures in a space with radiant cooling will remain cooler and more consistent throughout the day, even though the indoor air temperature is not held constant. Calculating the cooling load for a high thermal mass radiant system whilst constraining air temperature to a constant value would require simulation of impossible thermal conditions, and would produce an unrealistic cooling load estimate.

2.1.2. Recommendations

Therefore, we recommend that the formal definition of cooling load be updated to reflect the prevailing standards that address acceptable thermal environmental conditions for human occupancy.

2.1.3. Summary of our research on the subject

Several components of the research program Optimizing Radiant Systems for Energy Efficiency and Comfort (EPC-14-009) helped to extend the fundamental understanding of this issue:

- Essays by Duarte (2017) and Woolley (2017) developed literature reviews and exploratory analysis into how the fundamental thermodynamics underlying radiant cooling, and the control strategies utilized for these systems, influences human thermal comfort and the space heat extraction rate by actively cooled surfaces.
- Raftery et al. (2017) explored the way that different control strategies for high thermal mass radiant systems impact cooling load and thermal comfort. The article highlights that the control strategies for high thermal mass radiant systems do not maintain constant indoor temperature. It also presents a newly developed sequence of operations that uses measured indoor air temperature to automatically adjust slab temperature setpoints.
- An article by Dawe et al. (Dawe 2019) analyzed data from several sources to assess the typical difference between air temperature and mean radiant temperature in buildings with radiant cooling and those with all air cooling. In general, for both radiant and all air buildings, the mean radiant temperature is close (within ± 0.5 °C) to air temperature. The data from buildings in operation show that in both radiant and all air buildings, air temperature varied over the course of a day during typical hours of occupancy. In all air buildings, the air temperature varied by 2.3 °C, on average, during the day. Meaning that even all air buildings are not able to maintain a constant air temperature.
- The web-based radiant design tool (CBE Rad Tool), documented in Rad Tool user's guide and specifications report, predicts operative temperature in a space with high thermal mass radiant cooling during the cooling design day. CBE Rad Tool can retrieve the operative temperature prediction based on EnergyPlus simulation for over 2.5 million zone and radiant system designs. CBE Rad Tool can help building designers verify that a specific zone and radiant design is operating within comfort criteria outlined in ASHRAE 55 during the cooling design day.

- One of our FLEXLAB experiments – documented by Pantelic et al (2018) – evaluated the operative temperature variations in the floor area exposed to direct solar. Results show that regions with direct solar exposure have up to 4 °C higher than the regions without solar. Results from our experiments suggested that this supply water temperature doesn't make a significant impact on the operative temperature in sun-exposed regions.

2.2. The formal definition of "cooling load" does not reflect the most advanced methods used by modern building energy simulation software for calculation of space heat extraction rates by different cooling system types

2.2.1. Explanation of the shortcoming

ASHRAE Fundamentals 2017 Chapter 18 recommends two different mathematical methods to calculate the cooling load: a Heat Balance (HB) method, and the Radiant Time Series (RTS) method. However, neither of these methods – as currently implemented by ASHRAE – fully reflect the current best practice for simulation of thermal energy in buildings. Most importantly, both methods assume that convection is the only heat transfer mechanism by which heat can be removed from a space; and consequently they do not properly estimate the space heat extraction rates by radiant cooling systems – since radiant cooling transfers heat by convection and by radiation. This difference is important because it impacts the time and rate at which heat must be extracted from a space. Research has proven clearly that to maintain equal operative temperature as an all-air system: a radiant cooling system must extract heat from gains earlier; its peak space heat extraction rate must be larger; and its peak space heat extraction must occur earlier (Niu 1995, Niu 1997, Feng 2013, Feng 2014-A, Feng 2014-B, Woolley 2018, Wooley 2019, Novalesec 2018, ASHRAE RP-1729). In addition to changing the space cooling load, radiant cooling also changes the heat gain to (and heat loss from) a space because it changes envelope heat transfer and reduces the amount of heat that is stored in non-active masses, which reduces the amount of heat that can be released to the environment passively when there is a diurnal opportunity for passive cooling. Since the ASHRAE conception of "cooling load" does not account for space cooling by radiant heat transfer, it does not account for these differences in the heat gain, and the cooling load.

