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Authors

Woolley, Jonathan
Schiavon, Stefano
Bauman, Fred
et al.

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Side-by-side laboratory comparison of radiant and all-air cooling: how natural ventilation cooling and heat gain characteristics impact space heat extraction rates and daily thermal energy use

Jonathan Woolley@ [a], Stefano Schiavon[a] , Fred Bauman[a], Paul Raftery[a]
[a] Center for the Built Environment, University of California Berkeley
@Address for correspondence:
Center for the Built Environment
University of California Berkeley
390 Wurster Hall
Berkeley, CA 94720, USA
Phone: +1 530-204-7619
Email: jmwoolley@berkeley.edu

ABSTRACT

For radiant cooling to maintain equivalent comfort conditions as all-air cooling it must remove more heat from a space, the peak space heat extraction rate must be larger, and the peak must occur earlier. In this article, we assess how the magnitudes of these differences are influenced by heat gain characteristics and by the use of natural ventilation night precooling. We present measurements from a series of multi-day side-by-side comparisons of radiant cooling and all-air cooling in a pair of experimental testbed buildings, with equal heat gains, and maintained at equivalent comfort conditions. In a five-day experiment with mixed internal heat gains, solar gains, and natural ventilation night precooling, radiant cooling had to remove 35% more heat than the all-air system in equivalent circumstances; and the peak heat extraction rate was 20% larger (median difference on multiple days). In a similar experiment with highly convective internal gains the differences were smaller (26% more thermal energy, 12% larger peak), while in an experiment with highly radiant gains the differences were larger (40% more thermal energy, and 21% larger peak). The differences were much smaller in an experiment without natural ventilation night precooling (7% more thermal energy, 5% larger peak). These findings have consequences for the choice, design, and control of mechanical cooling systems, especially in buildings that also use passive cooling strategies such as natural ventilation night precooling.

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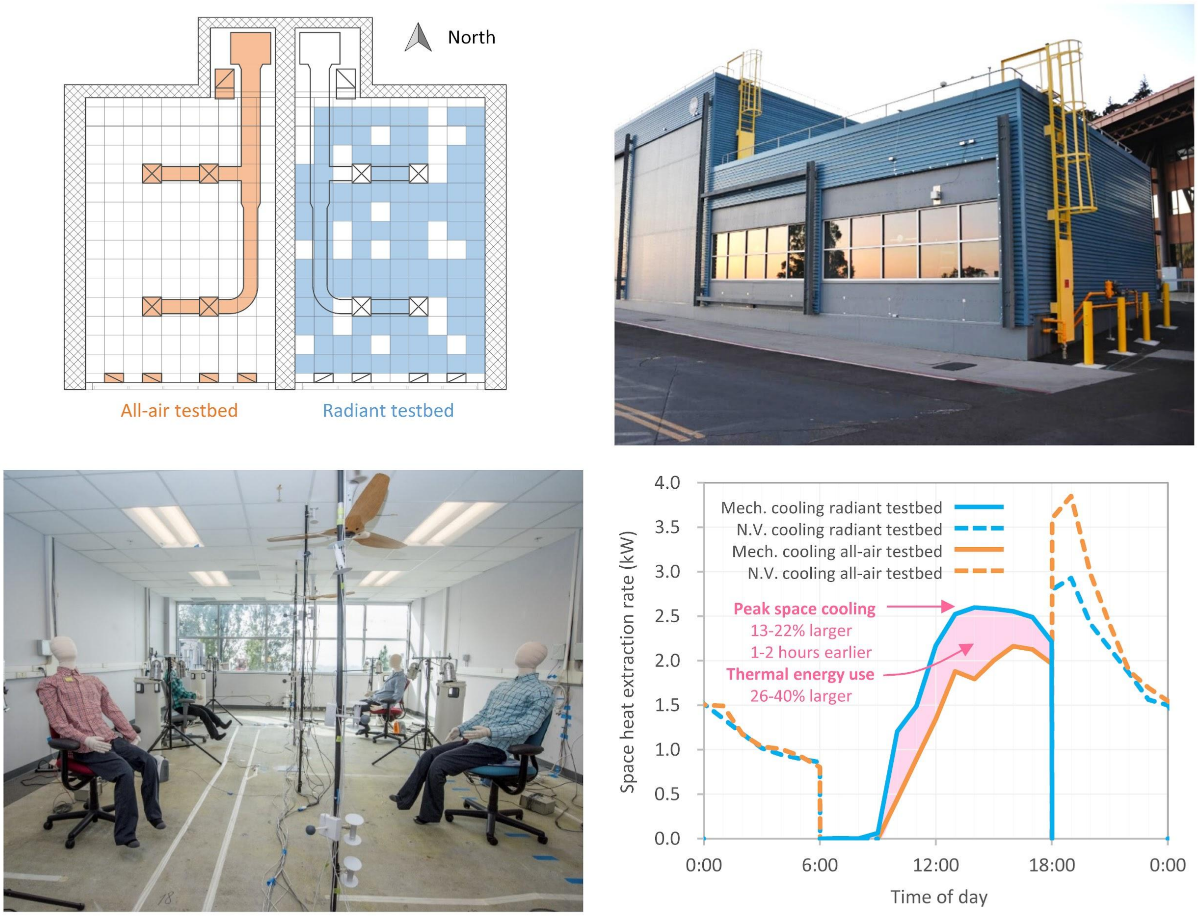
GRAPHICAL ABSTRACT



- Side-by-side comparison of radiant and all-air cooling
- Equal internal heat gains ▪ Equal solar gains ▪ Equal operative temperature
- Radiant uses more thermal energy and has higher peak space heat extraction rate

KEYWORDS

Radiant cooling, passive cooling, natural ventilation, precooling, cooling load, energy efficiency, HVAC, laboratory experiment, all-air

HIGHLIGHTS

- To maintain equal comfort radiant cooling must remove more thermal energy than all-air cooling
- Radiant cooled buildings store less heat in non-active mass than all-air cooled buildings
- All-air cooled buildings reject more heat by passive means than radiant cooled buildings
- The peak space heat extraction rate for radiant systems must be larger than for all-air systems
- The differences are larger where heat gains are highly radiant
- The differences are smaller where heat gains are highly convective

1. INTRODUCTION

Design, sizing, or simulation of any cooling system typically involves calculation of the dynamic space heat extraction rate that will be required to maintain desired comfort conditions over a particular range of time– this is commonly referred to as a "cooling load calculation". The space heat extraction rate is the rate at which heat is removed from a space by terminal heat transfer devices (ASHRAE 2017). For an all-air system, it is the enthalpy difference between airflow supplied to the space and air flow leaving the space. For a radiant system, it is the sum of convective and radiant (longwave and shortwave) heat transfer rates at the indoor face of the internally cooled surface.

Niu et al (Niu 1995, Niu 1997), Feng et al (Feng 2013, Feng 2014-A, Feng 2014-B) and Woolley et al. (2018) have all shown that for radiant and all-air systems to maintain equal comfort conditions as one another: radiant cooling must remove more heat from a space than all-air cooling, and the peak space heat extraction rate for radiant must be larger than for all-air cooling.

The differences between required space heat extraction rates (space cooling load) for radiant and all-air systems are mainly due to the ways that non-active surfaces and their thermal mass impact the dynamics of heat transfer and storage. In a space with all-air cooling, all radiant heat gains are absorbed by non-active surfaces. Whereas in a space with radiant cooling, a portion of the radiant heat gains is absorbed by non-active surfaces and a portion is absorbed by the internally cooled surfaces. Figure 1 compares the heat transfer pathways involved in radiant cooling and all-air cooling.

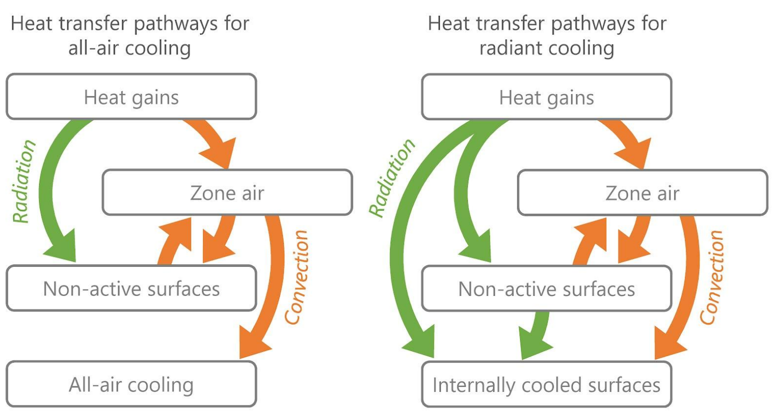


Figure 1 - Simplified schematic comparison of the convective (orange) and radiant (green) heat transfer pathways involved in all-air cooling (left) and radiant cooling (right).

As a result of the differences illustrated in Figure 1, for the same operative temperature, all non-active surfaces in a radiant cooled space are cooler than surfaces in a space with all-air cooling and less heat is stored in non-active thermal masses (Woolley 2018). The consequences of this are twofold. First: conductive heat transfer through outdoor-exposed surfaces is larger for spaces with radiant cooling because the temperature difference across outdoor-exposed surfaces is larger. Second: since less heat is stored in non-active thermal masses, less heat can be released passively to the environment when there is an opportunity to do so – such as with natural ventilation night precooling.

As these heat transfer mechanisms play out dynamically, they require that radiant cooling extract heat earlier, with a larger peak, that occurs earlier. Figure 2 – adapted from Woolley et al. (2018) – illustrates the dynamic heat extraction rates for an all-air system (left) and a radiant system (right) while maintaining equal operative temperature in response to equal heat gains. Figure 2 shows the sum of internal-and-solar heat gains (grey dashed line), and the space heat extraction rate (orange line) for each system. The space heat extraction rate is divided into the amount of heat extracted by convection (orange hatched area), and the amount of heat extracted by radiation (green hatched area). The grey hatched area highlights the difference between the internal-and-solar heat gains (grey dashed line) and the space heat extraction rate (orange line); this area indicates heat that was absorbed by non-active surfaces, stored in thermal mass, then eventually released passively to the environment. Note that Figure 2 does not show the rate at which heat was transferred through outdoor-exposed surfaces. Since heat was lost to the environment through outdoor-exposed surfaces overnight, the cumulative thermal energy extracted from each space by the radiant and all-air systems was smaller than the cumulative internal-and-solar heat gains.

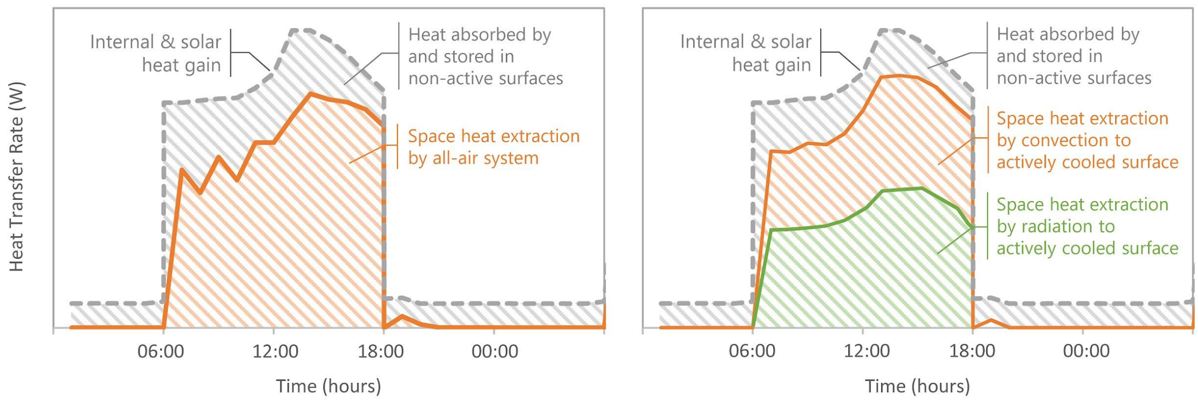


Figure 2 - Conceptual example of the dynamic space heat extraction rates by convective heat transfer (orange) and radiant heat transfer (green) required by an all-air cooling system (left) and by a radiant cooling system (right) to maintain equal operative temperature in response to equal internal heat gains (grey). Adapted from Woolley et al (2018).

