Energy and Buildings 43 (2011) 3082–3089

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Experimental and computational investigation into suppressing natural convection in chilled ceiling/displacement ventilation environments

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ARTICLE INFO

Article history:
Received 20 January 2010
Received in revised form 20 May 2011
Accepted 1 August 2011

Keywords:
Chilled ceiling
Displacement ventilation
Air distribution
Suppressing natural convection
Slats
CFD

ABSTRACT

The combination of chilled ceiling and displacement ventilation systems can cause destruction of the displacement flow pattern in some circumstances. This paper reports on the performance of a new technique for achieving stable conditions for displacement airflow in the presence of a chilled ceiling system. The technique is based on the attachment of a honeycomb slat system to the underside of a chilled ceiling, thereby suppressing downward cool natural convection. Investigations were carried out using both computational and experimental methods for a range of typical office environment conditions. The results showed that a slat depth to width ratio of 10 could suppress the natural convection by more than 80% when the Rayleigh number reached 7×10^6. This confirms that the technique is capable of minimising downward cool air currents, resulting in preservation of the displacement flow pattern in the presence of the chilled ceiling. The proposed slat system can raise the general air temperature in the space allowing some displacement flow pattern to occur. The outcome of this study is the emergence of a honeycomb slat-based approach for improving the performance, together with provision of general advice for designers as regards the combination of radiant cooling/displacement ventilation systems.

1. Introduction

Displacement ventilation is mainly characterised by buoyancy-driven airflow. In this system, low velocity air is supplied from a low level supply device in the occupied zone at a temperature slightly cooler than the design room temperature, in order to obtain the displacement effect. As a result of thermal comfort limitations given in BS EN ISO Standard 7730 [1] (namely that the vertical air temperature gradient should be less than 3 °C/m), a displacement ventilation system is limited to removing a convective load of up to 25 W/m^2 of floor area. However, a typical office might exceed 60 W/m^2 of heating load. Therefore, an additional cooling mechanism is required to meet this load, frequently a chilled ceiling. The chilled ceiling system provides an additional heat removal mechanism from the space of up to 100 W/m^2 [2]. In such a system, the ceiling temperature is maintained by circulating cooled water through pipe work. In principle, the combined system of displacement ventilation and chilled ceiling has the potential to remove the convective heat gains generated by people and equipment in the space with the chilled ceiling providing radiant cooling and reducing the overall temperature gradient by cooling air in the upper part of the room.

1.1. Combined chilled ceiling and displacement ventilation systems

Several researchers [3–7] have carried out work related to radiant cooling and displacement ventilation. Their results showed a number of features and potential advantages in common when both displacement ventilation and chilled ceiling are combined as one system. These advantages include the improved thermal comfort and the removal of higher heat loads of the order of 80 W/m^2 of floor area. Despite the advantages some problems have been reported, and await further investigation. These problems are related to destruction of the displacement flow pattern in the presence of the chilled ceiling system.

The warmer air from heat sources in a displacement ventilation environment will rise, will cool on contact with the chilled ceiling and will then fall as its density increases. This process promotes convective flows that result in mixing through the space. The effect, known as inversion, leads to an environment of poorer air quality and a failure to realise the enhanced comfort and air quality that these systems are individually claimed to bring. It has been shown that combination of chilled ceiling and displacement ventilation

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doi:10.1016/j.enbuild.2011.08.002

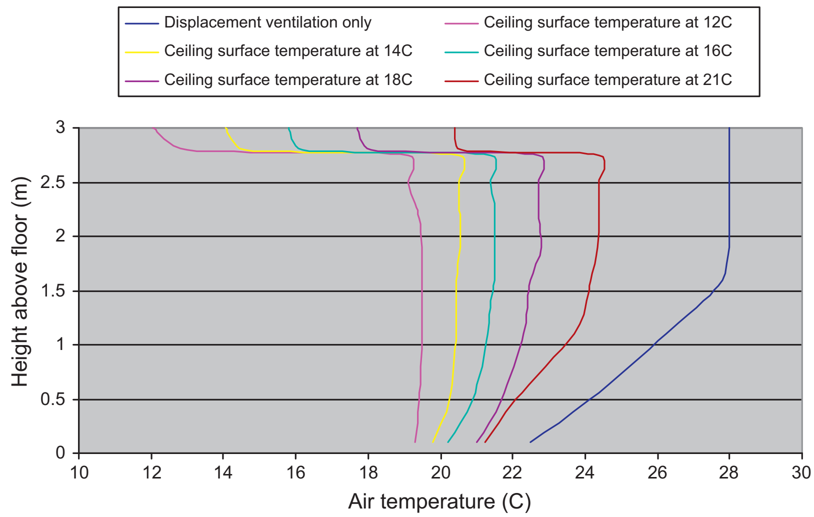

Fig. 1. Air temperature versus height above the floor for a range of ceiling temperatures at a heat load of 62 W/m^2 and ACH of 4 1/h.