Not all cooling load calculation methods impose the convection-only limitation. The U.S. Department of Energy's open source building energy simulation software (EnergyPlus) employs a method that accounts for space heat extraction by convective and radiant heat transfer to surfaces that are actively cooled by internal sources. Notably, the method used by EnergyPlus is the direct descendent of the ASHRAE Heat Balance method described in *ASHRAE Fundamentals 2017 Chapter 18*. The ASHRAE Heat Balance method was initially implemented by Kusuda (1974) and in the BLAST and TARP energy analysis programs (Walton 1983), then was described in full by Liesen and Pedersen (1997), McClellan and Pedersen et al. (1997), and Pedersen et al. (1998) as part of ASHRAE RP-875. Shortly afterward, Strand et al (1999), Strand and Pedersen (2002), and Strand and Baumgartner (2005) extended the Heat Balance method to consider the heat transfer dynamics of radiant systems, and developed the requisite features to incorporate the methods into EnergyPlus. Feng et al (2014-A) conducted laboratory experiments which validated the predictions from Strand's more comprehensive Heat Balance method; and simultaneously, proved that the Radiant Time Series method and the ASHRAE Heat Balance method do not accurately predict the space heat extraction rates for radiant systems.

2.2.2. Recommendations

Therefore, we recommend that the formal definition of cooling load be updated to reflect the more comprehensive Heat Balance method, and that the limitations of previous methods should be clearly explained.

2.2.3. Summary of our research on the subject

Several components of the research program Optimizing Radiant Systems for Energy Efficiency and Comfort (EPC-14-009) helped to extend the fundamental understanding of this issue:

- We conducted experiments at FLEXLAB to compare the space cooling load for radiant and all-air systems. As documented by Woolley et al. (2018), these experiments proved that to maintain equal operative temperature as an all-air system, radiant cooling must remove more heat overall, the peak space heat extraction rate must be larger, and it must occur earlier. The magnitude of these differences depends on many factors. As documented in a second paper from the experiments (Woolley 2019), the differences are larger for cases with highly radiant heat gains, and larger in scenarios that benefit from passive cooling of the thermal mass in a building. For some scenarios radiant cooling increased the peak cooling load by 25%, and the cumulative daily cooling load by 40%.
- Results from Pantelic et al (2018) for one water supply temperature (e.g., 15 °C) show that two distinct cooling capacity and surface temperature regions exist. Cooling capacity of chilled radiant floor can be increased from 30 W/m^2 up to 110 W/m^2 with direct solar radiation based on the results of this experiment. Changes of the chilled water supply temperature from 12 to 18 °C led to decreased cooling capacity from ~110 W/m^2 to ~95 W/m^2. In the middle region of the test room, the cooling capacity decreased from ~40 W/m^2 to below 30 W/m^2. The region close to the window that was affected by direct solar had a peak floor surface temperature of 26 °C, while the unaffected region away from the window had floor surface temperatures between 20 and 21 °C. Although floor cooling capacity increased, the floor area affected by the direct solar has a higher temperature compared to the area unaffected by the direct solar radiation. This has impact on thermal comfort of the occupants and requires consideration during positioning and selection of the slab temperature sensors.
- Ceiling fans can increase radiant slab cooling capacity by approximately 16 % at the same operative temperature - from 32 W/m2 in the baseline operation at the operative temperature of 24 °C up to 36 W/m2. Radiant slab cooling capacity can be further increased up to 42 W/m2, or by approximately 26 %, when the operative temperature is increased to 26 °C to account for the effect of increased air movement on thermal comfort. The combination of radiant floor and ceiling fans have the potential to be an important low energy cooling solution
- Based on the FLEXLAB results model by Feng et al over predicts area weighted floor surface heat flux by 50 %. The parametric analysis shows that model by Feng et al predicts with reasonable accuracy floor cooling capacity when 40 % to 60 % of the floor is exposed to direct solar. This percentage is based on the window geometry and characteristics in the FLEXLAB (Pantelic 2018). Percentages of the floor coverage might change but results point out that it is very challenging to include solar into calculation without including information about the area of the floor that is exposed to direct solar. Field measurement results from the ARTIC building show that the model underpredicts the cooling capacity when a large area of the floor is exposed to direct solar.
- The web-based CBE Rad Tool, documented in Rad Tool user's guide and specifications report provides a simple to use tool for designers to accurately estimate the space heat extraction rates from high thermal mass radiant systems during the cooling design day. The CBE Rad Tool is based on EnergyPlus simulations that account for both radiant and convective space heat extraction rates at the active surface of the radiant cooling system. The tool can estimate space heat extraction rates for over 2.5 million zone and radiant system designs.
- 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%.

2.3. The formal definition of "cooling load" does not account for the impact of system control strategies

2.3.1. Explanation of the shortcoming

ASHRAE 2017 Chapter 18 defines "cooling load" as the space heat extraction rate that would be required "to maintain a constant space air temperature and humidity". The definition is not explicit about the time period in which "constant air temperature" should be maintained, and thus, overlooks the fact that the setpoint schedule and sequence of operations will impact the space cooling load. For example, scheduling a setback during unoccupied periods could cause a larger peak space cooling load than continuous setpoints, because surfaces will begin each day at a higher temperature, and so will store a smaller portion of the heat gains imposed during the day. For the same reasons, a pre-cooling setpoint schedule would reduce the peak space cooling load. As the expectations for dynamic control of electrical demand from buildings continues to evolve, the dynamic control of cooling systems requires more sophisticated system design than what is promulgated by the current "cooling load" definition.

