Evaluation of air change rates for estimating particle dispersion on a reduced scale model

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Abstract. Similarity between a model and a prototype is important for scale model experimental studies. Proper scaling by considering similarity parameters can lead to valuable results. The objective of this study is to investigate dispersion of fine particles under different air change rates by experimental and numerical techniques. Experimental studies are performed on a 1:5 reduced scale model. Similarity parameters are considered for kinematic and particle dispersion similarities. The RNG \( k - \varepsilon \) turbulence model is used in the numerical predictions. It is shown that the average room and outlet concentrations get similar values with the removal of accumulation as the air velocity increases. Moreover, it is disclosed that the advantages of the increasing air change rates may have limits in reducing contaminant level.

1. Introduction

Nowadays, people spend a significant part of their time in enclosed environments. Particles found in these environments draw attention with their negative effects on human health. Particularly fine particles (< 2.5 \( \mu m \)) can cause serious damage to respiratory tract and related systems [1-4]. It is feasible to provide a healthy indoor environment if an appropriate ventilation approach is designated. The number of air changes is one of the important parameters that affect the performance in a ventilation system. The general opinion in practice is that there is a direct relation between high air change rates and a clean indoor environment. However, operating at high air change rates is not economical. For this reason, the influence of the air change rate on contaminant distribution should be investigated in detail to determine an optimum solution between efficiency and cost.

The studies in the literature covers variety of release conditions and particle diameters with different air change rates. Wang et al. [5] stated that increasing air change rate reduced the average particle concentration in case of release of 3.1 \( \mu m \) particles from floor level. Faulkner et.al. [6] performed an experimental study for the size of 17.95 \( \mu m \) particles that released to the flow domain from inlet air with constant concentration. It was shown that concentrations at the outlet increased linearly with an increase in the air change rate while concentrations in the occupied zone did not increase linearly. In another study, Faulkner et al. [7] found out that increasing air change rate reduced concentration levels in the occupied zone and in the exhaust. Zhuang et.al. [8] and Zhou et al [9] stated that increasing air change rates reduced the removal time of homogeneously distributed particles.

The literature review reveals that studies investigating the effect of air change rate on distribution behaviour of fine particles released from the inlet at constant particle flow rate is limited. Motivated by this fact, the aim of this study is to reveal the influence of air change rates on distribution of fine particles released by incoming air, experimentally and numerically. Experimental part is conducted in a reduced scale model by considering similarity parameters to provide viable outputs for full scale rooms. Experimental results obtained are then used for the validation of numerical predictions.
Results of this study is expected to contribute to the comprehension of the advantages and limitations of
the increasing the air change rates in confined spaces. Thereby, energy efficient ventilation applications
can be realized by determining optimum air change rates.

2. Methods

2.1 Similarity principle

In the experimental studies, it is more economical to prefer reduced scale models than a full scale
building or room. In order to achieve flow similarity between models, some dimensionless flow
parameters such as Reynolds number, Grashof number and Prandtl number must be kept constant in
both scales. These parameters can be found from the governing equations of the flow. Derivation of
these parameters were discussed previously [10,11]. Regarding on the isothermal structure of the system,
kineamtic similarity is satisfied with the equality of Reynolds number. Moreover, settling velocity ratio
is considered for the contaminant distribution similarity.

2.2 Experimental method

The experimental study is conducted in a reduced scale (1:5) model representing a room (3 m x 3 m x 3
m (=27 m$^3$)), made up of 10 mm thick plexiglass, with the dimensions of 0.6 m x 0.6 m x 0.6 m (= 0.216
m$^3$). The sizes of air inlet and outlet openings seen in figure 1 are 0.12 x 0.12 m$^2$. The center of the
openings are in vertical centerline of the corresponding walls. The bottom side of the inlet and the top
side of the outlet is 2 cm away from the sides of the room. Air flow is provided by a variable frequency
driven fan (0-420 m$^3$/h) located in the exit of the outlet duct which is followed with a vane anemometer
(Extech 407113). 0.5 µm monodisperse polystyrene latex particles (1.05 g/cm$^3$) are released to the room
with incoming air flow. Background concentration is minimized by a HEPA filter installed at the inlet
duct. A hot wire anemometer (Testo 0635 1025) and a laser diode optical particle counter (Handilaz
mini) are used for the measurements of the x-velocity and concentration, respectively.

