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The impact of the air distribution method in ventilated rooms on the aerosol particle dispersion and removal: The experimental approach

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ABSTRACT

The ventilation strategy, air distribution method and air change rate may affect building energy consumption significantly. However, this strategy is also related to contaminant dispersion, its removal efficiency and the risk of cross-infection in buildings. In this study, the effects of air distribution methods on aerosol particle behaviour in a ventilated room have been experimentally tested. Experiments were conducted in a full-scale test chamber with the source of contaminant (a nebulised solution of sodium chloride) positioned at the air supply and air exhaust sides. Displacement ventilation and mixing ventilation with one-way and four-way air supply through ceiling diffusers were tested at 1, 2, 3 and 4 air changes per hour. The concentration of particles was monitored within 10 min after the injection using six optical particle counters located in one plane section of the room. Aerosol particle decay was used for calculating the age of the air and analysing the ventilation efficiency. Computational fluid dynamics (CFD) predictions were performed to determine the spatial particle dispersion in the room and were compared to the results of the experiment.

Experimental results showed that at lower air change rates, one-way mixing ventilation directed particles towards air exhaust diffusers more efficiently, while four-way mixing ventilation enabled more particles to remain airborne. At higher air exchange rates (3 and 4 ach), mixing ventilation with one-way air supply prevented aerosol particle transport to the opposite side of the room. The displacement air distribution appeared to be rather inefficient in the removal of particles from the chamber, which was reflected by the relatively high age of the air (of average 16.7 s at 3–4 ach) compared to the mixing ventilation (of average 9.9 s at 3–4 ach).

1. Introduction

Various air distribution methods are used in rooms to ensure good indoor air quality (IAQ) and removal of particles from the zones occupied by people. Indoor aerosol may be of various origins, including fuel burning, food preparation and clean-up activities. Biological particles are of special interest due to their adverse effects on human health; thus, most studies on aerosol dispersion in ventilated spaces investigated bioaerosols. In 2003, the SARS outbreak revealed a need for proficient ventilation systems followed by the outbreak of the H1N1 virus in 2009–2010, thereby causing an influenza pandemic [1,2].

The effects of various ventilation regimes on the dispersion of aerosol particles were studied by several researchers. Yin et al. [3] investigated the transportation of particles generated by simulated coughing and breathing and evaluated the performance of mixing (with a four-way overhead air supply diffuser) and displacement ventilation in a full-scale chamber. In the case of mixing ventilation, the differences in the contaminant distribution patterns were insignificant, depending on the intensity of the contaminant source. In the case of displacement ventilation, a significantly higher concentration of the contaminant in the upper part of the room was registered. Higher concentration of contaminants in the case of displacement ventilation was also registered by Olmedo et al. [4]. Lindsley et al. presented a laboratory study simulating a patient's coughing represented by aerosol particles (optical diameters from 0.3 to 7.5 μm) analysed together with the breathing rate, room ventilation, and the locations of the coughing and breathing simulators [5]. Cough aerosols were initially carried in a plume capable of

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travelling across a room, and after several minutes, aerosol particles were dispersed throughout the room. The coughing orientation also proved to be an important factor in aerosol transport [6]. The size of the aerosol particles is an important factor as well. For example, the unidirectional-upwards system was found to be more efficient in removing the smallest droplet nuclei by air extraction, but it became less effective for larger droplets and droplet nuclei [7].

Computational fluid dynamics (CFD) simulation tools have been frequently utilised for the simulation of the transportation of contaminants with ventilation flows [8–12]. These studies are capable of indicating various factors responsible for aerosol dispersion, as well as examining the source and airflow characteristics of the room that are driven by ventilation and temperature gradients. It also allowed for the comparison of different ventilation techniques. For example, Lin et al. revealed that particle concentrations in the breathing zone were significantly lower under stratum ventilation compared to displacement ventilation [13].

The reviewed studies reveal the complexity of the processes occurring in ventilated rooms and aerosol removal. Most experimental studies relied on the measurements of low spatial resolution and not simultaneous measurements of aerosol concentration in space, thus suffering from not providing a detailed outlook on the real-time processes. While CFD provides highly time- and space-resolved simulations, laboratory measurements are also valuable because they present real fluids and particle dispersion mechanisms.

Many scientific investigation and several theories have been presented to ensure good air quality, efficient HVAC work and the minimisation of energy use. Nilsson [14] stated that two major barriers to ensuring an efficient system design are the lack of performance specifications when procuring systems and the incentive structure in the building sector.

Yu et al. [15,16] presented a study on an integrating air-handling unit (IAHU), which coordinates the AHUs based on the dynamic outside air conditions and system operation modes to achieve synergised energy performance and maintain indoor air quality.