This aspect of the current "cooling load" definition is especially problematic for high thermal mass radiant systems, for which the slab temperature setpoint, the supply water temperature, and system availability schedule will substantially change the shape and magnitude of the space cooling load. It is also problematic for buildings that rely on multiple cooling systems. For example, the choice of control sequence to coordinate radiant cooling and supplemental air cooling will have a major impact on the space cooling load for each system. Similarly, the choice of control sequence in buildings that utilize natural ventilation for precooling will have a major impact on the cooling load. Our research has revealed that because radiant cooling extracts a significant amount of heat from non-active thermal masses, it can preempt some of the benefits of natural ventilation for night precooling. For such a mixed-mode building, the sequence of operations would have a major impact on the space cooling load, as well as the cumulative mechanical cooling load.

2.3.2. Recommendations

Therefore we recommend that the formal definition of cooling load be updated to allow more flexibility in regard to control sequences. The definition should be generalized so as to encompass a multitude of control strategies, yet should encourage system designers to consider the possibility that control sequences might change over the life cycle of a building.

2.3.3. Summary of our research on the subject

Several components of the research program Optimizing Radiant Systems for Energy Efficiency and Comfort (EPC-14-009) helped to extend the fundamental understanding of this issue:

- The web-based CBE Rad Tool, documented in Rad Tool user's guide and specifications report, allows designers to select various radiant cooling system operation start times and durations during the cooling design day to evaluate the impacts on zone operative temperature and space and plant heat extraction rate. In addition, it allows designs to consider the impact of other design decisions including: chilled water temperature setpoints, design difference between supply and return water temperatures, and pipe spacing. The analysis of the results help designers select a control strategy that can reduce energy consumption, electricity costs, and/or provide uniform temperatures in the zone by shifting radiant system operation during times when the cooling plant operates the most efficient, electricity rates are low, and/or the peak space heat extraction rate coincide with the peak heat gains of the zone.

- We developed and tested a new sequence of operation for high thermal mass radiant systems, as documented in Sequences of Operations for High Thermal Mass Radiant Systems, Field Study #2: Sacramento Municipal Utility District (SMUD) East Campus Operation Center, and Field Study #3: David Brower Center Building (DBC) reports. The new sequence slowly adjusts slab temperature setpoints to control radiant system operation to maintain comfort in the zone. The main advantage of the control sequence is that the radiant system operation does not have to be concurrent with the occupied hours of the building. The sequence is designed to take advantage of thermal inertia by extracting heat from the slab only during certain periods of time. This allows designers to select for either: more efficient and cost effective operating hours, longer operating hours to yield smaller heating or cooling plant sizes, or aim to provide a more uniform daily range of comfort conditions. The field studies showed that these sequences maintained comfort and reduced the time manifold valves were actuated when compared to existing radiant controls in the buildings.
- We conducted a series of experiments at FLEXLAB to compare the space heat extraction rates by radiant and all-air cooling systems to maintain equal operative temperature. As documented by Woolley et al (2018, 2019) the control strategy – in particular, the space cooling setpoint schedules, and timing of hydronic system operation – interact with the diurnal ebb and flow of heat between building thermal masses the environment, in ways that significantly impact space cooling loads, and the difference between space cooling loads for radiant and all air systems.. For example, when the air and radiant systems were controlled to maintain constant operative temperatures setpoint during occupied hours, but then utilized natural ventilation to precool building thermal mass overnight, radiant cooling had a 40% larger cumulative thermal load. However, we expect that for buildings with high thermal mass radiant cooling, natural ventilation and radiant system operation could be coordinated more strategically to significantly reduce the additional thermal burden carried by the radiant cooling system.

2.4. The “cooling load” is defined ambiguously

2.4.1. Explanation of the shortcoming

ASHRAE 2017 Chapter 18 does not provide an unambiguous explanation of the “cooling load” and related concepts, and does not provide a clear sense for how the “cooling load” fits within the context of whole system design.

