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The effect of thermal load configuration on the performance of passive chilled beams

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ABSTRACT

Experiments were conducted in a temperature controlled test room with a passive chilled beam and thermal manikins to measure the effect of heat source locations on the beam cooling capacity. Two configurations of thermal manikins and one configuration using radiant panels were tested through a range of conditions of the supply water to the passive chilled beam. The results of the experiments showed a dependence on the location, but not the type, of heat source on the cooling delivered to the test room by the beam. Thermal manikins placed asymmetrically to the beam location resulted in a 16% reduction in beam capacity as compared to thermal manikins placed symmetrically. Radiant panels oriented symmetrically on the floor of the test room resulted in an equivalent beam cooling rate compared to the symmetrically placed thermal manikins. A model based on fundamental heat transfer equations predicted the beam capacity of the symmetric thermal manikins but could not account for the reduced cooling capacity of the asymmetric configuration.

1. Introduction

The description of room airflow characteristics in buildings is necessary to evaluate the thermal comfort of occupants and optimize the energy use of the climate control system [1]. Radiation, conduction and forced and natural convection heat transfer between surfaces, occupants and room air define the flow of energy in indoor spaces. Natural convection heat transfer produces a buoyant force of the locally heated or cooled air that interacts with other sources of fluid momentum [2]. The primary airflow characteristics that can be used to predict thermal comfort in a space are the air temperature, air speed, radiant temperature and humidity [3]. Buoyant flows may impact thermal comfort based on the temperature and velocity of plumes and the differences in radiant sources.

Buoyancy is the driving force of the airflow in rooms supplied by stratification-based heating, ventilation and air conditioning (HVAC) designs and in traditional mixed air systems incorporating passive cooling or heating [2]. Passive cooling technologies provide controlled heat rejection in a space utilizing chilled surfaces that generate buoyant flows [4]. Chilled beams directly cool room air with exposed water coils supplied with chilled water and can be classified into two types: passive and active. Passive beams deliver cooling to the room by induction only. The room air rejects heat to the coil through natural convection. As the room air is cooled by the coil, the increased density creates a buoyancy force that causes the mass of air to sink directly beneath the beam [5]. The volumetric flow rate from a passive beam depends on the heat exchange at the coil that results from a difference in temperature between the room air and the coil surface. On the coil side, the chilled water supply flow rate and temperature are control set points for the beam operation. Whereas, the room air temperature is the result of the heat gain in the space. Time-dependent internal loads result in time-dependent beam characteristics, such as cooling capacity and plume velocity. The airflow generated by passive beams has been described using simplified models and experimental flow visualization in few publications.

Many studies have characterized the interaction between buoyant sources of indoor air [6]. This research has been primarily focused on system designs of cooled ceilings coupled with displacement ventilation [5]. The thermal comfort of occupants exposed to buoyant flow conditions is an active area of research and the results from studies [7–10] show that the surface temperatures and locations of buoyancy sources in indoor spaces govern the airflow characteristics. Some studies of displacement ventilation

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systems using chilled ceilings isolate the variations in buoyancy sources responsible for airflow characteristic changes [7,11]. In one study [11], experiments were conducted to assess thermal comfort in offices with chilled ceilings and displacement ventilation. It was observed that at low ceiling temperatures (14 °C–16 °C) the combined system did not function with a stratified air distribution because of the disruptive convective currents caused by the natural convection at the ceiling. In spaces with more than one buoyancy source, the combined airflows were found to disrupt thermal comfort. Additional experiments were conducted to study the indoor air quality of a cooled ceiling ventilated by displacement compared to mixed air distribution [7]. The surface temperature of the cooled ceiling affected the room airflow by disrupting the displacement ventilation stratification and developed airflow patterns similar to the mixed air distribution in the occupancy zone. In another study, the magnitude of room air stratification was found to be dependent on the ratio to total cooling that the chilled ceiling removed [12].

