Energy and Buildings 111 (2016) 87–97

Contents lists available at ScienceDirect

Energy and Buildings

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

Parametrical analysis on the diffuse ceiling ventilation by experimental and numerical studies

Chen Zhang*, Martin Heine Kristensen, Jakob Søland Jensen, Per Kvols Heiselberg, Rasmus Lund Jensen, Michal Pomianowski

Department of Civil Engineering, Aalborg University, Sofiendalsvej 11, Aalborg 9200, Denmark

ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
12 November 2015
Accepted 13 November 2015
Available online 18 November 2015

Keywords:
Diffuse ceiling ventilation
Thermal comfort
Design chart
Parametrical study
CFD

ABSTRACT

This paper aims to investigate the performance of diffuse ceiling ventilation in a classroom. An experimental study is carried out in a test chamber to examine the impact of diffuse ceiling opening area on the system cooling capacity and thermal comfort. The results indicate that diffuse ceiling ventilation provides a satisfied thermal comfort level in the occupied zone even under a high ventilation rate and a high heat load condition. A design chart method is adopted to compare different diffuse ceiling configurations, and the results indicate that the system with a 18% diffuse ceiling opening area is able to handle the highest heat load without discomfort. On the other hand, a CFD model is built where the diffuse ceiling is simulated with a porous media zone. This model is validated by experimental results and further used to analyze the effect of heat load distribution and room height. The numerical results reveal that even distribution of heat sources gives a lower draught risk environment than centralized distribution. In addition, there is a significant increase on the draught risk with increase of room height.

1. Introduction

Nowadays, the most widely used ventilation systems in school buildings are mixing ventilation and displacement ventilation. In mixing ventilation, air is supplied to the room with high initial velocity and turbulence, which promotes good mixing with uniform temperature and pollution distribution in the occupied zone. On the contrary, the principle of displacement ventilation is to replace but not to mix the room air with fresh air, where the fresh and cold air is supplied close to the floor. Consequently, the highest velocity and the lowest temperature occur near the floor, and there is a vertical temperature gradient in the room [1]. Due to the concentrated flow through the inlets, draught problem always occurs in these two ventilation systems when high ventilation rate is required and air is supplied with low temperature [2]. As reported by Jacobs [3], high draught risk often leads to insufficient ventilation and poor air quality in the classroom. The indoor environment of classrooms has significant impact on pupils' health and learning efficiency. A recent study found that more than half of school children have some kind of allergy or asthma in the traditional school buildings [4]. In addition, with a widespread study of Danish school, Toftum et al. [5] concluded that there is a strong association between classroom ventilation mode and learning outcome.

A novel ventilation concept was proposed recently, named as diffuse ceiling ventilation. In this air distribution system, the space above a suspended ceiling is used as a plenum and fresh air is supplied into the occupied zone through perforations in the suspended ceiling panels. Due to the large opening area, air is delivered into the occupied zone with very low velocity and with no fixed jet direction, hence the name 'diffuse'. Diffuse ceiling ventilation was widely used in livestock buildings due to its low investment cost and high thermal comfort level [6,7]. Recently, there has been a growing focus on the application of diffuse ceiling concept in indoor spaces for humans, especially for offices and classrooms with intense heat loads and high ventilation demands.

Nielsen et al. [8,9] investigated the performance of diffuse ceiling ventilation in an office room and compared it with five other air distribution systems. Their investigation showed that diffuse ceiling ventilation presented superior performance on handling high heat loads with low draught risk in the occupied zone. Hviid et al. [10] performed an experimental study in a climate chamber with two types of diffuse ceiling panels. The results were in good agreement with those of Nielsen that no local discomfort in the occupant zone was observed and the temperature and ventilation effectiveness were comparable to mixing ventilation. On the other hand,

* Corresponding author at: Aalborg University, Sofiendalsvej 11, Aalborg 9200 , Denmark. Tel.: +45 9940 7232.
E-mail address: cz@civil.aau.dk (C. Zhang).

http://dx.doi.org/10.1016/j.enbuild.2015.11.041
0378-7788/

they pointed out that a low pressure drop of 0.5 Pa to 1.5 Pa was enough to sustain the pressure of the plenum which ensured unidirectional flow through diffuse ceiling and there was a radiation cooling potential of the diffuse ceiling. The other advantages such as modest investment costs, low energy consumption and low noise level were reported by Jacobs et al. [2] with a pilot study in a Dutch classroom.