- Does not clearly separate the idea of “space cooling load” from “plant cooling load”, It is concerned only with the room heat balance and does not consider the difference between “space heat extraction rate”, “terminal heat extraction rate”, “plant heat extraction rate”
- “Design procedure” is covered independently in other chapters, but its relationship to the “cooling load” calculation should be defined in this chapter.
    - For example:
        - How should cooling load from multiple spaces aggregate to become the plant cooling load?
        - Is the “cooling load” a point in time concept? .. or is the “cooling load” a time series result of the “dynamic space heat extraction rate required over the course of one day, (or perhaps) multiple days?” (it is currently not specified).
        - For what conditions should a “cooling load calculation” be performed? Currently the chapter does not include in discussion of how to choose appropriate “design day” conditions, nor about how to choose appropriate initial conditions (unless this is covered implicitly by the HB method and/or RTS method).
        - It is not clear how the “cooling load” changes in a case when the “space heat extraction rate” does not match the cooling load, or in a case when setpoint changes. For EnergyPlus, in the “cooling load” is not met in one timestep, the

“cooling load” in the next time step accounts for what it will take to return to the setpoint, in addition to what it will take to maintain the setpoint (ie: cooling load in each time step is a measure of what it would take to return to the setpoint in that time step, and so accumulates when the “cooling load” is not satisfied). Moreover, at point when setpoint changes, depending on time step size, the “cooling load” could be incredibly large,
        - The definition of “cooling load” does not address how to deal with the precision errors that arise in numerical simulation. It could be defined as if the cooling load calculation had perfect resolution (ie: “continuous” time, instead of finite time steps), but perhaps the chapter ought to discuss this practical issue. EnergyPlus employs a dynamic timestep approach that actively reduces error in the overall heat balance.
    - Problems with the idea of “cooling load” on a “design day” as the basis for design when there are different aims of a system (sensible, latent, ventilation) ... and thermal energy storage, etc
- Does not give adequate definition of “heat gains” in relationship to “heat losses”. Most importantly:
    - Does not clearly define the control volume for “space” from which heat is “gained” , “lost”, “stored in mass” or “extracted” by a cooling system.
        - Specifically, heat gain by conduction through an envelope is generally thought of as a “gain” once it is transferred to the indoor air by convection, yet the heat in the walls changes the interior surface temperature and influences operative temperature, which would impact the “cooling load”, even though heat may not be transferred to the air. In fact, at some point in time these walls might be absorbing heat by convection, yet still causing an increase in the cooling load because they impact operative temperature as they warm.
    - Does not provide “control volume” for the terminal cooling device (ie: to characterise the disconnect between “space cooling rate” and “hydronic cooling rate”). Accordingly, *ASHRAE Fundamentals 2017 Chapter 18* does not explain how “response time” for an element in the system influences the each “cooling load”. Chapter 18 could also be an appropriate place to formally advance a definition for “self control”, at least in regard to how rapidly “space cooling rate” responds to change in heat gain without change in the controlled inputs.
    - Offers diagrammatic explanations that do not map directly to physical principles. For example, diagram suggests that the difference between “cooling load” and “space heat extraction” returns to the mass storage element, when in fact it would return to the air mass as well causing air temperature rise.
    - Does not give a description of gain from opaque envelope
    - Uses the term “fenestration” incorrectly
- Not account for time lag in high mass systems
    - Engineers use steady state calculations to predict cooling capacity.
- Does not adequately distinguish between latent and sensible load .. definition seems to mix the two.

2.4.2. Recommendations

Therefore we recommend that *ASHRAE Fundamentals 2017 Chapter 18* be revised to provide a clearer definition of terminology, and a clearer explanation of the purpose of the “cooling load” within the context of whole system design.

2.4.3. Summary of our research on the subject

Several components of the research program Optimizing Radiant Systems for Energy Efficiency and Comfort (EPC-14-009) helped to extend the fundamental understanding of this issue:

- Essays by Duarte (2017) and Woolley (2017) developed literature reviews and exploratory analysis into how the fundamental thermodynamics underlying radiant cooling, and the control strategies utilized for these systems, influences human thermal comfort and the space heat extraction rate by actively cooled surfaces. Duarte's essay focused explicitly why the current standard definition of "cooling load" does not apply to radiant cooling systems, and Woolley's essay explored the topic of "self control": an aspect of radiant system performance that is discussed in literatures, but is currently not formally addressed by any standard or design guideline.
- Ning et al. (2017) published a paper that evaluates the time constant for different types of radiant systems. This paper used simulations to reveal that the current conceptual classification for radiant cooling system types does not provide adequate differentiation in regard to their dynamic control.

