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Experimental comparison of zone cooling load between radiant and air systems

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ABSTRACT

Radiant cooling systems work fundamentally differently from air systems by taking advantage of both radiant and convective heat transfer to remove space heat. This paper presents an experiment investigating how the dynamic heat transfer in rooms conditioned by a radiant system is different from an air system, and how such differences affect the sensible cooling load and cooling load calculation methods for radiant systems. Four tests with two heat gain profiles were carried out in a standard climatic chamber. For each profile, two separate tests were carried out to maintain a constant operative temperature: one with radiant chilled ceiling panels; and a second with an overhead mixing air distribution system. The experiments show that, during the periods the heat gain was on, the radiant system has on average 18–21% higher instantaneous cooling rates compared to the air system, and 75–82% of total heat gains were removed, while for the air system only 61–63% were removed. Based on the study, we conclude that a new definition must be used for radiant system cooling load. Calibrated dynamic energy simulation based on a fundamental heat balance approach showed good accuracy. Simplified cooling load calculation methods may lead to incorrect results for radiant systems.

1. Introduction

Interest and growth in radiant cooling and heating systems have increased in recent years because they have been shown to be energy efficient in comparison to all-air distribution systems [1,2]. Olesen and others have discussed the principles of designing radiant slab cooling systems, including load shifting, the use of operative temperature for comfort control, and cooling capacity [3,4]. Several case study examples with design information have been reported for an airport [5], large retail store with floor cooling [6], and other thermally active floor systems [7]. However, it is difficult to find detailed standardized guidelines for calculating cooling loads for radiant cooling systems, which is the subject of this paper.

Cooling load calculations are a crucial step in designing and sizing any HVAC system. Compared to air systems, the presence of an actively cooled surface changes the heat transfer dynamics in a zone of a building. The chilled surface is able to instantaneously remove radiant heat (long and short wave) from any external (solar) or internal heat source, as well as interior surface (almost all will be warmer than the active surface) within its line-of-sight view. This means that radiant cooling systems may impact zone cooling loads in several ways: (1) heat is removed from the zone through an additional heat transfer pathway (radiant heat transfer) compared to air systems, which rely on convective heat transfer only; (2) by cooling the inside surface temperatures of non-active exterior building walls, higher heat gain through the building envelope may result; and (3) radiant heat exchange with non-active surfaces also reduces heat accumulation in building mass, thereby affecting peak cooling loads. Using simulations we previously demonstrated that dynamic responses of rooms when conditioned by radiant cooled surface(s) are significantly different from the case of air systems and consequently the cooling loads for system sizing are also drastically different (in fact, often higher for the studied cases) [8]. Thus, current cooling load calculation and modeling methods may not be applicable for radiant systems.

The objectives of the study reported below are: (1) experimentally compare sensible zone cooling loads between a radiant and well-mixed air system; and (2) provide guidance on radiant system cooling load prediction and energy modeling methods.

2. Review of current zone cooling load prediction methods for radiant systems

Based on the standard cooling load calculation methods described in ASHRAE Handbook—Fundamentals [9], the zone

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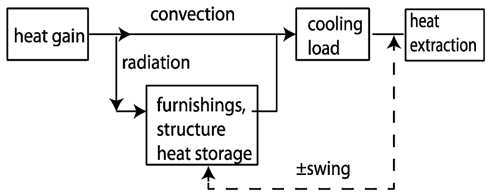

Fig. 1. Cooling load diagram from ASHRAE Handbook—Fundamentals.

sensible cooling load is the rate at which sensible heat must be removed from the zone air to maintain a constant air temperature. Currently, there are two recommended cooling load calculation procedures, the heat balance (HB) method and the radiant time series (RTS) method. There are, however, important limitations when these methods are applied to radiant systems.

The procedure based on HB method is considered the most scientifically rigorous method [10]. The heat balance model ensures that all energy flows in each zone are balanced by iteratively solving for a set of energy balance equations in the following loops: outside surface and the environment, conduction through building envelope, inside surface heat balance, and finally the air heat balance. This procedure calculates the cooling load by balancing the air loop heat transfer convectively according to the ASHRAE cooling load definition. However, for radiant systems, heat is removed at the actively cooled surface both convectively and radiatively. Therefore, although the heat transfer fundamentals are properly accounted for, it is questionable whether the current cooling load calculation procedure based on HB method and ASHRAE definition of cooling load is appropriate for radiant applications.