systems could cause destruction of the displacement flow pattern at low ceiling temperatures of 14–16 °C. It can be clearly seen from Fig. 1, as reported by Taki et al. [7] that there is complete mixing of air throughout the room as shown by the vertical air temperature profiles from floor to ceiling. At higher ceiling temperatures of 18–21 °C, some displacement flow is still present but the stratified boundary layer is strongly suppressed. Thus, the combination of these systems could cause deterioration in air quality as a result of diminished displacement flow pattern, and that careful design is needed if this situation is to be avoided or minimised. Chilled ceilings and displacement ventilation systems can be successfully operated together only if the downward cold air currents are significantly minimised, thereby stabilising the room air flow. A new technique for achieving this is investigated and reported in this paper.

1.2. Objectives of present study

This paper aims to investigate (computationally and experimentally) a new technique for achieving stable conditions for displacement airflow, thereby ensuring that the combined arrangement can work together more effectively, while maintaining an aesthetically-pleasant interior. The technique proposed here is attachment of a 'slat'-type system to the chilled ceiling (see Figs. 2 and 3), thereby suppressing downward cold natural convection. The outcome of the study will be the provision of optimum depth to width ratio for the proposed honeycomb slat system which can suppress the natural convection at higher Rayleigh numbers for typical temperature difference between the chilled ceiling and the room air temperature.

2. Computational fluid dynamics (CFD) modelling

CFD modelling is the process of representing a fluid flow problem by mathematical equations based on the fundamental conservation laws of physics, and solving those equations to predict the variation of the relevant parameters within the flow field. Usually these could be velocity, pressure and temperature, and also concentrations of chemical species. These conservation laws can be expressed in terms of non-linear "elliptic" partial differential equations, the solutions of which provide the basis for the CFD model. The CFD models solve, numerically, the equations and produces field values for the temperature, velocity and the chemical species. The CFD code used in this study, 'Sabre-One', has the ability to perform advanced computation of three-dimensional airflow and temperature in and around enclosures (Wittles and Jones [8,9]).

2.1. The suitability of CFD code 'Sabre-One'

The CFD code 'Sabre-One' was initially used for prediction of temperature and flow fields within displacement ventilation environments only over a range of heat loads and at different heights above the floor. The Environmental Test Room facility based at

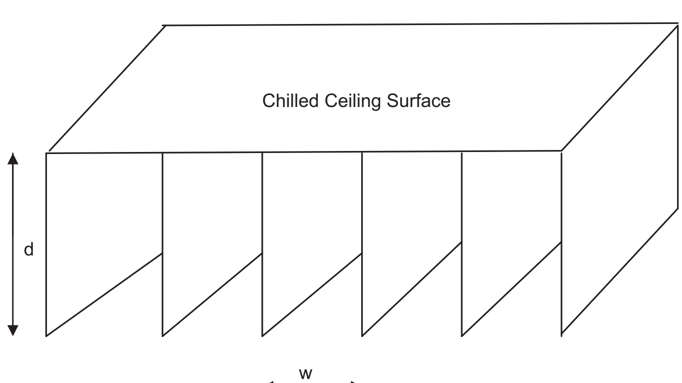

Fig. 2. Schematic of depth to width ratio (d/w) for the honeycomb slat. The top solid surface represents the chilled ceiling and the porous base represents the room environment.

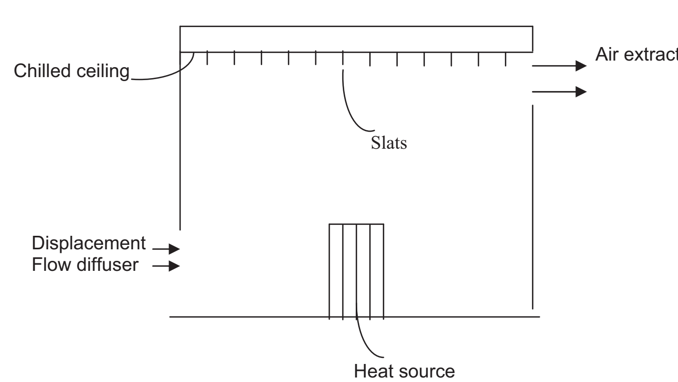

Fig. 3. Schematic diagram of the test room consisting of displacement ventilation and honeycomb slat system attached to the chilled ceiling environment.