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The effects of ventilation and floor heating systems on the dispersion and deposition of fine particles in an enclosed environment

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ABSTRACT

Recent years, most cities in China suffer from ambient particulate matter pollution, especially in winter. The absence of fresh air system in most northern heating buildings in winter results in the poor indoor air quality. This work aims to deal with the particle dispersion in a ventilated and floor-heated indoor environment by using experimental measurements and computational fluid dynamics (CFD) methods. Two ventilation systems were considered, i.e., top & down supply. Firstly, experiments were conducted to validate the velocity and particle concentrations by CFD simulation. Secondly, unsteady particles (with the diameter of 1 μm) dispersion was simulated with different inlet velocities (i.e., 0.3, 0.4 and 0.5 m/s) and floor temperatures (i.e., 293, 298, 303 and 308 K) in a ventilated and floor-heated chamber. Lagrangian method was employed for particles tracking. It is found that the higher the inlet velocity, the faster particle concentration decayed. For the same inlet velocity, particles in the chamber were removed faster with the increase of floor temperature. When the inlet velocity was 0.5 m/s and the floor temperatures were 293 and 308 K, it took 391s and 200s respectively for normalized concentration decreasing to 0.1. The number of particles deposited on the floor decreased with the increase of the inlet velocity and the floor temperature. This study also identifies that when the floor temperature was 308 K, the removing time is reduced by 15% for normalized particle concentration with the down-supply ventilation mode. These findings would be facilitating for the future design of ventilation and heating systems.

1. Introduction

People spend more than 80% of time indoors [1]. It is important to ensure good indoor air quality for people's health. Epidemiologic studies show that exposure to aerosol particles has adverse effects on people's health [2–4]. These adverse effects include respiratory diseases, lung diseases, asthma attacks, heart attacks etc. Therefore, more attention should be paid to improve indoor air quality. There are many sources of indoor particles such as cooking, smoking and infiltration [5–8]. Annesi-Maesano et al. [9] investigated the relationship between indoor air quality (IAQ) in classrooms and respiratory health of schoolchildren. Concentration of fine particles with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$), nitrogen dioxide (NO_2) and three aldehydes were assessed in 401 randomly chosen classrooms. The results showed that children were differently exposed to poor air quality in classrooms and an increased prevalence of past year asthma was found in the classrooms with high levels of $PM_{2.5}$. Therefore, it is of great importance to have good indoor air quality.

In recent years, most cities in China are suffering from severe atmospheric particulate pollution especially in winter [10–12]. Yang et al. investigated [13] airborne fine particulate pollution in Jinan. Daily $PM_{2.5}$ samples were collected at an urban site and a rural site from March 2006 to February 2007. The annual average concentrations of $PM_{2.5}$ were 148.71 μg/m³ and 97.59 μg/m³ at urban and rural sites, respectively. Wei Li et al. [14] measured atmospheric PM_{10} for 18 sites over 12 months. Their results showed that annual mean PM_{10} concentrations in urban, rural village and rural field sites were 180 ± 171, 182 ± 154 and 128 ± 89 μg/m³, respectively. They also found that particulate air pollution was much higher in winter and spring than that in summer and fall. During the particulate pollution episodes occurred in northern China in January 2013, hourly maximum values of 1000 μg/m³ for PM2.5 were

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recorded in Beijing and Shijiazhuang [11]. In January 2017, the daily average concentration of $PM_{2.5}$ exceeded hazardous level (300 μg/m³) accounted for 30% in Beijing [15].

Thus, due to higher level of atmospheric pollution in winter, it is urgent to consider improving residential indoor air quality rather than merely heating for thermal comfort. In winter, different heating systems (such as floor heating, radiator heating or air conditioning) are employed to achieve indoor thermal comfort. Floor heating system is gradually promoted in indoor heating due to its advantages of good thermal comfort and less energy consumption [16,17]. Floor heating is to achieve indoor climate control for thermal comfort sensation through conduction (feet on floor), radiation and convection. Modern floor heating systems typically use either electrical resistance elements ("electric systems") or fluid flowing in pipes ("hydronic systems") to heat the floor [18,19]. However, there is no fresh air system in most floor heating buildings in winter, which would lead to poor indoor air quality [20,21]. The essential function of ventilation is to remove indoor pollutants and further improve indoor air quality [21–23]. Thus, air purification [24,25] and ventilation [26,27] are two main methods to remove indoor particles.