Energy savings can also be achieved with sensor-based demand-controlled ventilation (SBDCV). Fisk and De Almeida [17] suggested that SBDCV produces significant energy savings with a typical payback period of several years.

Hekmat el al. [18] compared the impact of five different ventilation strategies (natural ventilation, balanced ventilation with an air-to-air heat exchanger, exhaust ventilation without heat recovery, exhaust ventilation connected to a heat pump to provide space heating, and exhaust ventilation connected to a heat pump to heat domestic water) on the overall energy consumption of houses. The results showed that the total energy consumption can be reduced by 9 to 21% using mechanical ventilation systems with heat recovery and that houses with mechanical ventilation systems have better indoor air quality.

Montgomery et al. [19] investigated the energy use and operation cost of HVAC air filters. It was found that the concentration of particles in the air stream and the cost of electricity had the largest effect on the annual cost of operation.

Mentioned studies confirm that different methods with various control techniques can be used to increase energy efficiency. At the same time, it is important to calculate the amount of energy that can be saved parallel with insurance of IAQ. This consideration is very important for hospitals, where different contaminants are released by patients [20].

The selection of a ventilation strategy and air distribution method, as well as the air change rate, may affect both building energy consumption and indoor environmental health. The aim of this paper was to examine the effect of various air supply strategies on the dispersion of aerosol particles in a full-scale test chamber by utilising highly time and size resolved measurements of aerosol concentration. The effectiveness of certain ventilation strategies were evaluated by several calculated indicators, such as the age of air and the particle removal efficiency.

2. Methods

2.1. Test chamber and experiment design

A test chamber (the floor area of 13 m^2 and a volume of 35.8 m^3) representing a standard room/office was used as a model space for particle dispersion analysis. The walls, floor and ceiling of the chamber were fabricated using conventional construction materials, such as painted dry-wall, PVC lining and a panel ceiling. The chamber was equipped with an air supply system, consisting of in-ceiling diffusers for mixing air supply and low air supply velocity wall diffusers for displacement ventilation. In-ceiling air exhaust diffusers were installed on the opposite side of the chamber (Fig. 1). The chamber was installed in the laboratory with the constant air temperature of approximately +22 °C. Air temperature in the chamber was controlled using the air handling unit (GOLD 04, Swegon AB, Sweden). The temperature of the supplied air was +21 °C in the case of mixing ventilation and +19 °C in the case of displacement ventilation. The exhaust air temperature was approximately equal to the air supply temperature in the case of mixing ventilation and $+22 \pm 0.5\,°C$ in the case of displacement ventilation.

The cross-section of the chamber representing the locations of the diffusers and particle counters is shown in Fig. 2. Air distribution patterns were tested before the experiments by using the smoke, and the plane for analysis was selected accordingly. In the case of displacement ventilation, air was distributed at a lower level of the chamber and moved upwards. This pattern was uniform for the whole test chamber. The assumption was made that the plane was representative of both mixing and displacement ventilation cases, although the heat source was present in the chamber during experiments with displacement ventilation only.

The following variables were utilised: air distribution type (mixing ventilation with one-way air supply, mixing ventilation with four-way air supply, displacement ventilation), air exchange rate (1, 2, 3, and 4 ach), and the location of pollution source both at the side of the air supply diffusers and air exhaust diffusers.

Two multi-nozzle air supply diffusers of 0.5×0.5 m with plenum boxes were used for the air supply in the mixing ventilation cases. One-way mixing air supply was achieved by directing all of the 47 nozzles of the diffuser towards the closest wall. The four-way mixing was created by directing the nozzles in four directions. The displacement air supply was organised by directing air flow via a wall-mounted, semi-circular, low velocity air supply diffuser. The height of the used diffuser and the grille area was 0.55 m and 0.28 m^2, respectively. In the case of displacement ventilation, a heating device was installed in the centre of the test chamber to create a vertical temperature gradient of approximately 1 °C/m (Fig. 1); therefore, a stable air distribution pattern in the case of displacement ventilation was achieved.

The amount of air supplied to the chamber was regulated by the air handling unit and was set to 1–4 ach for the mixing air supply and 3–4 ach for the displacement air supply.

The release of a contaminant was simulated by supplying aerosol at two locations: A—located at the same side as air supply, and B—located on the opposite side of the air supply. An aerosol injection port was installed in the wall of the test chamber and the aerosol injection direction was perpendicular to the wall surface. The port represented a cough and breathing of a person without simulating an actual aerosol injecting object, such as a manikin. The setup was designed as a controlled environment to isolate the effects of additional factors.