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The effect of typical buoyant flow elements and heat load combinations on room air temperature profile with displacement ventilation

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ABSTRACT

Typically vertical temperature gradient is modelled to be linear over the room height. More advanced models consist of several nodes that allow different slopes for the temperature profile between the nodes. Validation and development of all those models have been based mainly on measurement using low ceiling height (below 3 m). Also, the previous studies have not covered typical flow elements that exist in office buildings. In this study, the performance of a displacement ventilation system is studied using 3.3 m and 5.1 m ceiling heights in a variety of load conditions. Typical buoyant flow elements and heat load combinations were measured in a simulated office room. The experimental study included room air temperature measurements at different heights and locations over the occupied zone in addition to surface measurement and supply and exhaust air temperature measurements. The measurement data was compared with current models. The results show that the major part of the vertical temperature gradient occurs already at low level. With some typical buoyant flow elements there is no benefit if the ceiling is lower or higher level. Also, measurements depict that modelled non-dimensional temperature profile using low ceiling height (about 3 m) is not valid for high ceiling applications (more than 4 m). Multi-node models works quite well with several buoyant flow elements. Still, the proposed multi-node models did not give good estimation of the vertical temperature gradient when warm window surface or heat gains at ceiling level were introduced in the room space.

1. Introduction

Displacement ventilation (DV) is based on low velocity cool air supply near floor level and it is characterized by a two layer structure (stratified and mixed) as result of the natural buoyancy forces. The buoyancy forces are induced by temperature difference between supply and room air temperature. The colder air supply spread over the floor until it reaches a heat source, then an upward convective flow called thermal plume is created. The air movement induced by thermal plumes, from low to high level, is capable to transport heat and pollutants above the occupied zone, promoting a vertical temperature and contaminants stratification.

The transition level between mixed upper layer and stratified layer is called the neutral height corresponding to the height where the supply airflow rate matches the airflow induced by the thermal plumes. Controlling the neutral height position is one of the most challenging tasks in DV system design [1]. Based on the main assumptions of the classical plume theory by Morton et al. [2] and Baines and Turner [3] proposed the filling box model which describes the production of a stable stratification by a buoyant plume in a closed container. This concept was applied by Linden [4] for the buoyancy-driven displacement ventilation and developed by Cooper and Linden [5] for two point and multiple point sources by Linden and [6]. Multi-layer stratification model for displacement ventilation was also presented by Chen et al. [7] and Li [8].

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The methods to calculate the neutral height above a heat source were introduced by Morton et al. [2], Mundt [9] and Nielsen [10].

The increase of the supply airflow rate raises the neutral height by raising the point where the total thermal plume flow matches the inflow. Two different approaches can be used to control the supply air flow rate: 1) temperature based design where the room air temperature in the occupied zone is the design criteria and 2) air quality based design where air quality is the design criteria and contaminant is let to stratify over the occupied zone.

The design of displacement ventilation is descripted in REHVA's design guide [1]. Air quality based design is typically used in industrial applications where the contaminant stratification is playing an important role. Also in office applications, displacement air distribution may perform better than mixing air distribution because the free convection layer around human body is less disturbed and its ability to transport clean air from the lower room level to the breathing zone can be better utilised. It should be noted that only contaminant sources with heat production can be treated effectively by displacement ventilation [11]. However, the ability of displacement air distribution to provide clean air for breathing depends on several other factors (type and location of heat sources, movement of occupants, etc.) [12–15].

In commercial building where the cooling is the main issue, the temperature based design is the most common method. In this paper, the focus is on commercial buildings where thermal comfort is the main concern.

In design process, the challenging task is to predict vertical contaminant or temperature gradient in the room space. While the contaminant stratification level is mainly affected by the relation of supply air flow rate and convective air flow rate, thermal stratification is also affected by thermal radiation exchange between different room surfaces [16]. The thermal radiation from upper level surfaces warms up lower level surfaces and consequently the air temperature at floor level and in the occupied zone get higher.

The first displacement ventilation design methods applicable for manual calculations are based on the empirical coefficients and nomograms, in which the influence of the thermal radiation exchange between upper and lower part of the room is built in. Such methods are presented as an example by Skistad [11] and Halton [17]. The value of these methods is their ease of use and also the accuracy of the estimation especially in industrial type of applications.