The previous studies have proved that buoyancy flow generated by heat sources is the dominant flow in a room with diffuse ceiling ventilation [10–12]. Because of the low impulse supply flow, the mixing in the room is dependent on the buoyance force. A tendency of displacement effect occurs at low heat loads and a development towards fully mixing with increasing heat load, as reported by Petersen [13]. Venkatasubbaiah et al. [14,15] conducted intensive studies on the buoyancy-induced flow in the ceiling vented room, and they revealed that flow behavior is significant influenced by the size and location of heat source. This finding was verified by Choder et al. [16] via an experimental study. They observed that equally distributed heat sources enable a higher cooling capacity of diffuse ceiling ventilation than the other heat sources locations, and that heat sources placed at floor level give a higher draught risk than if placed in the upper zone. Nielsen [17] further proved the benefit of an even distribution of heat sources and mentioned that the geometry of a room also impacts the performance of a diffuse ceiling ventilation.

Unlike the momentum driven ventilation systems, the inlet opening of diffuse ceiling ventilation is more flexible. As mentioned by Zhang et al. [18], the diffuse ceiling inlet can be divided into three types based on their air path. The air can be either supplied through the connection slots between ceiling panels (crack flow), or through perforations in the ceiling panels, or a combination of these two paths. In addition, the inlet can either occupy the whole ceiling area or part of the ceiling. However, the impacts of different air path and diffuse ceiling opening area on the system performance have not been discussed in detail in the previous studies.

This paper will conduct a parameter study on the supply opening area of diffuse ceiling with a full-scale experiment of a classroom layout. Besides thermal comfort evaluation, a design chart method is applied to compare different diffuse ceiling configurations and to find the optimal solution. Furthermore, a numerical model is built and validated by the experimental results. The validated CFD model is further used to analyze the effect of heat load locations and room height on the airflow pattern and draught risk in the room with diffuse ceiling ventilation.

Fig. 1. Cement-wood ceiling panel.

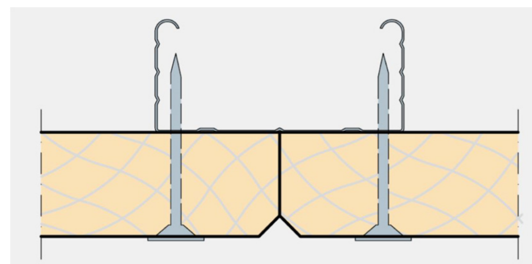

Fig. 2. Suspension system of diffuse ceiling.

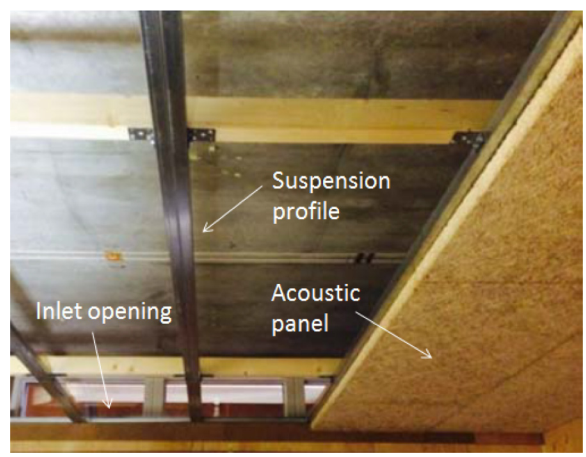

Fig. 3. Diffuse ceiling setup.

2. Experimental study

2.1. Diffuse ceiling and its physical properties

In this study, the diffuse ceiling is made by cement-wood panels, which are originally for acoustic purpose, as shown in Fig. 1. Each panel has a dimension of 35 mm in thickness, 600 mm in width and 1200 mm in length. The density of the ceiling panel is measured to be 359 kg/m^3. The porosity is estimated through volumetric measurement, which is 65%. The thermal conductivity is measured by λ-Meter EP500 based on a guarded hot plate method, and the value is 0.085 W/m K with a measurement error less than 1.0%.

The ceiling panels are installed in the test room with a specific suspension system, as illustrated in Fig. 2. Because of the non-overlapping layout of the panels, it could be predicted that the air is supplied through both perforations in the panels and the slots between the panels. The amount of panel flow and crack flow can be evaluated by a pressure drop measurement.

2.2. Test chamber

The experiments are carried out in a climate chamber with an inner dimension of 4.8 m × 3.3 m × 2.72 m (length × width × height), which is located at Aalborg University, Denmark. The test chamber is well-insulated and surrounded by a guarded zone with the purpose of reducing the heat gain or heat loss from the outside laboratory. The diffuse ceiling is installed 0.35 m below concrete slabs with the specific suspension system, as illustrated in Fig. 3. The diffuse ceiling panels cover the entire ceiling area and separate the space into two zones: a plenum and a conditioned space. The air is supplied into the plenum through three small windows located above the diffuse ceiling, with a total geometric opening area of 0.0675 m^2. The exhaust is mounted 80 mm below the diffuse ceiling in the wall opposite to the inlet, see Fig. 4. The air is drawn from the test chamber into a connected cold chamber by means of an exhaust fan, and the air will be re-supplied into the test chamber after it is conditioned by an air-handling unit located inside the cold chamber.