Although researchers and practitioners generally understand that different types of terminal cooling devices extract heat from a space using different heat transfer mechanisms, they often do not recognize that these differences influence the rates at which heat must be extracted from a space to maintain desired comfort conditions (space cooling load). Consequently – as Feng et al. (2014-B) showed – researchers and practitioners commonly size radiant cooling systems using cooling load calculations methods which assume that all space heat extraction occurs by convection with a well-mixed air volume.

This assumption is not accurate for radiant systems, yet is perpetuated by most industry standard cooling load calculation procedures (ASHRAE 2017), radiant system design procedures (ASHRAE 2016, Babiak 2009), and by some building energy simulation tools. As discussed in the following paragraphs, each of these guiding resources: (1) fail to recognize that the required space heat extraction rate (space cooling load) depends on the type of terminal cooling device used, and (2) promote cooling load calculation methods that only account for space heat extraction by convection with a well-mixed air volume.

Chapter 18 of 2017 *ASHRAE Fundamentals: Nonresidential Cooling and Heating Load Calculations* (ASHRAE 2017) presents definitions and explanations that systemically fail to consider the implications of space heat extraction by any mechanisms other than convection with a well-mixed air volume. Further, the chapter presents two cooling load calculation methods that were developed for all-air systems and are mathematically limited to convection with a well-mixed air volume. Although Chapter 6 of 2016 *ASHRAE Systems and Equipment: Radiant Heating and Cooling* (ASHRAE 2016) clearly explains that radiant cooling transfers heat by convection and radiation, it does not recognize that the magnitude and timing of the required space heat extraction rate (space cooling load) is fundamentally different from that of all-air systems. Additionally, Chapter 6 of 2016 ASHRAE Systems and Equipment specifically references the methods in Chapter 18 of 2017 ASHRAE Fundamentals, even though these methods do not account for the effects of space heat extraction by radiation with internally cooled surfaces.

In the widely referenced guidebook *Low temperature heating and high temperature cooling,* Babiak et al. (2009) thoroughly explain the combined radiant and convective heat transfer rates that a radiant system can be expected to produce for different steady state conditions (space cooling capacity). However, the guidebook provides no explanation about how to determine the dynamic space heat extraction requirement (space cooling load) for a radiant system, and do not specifically recognize that it can differ substantially from that of all-air systems.

Among standards focused on the topic of space cooling loads, *ISO Standard 52016* (ISO 2017) – which supersedes prEn 15255 (CEN 2007) – is the only resource we are aware of to explicitly state that the dynamic space heat extraction requirement (space cooling load) depends on the system type. In an equation for determining the space heat balance, the standard introduces a variable called the "convective fraction of the heating/cooling system". However, the standard currently provides no guidance on how to determine this fraction for different systems and circumstances.

Researchers have developed and validated numerical methods that properly estimate the fundamental heat transfer mechanisms involved with radiant cooling systems (Stetiu 1995, Niu 1995, Niu 1997, Strand 2002, Laouadi 2004, Strand 2005, Yu 2014). Although such methods have been incorporated into building energy simulation software, the problematic assumption – that all space heat extraction occurs by convection – still persists in some aspects. For example, for each simulation timestep EnergyPlus (EnergyPlus 2019) uses the numerical methods developed by Strand et al (2002, 2005) to calculate the rate at which internally cooled surfaces extract heat from a space, yet the cooling load calculations performed to autosize components of a radiant system and cooling plant only account for space heat extraction by convection with a well-mixed air volume. Additionally, there are several widely-used building energy simulation tools have not addressed the problematic assumption in any way, yet researchers and practitioners often use these tools for design and simulation of radiant cooling systems (Feng 2014-A).

Although previous laboratory and simulation work has carefully demonstrated the fundamental differences between required space heat extraction rates (space cooling load) for radiant and all-air systems, research has not thoroughly evaluated the factors that influence the magnitude of these differences. Woolley et al. (2018) explained that the magnitude of the differences should be driven mainly by the extent to which heat is absorbed by, and stored in non-active masses, and the extent to which such heat can be released to the environment by passive means. Furthermore, in a simulation study, Feng et al. (2013) found that the difference between the required space heat extraction rates (space cooling load) is impacted by the presence of solar gains, by the characteristics of building construction, and by the radiant-to-total ratio for internal gains.

To build upon previous findings, we conducted a series of experiments designed to assess how the differences between required space heat extraction rates (space cooling load) for radiant and all-air systems are influenced by characteristics of heat gain and by the availability of passive cooling. In this article, we present measurements from a series of multi-day side-by-side comparisons of radiant cooling and all-air cooling in a pair of experimental testbed buildings, with equal heat gains, and maintained at equivalent comfort conditions (operative temperature). We document our experimental methods in Section 2, Appendix A.1, and Appendix A.2.

Our first hypothesis was that natural ventilation cooling overnight would increase the differences between required space heat extraction rates (space cooling load) for the two systems. Consider a building in a climate with large diurnal temperature swings, that uses natural ventilation overnight to precool thermal mass: in such a building, the non-active thermal masses absorb and store a portion of the heat from gains during the day, then these warm masses release heat passively overnight to the cool air from natural ventilation. Since radiant cooling preempts non-active masses from storing as much heat during the day, it also reduces the opportunity for passive heat rejection overnight. To assess this hypothesis, in Section 3.1 we present scenarios with and without natural ventilation cooling used to precool building masses overnight.

Our second hypothesis was that the radiant-to-total heat gain ratio would impact the differences between required space heat extraction rates (space cooling load) for the two systems. Radiant heat gains include radiation from the sun, radiation from indoor lighting, and radiation emitted by objects within a space. As illustrated in Figure 1, radiant heat gains are absorbed directly by surfaces, and influence the heat transfer networks for each cooling system type differently than a similar magnitude of convective gains. We expect that more highly radiant heat gains would cause a larger difference between the required space heat extraction rates (space cooling load) for radiant and all-air systems. To assess this hypothesis, in Section 3.2, we present scenarios with highly convective internal heat gains, highly radiant internal heat gains, and mixed internal heat gains.

In Section 4 we discuss the practical implications of our findings and highlight needs for further research, then finally in Section 5 we conclude with a thorough summary of the key findings.

2. METHODOLOGY

2.1. Overview of methodology

We conducted six controlled experiments in a pair of equivalent testbed buildings – one with radiant cooling and one with all-air cooling – at FLEXLAB: the US DOE's building energy efficiency testbed at Lawrence Berkeley National Laboratory (FLEXLAB 2018). This facility enables thorough assessment of building energy systems at a realistic physical scale, with naturally occurring solar gains, and natural interaction with the surrounding environment. For each experiment we operated the two testbeds simultaneously, imposed equivalent internal gains, and controlled each system to maintain equivalent operative temperatures during normally occupied hours. The facility is illustrated in Figure 3.

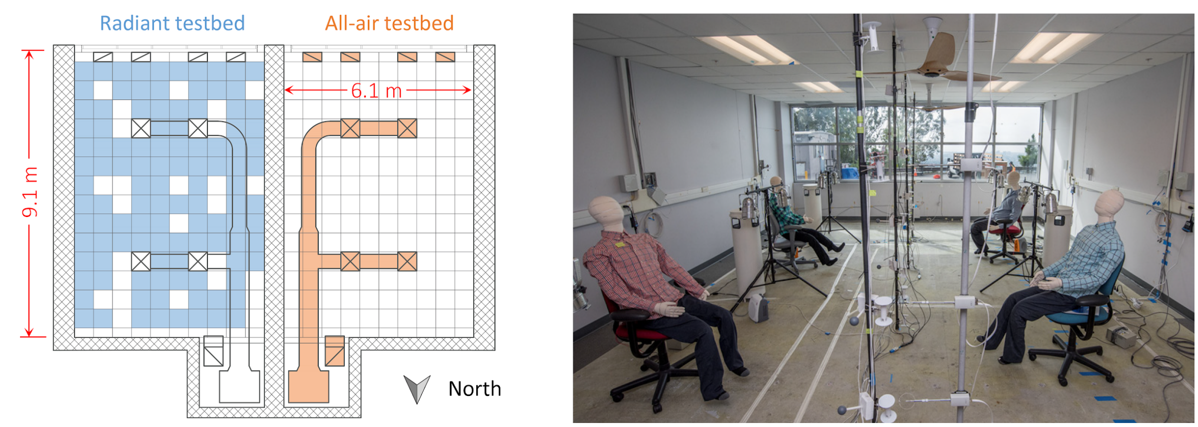


Figure 3: Plan view of testbed buildings (left), and photo of experimental setup (right). Air handler, overhead ductwork, supply diffusers, and return registers in the all-air testbed are highlighted in orange. Low thermal mass metal ceiling panels in the radiant testbed are highlighted in blue.

We operated each experiment for several days, during which we monitored thermodynamic states and heat transfer rates in both testbeds. This is essential when comparing these systems, as it ensures that the temperature of masses in each testbed reach steady-state oscillations and are no longer influenced by the initial states of each system.

In each testbed we measured: air temperature distribution, operative temperature distribution, temperature of surfaces and masses, dynamic space heat extraction rates, and the cumulative amount of thermal energy extracted by each system. We were focused on comparing the sensible space heat extraction rates by each system, and so we were careful to ensure that humidity in each testbed remained low enough that supply water temperature would not cause condensation (latent space heat extraction). We did not assess the electrical performance for either system; instead, our investigation focused on the fundamental thermodynamic differences between radiant cooling and all-air cooling, regardless of the primary cooling sources and mechanical system elements that either may employ.

The six experiments discussed in this article were part of a larger series of experiments which also included those presented in a previous article (Woolley 2018). The previous article included an extensive description of the experimental facility, details about measurements, uncertainty, and explanation of a baseline calibration of the two testbeds when operating with identical all-air systems. For completeness in this article, and to document some small differences from the methods published previously, we describe the experimental facility in Appendix A.1, and we describe our measurement methods and uncertainty in Appendix A.2.

2.2. Design of experiments

In this article, we compare the dynamic space heat extraction rates required to maintain equivalent operative temperatures in each testbed. We present results from six separate experiments with periodic heat gains. The first two experiments (exp. #1–2) assessed how natural ventilation night precooling influenced the difference between dynamic space heat extraction rates for the two testbeds. The other four experiments (exp. #3–6) assessed how the radiant-to-total heat gain ratio for internal heat gains influenced the difference. Within the second set of experiments, we also investigated one way that the thermal properties of interior surfaces interact with heat gains so as to affect the space heat extraction rates required by each system type (exp. #5–6). For this later assessment, in one experiment (exp. #5) we oriented highly radiant internal heat gains downward toward the concrete slab floor, and in a similar experiment (exp. #6) we oriented the same heat gains upward toward the suspended ceiling. The following numbered list (used as reference throughout the article) describes the heat gain characteristics of the six experiments and whether or not each included natural ventilation night precooling.