3. THE STANDARD DESIGN SIZING PROCEDURE FOR RADIANT COOLING SYSTEMS IS UNSATISFACTORY

3.0.1. Explanation of the shortcoming

ASHRAE Systems and Equipment 2016 Chapter 6: Radiant Heating and Cooling provides a step-by-step procedure to guide the design of radiant cooling systems. In general, this process directs engineers to calculate the peak "space cooling load" (determined according to *ASHRAE Fundamentals 2017 Chapter 18*) then to design a radiant system with steady state "space cooling capacity" to match. Apart from the fact that the current formal definition of "space cooling load" does not accurately represent radiant cooling systems, this design sizing procedure is unsatisfactory because in practice many radiant cooling systems do not operate at steady state, so do not generate the space cooling capacity predicted by steady state characterizations of performance.

High thermal mass radiant systems do not operate at steady state because the thermal resistance and thermal capacitance of the internally cooled construction elements introduces a time delay for heat flux across the terminal cooling device. As a result, the space heat extraction rate will differ considerably from the hydronic heat extraction rate. For example, in laboratory tests of a hydronically cooled 6 inch thick concrete slab floor, we observed that more than 30 minutes was required to register 0.1 °C change in surface temperature following a 6 °C step change in chilled water temperature. More than 90 minutes was required for slab surface temperature to change by 1 °C. The delay for heat flux across the cooling device behaves as a classic first order response, and can be quantified by a "response time" or "time constant". For terminal cooling devices with a short response time, it is reasonable to assume that the instantaneous space heat extraction rate will be equal to the instantaneous hydronic heat extraction rate and that the device will generate space heat extraction rate that agrees with its steady state cooling capacity at coincident conditions. But, for terminal cooling devices with a long response time, this assumption is not reasonable.

Interestingly, the instantaneous "space heat extraction rate" for a high thermal mass radiant system may be smaller or larger than predicted by steady state assumptions, depending on the initial thermal conditions of the slab, and the way that the inputs change at the boundaries of the terminal cooling device. As the previous example indicates, for a high thermal mass radiant system it can take a long time for change in chilled water temperature to influence the space heat extraction rate, and in the interim the space heat extraction rate will be different from what would occur at steady state. Following a decrease in chilled water temperature the instantaneous space heat extraction rate would be smaller than at steady state and following an increase in chilled water temperature the instantaneous space heat extraction rate would be larger than at steady state. Although the space heat extraction rate is slow to change in response to a change in the chilled water temperature or flow rate, it can also change rapidly in response to a change in heat gains without the need for an active change in chilled water temperature and flow rate. In this case, the instantaneous space heat extraction rate may be much larger than the steady state heat extraction rate.

The standard design procedure for radiant cooling directs engineers to assume that there is no delay in heat flux across the cooling device. As a result, engineers generally size hydronic systems, pumps, and cooling plants to handle the peak space heat extraction rate, when for high thermal mass radiant systems the peak heat extraction rate for the cooling plant can be much smaller than the peak space heat extraction rate. Consequently, the standard design sizing procedure for radiant cooling systems leads to sub-optimal design. The standard “cooling load calculation” sets a target for the peak a space heat extraction that is smaller than what will be needed in reality, and the standard “design procedure” leads to sizing equipment that is larger than necessary.

Furthermore, the current design procedure for radiant cooling systems requires that a designer know the relationship between temperature of the actively cooled surface, temperature of the non-active surfaces, and temperature of the air in the space. In reality, these temperatures change dynamically in response to the heat gains and the control strategy implemented, and our research has revealed that there is very little information to guide designers about what to expect during normal operation or during design day conditions. The relationship between these temperatures is best predicted by numerical simulation with the extended Heat Balance method, so without clear empirical, and without numerical simulations, the current standard design procedure effectively expects designers to guess.

3.0.2. Recommendations
Therefore we recommend that the standard design procedure for radiant cooling systems – as presented in ASHRAE Systems and Equipment 2016 Chapter 6 Radiant Heating and Cooling – be rewritten in such a way that it considers the dynamic heat transfer behaviors associated with radiant cooling systems so as to more accurately represent the instantaneous space cooling capacity that can be expected from high thermal mass radiant cooling systems, and to demtermine this separately from the rate at which heat is extracted by the hydronic systems.

3.0.3. Summary of our research on the subject
Several components of the research program Optimizing Radiant Systems for Energy Efficiency and Comfort (EPC-14-009) helped to extend the fundamental understanding of this issue:

- The web-based CBE Rad Tool, documented in Rad Tool user’s guide and specifications report, allows designers to accurately estimate both the space and hydronic heat extraction rates from high thermal mass radiant systems during the cooling design day.The tool can estimate these heat extraction rates for over 2.5 million zone and radiant system designs. The estimates are based on EnergyPlus simulations that account for the heat flux delay across the high thermal mass terminal cooling device after a change in operation of the radiant system. Thus, it allows designers determine time and magnitude of peak space heat extraction rate necessary to maintain thermal comfort in the zone and time and magnitude of peak hydronic heat extraction rate necessary for plant sizing calculations.

