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Side-by-side laboratory comparison of space heat extraction rates and thermal energy use for radiant and all-air systems

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ABSTRACT

Radiant cooling systems extract heat from buildings differently than all-air cooling systems. These differences impact the time and rate at which heat is removed from a space, as well as the total amount of thermal energy that a mechanical system must process each day. 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). The results show that radiant cooling must remove more heat than all-air cooling – 2% more in an experiment with constant internal heat gains, and 7% more with periodic scheduled internal heat gains. Moreover, the peak sensible space heat extraction rate for radiant cooling (heat transfer at the cooled surface, not the cooling plant) must be larger than the peak sensible space heat extraction rate for all-air systems, and it must occur earlier. The daily peak sensible space heat extraction rate for the radiant system was 1–10% larger than for the all air system, and it occurred 1–2 hours earlier. These findings have consequences for the design of radiant systems. In particular, this study confirms that cooling load estimates for all-air systems will not represent the space heat extraction rates required for radiant systems.

1. Introduction

Radiant cooling and heating could be a pathway to reduce energy use and peak electrical demand in buildings compared to conventional all-air systems. A recent survey assessment of commercial building energy consumption in the United States indicated that the median energy use intensity for buildings with radiant cooling is 14–66% lower than standard buildings of comparable type and climate zone [7]. Although radiant cooling is currently installed in a small portion of buildings overall, it is a common strategy among buildings with the lowest energy use intensity [11,12,16]. The number of high performance buildings with zero net energy aspirations has increased rapidly in recent years [6], and consequently application of radiant cooling appears to be expanding.

Several researchers have identified reasons that radiant cooling can reduce energy consumption and peak electrical demand compared to all-air systems. We summarize the variety of explanations as five specific advantages by which radiant cooling can reduce energy consumption:

1. Electricity use for thermal distribution in radiant buildings can be lower than in all-air buildings. Airflow in radiant buildings can be limited to the minimum ventilation requirements. So, although radiant buildings require more electricity for pumping, the fan electricity savings in radiant buildings can be much larger than the increase in electricity use for pumping.
2. Radiant cooling can operate with relatively warm chilled-water temperatures. Cooling plant efficiency can be better than for all-air systems if chillers are designed and controlled to operate at warmer temperatures. Further, radiant cooling can also allow use of very high efficiency cooling plants, such as evaporative fluid coolers and direct ground or water body heat exchange.
3. The air temperature in buildings with radiant cooling is somewhat warmer than in buildings with all-air systems at equivalent comfort conditions. Consequently, heat gains from ventilation air are somewhat smaller for radiant and there are more hours when outdoor air provides free cooling.
4. By decoupling ventilation from space cooling, radiant systems can avoid the need for terminal reheat, and can avoid energy consumed by incidental dehumidification that occurs when air is cooled with low temperature chilled-water, or direct expansion.
5. High thermal mass radiant systems can allow for cooling plant operation during non-peak periods when electricity tariffs are

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lower, and when primary cooling sources may operate more efficiently.

When these advantages operate together, the potential energy savings for radiant cooling can be high. Numerous simulation studies and field evaluations have concluded that radiant cooling can consume much less energy than conventional all air systems.

There has been substantial research to develop and validate building energy simulation tools that properly capture the fundamental heat transfer mechanisms involved with radiant cooling systems [13,14,21–23]. Yet despite the variety of simulation studies that have utilized these tools to compare the primary energy performance of radiant and all-air systems, only Feng et al. and Niu et al. have explicitly compared the dynamic space heat extraction rates for radiant and all-air cooling systems [3–5,13–15]. Through simulation and laboratory experiments these researchers demonstrated that:

1. Radiant cooling systems extract heat from gains earlier than all-air cooling systems.
2. Envelope heat transfer rates are different for radiant and all-air cooling systems.
3. The daily maximum space heat extraction rate is larger for radiant cooling systems.
4. The total amount of heat extracted each day is larger for radiant cooling systems.

