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Investigation of the displacement effect of a diffuse ceiling ventilation system

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ABSTRACT

This paper reports on an experimental and analytical investigation on the potential displacement effect of a diffuse ceiling ventilation system. Experimental data was generated in a test chamber where measurements of four test series were conducted for two different placements of the exhaust. Furthermore, CFD calculations were performed to support the analysis of the experimental results. The results show that tendencies known from conventional displacement ventilation occur at low heat loads and a development towards full mixing with increasing heat load. It has been demonstrated that the vertical air velocity profiles, temperature distribution and ventilation effectiveness are independent of the Archimedes number.

1. Introduction

Diffuse ceiling ventilation (DIFCV) is a ventilation concept for building ventilation where the space above a suspended ceiling (plenum) is used as a pressure chamber to supply fresh air to the occupancy zone through perforations and cracks in the suspended ceiling. DIFCV systems have been demonstrated to be on par with, and even outperform, conventional air distribution systems with regard to ventilation effectiveness and draught risk in laboratory experiments imitating office spaces [1–3] and a class room [4]. Similar tendencies have also been reported in field studies of classrooms [5–7]. Furthermore, Hviid and Petersen [8] demonstrated that diffuse ceiling ventilation may improve the thermal climate of a classroom by increasing its night cooling potential.

Despite of these promising results, there is still a need for further investigations on a number of issues to fully understand the potentials and limitations of the DIFCV ventilation concept. One of these issues is the observed tendency towards displacement ventilation [4,7]. Numerical studies by Hviid and Svendsen [4] show that sudden drops of cold inlet air to the floor of the occupancy zone may occur at the areas near the ventilation inlet to the plenum or in areas without buoyancy from heat sources. This could explain a certain displacement effect, but the numerical findings were not confirmed by their experimental studies. To the knowledge of the authors, the current literature does not hold any experimentally confirmed explanations for the observed displacement effect. This lack of knowledge is the reason for the experimental investigations on the potential displacement effect of a DIFCV system reported in this paper.

2. Methods

The ventilation effectiveness of conventional displacement ventilation is highly dependent on the placement of the exhaust. Data for investigating the potential displacement effect of a DIFCV system was therefore generated in an experimental setup where measurements of four test series were conducted for two different placements of the exhaust. Furthermore, CFD calculations were performed to validate measurements and to support the analysis of the experimental results.

2.1. Experimental investigation

2.1.1. Test series

The velocity of the air entering a room with DIFCV is small and has therefore a low impulse. The current recognition is therefore that the air flow pattern in rooms with DIFCV is not governed by inertia-driven (forced) convection as in conventional mixing distribution systems but by the buoyancy-driven (natural) convection generated by heat sources in the room [1,4]. Therefore it seems

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Table 1
List of the four test series and their three associated combinations of air change rate and temperature difference with approximately the same Archimedes number.

Test series	Combination name	*Ar* [–]	Air flow rate [m³/h]	Air change rate [h⁻¹]	$\Delta T = T_a - T_i$ [K]
	T.1.0	351,815	33	1.2	3
T.1	T.1.1	351,539	54	2.0	8
	T.1.2	375,398	64	2.4	12
	T.2.0	78,451	70	2.6	3
T.2	T.2.1	64,568	126	4.7	8
	T.2.2	71,157	147	5.5	12
	T.3.0	36,234	103	3.8	3
T.3	T.3.1	29,951	185	6.9	8
	T.3.2	32,645	217	8.1	12
	T.4.0	14,292	164	6.1	3
T.4	T.4.1	11,941	293	10.9	8
	T.4.2	11,997	358	13.4	12

reasonable to assume that the flow regime in rooms with DIFCV systems is governed by the Grashof number rather than the Reynolds number. Following the line of this assumption, the potential displacement effect in DIFCV systems may be dependent on the size of the Archimedes number (*Ar*), i.e. the relation between buoyancy forces and inertia forces, expressed as:

$$Ar = \frac{H \cdot g \cdot (T_a - T_i)}{T_a \cdot v_i^2} \quad (1)$$

where H is the room height (m), g is the gravitational acceleration (m/s²), T_a is the average room air temperature (K), T_i is the inlet air temperature to the occupied zone (K), and v_i is the inlet air velocity (m/s).