3.0.4. Impact of direct solar on the design of radiant floors
ISO 11855 describes a method currently used for engineering calculations of the cooling floor capacity. This method is under predicting floor heat extraction rates in the areas with direct solar exposure. Pantelic et al. (2018) demonstrated this effect in the laboratory measurement.

To improve the predictability of the current cooling capacity estimation method for cases with direct solar heat gain, Feng et al. proposed:

$$q''_{sw\_sol} = -1.993(q''_{sol,,win})^{0.7476} - 5.038\,(q_{sol,,win}\ \Delta T_h)^{0.2793}$$

We performed validation of the proposed model by measuring input and output parameters in the equation. We then compared measured output and calculated based on the Feng et al. model with input parameters in parallel measured.

q''_{sw_sol} – was measured with 3 heat flux sensors as depicted in Figure 1 and Figure 2, but the quantity presented in the diagram was averaged based on the weighted floor area exposed to the direct solar. Area directly exposed to the solar was only ~10 % of the total floor area and the remaining ~90 % was calculated based on equal weightage of sensor in the middle and north side of the chamber. In the diagrams below this is depicted with red color and titled Area weighted surface heat flux average. Green, purple and cyan are readings from the sensors.

$q''_{sol,,win}$ – was measured with Eppley Pyranometer placed vertically next to the window as depicted in Figure 1.

ΔT_h – operative temperature was average of 3 operative sensors placed at 0.6 m from the floor and were never exposed to direct solar; supply water temperature that was supplied to each of loops and combined return water temperature reading. Return chilled water temperature between the loops was within 0.5 ^{o}C.

Results

Results in Figure 1 show that the model by Feng et al overpredicts the area weighted floor surface heat flux by 50 %. Results in Figure 2 show a similar trend of overprediction of Feng et al. model, but parametric analysis show that model by Feng et al. predicts with reasonable accuracy floor cooling capacity when 40 % to 60 % of the floor is exposed to the direct solar. This percentage is based on the window geometry and characteristics in the FLEXLAB (Pantelic 2018).

Results in Figure 3 from field measurements in the ARTIC building (see Field Study #1 Report) show that the model underpredicts cooling capacity when a large area of the floor is exposed to direct solar. This trend can be observed in Figure 2 also. Percentages of the floor coverage might change but the above results point out that it the inclusion of solar radiation into cooling capacity calculations must be done with care and should contain information about the area of the floor that is exposed to direct solar.

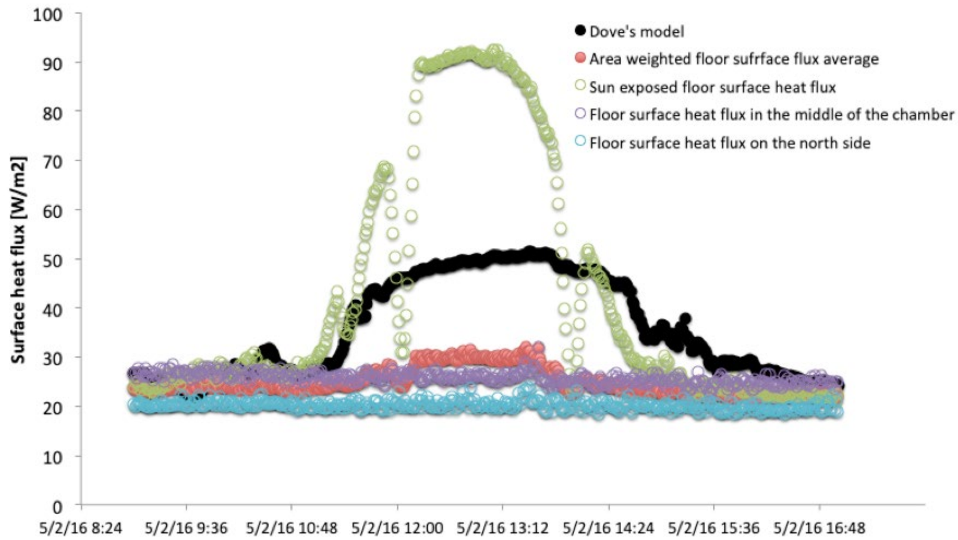

Figure 1. FLEXLAB validation of Feng et al model for May 2nd 2016.