Many studies are available in the literature on indoor particle transport and distribution from either different ventilation methods or different heat sources. These studies indicated that different ventilation modes had important effects on the particle dispersion and distribution. For instance, Zhang and Chen [28] investigated the distributions of particles under three ventilation systems including ceiling, sidewall supply systems and an underfloor air distribution (UFAD) system. The results showed that the UFAD system had a better particle removal performance than the other two ventilation systems. However, the particles deposited on the floor will be re-suspended in an UFAD system. Gao and Niu [29] investigated particle dispersion and deposition with three typical ventilation systems: mixing ventilation (MV), displacement ventilation (DV) and underfloor air distribution (UFAD). They found that for particles released from an internal heat source, the concentration stratification of small particles (diameter <10 μm) would appear in the vertical direction with DV and UFAD ventilation systems. Jurelionis et al. [30] investigated the impact of air distribution on the aerosol particle dispersion and removal with the experimental approach. Experimental results showed that one-way mixing ventilation drove particles towards air exhaust diffusers more efficiently at relatively lower air change rates (1 and 2 ACH). The displacement air distribution appeared to be inefficient in removing particles from the chamber, which could be explained by the higher age of the air. Chen et al. [31] investigated the removal and deposition of particles in a room equipped with two different air-conditioning systems. The results showed that the central-type air conditioner removed the particles more efficiently. They also found that increasing the air supply velocity could remove the particles faster but it could not reduce the ultimate contamination level. Ansaripour et al. [32]investigated particle transport and distribution in a ventilated room with different ventilation configurations. They found that in case of the heated manikin, the particle concentration was significant in the breathing zone of the manikin. The results also showed that the mixing ventilation system would lead to a lower mean particle concentration in the breathing zone compared with the displacement ventilation systems. Habchi et al. [33] investigated ceiling personalized ventilation combined with desk fans to reduce cross-contamination. The results showed that the new ventilation configuration performed better to reduce particles compared with the mixing ventilation system.

Compared to influence of ventilation on indoor particle dispersion, however, few studies were carried out to investigate the influence of heat sources on the particle distribution. Ardkapan et al. [34] studied the ultrafine particle dispersion in a room with a heat source. This work indicated that the particle concentration was associated with the position of particle source and heat source. Chen and Li [35] investigated the impact of the near-wall heat source on the particle deposition with experiments. The results showed that the particles above the near-wall heat source had larger deposition rate than that in the adjacent indoor air. In addition, the results also showed that the particle decay rate loss coefficient increased as the heat source surface temperature increased. Their findings further indicated that the heat sources had considerable effects on particle dispersion. Golkarfard and Talebizadeh [36] investigated the particles deposition and dispersion under radiator and floor heating systems. The influence of heat source location and intensity on indoor particle dispersion was discussed. It was found that the floor heating system removed more suspended particles in comparison with radiator heating system. However, there was no ventilation in their study so that the particles were deposited on the walls.

Based on literature above, it is noticed that rare studies were conducted to investigate the combined effects of ventilation and heat sources on the particle dispersion, i.e., the complex correlations between velocity, temperature and particle concentration. Therefore, in this study the relationships between ventilation, heat sources and particle dispersion for indoor environment were investigated. More specifically, this study will evaluate the influences of inlet velocities and floor temperatures on the unsteady particle dispersion and distribution in a ventilated and floor-heated chamber. This work is expected to be facilitate the future ventilation design for residential heating period in winter, when severe atmospheric particle pollution occurs. There are two main methods for investigation of particle transport and distribution: experiments [30,35] and numerical simulations [37,38]. Numerical method is employed to reveal the combined effects of ventilation and heat source on particle distribution meanwhile extensive experiments will be carried out to validate numerical simulation and ensure the accuracy of findings. The computational fluid dynamic (CFD) methods have been widely applied in simulating particle dispersion and distribution. There two treatments for particle transports: the Eulerian method [38–41] and the Lagrangian method [42–44]. Zhang and Chen [37]compared the two methods for predicting particle transport. They found that under steady state conditions, both methods were capable to simulate particle concentration distribution well. However, for unsteady particle dispersion with limited amount of particles, the Lagrangian method performed better. In this paper, the Lagrangian method was applied to track the dispersion of particles.

The whole analysis was conducted as follows: firstly, experiments were conducted to measure velocity and particle concentration in the chamber and the experimental data was used to validate the numerical simulations. Secondly, the dispersion and distribution of particles in an up-supply ventilated chamber with different inlet velocities and floor temperatures were investigated. Finally, the dispersion and distribution of particles in a down-supply ventilated chamber with different floor temperatures were also discussed. The removal efficiency of particles in two ventilation modes was compared.

2. Methods

Experimental and numerical methods are both employed in this work. The experiments were conducted in a chamber to validate the velocity and particle concentration simulated by CFD simulation. The CFD methods were applied to investigate the airflow and particle dispersion with different inlet velocities and floor heating temperatures.