Four test series with different Archimedes numbers were designed to investigate whether a governing buoyancy force could be the reason for any observed displacement effect. In this design situation, it is difficult to determine the change of the inlet air temperature to the plenum as it penetrates the suspended ceiling. For practical reasons, it is therefore suggested that the determinable inlet air temperature to the plenum is used as a reasonable approximation of T_i. v_i is also difficult determine because all or a significant part of the fresh air enters the occupied zone through unevenly distributed cracks of unknown size. Furthermore, v_i may vary cross the ceiling as the crack sizes vary slightly across the ceiling. For practical reasons, it is suggested that v_i in a design situation can be approximated as:

$$v_i = \frac{q}{A_i} \quad (2)$$

where q is the air flow rate (m³/s) and A_i is the area of the suspended ceiling (m²).

Eqs. (1) and (2) were used to define three combinations of air flow rate and inlet air temperature at a constant T_a of 23 °C, i.e. a total of 12 combinations in each test series. The purpose was to identify any similarities in the distribution of temperature, flow pattern and air change effectiveness within the different combinations with the same Archimedes number. The design conditions of the four test series and their combinations are listed in Table 1. However, it was practically impossible to establish the exact combinations, mainly due to the unstable wind conditions at the test chamber. The actual combinations of air flow rate and inlet air temperature in the individual experiment were therefore slightly different, but the Archimedes numbers were still within the same range as designed.

All four test series were executed twice for the two different placements of the exhaust described in Section 2.1.2. In the first execution, air temperatures and velocities were measured as described in Section 2.1.3. In the second execution, the air change effectiveness was measured as described in Section 2.1.4.

2.1.2. The test chamber

The test series were executed in an outdoor, on-ground test chamber located at Aarhus University School of Engineering in Denmark. The full setup of the test chamber is illustrated in Figs. 1 and 2.

The test chamber was a thermally insulated box with fully controlled mechanical ventilation including control of the inlet air temperature to the plenum. The inlet was located in the centre of the room above a suspended ceiling. The suspended ceiling was installed and consisted of acoustic plates mounted in an aluminium profile suspended from the deck with steel wires. The intention of this ceiling design was to have air from the plenum entering the room through cracks between the horizontal aluminium profile and the acoustic plates. Two outlets were located in the wall next to the door: one just below the suspended ceiling and one just above the floor. The outlets could be activated one at the time. The exhaust air was directly discharged to the outside.

The thermal loads consisted of four 160 W point heat sources. The point heat sources were placed in the north end of the room away from the south-facing windows. This placement was chosen to make ideal conditions for any displacement effect to occur. The windows were screened with wooden panels to rule out the thermal disturbance of solar heat gain on the experiments. A 200 W/m² controllable underfloor heating loop was placed beneath the point heat sources with the sole purpose of maintaining the overall heat balance in the chamber during the experiments.

2.1.3. Control and measurement of ventilation rate

The ventilation rate of the test chamber was controlled using dampers with differential pressure transmitters placed in the inlet and outlet ducts. The dampers had a recommended range of 70–1000 m³/h. Ventilation rates below 70 m³/h were possible but would increase the risk of unstable ventilation rates. The

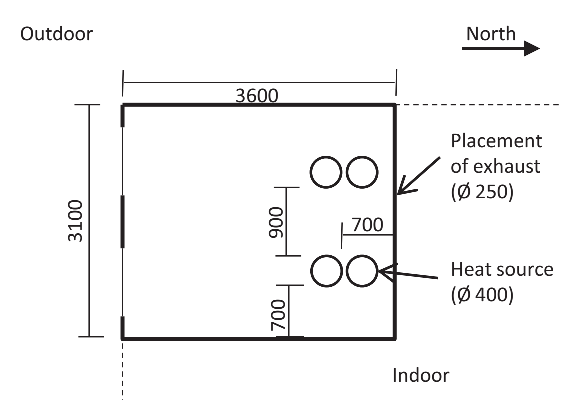

Fig. 1. Illustration of the test chamber dimensions and setup. The room height is 2.4 m. The windows in the south façade were screened with wooden panels.