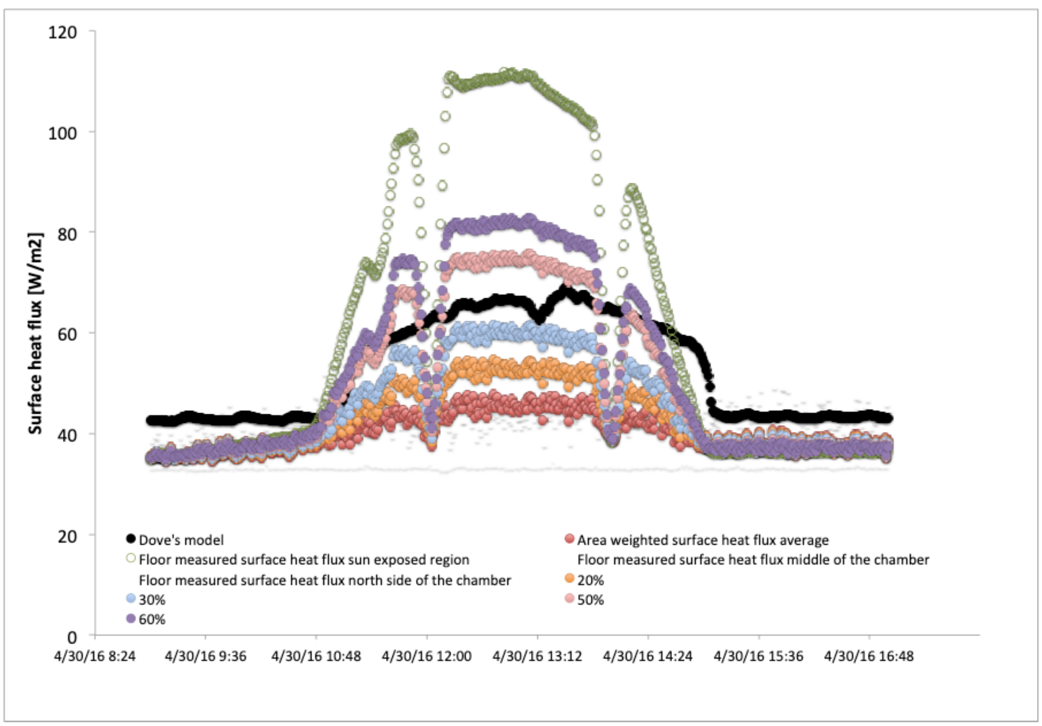

Figure 2. FLEXLAB validation of Feng et al. model for April 30th 2016 with area weighted heat flux and parametric analysis on the floor exposure percentage.

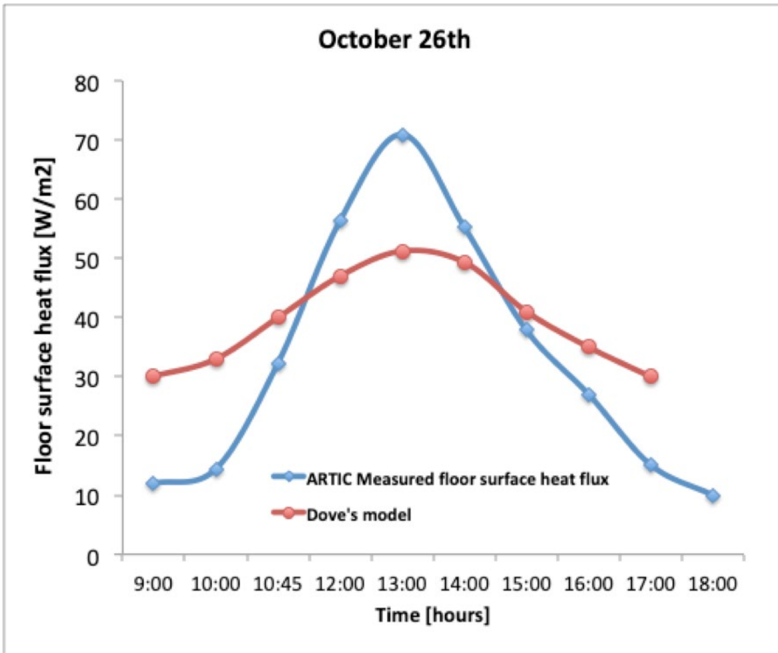

Figure 3. Validation based on the field data collected in ARTIC in Anaheim.

4. REFERENCES

ASHRAE Handbook, HVAC Systems & Equipment, American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2016.

ASHRAE Handbook, Fundamentals, American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2017.

ASHRAE RP-1729. Final report on difference in cooling load for radiant and all-air systems. (Expected 2019).

M. Dawe, P. Raftery, J. Woolley, S. Schiavon, F. Bauman. Are all temperatures created equally? Comparison of mean radiant and air temperatures in mechanically-conditioned commercial buildings. 2019. (In Press).

C. Duarte. Cooling load methodologies. An essay prepared in partial fulfilment of the requirements of the qualifying examination for the doctoral degree in Architecture, University of California Berkeley. November 2017.