The RTS method is a simplified calculation procedure [11], originally developed to provide an approximation to the HB Method. According to this procedure, each heat gain (conduction portions along with lights, occupants, and equipment) is split into radiative and convective portions. The convective portion is assumed to instantly become cooling load and, therefore, only needs to be summed to find its contribution to the hourly cooling load. Radiant heat gain, on the other hand, must first be absorbed by the non-active surfaces that enclose the zone (floor, walls, ceiling) and objects in the zone (e.g., furniture). These surfaces will eventually increase their temperature above the air temperature to allow heat to be transferred by convection to the air, thereby contributing to the convective zone cooling load. So for all-air systems, it is always assumed that radiant heat gains become cooling load only over a delayed period of time. This process is graphically presented in Fig. 1. The method for converting the radiative components to cooling loads involve calculations of a series of radiant time factors, which were generated with the assumption of a well-mixed all-air system with no active radiant cooling surface(s) [11].

In addition to these two methods, there are several other simplified methods (e.g. cooling load temperature difference/cooling load factor/solar cooling load factor (CLTD/CLF/SCL) method [12], weighting factor method [13], etc.) that are widely used in modeling software for cooling load prediction purposes. All these methods are developed with an underlying assumption that convective heat transfer by air is the only mechanism to remove heat from a zone.

Due to the mismatch between how radiant heat transfer is handled in traditional cooling load calculation methods compared to its central role in radiant cooling systems, this research examined the fundamentals of cooling load calculations for radiant cooling systems.

3. Experimental comparison of cooling load between radiant and air systems

Current methods for testing radiant system performance are based on steady state conditions [4,14,15], which is not adequate for cooling load prediction. A testing method was established in this study to investigate the dynamic behavior of radiant systems and the resultant zone cooling load.

3.1. Experimental facilities and setup

The experiments were carried out in a climatic chamber (4.27 m × 4.27 m × 3.0 m). This chamber has been used for standard radiant cooling panel testing and meets the requirements stated in DIN EN 14240 [15]. The climatic chamber is located within a large conditioned laboratory space. The room has no windows. The walls, ceiling and floor have similar construction and thermal properties. Starting from the exterior, the chamber wall is comprised of 3.522 m^2 K/W insulation, a stagnant 0.102 m air gap (0.352 (m^2 K)/W), aluminum extruded walls with water tubes attached, and another layer of 0.102 m of polyurethane board (3.522 (m^2 K)/W). By adding up this assembly, the overall resistance is 7.396 (m^2 K)/W).

For the radiant cooling test, 12 aluminum radiant panels were connected in parallel and installed in the suspended ceiling placed at a height of 2.5 m above the floor, and each was 1.83 m long and 0.61 m wide (73.5% of the ceiling area was covered by panels). Copper pipes are thermally connected to aluminum channels in panels with a spacing of 0.15 m. Cotton fiber insulation was placed on the topside of the panels (1.76 (m^2 K)/W). The same chamber was used for the air system test, during which one radiant panel was replaced with an insulation board with opening cut to accommodate one air diffuser for conditioning the zone. See Fig. 2 for test chamber setup.

Thermal mass was a crucial element in this experiment. In the test, 64 pieces of concrete pavers (0.46 m × 0.46 m × 0.04 m) with a

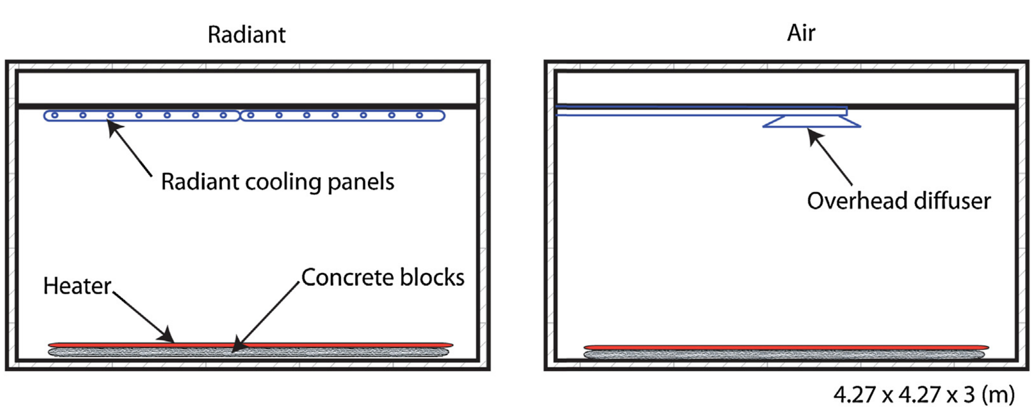

Fig. 2. The test chamber setup.