Numerical investigation of particle distribution in a floor heated room with different air change rates

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Abstract. Airborne particles have a significant effect on human health in enclosed volumes like rooms and office areas. Particle distribution in these spaces should be well known to understand how heating systems may harm to human regarding to respirable particles. In this study, being a major low temperature system aiming energy efficiency, the floor heating system was examined in terms of on particle distribution in a room numerically. When particle concentration come into question, floor heating systems should be evaluated and compared with other heating choices. The effects of five different air change rates on five different particle size were investigated by finite volume method using Eulerian-Lagrangian model. In this study, the effect of drag, lift, thermophoretic and Brownian forces were considered. It is found that, air change rate is a critical factor to obtain desired indoor air quality but outdoor air conditions may worsen the indoor quality due to air pollution.

1. Introduction

Indoor air quality should be evaluated not only by obtaining optimal thermal conditions but also supplying ideal conditions related to pollutants. Pollutants spread out from any sources in houses could seriously harm residents in it [1]. Indoor pollutant concentration is significantly affected by velocity and temperature distributions in the environment. Especially, in the heating season, the velocity and temperature distributions in a room are entirely different from the summer conditions as a result of the heating system which causes variations in temperature differences as well as velocity profiles in an enclosed environment. These different indoor conditions resulting from the heating system usage, affect the particles movements in the environment.

Numerical methods are frequently preferred because of the difficulties of an experimental study in investigating the particles. Holmberg and Li [2] studied the particle motion around the human using a drift-flux model. They showed that when the ventilation is low or zero, deposition of particles on the surfaces are important as total concentrations in the environment can change considerably. Holmberg and Chen [3] emphasized that respirable particle concentrations are also high in the respiratory region and they showed that it could be reduced by placing a suction vent below the breathing zone. Zhao et al. [4, 5] showed that the particle concentration is significantly affected by the ventilation system. Higher concentration values have been calculated in the mixed ventilated system than in the displacement ventilation. Gao and Niu [5], compared three different ventilation systems by a numerical method and stated that the effect of the ventilation system on the deposition rate of the particles is negligible. The particle concentration in the environment was found to be lower in displacement ventilation and underfloor air distribution systems. The air flow characteristic is very dominant in particle concentrations. Rim and Novoselac [6] examined the concentration variations in the environment when the fan of the ventilation system stopped. Zhong et al. [7] examined mixed ventilation and the underfloor air distribution system in terms of the location of the particulate source and reported that the concentration and deposition of particles were slightly affected by the source location when the mixed ventilation system is used. On the other hand, they showed that particle source becomes essential in
case of under floor air distribution is used. Unlike the ventilation systems, Golkarfard and Talebizadeh examined particle distributions in underfloor heating and radiator heating systems [8]. They have stated that particle deposition is higher in the underfloor heating system and the particles tend to deposit on the ceiling and the floor in underfloor heating and radiator heating systems, respectively. Zhao et al. [9] studied particle distribution in an underfloor heated and ventilated environment using both experimental and numerical methods. They reported that the particle deposition rate on the floor decrease with the increase of the inlet speed and surface temperature. Zhuang et al. [10] examined the central and split air conditioners in terms of particle concentration and found that increasing air velocity did not reduce final particle concentrations although air quality improves rapidly. Dehghan and Abdolzadeh [11] examined the distribution of particles in a room for three different heating systems which are the underfloor, radiator and skirt boarding heating. They compared the particle concentrations in the breathing zone of a mannequin which is placed in the middle of the room, and they calculated that the lowest concentration is for the skirt boarding system. They stated that due to the presence of the heat source in the environment, the particles tend to trap on the walls instead of leaving the medium. In addition to the CFD tool, Gheziel et al. [12] tried to predict particle concentrations in the environment using artificial neural networks.

In this study, air velocity and temperature distributions in an environment heated by underfloor heating were determined using numerical methods and five different sized particles were tracked by discrete phase modeling (DPM). In the literature, the effects of different ventilation and heating systems were investigated while the effect of air change rates has not been discussed. In this study, the effect of five different air change rates on particle concentrations in a room was reported.

2. Geometric model

In order to investigate the underfloor heating system, experimental data of Olesen et al. [13] were taken as a reference. The model of this room was created and velocity and temperature distributions and particle concentrations were calculated. This model has been accepted in the literature and it has been preferred by other researchers [11, 14-17] so that it is possible to be compared with similar studies. The schematic view of the room was given in the figure. 1.

![Figure 1. Schematic view of the model](image)

3. Numerical Method and Boundary Conditions

In this study, commercial software FLUENT was used for solving mass, momentum, energy equations and calculating DPM variables. PRESTO! method was chosen and second order discretization was applied for other quantities while the SIMPLEC algorithm was used for pressure-velocity coupling. The Low Reynolds k-ε turbulence model, which was developed to be used at low velocity, was chosen. This turbulence model is also have preferred in similar studies [14, 18]. Boundary conditions are given in figure 1 and the total heat transfer coefficient values for surfaces were taken same as the values of the experimental setup of Olesen et al. [13]. The heat losses from the surfaces, in case the air change rate is 0.8 ach, were calculated when the outdoor and indoor temperatures were -5 °C and 22 °C respectively.
Then the heat flux was calculated by heat loss value and was applied to the floor surface as heat flux boundary condition. The heat flux applied to the ground was determined as 64 W/m² according to the calculations mentioned above. It has been accepted that heat is transferred from outer surfaces by both convection and radiation to the environment and the heat transfer coefficient of surfaces is taken as 7 W/m²K being an average value of similar research [11] examining the same geometry. The heat flux, applied to the floor, were determined by using user-defined functions to keep the room at 22 °C. Thus the effect of other air exchange rates was examined at the same temperature. The air inlet was provided with 48 holes around the window similar to the study in reference [13], and the outlet was defined on the back wall.