EnergyPlus, U.S. Department of Energy Building Technologies Office, 2018. https://energyplus.net/.

J. (Dove) Feng, F. Bauman, S. Schiavon, Critical review of water based radiant cooling system design methods, in: Proceedings of Indoor Air 2014, International Society of Indoor Air Quality and Climate, Hong Kong, 2014. http://escholarship.org/uc/item/2s00x6ns.

J. (Dove) Feng, F. Bauman, S. Schiavon, Experimental comparison of zone cooling load between radiant and air systems, Energy and Buildings. 84 (2014) 152–159. doi:10.1016/j.enbuild.2014.07.080.

J. (Dove) Feng, S. Schiavon, F. Bauman, Cooling load differences between radiant and air systems, Energy and Buildings. 65 (2013) 310–321. doi:10.1016/j.enbuild.2013.06.009.

C. Karmann, F. Bauman, P. Raftery, S. Schiavon, M. Koupriyanov, Effect of acoustical clouds coverage and air movement on radiant chilled ceiling cooling capacity, 158 (2018) 939–949. doi:10.1016/j.enbuild.2017.10.046.

T. Kusuda, NBSLD, computer program for heating and cooling Loads in buildings, Final Report National Bureau of Standards, Washington, DC. Center for Building Technology. (1974).

R.J. Liesen, C.O. Pedersen, An evaluation of inside surface heat balance models for cooling load calculations, (1998). https://www.osti.gov/biblio/349985 (accessed November 30, 2018).

T.M. McClellan, C.O. Pedersen, Investigation of outside heat balance models for use in a heat balance cooling load calculation procedure, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA (United States), 1997.

B. Ning, S. Schiavon, F.S. Bauman, A novel classification scheme for design and control of radiant system based on thermal response time, Energy and Buildings. 137 (2017) 38–45. doi:10.1016/j.enbuild.2016.12.013.

A. Novalesec, Personal communication regarding the difference in cooling load for radiant and all-air systems for different load scenarios. (2018).

J. Pantelic, S. Schiavon, B. Ning, E. Burdakis, P. Raftery, F. Bauman, Full scale laboratory experiment on the cooling capacity of a radiant floor system, Energy and Buildings. 170 (2018) 134–144. doi:10.1016/j.enbuild.2018.03.002.

C. Pedersen, D. Fisher, J. Spitler, R. Liesen, Cooling and heating load calculation principles. ASHRAE; 1998, ISBN 1883413-59-1, 1998.

C.O. Pedersen, D.E. Fisher, R.J. Liesen, Development of a heat balance procedure for calculating cooling loads, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA (United States), 1997.

P. Raftery, C. Duarte, S. Schiavon, F. Bauman, A new control strategy for high thermal mass radiant systems, (2017). https://escholarship.org/uc/item/5tz4n92b (accessed November 30, 2018).

R.K. Strand, K.T. Baumgartner, Modeling radiant heating and cooling systems: integration with a whole-building simulation program, Energy and Buildings. 37 (2005) 389–397. doi:10.1016/j.enbuild.2004.07.009.

R. Strand, F.W.F. Buhl, J. Huang, R. Taylor, Enhancing and Extending the Capabilities of the Building Heat Balance Simulation Technique for use in EnergyPlus, in: In Proceedings of Building Simulation '99, Volume II, 1999: pp. 653–660.

R.K. Strand, C.O. Pedersen, Modeling radiant systems in an integrated heat balance based energy simulation program, ASHRAE Transactions. 108 (2002) 979.

G.N. Walton, United States, National Bureau of Standards, United States, Department of Energy, Building Energy Sciences Branch, Thermal analysis research program reference manual, U.S. Dept. of Commerce, National Bureau of Standards ; [National Technical Information Service, distributor, Washington, DC; [Springfield, VA, 1983.

J. Woolley. The mechanisms and limits of self regulation for high thermal mass radiant cooling. An essay prepared in partial fulfilment of the requirements of the qualifying examination for the doctoral degree in Architecture, University of California Berkeley. November 2017.

J. Woolley, S. Schiavon, F. Bauman, P. Raftery, J. Pantelic, Side-by-side laboratory comparison of space heat extraction rates and thermal energy use for radiant and all-air systems, Energy and Buildings. 176 (2018) 139–150. doi:10.1016/j.enbuild.2018.06.018.

J. Woolley, S. Schiavon, F. Bauman, P. Raftery, J. Pantelic, Side-by-side laboratory comparison of radiant and all-air cooling: the impact of passive cooling and heat gain characteristics on space heat extraction rates and daily thermal energy use. 2019. (In press).