The dynamic space heat extraction rate required to maintain comfort is crucial for design, sizing, and control of any cooling system, yet as Feng et al. [3,5] highlighted, industry common practice methods for design sizing of cooling systems do not properly capture the differences between radiant and all-air systems.

The space heat extraction rate is the rate at which heat is removed from a space by terminal heat transfer devices. The instantaneous space heat extraction rate required to maintain comfort is not equal to the instantaneous sum of heat gains in a space because a portion of the heat gains is absorbed by non-active masses and does not immediately result in a need for active cooling. For all-air systems the space heat extraction rate is the sensible enthalpy difference between supply and return (or room air outlet) air flows. For radiant systems the space heat extraction rate is the sum of convective and radiant (longwave and shortwave) heat transfer rates at the actively cooled surface. For high thermal mass radiant systems, the space heat extraction rate will be much different from the rate at which heat is transferred to the hydronic system. Generally, design of a cooling system should begin with an assessment of the space heat extraction rates that will be required to counterbalance the effect of expected heat gains in order to achieve desired comfort conditions. When this is known, mechanical systems and controls can be designed with the ability to provide the required space heat extraction rates. Each of these heat transfer rates are defined in Fig. 1.

In this article we expand on the current understanding of radiant cooling with observations from simultaneous tests of radiant cooling and all-air cooling in side-by-side experimental testbed buildings. The specific objectives of the comparison were to observe differences in:

1. The dynamic space heat extraction rates required to maintain equivalent comfort in both testbeds.
2. The cumulative amount of thermal energy extracted by each system.
3. The distribution of thermal energy in masses in each testbed.

To be clear, this article is principally concerned with comparing the space heat extraction rates that are required by radiant cooling and all-air cooling systems to maintain a desired operative temperature. We do not address the multitude of considerations that must be made for design of the cooling plant, thermal distribution systems, and controls which ultimately result in space heat extraction.

Only one previous laboratory study [3] has compared the space heat extraction rates for radiant and all-air systems. That study provided clear foundational evidence about the differences between these systems, but it imposed atypical heat gains, used a relatively small adiabatic environmental chamber, imposed somewhat inequivalent initial conditions, and only observed differences in the dynamic space heat extraction rates over a single heat gain cycle. We build on the conclusions of Feng et al. by comparing the two system types in more realistic circumstances, with various heat gain schedules, and over an extended period of time.

2. Methodology

We conducted a series of controlled experiments in a pair of equivalent testbed buildings – one with radiant cooling and one all-air cooling. The testbed buildings at Lawrence Berkeley National Laboratory FLEXLAB ([24]) enable 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.

In this article, we present results from two experiments, one with constant internal gains, and one with periodic internal gains. We operated each experiment for several days, during which we monitored thermodynamic states and heat transfer rates in both testbeds. It is important to compare these systems over the course of several days to ensure that the temperature of masses in each testbed reach steady-state oscillations that are no longer influenced by the initial states of each system.

For our comparison of radiant and all-air cooling 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 did not assess the electrical performance for either system; our investigation focused on fundamental thermodynamic differences between radiant cooling and all-air cooling, regardless of the primary cooling sources and mechanical system elements that either may employ.

2.1. Experimental facility

The experimental facility consisted of two side-by-side testbed buildings, illustrated in Fig. 2. Each testbed had 57.6 m^2 (620 ft^2) floor area (6.1 m (20 ft) by 9.1 m (30 ft) interior dimensions, excluding the equipment room) and 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 [1], with 30% window-to-wall ratio and no exterior shading. All other walls, the ceiling, and the floor were very well insulated ($U \leq 0.017\,W/m^2$-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 135 m^3/hr (80 cfm), a flow rate representative of typical ventilation rates in radiant buildings ([2,17]). The circulated air in the radiant testbed was not conditioned. We chose to include air circulation in the radiant testbed to mimic the air move-