4. Validation
In order to validate the simulation, experimental data of Olesen et al. [13] were compared with numerical results. The experimental result of Olesen et al. [13] in case the ventilation rate is 0.8 ach, is taken as a reference case and the comparison with numerical results was given in figure 2. For mesh independence, analyses were performed on with five different tetrahedral mesh sizes (6×10⁵, 1×10⁶, 2×10⁶, 3×10⁶, 4×10⁶) and it has been observed that results were to be unchanged more than 2×10⁶ elements. Therefore, solutions were run with this mesh size.

![Figure 2. Comparison of temperature variation with experimental data and numerical results](image)

Measured velocities of Olesen et al. [13] at 0.6 m in front of the window with a height of 0.1 m and 1.2 m was 11 cm/s and 6 cm/s respectively while in this study velocity values at same locations were calculated as 15 cm/s and 5 cm/s respectively. Additionally, velocity value at 1.8 m in front of the window with a 0.1 m height has been measured as 14 cm/s while it was calculated as 17 cm/s in the present study. Considering the standard deviation of the measurements, it can be said that the calculated values are consistent with the experimental data.

5. Particle Tracking
In order to determine the motion of the particles in the environment, after steady state results had been obtained, 15000 particles with the density of 1550 kg/m³ and specific heat of 1680 J/kgK was randomly distributed in the environment. It was assumed that the same size of particles enters the room due to infiltration from the outdoor environment. The mass flow rates of the particles were considered for a room in a dirty environment and a high value is taken (7 × 10⁻¹² kg/s). Tracking of particles was carried out under transient conditions and it was observed that the results did not alter after 1200 s. In this study, it has been accepted that lift, drag, thermophoresis and Brownian forces affect the particles. Cell concentrations were normalized by dividing the concentration rate in the inlet in order to compare the results and evaluate the effect of particle size (Eq. 1).
6. Results

When the temperature distributions in the room were examined (figure 3), the temperature difference between floor and ceiling increased with the increase of air change rate. The temperature difference is 1.1 K for 0.4 ach, while it is more than 3.3 K for 2.0 ach. Although the average temperatures in the room are the same, these differences in the temperature distribution can create discomfort. The heat flux applied to the floor can be increased up to two times to keep the room at a constant temperature due to the increase in air change rate. When the velocity distributions are examined (figure 3), the velocities in the room is found lower than that of expected in high air exchange rates. The cold air entering through the window moves towards the ground due to the density difference, even though its flow rate is high. As the floor surface is hot, the movement of air here is upward. Air movements in two different directions combine and begin to move towards the back wall behind the room at the height of about 0.5 m from the floor. As air change rate increases, movement of cold air become dominant and velocities in the middle of the room reduce, because of air movement taking place through behind the room. On the other hand, due to the increase of the heat flux, the more heated air goes upward from rear part of the room over the back wall and hot areas are formed near the ceiling surface. Therefore, the temperature difference between the floor and the ceiling is increasing.

Normalized concentration values on a line in the center of the room are given in figure 4. The air change rate has a significant effect on concentrations, while the particle diameter slightly affects the concentration values. It was seen that the concentration values near the floor level were higher than other
parts of the room as the thermophoretic forces have a significant influence on particles that enter the room by infiltration. In particular, there was no difference between the concentration values in the upper part of the room. On the other hand, figure 5 shows that small particles are better distributed in the room.

Figure 4. Normalized concentration values altering with height (a) \(d_p = 1 \, \mu m\), (b) \(d_p = 10 \, \mu m\)

The calculated concentration values in the center of the room \((z = -1.2 \, m)\) are given in figure 5. The particles can be spread over the entire room due to the air distribution inside the chamber as particle size decreases. The particles cannot move towards the upper part of the chamber due to cold air movement which is dominant in high air change rates. However, at low air change rates, particles barely reach to places higher than 0.5 m from the floor except at the back of the room, but at higher air change rates particles can reach higher than 0.75 m. It can be concluded that the most suitable location of an air purifier for extremely dirty air outdoor conditions is where the infiltration takes place and areas close to the floor.

Figure 5. Normalized particle concentration in the center of the room

7. Conclusion
In this study, the motions of high concentration particles originating from the external environment in a room were calculated using CFD. The concentrations of particulate matter in many regions has reached the harmful levels as the increase of environmental pollution. The results can be summarized as follows:
• The high air change rate causes the heat flux to be doubled in order to keep the room at a constant temperature. Moreover, higher heat flux increases the temperature difference by changing the velocity and temperature distribution in the room. The formation of temperature differences in the room may cause to develop uncomfortable areas.

• The most suitable placement of an air purifying device has been found to be near to the infiltration source like windows and doors and close to the floor surface. In particular, it is recommended that air intake of such devices should not be placed higher than 0.75 m from the floor level.

• Although the particle concentration in the room increases with higher air change rates, the concentration values in the upper parts of the room altered slightly. However, any infiltration rate in a room where located in a region that environmental pollution, including any particulate diameter exists, is a risk for human health, since as the change in the particle diameter does not affect the distribution within the room.

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