1. Mixed internal heat gains + solar gains (no natural ventilation night precooling)
2. Mixed internal heat gains + solar gains + natural ventilation night precooling
3. Highly convective internal heat gains + solar gains + natural ventilation night precooling
4. Mixed internal heat gains + natural ventilation night precooling (no solar gains)
5. Highly radiant internal gains (oriented down) + solar gains + natural ventilation night precooling
6. Highly radiant internal gains (oriented up) + solar gains + natural ventilation night precooling

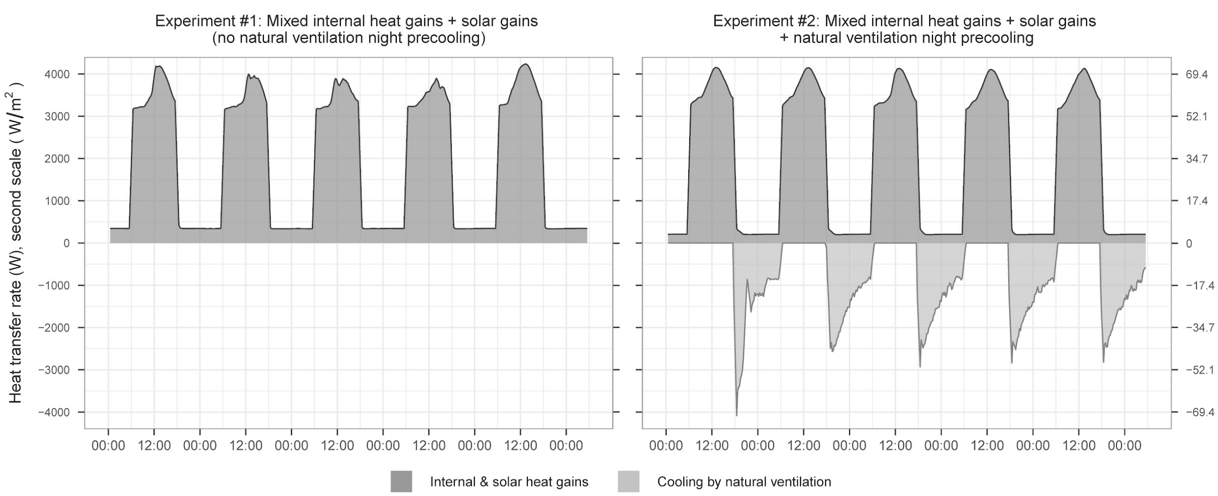


Figure 4: Internal and solar heat gain rates (positive axis) and natural ventilation cooling rates (negative axis) for an experiment without natural ventilation night precooling (exp. #1, left) and an experiment with natural ventilation night precooling (exp. #2, right). The figure plots heat transfer rates as one-hour rolling averages at fifteen-minute intervals. The patterns for the experiment with natural ventilation night precooling (exp. #2, right) are typical of all five experiments that included natural ventilation night precooling.

Figure 4 illustrates the patterns of periodic heat gains and night ventilation cooling for one experiment with natural ventilation night precooling (exp. #2), and one experiment without natural ventilation night precooling (exp. #1).

We supplied internal heat gains to each testbed equally. In every experiment, we turned on the internal heat gains from 06:00–18:00 each day. The median value for internal heat gains during that period in each experiment was between 3160–3760 W (55–65 W/m^2 floor area). During each experiment, internal heat gains varied from the median by as much as ± 150 W as grid voltage varied. Heat gains in both chambers varied together, so across all six experiments the median difference between internal heat gains in each chamber was only 2.5 W, and the percent difference in cumulative heat gain was only 0.05%. Heat gains during the off periods were approximately 200 W (3.5 W/m^2 floor area) due to controls and fan energy.

For the first experiment (exp. #1) the operative temperature setpoint in each testbed was 26 °C for all hours, and neither system required mechanical cooling from 18:00–06:00 because passive heat rejection to the environment exceed the background internal heat gains. For the other five experiments, the operative temperature setpoint in each testbed was 26 °C from 06:00–18:00, then from 18:00–06:00 we cooled both testbeds to 20 °C operative temperature in mode designed to mimic natural ventilation night precooling. We did not actually use natural ventilation. Instead, we used the air handlers in each testbed to impose an idealized imitation of natural ventilation night precooling that was more consistent, measurable, and repeatable than natural ventilation. We calculated the sensible space heat extraction rates in this mode ("cooling by natural ventilation" in Figure 4) exactly the same way that we calculated the sensible space heat extraction rates for each testbed during the 06:00–18:00 periods: by measuring the flow rate and temperature difference across the chilled-water loops that served each testbed separately. When comparing the dynamic space heat extraction rates and cumulative heat extraction (Figure 5,, Figure 7) we only counted the cooling in each testbed from 06:00–18:00. The heat extracted from each testbed between 18:00–06:00 was treated as if it were provided by natural ventilation, therefore it was not counted as a part of the mechanical heat extraction required in either testbed.

The experiments with mixed internal gains (exp. #1–2 & 4) used combination of different electric resistance heating apparatuses – including thermal mannequins – to generate heat gains with radiant-to-total heat gain ratio ~0.5. The experiment with highly convective gains (exp. #3) used electric resistance fan heaters to generate heat gains with radiant-to-total heat gain ratio ~0, and the experiments with highly radiant gains (exp. #5–6) used an array of incandescent heat lamps to generate heat gains with radiant-to-total heat gain ratio ~0.8. We did not measure the radiant-to-total heat gain ratios for each heating apparatus; instead, we developed estimates based on other researchers' measurements of similar sources. We used ASHRAE Fundamentals 2017 Chapter 18 (ASHRAE 2017) for representative rates of radiant, convective, and latent heat gain from human beings in different activities, and we referenced Jones et al. (1998) and Hosni et al. (1999) to guide estimates for other heating apparatuses used in the experiments with "mixed internal gains". We used results from Chantrasrisalai and Fisher (2006, 2007-A, 2007-B) to estimate the radiant-to-total heat gain ratio for infrared heat lamps in the experiments with highly radiant gains (exp. #5–6). Although Chantrasrisalai and Fisher did not measure heat lamps specifically, we based our estimate on the values measured for incandescent lamps because heat lamps are simply incandescent lamps with tungsten filaments tuned to operate at a lower temperature.

Solar gains reached 500–1,500 W each day, depending on the weather and on the sun angle. We conducted the series of experiments between August and October, when the solar altitude was changing most rapidly from day-to-day, so experiments at the end of the series received larger solar gains. Meteorological conditions during the experiments were mild, median outdoor temperature was 14.3 °C with interquartile range of 7.75 °C. Heat transfer through outdoor-exposed surfaces was relatively small; it ranged from 30 W/m^2 gains to 15 W/m^2 losses, and changed direction diurnally. Overall, losses through outdoor-exposed surfaces were more dominant than gains. Consequently, the cumulative thermal energy extracted from each testbed by mechanical cooling and natural ventilation cooling was 10-30% smaller than the cumulative thermal energy from internal and solar gains. We've included more details in the appendix. Figure A1 in the appendix presents a detailed disaggregated time series view of the different internal and solar heat gain components. Figure A4 in the appendix compares the cumulative thermal energy from internal and solar gains to the cumulative thermal energy extracted by each system type, and by natural ventilation night precooling.

3. RESULTS AND INTERPRETATIONS

3.1. The impact of natural ventilation night pre-cooling

Figure 5 compares the dynamic space heat extraction rates required by each system in experiments with and without natural ventilation night precooling. For an all air system, the space heat extraction rate is the enthalpy difference between airflow supplied to the space and air flow leaving the space. For a radiant system, the space heat extraction rate is the sum of convective and radiant (longwave and shortwave) heat transfer rates at the indoor face of the internally cooled surface.

First, the results from both experiments in Figure 5 reveal that to maintain equal comfort conditions: (1) radiant cooling must extract heat from gains earlier than all-air cooling, (2) the peak space heat extraction rate for radiant must be larger than for all-air cooling, (3) the peak space heat extraction rate for radiant must occur earlier than for all air cooling, and (4) radiant must remove more heat from a building than all-air cooling. This reinforces previous research findings (Niu 1995, Niu 1997, Feng 2013, Feng 2014-A, Feng 2014-B, Woolley 2018).

Further, comparison of the two experiments in Figure 5 reveals that natural ventilation night pre-cooling strongly increases the magnitude of the difference between the dynamic space heat extraction rates required by each system. We quantify the impact on each aspect of this difference in the following three paragraphs.

The comparison reveals that natural ventilation night pre-cooling increases the difference between the peak space heat extraction rates for each system type. In the experiment without natural ventilation night precooling, the daily peak space heat extraction rate for the radiant testbed was 2–10% larger than for the all-air testbed; while in the experiment with natural ventilation night precooling it was 16–22% larger. The median differences for each five-day experiment were 5% and 20% respectively. In terms of heat transfer rates, these differences equate to 1.3–5.8 W/m^2 (median 2.4 W/m^2) and 6.5–8.2 W/m^2 (median 7.8 W/m^2) respectively.

Natural ventilation night pre-cooling also increased the difference between the times at which the peak space heat extraction rate occurred for each system type. In the experiment without natural ventilation night precooling, the peak space heat extraction rate for the radiant testbed occurred 30–50 minutes earlier than for the all-air testbed; while in the experiment with natural ventilation night precooling, the peak space heat extraction rate for the radiant testbed occurred 45–100 minutes earlier.
The comparison also reveals that natural ventilation night precooling can have a very large impact on the difference between the total amount of thermal energy that each system must remove. In the experiment without natural ventilation night precooling the radiant system extracted 7% more thermal energy over the course of five days, whereas in the experiment with natural ventilation night precooling the radiant system extracted 35% more thermal energy. These differences equate to an average difference in the space heat extraction rate of 183 W (3.2 W/m^2) and 458 W (8.0 W/m^2) respectively.

Summary metrics for all six experiments are presented in Table A2, in the appendix. The multiple day time series results for all six experiments are presented in Figure A2 in the appendix, and multiple day time series for the cumulative space heat extraction energy for all six experiments are presented in Figure A3 in the appendix.

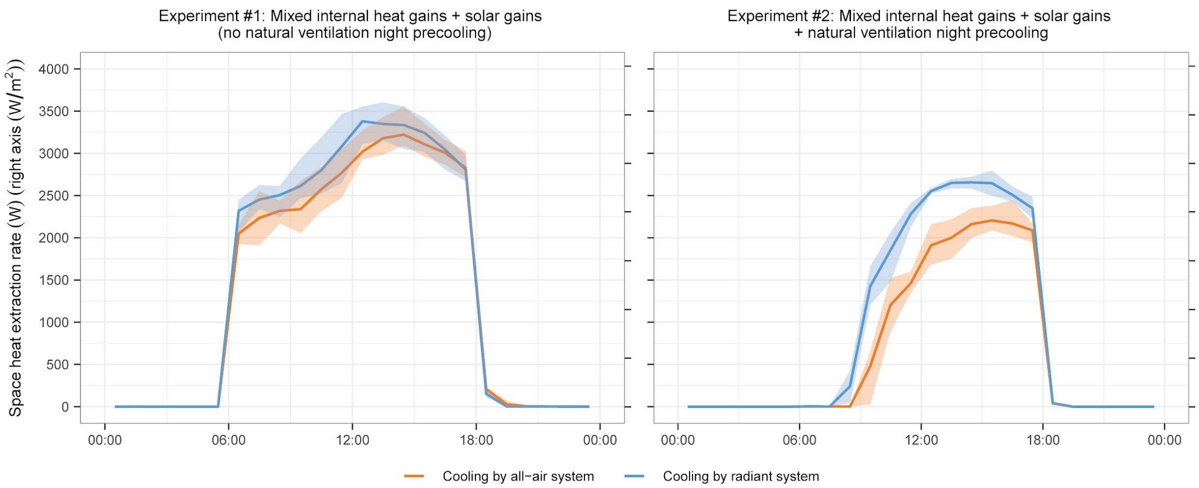


Figure 5: Space heat extraction rates for radiant (blue) and all-air systems (orange) in comparable experiments without natural ventilation night precooling – exp. #1 (left) and with natural ventilation night precooling – exp. #2 (right). Each 24 hour time series is a composite of data from five days; the lines indicate the mean of one-hour rolling means on one-hour intervals, while the ribbons indicate the minimum and maximum one-hour rolling mean values on one-hour intervals. The multiple day time series results for all six experiments are presented in Figure A2 in the appendix.

The fundamental difference between space heat extraction rates required by the two system types occurs because a portion of the heat gain that non-active masses would absorb (in a building with all air cooling) is instead removed by radiant heat transfer to the internally cooled surfaces (in a building with radiant cooling). For the same reason, all interior surfaces in a space with radiant cooling are cooler than in a similar space with all-air cooling. As a result, spaces with radiant cooling experience somewhat larger heat gains due to conduction heat transfer through outdoor exposed surfaces, and since less heat is absorbed by and stored in non-active masses, less heat is rejected to the environment by passive means. These fundamental differences should exist in any scenario where radiant cooling and all-air cooling maintain equal operative temperatures, but the differences are greater when there is greater opportunity for non-active masses to reject heat passively – as demonstrated by the larger differences in the experiment with night ventilation pre-cooling.

Figure 6 compares the disaggregated cumulative thermal energy flows in the all-air and radiant testbeds in an experiment with night ventilation cooling. This disaggregated view illustrates that the non-active masses in a space with all-air cooling absorb more heat during the day, and subsequently, can reject more heat to the environment by passive means. Therefore, in general, the percent difference in cumulative heat extraction for the two system types should increase as the opportunity for passive heat rejection increases, and as the proportion of heat gain due to heat transfer through outdoor-exposed surfaces increases.