In addition to the performance characteristics of combined systems and effects of thermal comfort, the interaction between buoyant airflow created by cooling equipment and heat loads has been studied. A scaled test room was used to study the interaction of convective currents and the relationship to thermal load intensity by visualizing the air distribution and by measurement of the air velocity over a range of heat loads generating thermal plumes from multiple sources along the floor [13]. The tests showed that at higher heat loads, the airflow pattern in the room became more turbulent than at lower heat load densities and was best characterized as a floor to ceiling vortex and that the maximum velocities recorded in the room increased proportionally with the recorded power input to the heat load. In a study of the thermal comfort of occupants in a room with active chilled beams, a test room was developed to measure the air temperature and velocity over a range of internal heat loads [14]. As heat loads increased, the non-uniformity of the thermal environment increased, which resulted in decreased thermal comfort. The study of the effect on occupant comfort in a room cooled with active chilled beams was continued by experimentally observing the air distribution in a test room with varying heat loads and air supply flow rates [10]. The effect of variations on the interior heat loads in a room cooled with active chilled beams was studied [8]. Solar loads from windows increase the local surface temperature on the floor creating convective airflow that in the experiments was observed to increase the air velocity of active chilled beam supply at the floor. Additionally, the position of the chilled beams in the ceiling was shown to significantly impact thermal comfort as the characteristics of the combined momentum and buoyancy sources of supply air jet and surface temperature convection were highly dependent on source location. The convective airflow patterns created by heat loads interacting with active chilled beam airflow was studied using computers, thermal manikins, lighting, and one window with a heated mat on the floor to simulate solar load [9]. The experimental results showed the maximum air velocity recorded in the room was proportional to the value of the total heat load in the space and also dependent on the heat load distribution through the room. In a similar study, the effect of internal loads on the airflow produced by chilled beams was studied with a simulated office test room [15]. Internal loads were simulated with computers, thermal manikins, lights, heated floor panels and one window. Smoke visualizations and temperature and velocity measurements showed that with heat loads above 56 W/m^2, the air distribution from the chilled beam was affected. The maximum velocities recorded in the space were shown to increase with the higher internal loads while the supply airflow rate was held constant. Additionally, the distribution of heat loads in the space was studied and found to affect the location of the maximum velocity but did not affect the magnitude of the maximum velocity.

For passive chilled beam installations that service stratified indoor environments where buoyancy determines the airflow patterns in the room, the buoyant flow indoor environments are characterized by low velocity airflow and non-uniform surface temperatures [2]. The few studies that have published the results of tested passive chilled beams have measured the thermal plume characteristics. The thermal plume created by an exposed passive chilled beam in an enclosed test room was studied using anemometers and thermocouples to characterize the velocity and temperature of the cooled air and the authors used thermal plume models to compare with the data captured from the experiments [16]. The application of the models to the experimental work showed an over-prediction of the thermal plume strength, defined by lower temperatures and higher velocities. Fluctuations in the plume location were attributed to the motion of thermals descending from the cooling coil. Using instability criterion theory and the calculated Rayleigh number of the air at the fins, the frequency of descending thermals was estimated to be 4 s. It was noted that the beam sensitivity to heat sources was a necessary continuation of the research. The thermal plume from heat loads directly underneath a passive beam was studied [17]. Using a simulated person at a workspace with a computer, positioned directly below or 0.5 m from the center of the beam, the results showed that the thermal plume from the beam was much stronger than the heat load plumes. The return openings in false ceilings were studied to access the impact on the cooling effectiveness of passive chilled beams [18]. The study found that the cooling effectiveness of the beam, the ratio of cooling delivered to heat generated in the space, was dependent on the area of return grating and the location.

More recently, several studies have focused on the operation and performance of passive chilled beams that have included incorporation with perforated ceilings [19] and for retrofit applications [20]. Additionally, models using computational fluid dynamics (CFD) have been developed to characterize the cooling capacity of passive chilled beams [21], [22]. The purpose of this study was to analyze passive chilled beam operation as effected by heat loads in the space. The main result of the project was a quantification of the effect of the heat load configuration on the passive chilled beam capacity and airflow characteristics of the plume. Experiments were conducted with a passive chilled beam and heat loads in a climatic chamber. Different spatial arrangements and types of heat loads were tested and the effect on the passive chilled beam capacity measured.

2. Methodology

2.1. Experimental setup

Experimental data was collected using a test chamber developed for the testing of chilled beams and radiant panels and featured temperature control and monitoring on each interior surface. The room was constructed with a 10.16 cm (4 in) layer of R-20 insulation, a 15.24 cm (6 in) air gap, radiant panels and a second 10.16 cm (4 in) layer of R-20 insulation, as listed from the exterior wall to the interior wall, as shown in Fig. 1. Temperature-controlled water was circulated through the radiant panel coils to provide a uniform and consistent surface temperature on the interior surfaces of the room. Each wall was designated as the North wall, East wall, South wall, or West wall. The opening shown in Fig. 1 was on the South wall.

The supply water was controlled with a direct digital control (DDC) valve adjusting the flow rate to the beam. A secondary loop