Nowadays, it is more common to use simulation software where the vertical contaminant and temperature gradients are modelled. In some models, vertical temperature gradient is modelled to be linear over the room height. Linear temperature modelling with two room air nodes has proposed by Mundt [9], Arens [18] and Nielsen [19].

Temperature based design methodology where the space is divided into zones: lower part occupied zone and the upper unoccupied zone is introduced by Livchak and Nall [21]. The heat gains are split into two zones according their type and locations. In the model, the radiation between upper and lower zones is also taken into account when the room zones air temperatures are iteratively solved.

ASHRAE Research Project (Chen et al. [22]) and the procedure outlined by Chen and Glicksman [23] provides an approach to determine the required supply air flow rate and supply air temperature by using fractional coefficients that are introduced for three selected heat gains. The fractional coefficients set the ratio of the convective heat gain that is released in the room space between the head and foot through convection.

Multi-nodes models have introduced a possibility to use different slopes for the temperature profile between the nodes. Models of three nodes has proposed by Li et al. [24], da Graça [25] and Mateus and da Graça [26]. Multi-nodes model where air jet and thermal flow elements are applied to track individual air jets from heat or mass sources has been introduced by Erikson et al. [27]. Multi-zone models where air flow rates between the nodes are predefined by a CFD method has also proposed (Rees [28] and Griffith [29]).

A lot of studies on displacement ventilation are devoted to analyze the performance of the combination of displacement ventilation and chilled ceilings (Alamdari [30], Novoselac et al. [31], Rees and Haves [32], Rees and Haves [33] and Mateus et al. [34]) and floor heating (Wu [35,36]).

While nodal models require less computation time compared with CFD simulations, they are more suitable for engineering calculations and therefore they could be added to whole building simulations. Some nodal models are currently available in thermal energy simulation tools. For example Rees model can be used with ESP-r (Hensen and Hamelinck [37]). Mundt [9] and da Graça [25] models are implemented in EnergyPlus [38] and Mundt [9] and Erikson et al. [27] are applied in IDA ICE [39]).

In the previous studies, the physical measurements using buoyant flow elements and combinations of heat gains have been carried out in laboratories of relatively low ceiling i.e. ceiling height of 3 m or below. For typical displacement applications having high ceiling height (ranging from 4 to 6 m), the non-dimensionless temperature approach has been introduced.

In this study, the performance of a displacement ventilation system is studied using 3.3 m and 5.1 m ceiling heights in a variety of load conditions. Typical buoyant flow elements and heat load combinations were measured in a simulated office room. By using the measurement data, typical models that are used in temperature based design are validated.

2. Experimental measurements

The test setup consists of three displacement diffusers and a ceiling exhaust. in a well-insulated room (100 mm polystyrene) having a floor area of 20.7 m^2 (4.6 m × 4.6 m). The performance was studied using two room heights of 5.1 m and 3.3 m. In Fig 1, there is shown the location of heat gains, supply units, exhaust unit, heated foils on floor and ceiling. Fig. 2 shows the marked the locations of room air temperature measurement poles (P1-P4) and the numbered heat dummies and computer simulators. The used computer simulators are made of non-painted galvanized steel. Personal dummies are respectively made of galvanized steel and also painted grey. The personal dummy is made according EN 14240 standard [40] where the cooling load simulator of person is described. The computer simulators are selected instead of real computer because of their simplicity to simulate the combination of flat screen and lap top computer. The breakdown of convective and radiant heat flux of the both simulators are about 50/50%.

The internal heat loads (Table 1) consist of heated cylinders representing people, heated cube-shaped boxes representing computers, fluorescent lighting units, heated foils on the wall, ceiling and floor representing solar load through window at different levels and also on roof and floor. Full-scale tests have been carried out in steady state conditions.

The measured single buoyant flow elements and the combinations of heat gains are presented in Tables 2 and 3 where the supply air temperatures and air flow rates are also presented. The total loads (from 982 W to 1762 W) presented in Table 3 cover the specific cooling load of 47.4–85.1 W/floor-m^2. Representing the heat gain level quite typical in the modern sustainable offices [41]. The combinations of heat gain shown in Table 3 describes typical loads in office workspace and meeting room.

Vertical temperature profiles are measured from four locations