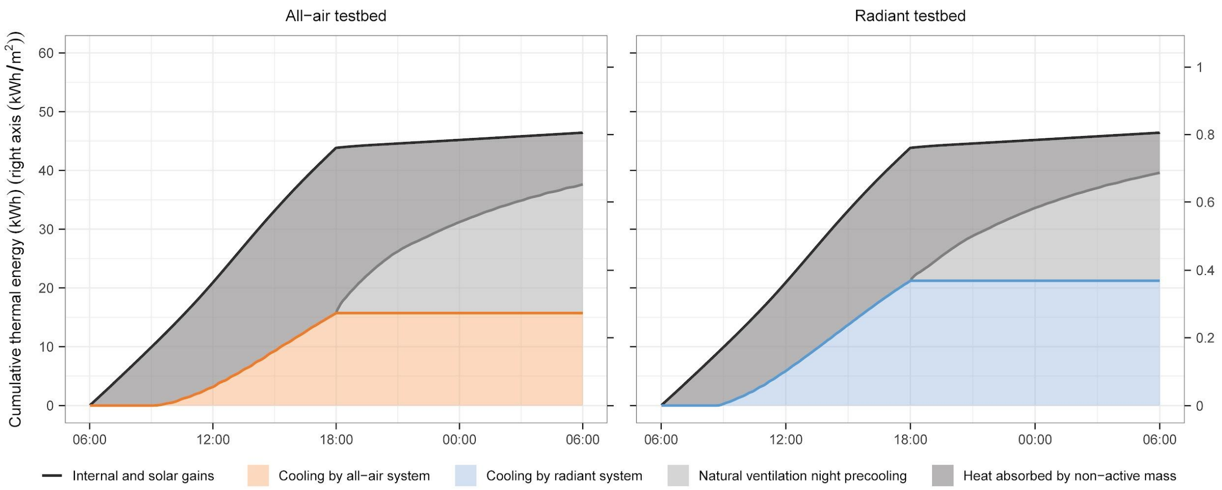


Figure 6: Cumulative thermal energy flows in the all-air (left) and radiant (right) testbeds in an experiment with natural ventilation night precooling (exp. #2). Each plot indicates the cumulative thermal energy extracted from the space by mechanical systems (orange or blue), the cumulative thermal energy extracted from the space by natural ventilation night precooling (light grey), and the cumulative thermal energy from internal or solar gains stored by non-active masses and/or released passively to the environment (dark grey). Data from multiple days in the experiment is plotted as composite 24-hour time series using median values on one-minute intervals. Figure A4 in the appendix shows similar results across multiple days for all six experiments.

These findings have substantial consequences for the design and control of radiant systems, especially in coordination with natural ventilation or other passive cooling strategies. First, as Feng et al. revealed (Feng 2014-A), industry common practice "cooling load calculation" methods underestimate the peak space heat extraction rates required for radiant cooling systems. Second, radiant cooling must remove more thermal energy than all-air cooling; and in some cases, the additional thermal burden can be very large. In the experiment with mixed internal gains, solar gains, and natural ventilation night precooling, radiant cooling had to extract 35% more thermal energy than all-air cooling. To consume less primary energy than an all-air system, buildings with radiant cooling must be designed so that the advantages for cooling plant efficiency and thermal distribution efficiency overcome the additional thermal burden.

3.2. The impact of heat gain characteristics

Comparison of the results from experiments with different radiant-to-total heat gain ratios reveals that heat gain characteristics can have a large impact on the difference between dynamic space heat extraction requirements for the two system types.

Firstly, the difference between the peak space heat extraction rate for the two system types was larger when heat gains were more highly radiant. In the experiment with highly convective internal gains (exp. #3), the peak space heat extraction rate in the radiant testbed was 10–17% larger (median 12%), which equates to 5.8–10.1 W/m^2 (median 6.8 W/m^2) and occurred 0–60 minutes earlier. In an experiment with highly radiant internal gains (exp. #5), the peak space heat extraction rate was 18–29% larger (median 21%), which equates to 8.1–9.8 W/m^2 (median 8.7 W/m^2), and occurred 60–80 minutes earlier.

Secondly, heat gain characteristics also have a large impact on the difference between the total amount of thermal energy that each system type must remove to maintain equal operative temperatures. In the experiment with highly convective internal gains (exp. #3) the radiant system extracted 29% more thermal energy over the course of the multi-day experiment, whereas in an experiment with highly radiant internal gains (exp. #5) the radiant system extracted 40% more thermal energy. Summary metrics for all six experiments are presented in Table A2 in the appendix.

For further reference, Figure A1 in the appendix presents the multiple day time series profile for internal and solar heat gain rates and Figure A2 in the appendix presents the multiple day time series profile for the dynamic space heat extraction rates for all six experiments.

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Heat gain characteristics impact the differences between the two systems because non-active masses absorb radiant gains more readily than convective gains, and because radiant cooling extracts heat from non-active masses more readily than all-air cooling. In a hypothetical scenario with only radiant gains, the space heat extraction required for the all-air system would be limited to the heat that is shed by convection from non-active masses that have absorbed the heat gains. If the non-active masses have high thermal diffusivity, and a large thermal capacity, they will absorb and store a large amount of heat without large change in surface temperature, and therefore, will not shed much heat by convection. In the same scenario radiant cooling would extract heat through multiple mechanisms: by radiant transfer directly from gains, by radiant transfer with non-active surfaces, and by convective transfer with the room air.

Figure 7 illustrates a relationship between heat gain characteristics and the difference between heat extraction requirements for radiant and all-air cooling systems. The figure plots the percent difference between cumulative space heat extraction energy (left) and peak space heat extraction rate (right) in the radiant and all-air testbeds during each 06:00–18:00 period for all five experiments with natural ventilation night precooling. Each of these experiments imposed a different radiant-to-total ratio for internal heat gains, so we plotted the results as a function of the coincident cumulative radiant-to-total heat gain ratio over each day. Solar gains varied naturally from day-to-day, and in one experiment with mixed internal gains solar was omitted altogether by blocking windows entirely with rigid insulation. The values of the daily cumulative radiant-to-total heat gain ratio in Figure 7 include the contribution from solar gains, but do not include the contribution from gains by conduction through outdoor-exposed surfaces because we could not measure this heat gain component accurately.

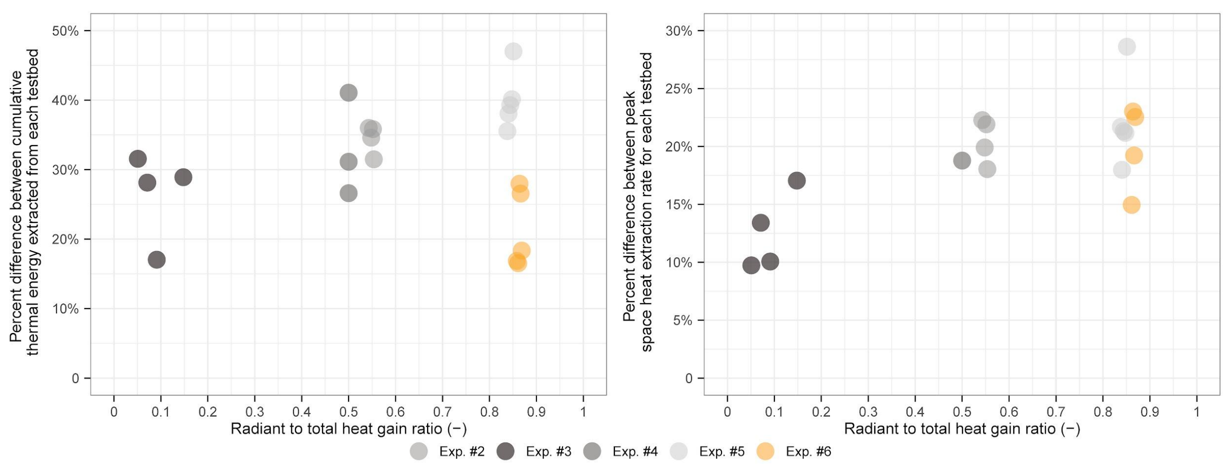

Figure 7: The percent difference between cumulative thermal energy extracted from each testbed (left) and the percent difference between the peak space heat extraction rate for each testbed (right) during each 06:00–18:00 period for all five experiments with natural ventilation night precooling. Each point represents a single 06:00–18:00 period, and each is plotted as a function of the cumulative radiant-to-total heat gain ratio on the corresponding day. The significant difference between cumulative space heat extraction in the experiments with highly radiant gains oriented downward (exp. #5: grey) and upward (exp. #6: orange) illustrates that heat gains and surface thermal properties interact in a way that impacts the difference between space heat extraction requirements for radiant and all-air cooling systems. Excluding the results with highly radiant gains oriented upward (orange) there is a strong positive correlation (Pearson's r=0.75) between radiant-to-total heat gain ratio and the percent difference between cumulative space heat extraction energy. Figure A5, in the appendix, presents similar plots that also include results from the the experiment without natural ventilation night precooling (exp. #1).

The results confirm a strong positive correlation (Pearson's r=0.75) between radiant-to-total heat gain ratio and the differences between cumulative thermal energy extracted from each testbed. The differences tend to be larger for highly radiant heat gains, and smaller for highly convective heat gains. In light of the accuracy of measurements in this study (see Appendix A.2), we can confidently conclude that the day-to-day differences within each multi-day experiment are mainly due to real variations in exogenous variables such: solar heat gains, heat transfer through outdoor-exposed surfaces, and infiltration.

However, the results also reveal that there are important interactions between heat gain type and the thermal properties of surfaces within and enclosing a space. We conducted two experiments with highly radiant heat gains. In one (exp. #5) we oriented infrared lamps downward – toward the non-active concrete slab floor – while in the other (exp. #6) we oriented infrared lamps upward – toward the suspended ceiling (an acoustic tile ceiling in the all-air testbed, and the internally cooled surface in the radiant testbed). When oriented downward, radiant gains in the all-air testbed were readily absorbed by and stored in the 15.25 cm (0.5 ft) thick concrete slab, but when oriented upward radiant gains absorbed by the suspended acoustic ceiling were rapidly converted to convective gains which were subsequently removed by the all-air cooling system. In the radiant testbed, radiant gains oriented upward were immediately removed by the internally cooled surface, and when oriented downward the direct exposure between floor and ceiling ensured that radiant gains were quickly removed by radiant heat transfer to the internally cooled surface. As a result, the percent difference between cumulative space heat extraction for radiant and all air systems was larger when radiant heat gains were oriented downward. When radiant heat gains were oriented upward the percent difference in cumulative space heat extraction was more similar to the scenario with highly convective gains.

When the non-active surfaces within and enclosing a space have high thermal diffusivity and high thermal capacity, the temperature of those surfaces will be more resilient to heat gain and will shed less heat by convection. High thermal mass surfaces – such as exposed concrete construction – have high thermal diffusivity and high thermal capacity; they can readily absorb heat from the radiant component of heat gains without a substantial increase in surface temperature. Low thermal mass surfaces – such as raised floors, suspended ceilings, floor coverings, or furniture – have low thermal diffusivity and/or low thermal capacity; they tend to decrease the difference between the cumulative heat extraction requirements for radiant and all-air systems.

Although the orientation of radiant heat gains impacted the percent difference between the cumulative space heat extraction, it did not have a significant impact on the percent difference between the peak heat extraction rates. This may seem surprising, after all a space with lots of non-active thermal mass would certainly be expected to reduce the peak cooling requirement for any system type, so it might seem natural to expect that orienting radiant heat gains toward the high thermal mass floor would decrease the peak space cooling requirement as well as the cumulative cooling requirement. However, we found that although the slab temperature increased by a greater magnitude each day in the case with radiant gains pointed toward the floor (it stored more heat overall), at peak the rate of temperature change for surfaces throughout the space was similar whether the radiant gains were oriented up or down. This indicates that most of the difference in thermal energy storage occurred early in the day. At peak, thermal conditions had equilibrated to a point that the division between gains stored and gains extracted by the mechanical system was similar whether the radiant gains were oriented up or down.

These findings have consequences for the practical design of radiant cooling systems. In particular, it is often noted that radiant cooling can have an especially large cooling capacity in spaces with solar gains, yet this characteristic can substantially increase the amount of thermal energy that a cooling plant must process each day when there is also an opportunity for passive heat rejection. Often, design of radiant cooling systems uses load calculation strategies intended for all-air systems, but in light of the results presented here, such practice could miss the actual cooling requirements by a substantial margin.

4. DISCUSSION

To maintain equal operative temperature in response to equal heat gains, the required space heat extraction rates (space cooling load) for radiant and all-air systems are different. Radiant cooling must extract more heat from a space than all-air cooling, and the peak space heat extraction rate must be larger and occur earlier. Previous experiments proved this is a fundamental difference that must occur in any circumstance where radiant cooling and all-air cooling maintain equal operative temperature (Feng 2014-

A, Woolley 2018). With the study presented in this article we have experimentally confirmed – far beyond the bounds of uncertainty – that heat gain characteristics, interior surface thermal properties, and the availability of passive cooling can have very large impacts on the relative difference between the dynamic space heat extraction requirements (space cooling load) for radiant and all-air systems.

The peak space heat extraction rate for radiant must be larger but the cooling plant can be smaller

In considering the results of this study, bear in mind that we compared the rates at which different cooling system types must extract thermal energy from a space; we did not assess cooling plant heat transfer rates. For a high thermal mass radiant system, the space heat extraction rate is very different from the heat extraction rate for the cooling plant, while for an all-air system, and for a low thermal mass radiant system, the two heat extraction rates may be nearly identical. So, while our results demonstrate that the peak space heat extraction rate for at the indoor face of internally cooled surfaces must be larger than the peak space heat extraction rate for an all-air system, we also acknowledge that a strategically controlled high thermal mass radiant system could allow the cooling plant to be much smaller than what would be required for an all-air system in equivalent circumstances. Bourdakis et al. assessed this issue directly with a simulation study (Bourdakis 2015). On the other hand, the cooling plant for low thermal mass radiant systems –like cooled metal ceiling panels – would need to have capacity to serve the larger peak space heat extraction requirements revealed by our experiments. Importantly, in addition to space heat extraction requirements (space cooling load), the cooling plant must also have capacity to overcome system heat gains such as fan energy, pump energy, and duct heat transfer. In some cases, the difference between system heat gains for radiant and all-air systems may be even larger than the differences between required space heat extraction rates (space cooling load) revealed in this study.

Our experiments span a realistic range of radiant-to-total heat gain ratios

Our experiments included scenarios with internal heat gains across a wide range of radiant-to-total heat gain ratios. Although some computers, laboratory equipment, and cooking appliances may independently have radiant-to-total heat gain ratios of 15% or less, it is very unlikely that many spaces would have an aggregate radiant-to-total heat gain ratio as low as in our experiment with highly convective gains. Most buildings include a wide variety of different heat gains and subsequently have mid-range radiant-to-total heat gain ratios. However, spaces with extensive solar gains – such as lobbies or atria – could easily match the upper end of radiant-to-total heat gain ratios in our experiments. Conspicuously, radiant cooling and natural ventilation cooling are commonly used together in lobbies and atria (Paliaga 2017) – often targeting reduced surface temperatures in spaces with large solar gains for thermal comfort reasons – yet our findings suggest that the cumulative mechanical cooling requirement for radiant systems can be 40% larger than for all-air systems in such a scenario.

The availability of passive cooling accentuates the impact of the radiant-to-total heat gain ratio

All of the experiments we used to test the impact of radiant-to-total heat gain ratio included natural ventilation night precooling; this undeniably accentuated the magnitude of the difference between the dynamic space heat extraction requirements (space cooling load) for radiant and all-air cooling systems compared to what would occur in similar scenarios without night ventilation pre-cooling. Since the magnitude of the difference between the dynamic space heat extraction rates was smaller without night ventilation pre-cooling, we expect that the magnitude of change due to differences in the radiant-to-total heat gain ratio would also be smaller.

The thermal properties of interior surfaces are important for design of either cooling system type

In addition to demonstrating the impact of radiant-to-total heat gain ratio, the results presented here confirm that the thermal properties of surfaces within and enclosing a space impact the difference between dynamic space heat extraction requirements (space cooling load) for radiant and all-air systems. This impact is mainly due to the way that different surfaces absorb and store heat, or more specifically: how rapidly the temperature of surfaces rise in response to heat gains. Our results indicate that surfaces with low thermal diffusivity and/or low thermal capacity tend to diminish the influence that radiant-to-

total heat gain ratio has on the difference between the dynamic space heat extraction requirements (space cooling load) for radiant and all-air systems. Notably, surfaces with low thermal diffusivity and low thermal capacity more rapidly convert radiant gains to convective gains. We showed that the interaction between surface properties and heat gains has a large impact, however we expect that the two scenarios we compared to make this assessment are among the most different that would reasonably be encountered: on the one hand radiant gains were incident on a concrete slab, and on the other hand they were incident on a low mass suspended ceiling. We recommend further simulation research to assess the extent to which typical construction practices and typical radiant-to-total heat gain ratios influence the difference.

The thermal properties of surfaces within and enclosing a space tend to be very important to the design of either radiant or all-air cooling systems; yet these properties are often not considered as a part of the design process, and generally are not fully accounted for by building energy simulation software. For example Raftery et al. (2014) showed that furnishings – which have low thermal diffusivity and low thermal capacity – tend to cover a substantial fraction of the floor area, block solar gains from being absorbed by the floor slab, rapidly convert solar gains to convective heat in the space, and consequently have substantial impact on the dynamic space heat extraction requirements (space cooling load). Furthermore, compared to buildings with all-air cooling, buildings with high thermal mass radiant cooling typically have fewer non-active surfaces with low thermal diffusivity and low thermal capacity – for example, they often do not have suspended acoustic ceilings, and often include exposed construction elements. Consequently we expect that the dynamic space heat extraction requirements (space cooling load) for 'typical' radiant buildings and 'typical' all-air buildings would be somewhat closer than what we have found through previous simulations and experiments, because low thermal diffusivity surfaces in buildings with all-air cooling would tend to decrease the amount of heat stored in masses, decrease the amount of thermal energy that can be rejected by passive means, and increase the peak space heat extraction requirement.

Supplemental cooling in radiant buildings would influence the dynamic space cooling rate

Most buildings with high thermal mass radiant cooling also include supplemental cooling using some type of forced-air system. Very few researchers have considered the coordination between high thermal mass radiant cooling and supplemental cooling, and it is not known how dividing the space cooling between these two systems would influence the dynamic space heat extraction requirements (space cooling load) compared to an all-air system. We expect that the differences addressed in this article would be smaller for a radiant cooled space with supplemental cooling, because such a building is really a hybrid of radiant cooling and all-air cooling.

The magnitude of our findings will vary with climate characteristics

The magnitude of the differences highlighted in this article depend largely on the availability of passive cooling opportunities. Some climates have extensive passive cooling opportunities while others have limited opportunities. We have focused on the impact of natural ventilation night precooling, but the idealized imitation of night ventilation cooling imposed for the laboratory experiments likely yielded the maximum impact that could be expected – we cooled the space toward the lower end of what is considered comfortable (ASHRAE 55). Further research could assess the way that night ventilation pre-cooling affects the difference between the annual cooling requirements for radiant and all-air systems, and to identify the geographic ranges where these differences are important.

Radiant cooling and natural ventilation pre-cooling should be coordinated strategically

In practice, there is rarely much strategy to the coordination of radiant cooling systems and natural ventilation cooling systems. Natural ventilation is common among buildings with high thermal mass radiant cooling, but these radiant systems are typically controlled to constant indoor air temperature or slab temperature setpoints for all hours and days of the week (Paliaga 2017). Similar to the case observed in our experiments, this control strategy will cause the cooling plant to operate in response to heat gains –

rather than ahead of heat gains – which will preempt some of the benefits of natural ventilation night pre-cooling compared to an all-air system with natural ventilation night precooling. It is likely that if a high thermal mass radiant system were controlled so that the cooling plant operated ahead of the typical heat gain period – as an "if needed" supplement to natural ventilation night pre-cooling – more heat could be absorbed by non-active masses during the day then rejected to natural ventilation night pre-cooling overnight. This issue deserves further research to develop, test, and demonstrate standard sequences of operation that optimize coordination between high thermal mass radiant and night ventilation cooling systems.

Evaporative water cooling could provide substantial efficiency benefits for radiant cooled buildings

Natural ventilation night precooling is not the only passive or very-low-energy cooling strategy that could be used to reduce the need for vapor compression chillers. In most climates, evaporative water cooling (waterside economizer cooling) can also be used to provide very-low-energy cooling for radiant systems. Similar to the control strategy recommended to coordinate radiant cooling with night ventilation pre-cooling, a high thermal mass radiant system could be controlled to allow the radiant slab to absorb and store heat during the day, then operate waterside economizer cooling to extract the heat overnight when wet bulb temperatures are lower. For some climates and scenarios, this strategy could completely eliminate the need for a vapor compression chiller (Moore 2008-A, Moore 2008-B, Duarte 2018, Tian 2009). Moreover, there are many climates where natural ventilation cooling at night is not quite adequate to provide substantial precooling, but where evaporative water cooling could provide very low energy cooling. In such a scenario, radiant cooling could be very advantageous – even if it has additional thermal burden – because it can benefit from waterside economizer cooling.

Careful design and control of radiant cooling is essential to minimize electricity consumption

These findings have compelling implications for the design and ultimate energy use of buildings. Although radiant cooling enables several efficiency opportunities – especially improved cooling plant and distribution efficiency – the large additional thermal burden revealed by our experiments could definitely cause a radiant cooling system to consume more electricity than an all-air system in the same application. Therefore, to save electricity compared to all-air systems, radiant cooling must be carefully designed and controlled to leverage the advantages offered by the strategy. Most importantly, cooling plants for buildings with radiant should be operated at a warmer chilled water temperature, and cooling plant operation should be strategically coordinated with the availability of passive or very-low-energy cooling opportunities – such as evaporative water cooling– so as not to preempt the benefits offered by such strategies.

Finally, while our results have confirmed that radiant cooling must remove more heat than an all-air system in order to maintain equivalent comfort conditions, we expect that – when designed with climate appropriate systems and control strategies – radiant cooling should be able to use substantially less electricity than all-air cooling. Many building energy simulation studies have concluded that in a wide variety of climates, radiant cooling can achieve substantial primary energy savings and peak electrical demand reduction compared to all-air cooling systems. However, no researchers have compared radiant cooling and all-air cooling in scenarios where both benefit from natural ventilation night precooling. Further research is needed to develop and demonstrate best practice design and control in such scenarios.

5. CONCLUSIONS

Previous research proved that to maintain equal operative temperature as an all-air system: (1) radiant cooling must extract heat from gains earlier; (2) the peak space heat extraction rate must be larger for radiant systems; and (3) the peak space heat extraction must occur earlier for radiant systems (Niu 1995, Niu 1997, Feng 2013, Feng 2014-A, Feng 2014-B, Woolley 2018). We conducted a series of laboratory tests to investigate whether or not the radiant-to-total heat gain ratio, or the use of natural ventilation night precooling, significantly affect the magnitude of these differences.

First of all, our results reaffirm previous findings, and underline the fact that the time and rate at which heat must be extracted from a space depend on the type of terminal heat transfer device used. Furthermore, we conclude that the difference between the dynamic space heat extraction requirements (space cooling load) for radiant and all-air systems depends on characteristics of the scenario. The use of natural ventilation night precooling, and the radiant-to-total heat gain ratio both have large impacts on the difference between dynamic space heat extraction requirements (space cooling load) for the two systems. In an experiment with mixed internal heat gains and without natural ventilation night precooling radiant cooling had to remove 7% more heat than the all-air system, and the peak space heat extraction rate was 2–10% larger (median 5%). Whereas in experiments with highly radiant gains and natural ventilation night precooling, radiant cooling had to remove 40% more heat than the all-air system and the peak space heat extraction rate was 18–28% larger (median 21%). Summary metrics for all six experiments are presented in Table A2 in the appendix.

The differences found are mainly due to the way that each system type influences the time and rate at which heat is absorbed by, stored in, and released from non-active thermal masses within and enclosing a space. Radiant cooling extracts heat directly from all surfaces in a space; consequently, non-active masses absorb and store less heat than they would in a space with all-air cooling. This causes radiant cooling systems to extract heat from gains earlier, causes the peak space heat extraction rate to be larger, and causes non-active surfaces to be cooler. Moreover, since non-active masses in spaces with radiant cooling absorb and store less heat, there is less opportunity to reject heat from non-active masses by passive means. In climates with significant opportunity for natural ventilation night precooling the difference between space heat extraction requirements (cooling load) for radiant and all air systems can be very large.

Finally, we also present results which reveal that the thermal properties of non-active surfaces within and enclosing a space interact with heat gains in ways that impact the differences between dynamic space heat extraction requirements (space cooling load) for radiant and all-air systems. In particular, surfaces with low thermal diffusivity and low thermal capacity will essentially convert radiant heat gains to convective heat gains, whereas surfaces with high thermal diffusivity and high thermal capacity will more readily absorb and store radiant heat gains.

Current practice for design and sizing of radiant cooling systems often utilizes cooling load calculation tools designed for all-air cooling systems, and thus fails to account for the differences we have observed. In some scenarios, the differences may be small, but – as we have demonstrated – in some scenarios the differences can be very large. Therefore, we encourage designers and researchers to use building energy simulation tools that properly represent the dynamic heat transfer characteristics of radiant cooling systems, so as to institute design strategies that can more fully capitalize on the potential energy benefits of radiant cooling. Further, we encourage standards organizations to develop more inclusive explanations and guidelines for cooling load calculations.

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DECLARATION OF INTERESTS

The Center for the Built Environment at the University of California Berkeley – with which the authors are affiliated, is advised by and funded in part by many partners that represent a diversity of organizations from the building industry – including manufacturers, building owners, facility managers, contractors, architects, engineers, government agencies, and utilities.

APPENDIX

A.1. Experimental facility

The experimental facility – illustrated in Figure 3 – consisted of two side-by-side testbed buildings. Each 57.6 m^2 (620 ft^2) testbed, had a 3.66 m (12 ft) high ceiling, with a drop ceiling at 2.74 m (9 ft). The floor was a 15.25 cm (0.5 ft) thick concrete slab with no additional floor covering. The southern wall conformed to ASHRAE 90.1-2010 (ASHRAE 90.1), with 30% window-to-wall ratio and no exterior shading. All other walls, the ceiling, and the floor were very well insulated (U≤0.017 W/m^2-K); in this way each testbed approximated a single perimeter zone in a larger office building, where the majority of the zone boundary is adjacent to other similarly conditioned zones.

Both testbeds included an independent air handler with overhead supply air distribution and drop-ceiling return plenum. The air handlers were in equipment rooms within the thermal boundary of each testbed. In the radiant cooling testbed the air handler circulated air at a constant 37.5 L/s (80 cfm), a flow rate representative of typical ventilation rates in radiant buildings (ASHRAE 62.1, Paliaga 2017). We chose to include air circulation in the radiant testbed to mimic the air movement characteristics (and related heat transfer coefficients) that could be expected in a real building with neutral temperature ventilation air flow. In the all-air testbed the air handler circulated air at a constant flow rate of 278 L/s (590 cfm) and a proportional integral control sequence adjusted supply air temperature to control the operative temperature. Neither testbed had ventilation air, and the infiltration rates in each testbed reflected typical construction. Tracer gas decay tests indicated infiltration rates of 0.169 and 0.329 air changes per hour (9.6 L/s (20.3 cfm) and 18.6 L/s (39.5 cfm)) in the all-air and radiant testbeds respectively.

In the radiant testbed, we used a cooled metal panel system installed in the drop ceiling (Twa model MOD-RP1, Nisku, Alberta, Canada) to provide cooling. The panels covered 73% of the floor area, as highlighted in blue in Figure 3. We covered as much of the ceiling area as possible to ensure relatively even surface temperature distribution, and to reduce the surface temperature that would be required to extract heat from the testbed. We arranged the panels in six parallel loops with 19-20 panels in each. Water flowed through the ceiling constantly at 1090 L/s (4.8 gal/min) and proportional integral control sequence adjusted supply water temperature to control the operative temperature in the space. The median supply water temperature across all experiments was 14.5 ˚C with an interquartile range of 5.62 ˚C . We were careful to ensure that humidity in the radiant testbed remained low enough that supply water temperature would not cause condensation. The median temperature rise across each loop was 2.6 ˚C with an interquartile range of 1.7 ˚C. Although a low mass radiant system has a distinctly different response time than a high thermal mass radiant system, the heat transfer rate for a surface is determined by the difference between the surface temperature and space air and surface temperatures. Consequently, the observations presented in this article should represent the surface temperatures and space heat extraction rates that are required for any type of radiant system – including high thermal mass radiant systems – to achieve the indoor conditions observed. Keep in mind that for a high thermal mass radiant system, the rate at which heat is transferred to the cooling plant will be considerably different from the space heat extraction rate – this article does not address heat transfer rates at the cooling plant.

In the all-air testbed we used a constant volume flow variable temperature control scheme to provide cooling. We used this strategy instead of a variable-air-volume control scheme so that we could precisely balance heat gain from the fan in the all-air testbed with equivalent heat gain in the radiant testbed. Since we were focused on comparing the sensible space heat extraction rates by each system, we were careful to ensure that humidity in the all-air testbed remained low enough that supply water temperature would not cause condensation (latent space heat extraction).

We supplied equal internal heat gains to each testbed using a combination of different electric resistance heating apparatuses, selected to generate the radiant-to-total heat gain ratio desired for each experiment (see section 2.2 Design of experiments). We measured and balanced all internal heat gains located within the thermal boundary of each testbed, including electricity use for fans, pumps, controls, and data acquisition equipment.

We controlled both testbeds to maintain equal operative temperature setpoints. Although buildings are not regularly controlled to operative temperature, doing so for this comparison ensured equivalent comfort conditions in both testbeds (ASHRAE 55). The controlled value in each testbed was the average of three operative temperature measurements, located along the centerline of each testbed, far enough from the south wall to avoid direct solar radiation (3.45 m, 5.3 m and 7.16 m from the south wall), and at 0.6 m height – according to ASHRAE 55 for a seated occupant. We measured operative temperature with fast response thermistors placed at the center of 40 mm diameter grey plastic globes, in accordance with findings from various researchers (DeDear 1987, Humphreys 1977, Simone 2007), and international standards for measurement of human thermal comfort (ISO 7726).

A.2. Measurements and uncertainty

We monitored more than 250 points in each testbed to assess thermodynamic states and heat transfer rates. Throughout each experiment we recorded data from all points as one-minute-average values on one-minute intervals. In summary, categories of measurements included:

- Wall indoor surface temperatures
- Wall internal temperatures
- Slab indoor surface temperatures
- Slab internal temperatures
- Ceiling indoor surface temperatures
- Indoor air temperatures
- Indoor operative temperatures
- Hydronic system temperatures
- Hydronic system water flow rates
- Air system temperatures
- Air system airflow rates
- Internal heat gain rates
- Solar heat gain rates
- Surface heat flux rates

We calculated the sensible space heat extraction rates reported in this article from flow and temperature measurements in the chilled-water loops that served each testbed separately. Flow and temperature measurements were located at the point where chilled water circulating in the cooling plant loop was injected into the loop that serves terminal heat transfer devices. These measurements were located at the thermal boundary of each testbed, and therefore capture all of the thermal energy extracted from each testbed. Since the radiant system was a low thermal mass metal panel ceiling with a fast response time, the hydronic heat extraction rate was a close approximation of the instantaneous space heat extraction rate associated with convective and radiant heat transfer at the indoor face of the internally cooled ceiling surface. The mechanical ventilation system in buildings with radiant cooling often provides some amount of space heat extraction, but our assessment assumes that ventilation is provided at room-neutral conditions and that all space heat extraction is provided by the internally cooled surfaces.

Table A1 summarizes the uncertainty for key measurements and calculated metrics. We used propagation of error calculations to determine the uncertainty of the space heat extraction rate for each testbed and to determine the uncertainty of the difference in heat extraction rate between the two testbeds.

Table A1: Calibrated uncertainty of measurements and calculated metrics

Measurement	Calibrated Uncertainty	Manufacturer and model
Water temperatures	± 0.02 °C	BAPI BA/10K
Air temperatures	± 0.02 °C	US Sensor Corp. PR103J2
Surface temperatures	± 0.02 °C	US Sensor Corp. PR103J2
Water flow rates	± 0.2% of measurement	Siemens MAG 6000 with MAG FM 1100
Internal heat gain rates (electric power)	± 1% of measurement	
Hydronic/space heat extraction rate	± <10 W	Calculated metric

The uncertainty values reported for temperature in Table A1 do not represent the absolute accuracy compared to a standard reference measurement; instead, they describe the calibrated repeatability among the group of measurements compared. Absolute uncertainty is important when values need to be compared to measurements from a separate study, in which case agreement with standard reference measurements is the only way to ensure accurate comparison. Since our experiments compared two cases side-by-side, we were able to calibrate all of our temperature sensors to one another in situ. Since our conclusions focus squarely on whether the space heat extraction rate for the radiant testbed was different from the space heat extraction rate for the all-air testbed, absolute uncertainty compared to a standard reference measurement is not especially relevant, while uncertainty of the difference is very important.

We conducted the in-situ calibration by placing all temperature sensors in a water bath to compare them against one another. The water bath used U.S. Sensor Corp USP 3021 (Littlefuse, Chicago, IL, USA) as reference (uncertainty ±0.01°C to standard reference measurement). We repeated the water bath comparison across a range of temperatures (18 steps between 0–70 °C). Then, we corrected the bias between sensors by adjusting the Steinhart-Hart coefficients for each sensor. This approach nearly eliminates bias between the sensors, consequently uncertainty of the difference between temperature measurements was reduced mainly to stochastic variation in repeated measurements.

Water flow rate measurements were factory calibrated to a standard reference measurement for a wide range of flow rates.

In parallel to propagation of error calculations, we also calibrated the testbeds to one another to improve our confidence in observing any difference between their space heat extraction rates. Prior to the experiments presented here, we conducted two baseline calibrations in which we operated both testbeds as identical all-air systems with constant internal gains for several days. Ultimately, these baseline calibrations yielded a difference in the daily average space heat extraction rates of 1 W – smaller than the magnitude of the uncertainty of the difference due to propagation of uncertainty from the associated measurements.

A.3. Summary metrics for each experiment

Table A2: Summary metrics for each experiment

		Difference between peak space heat extraction rate				Difference between daily thermal energy use		
		min–max (median)				min–max (cumulative)		
	Experiment Description	%	W	W/m²	minutes earlier	%	Wh	Wh/m²
1	Mixed internal heat gains + solar gains (no n.v. night precooling)	2–10% (5%)	72–331 (140)	1.25–5.7 (2.43)	30–51 (46)	5–11% (7%)	1,599–3,480 (10,992)	27.8–60.4 (192)
2	Mixed internal heat gains + solar gains + n.v. night precooling	18–22% (20%)	376–472 (448)	6.5–8.2 (7.8)	45–100 (66)	31–37% (35%)	5,126–5,963 (27,482)	89–103 (477)
3	Highly convective internal heat gains + solar gains + n.v. night precooling	10–17% (12%)	334–579 (393)	5.8–10.1 (6.8)	0–66 (61)	17–32% (26%)	4,555–8,399 (28,212)	79–145 (490)
4	Mixed internal heat gains + n.v. night precooling (no solar gains)	19%	322	5.6	0	27–41% (33%)	3,901-4,878 (12,857)	68–85 (223)
5	Highly radiant internal gains (oriented down) + solar gains + n.v. night precooling	18–29% (21%)	465–568 (501)	8.1–9.9 (8.7)	59–78 (67)	36–47% (40%)	5,638–6,633 (30,446)	98–115 (529)
6	Highly radiant internal gains (oriented up) + solar gains + n.v. night precooling	15–23% (21%)	265–566 (517)	4.6–9.8 (9.0)	79–102 (90)	17–28% (21%)	1,971–4,926 (17,366)	34–85.5 (301)

A.4. Disaggregated internal and solar heat gain rates for each experiment

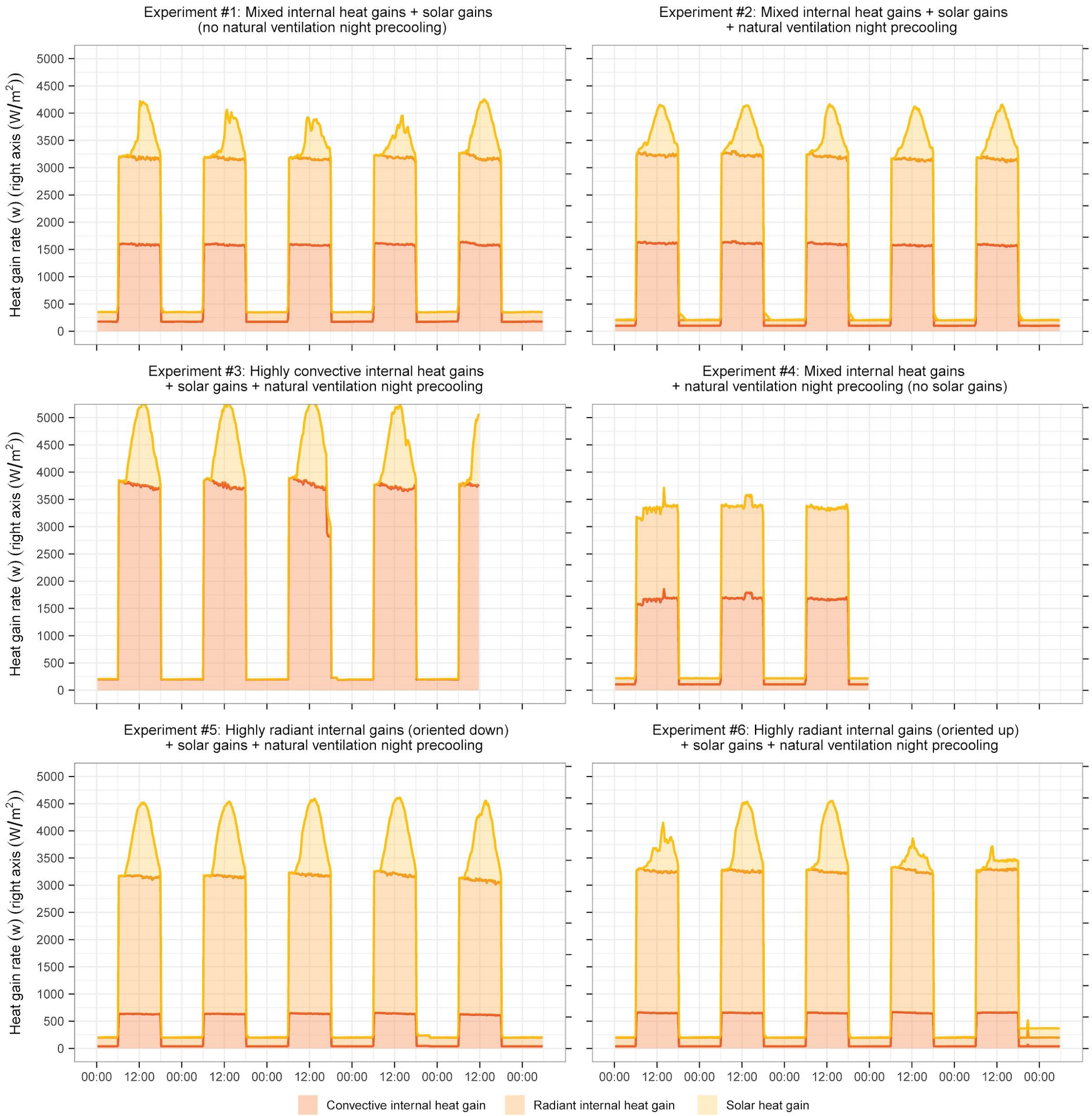

Figure A1: Internal and solar heat gain rates in each of the six experiments. The plots disaggregate the estimated radiant and convective components of internal heat gains, and present data across multiple days. Internal heat gain data are plotted at one-minute intervals, solar heat gain data are plotted as 30 minute rolling averages on 15 minute intervals.

A.5. Dynamic space heat extraction rates for each experiment

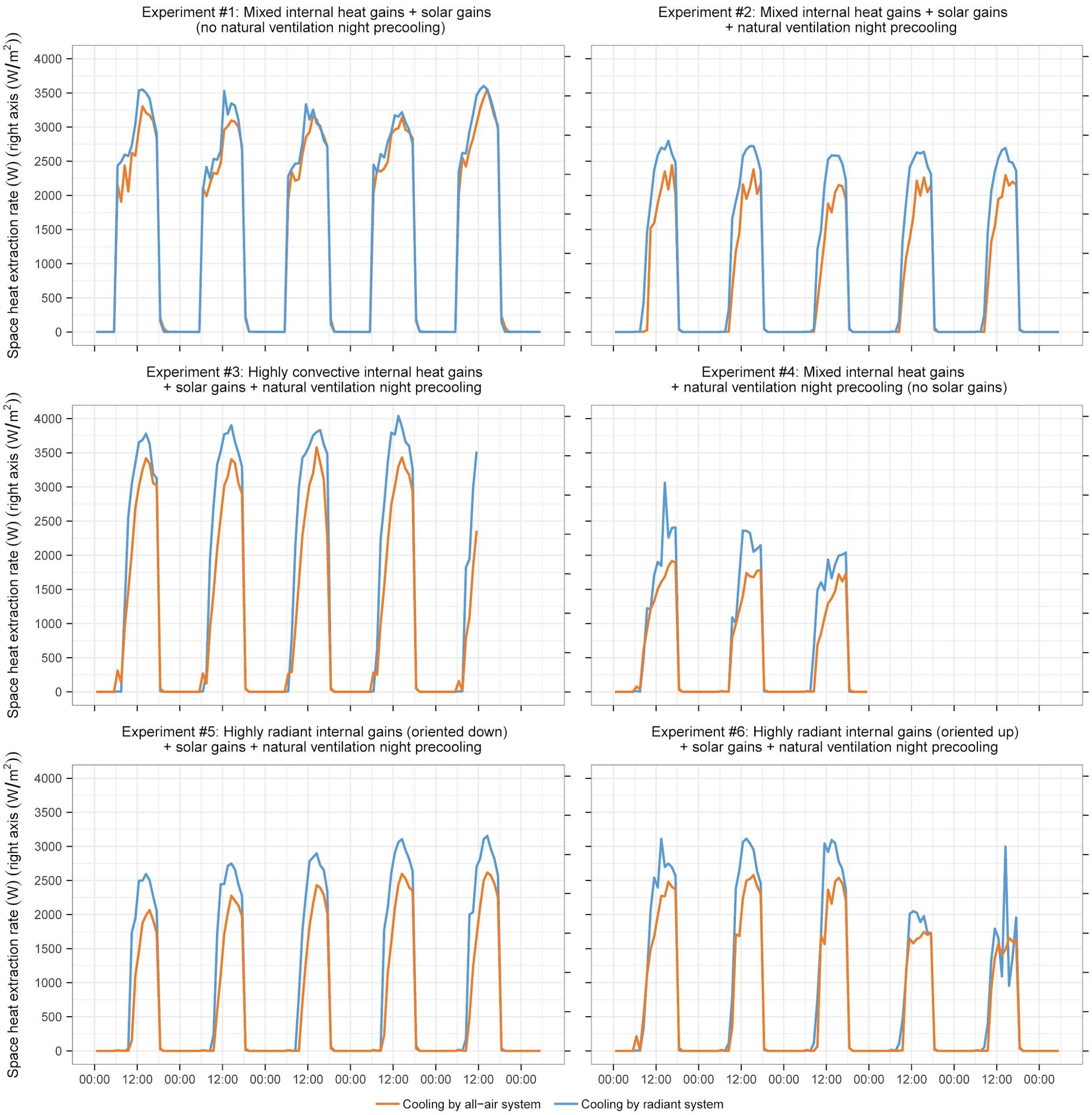

Figure A2: Space heat extraction rates for radiant (blue) and all-air systems (orange) in each of the six experiments. The plots present data across multiple days as one-hour rolling averages at one-hour intervals.

https://doi:10.1016/j.enbuild.2019.07.020
https://escholarship.org/uc/item/4w94k709

A.6. Cumulative thermal energy use for each experiment

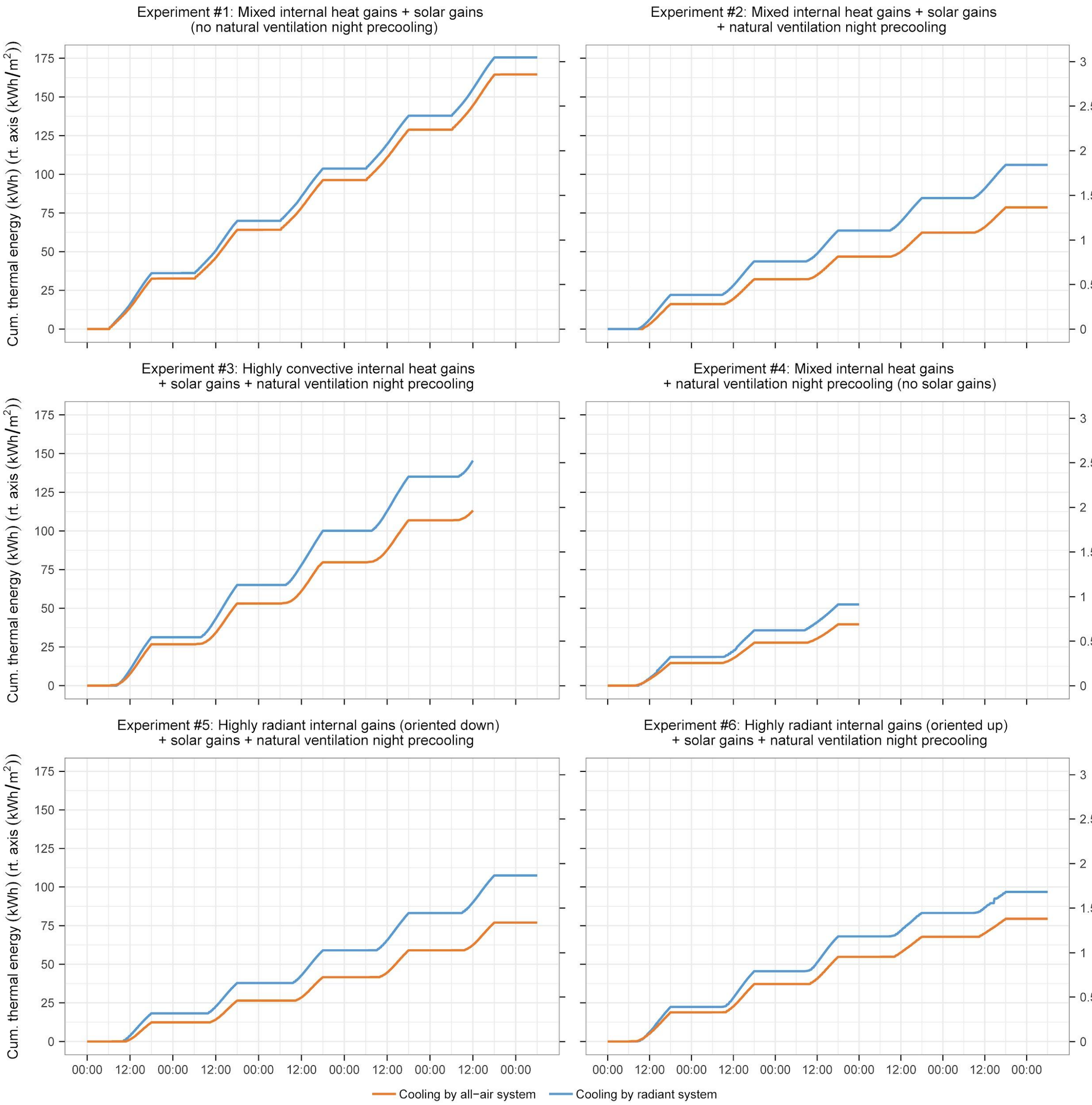

Figure A3: Cumulative space heat extraction energy for radiant (blue) and all-air systems (orange) in each of the six experiments. The plots present data across multiple days at one-minute intervals.

A.7. Disaggregated cumulative thermal energy flows for each experiment

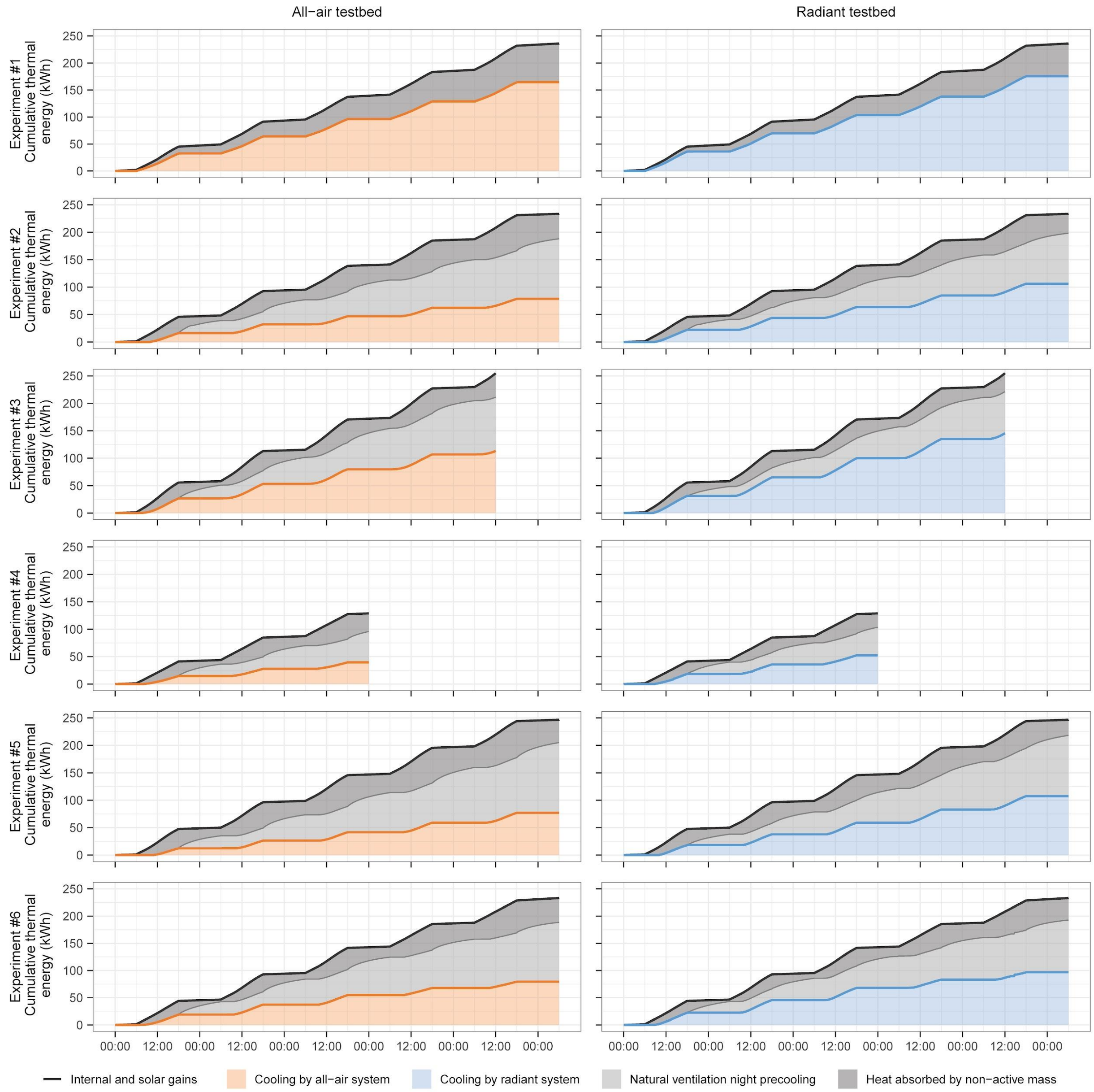

Figure A4: Cumulative thermal energy flows in the all-air (left) and radiant (right) testbeds in each of the six experiments. Each plot indicates the cumulative thermal energy extracted from the space by mechanical systems (orange or blue), the cumulative thermal energy extracted from the space by natural ventilation night precooling (light grey), and the cumulative thermal energy from internal or solar gains stored by non-active masses and/or released passively to the environment (dark grey). Data is plotted across all days in each experiment on one-minute intervals.

A.8. Correlation between heat gain characteristics and space heat extraction requirements

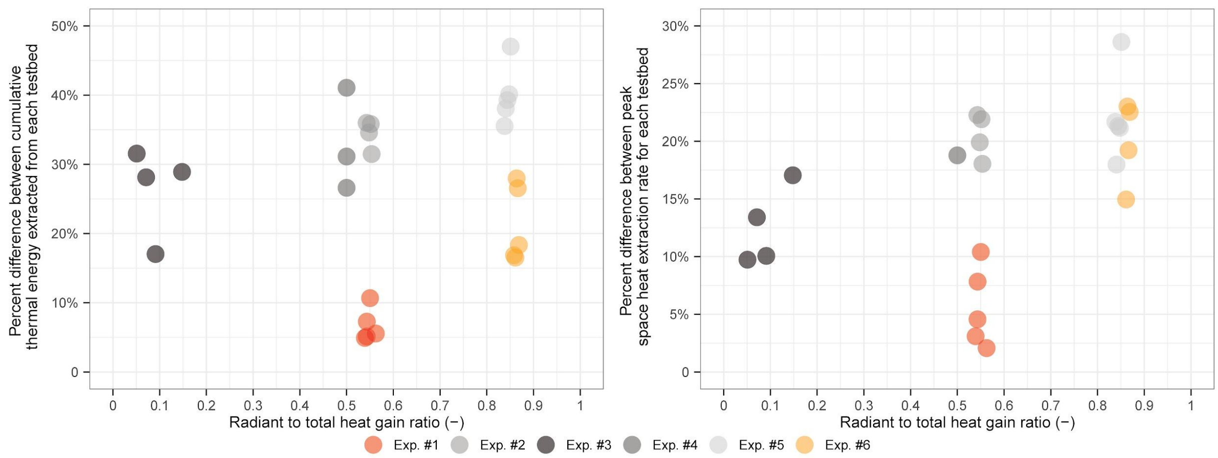

Figure A5: The percent difference between cumulative space heat extraction energy (left) and peak space heat extraction rate (right) in the radiant and all-air testbeds during each 06:00–18:00 period for all six experiments, presented as a function of the cumulative radiant-to-total heat gain ratio on the corresponding day.

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REFERENCES

J. Babiak, B.W. Olesen, D. Petras, Low temperature heating and high temperature cooling: embedded water based surface heating and cooling systems, 2nd rev. ed, Rehva, Brussels, 2009.

E. Bourdakis, O.B. Kazanci, B.W. Olesen, Load Calculations of Radiant Cooling Systems for Sizing the Plant, Energy Procedia. 78 (2015) 2639–2644. doi:10.1016/j.egypro.2015.11.333.

C. Chantrasrisalai, D.E. Fisher, Lighting Heat Gain Parameters: Experimental Method (RP-1282), HVAC&R Research. 13 (2007) 283–303. doi:10.1080/10789669.2007.10390955.

C. Chantrasrisalai, D.E. Fisher, Lighting Heat Gain Parameters: Experimental Results (RP-1282), HVAC&R Research. 13 (2007) 305–324. doi:10.1080/10789669.2007.10390956.

C. Duarte, P. Raftery, S. Schiavon, F. Bauman, How High Can You Go? Determining the Highest Supply Water Temperature for High Thermal Mass Radiant Cooling Systems in California, (2018). https://escholarship.org/uc/item/0s06q03g.

R. De Dear, Ping-Pong Globe Thermometers for Mean Radiant Temperature, Heating and Ventilation Engineer and Journal of Air Conditioning. 60 (1987) 10–12.

EnergyPlus, U.S. Department of Energy Building Technologies Office, 2019. https://energyplus.net/.

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.

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, 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.

D. Fisher, C. Chantrasrisalai, Lighting Heat Gain Distribution in Buildings (RP-1282), Oklahoma State University, 2006.

M.H. Hosni, B.W. Jones, H. Xu, Experimental results for heat gain and radiant/convective split from equipment in buildings, ASHRAE Transactions. 105 (1999) 527–539.

M.A. Humphreys, The optimum diameter for a globe thermometer for use indoors, Ann Occup Hyg. 20 (1977) 135–140. doi:10.1093/annhyg/20.2.135.

B.W. Jones, M.H. Hosni, J.M. Sipes, G. Wichenko, Measurement of radiant heat gain from office equipment using a scanning radiometer/Discussion, ASHRAE Transactions. 104 (1998) 1775.

A. Laouadi, Development of a radiant heating and cooling model for building energy simulation software, Building and Environment. 39 (2004) 421–431. doi:10.1016/j.buildenv.2003.09.016.

Lawrence Berkeley National Laboratory. FLEXLAB – The world's most advanced building efficiency testbed, 2018. https://flexlab.lbl.gov/.

T. Moore, Simulation of radiant cooling performance with evaporative cooling sources, (2008). https://escholarship.org/uc/item/9qm3670s

T. Moore, Potential and limitations for hydronic radiant slabs using waterside free cooling and dedicated outside air systems, in: Third National Conference of IBPSA-USA, International Building Performance Simulation Association, Berkeley, California, 2008: pp. 148–155. http://www.ibpsa-usa.org/index.php/ibpusa/article/view/247.

J. Niu, J. v.d. Kooi, H. v.d. Rhee, Energy saving possibilities with cooled-ceiling systems, Energy and Buildings. 23 (1995) 147–158. doi:10.1016/0378-7788(95)00937-X.

J. Niu, J. v.d. Kooi, H. v.d. Rhee, Cooling load dynamics of rooms with cooled ceilings, Building Services Engineering Research and Technology. 18 (1997) 201–207.

G. Paliaga, F. Farahmand, P. Raftery, J. Woolley, TABS Radiant Cooling Design & Control in North America: Results from Expert Interviews, (2017). http://escholarship.org/uc/item/0w62k5pq (accessed July 24, 2017).

P. Raftery, E. Lee, T. Webster, T. Hoyt, F. Bauman, Effects of furniture and contents on peak cooling load, Energy and Buildings. 85 (2014) 445–457. doi:10.1016/j.enbuild.2014.09.081.

A. Simone, J. Babiak, M. Bullo, G. Landkilde, B. Olesen, Operative temperature control of radiant surface heating and cooling systems, in: Proceedings of Clima 2007 Wellbeing Indoors, Federation of European Heating, Ventilation and Air Conditioning Associations, Helsinki, Finland, 2007.

C. Stetiu, H.E. Feustel, F.C. Winkelmann, Development of a Simulation Tool to Evaluate the Performance of Radia nt Cooling Ceilings, (1995).

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

Z. Tian, J.A. Love, Application of radiant cooling in different climates: assessment of office buildings through simulation, in: International Building Performance Simulation Association, Glasgow, Scotland, 2009: pp. 2220–2227.

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.

T. Yu, P. Heiselberg, B. Lei, M. Pomianowski, Validation and modification of modeling thermally activated building systems (TABS) using EnergyPlus, Building Simulation. 7 (2014) 615–627. doi:10.1007/s12273-014-0183-6.

ISO Standard 7726-1998 - Ergonomics of the thermal environment — Instruments for measuring physical quantities, 1998.

ANSI/ASHRAE/IENSA Standard 90.1-2010 Energy Standard for Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

ANSI/ASHRAE Standard 55.1-2017 - Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2017.

ANSI/ASHRAE Standard 62.1-2013 - Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2013.

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.

ISO Standard 52016-1:2017 — Energy performance of buildings — Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads — Part 1: Calculation procedures, n.d. https://www.iso.org/standard/65696.html.

ISO Standard 7726:1998 — Ergonomics of the thermal environment — Instruments for measuring physical quantities., 1998. https://www.iso.org/standard/14562.html.

European Standard prEN 15255:2007 — Thermal Performance of Buildings — Sensible room cooling load calculation — General criteria and validation procedures, n.d.