The optical particle counters measures the concentration of particles by means of light scattering.
For this purpose, a stream of aerosol is drawn through a condensed light beam. Light flashes scattered
from single particles are received by a photodetector and converted into electrical pulses. From the count
rate of the pulses, the number of concentration, and from the pulse height, the size of the particles is
derived [12]. More information about the method to measure particle concentration can be found in
Kulkarni et. al. [12].

During the experiments, each measurement is repeated three times to give averaged results.
Measurement procedure is as follows: (a) x-velocity measurements, (b) Background concentration
measurement, (c) Initializing the particle release, (d) Concentration measurements at least 10 minutes
after the start of the particle release.

The measured concentration is subtracted from the background and measurement lines are 12 cm
away from the closest walls.
2.3 Numerical method
Simulation of the air flow and particle distribution is performed using a computational fluid dynamics software ANSYS Fluent. For the turbulence modelling, the RNG $k-\varepsilon$ turbulence model is applied. The governing equations of the flow are discretized into algebraic equations by the finite volume method (FVM). The general form of the governing equations can be written as follows:

$$\frac{\partial}{\partial t} (\varphi) + \nabla \cdot (u\varphi) = \nabla \cdot (\Gamma_\varphi \nabla \varphi) + S_\varphi$$  \hspace{1cm} (1)

where $\varphi$ represents each of the three velocity components ($u$, $v$, $w$), the kinetic energy of turbulence, $k$, and the dissipation rate of the kinetic energy of turbulence, $\varepsilon$, and air enthalpy, $h$. $\Gamma_\varphi$ is the effective exchange coefficient for the dependent variable $\varphi$. $S_\varphi$ is the source term of the general equation.

The discretization scheme is second order upwind scheme and SIMPLE algorithm is adopted to solve pressure-velocity coupling. The discrete phase modelling (DPM) is used for the tracking of particles in the flow domain. Stochastic behaviour of the turbulence on particle movement is adopted by the Discrete Random Walk Model (DRW).

Velocity inlet and outflow boundary conditions are assigned for the inlet and outlet, respectively. All the walls are considered as adiabatic, and no slip boundary condition is specified. For the particle phase, trap boundary condition is defined for the walls, and escape boundary condition is selected for the outlet. Grid independency test is performed by comparing the air velocity and particle concentration values of three different mesh densities.

2.4 Cases description
Studies are performed for four different inlet velocities with 0.5 μm particles which corresponds to 0.181 μm particles in full scale rooms. The parameters of the Cases are given in Table 1. Inlet velocities for the full scale room are considered in the range of 0.036 to 0.16 m/s. In this instance, air change rate of the full scale room varies between 1.73 to 7.68. Depending on the Reynolds number equality, inlet air velocities of reduced scale model must differ from 0.18 to 0.8 m/s. As a result, the air change rate of the reduced scale model changes between 43.2 to 192 which is feasible with the fan (0-420 m$^3$/h (0-1944 ACH)) used.

| Table 1. Inlet velocity magnitudes and air change rates of different scales |
|-------------------|-------------------|-------------------|-------------------|-------------------|
| Scale (1:1)       | Scale (1:5)       |
| Re                | $u_0$ (m/s)       | ACH               | $u_0$ (m/s)       | ACH               |
| (a) 1520          | 0.036             | 1.73              | 0.18              | 43.2              |
| (b) 2534          | 0.06              | 2.88              | 0.3               | 72                |
| (c) 5068          | 0.12              | 5.76              | 0.6               | 144               |
| (d) 6757          | 0.16              | 7.68              | 0.8               | 192               |

3. Results and discussion
3.1 Validation of the model
Validation of the numerical simulation is conducted for Re=5068. Figure 2 shows the agreement of air jet flow pattern and corresponding velocity vector distribution in the center plane of the room. Velocity vectors indicate high velocity values in the direction of inlet opening, as expected. As it is seen, the main pattern deflected upward through outlet opening and lower velocity magnitudes that are generally directed to downward are observed in the rest of the plane.
Figure 2. Air flow pattern of the jet and velocity vectors at Re=5068.

The comparison of x-velocity magnitudes and concentration measurements with simulation results are given in Fig. 3. Concentration values are normalized with particle mass per supplied air volume for Re=1520. Velocity magnitudes are higher near the inlet, and higher concentration values are also obtained in the projection of inlet because of the particle load released from inlet opening. Experimental measurements show a harmony with numerical predictions. As a result, it can be stated that preferred numerical model is sufficient to determine velocity and particle distributions effectively.

Figure 3. Comparison of experimental measurements and simulation results.

3.2 Air flow and particle distribution

Figure 4 depicts velocity contours and streamlines at four different air change rates. Higher velocity magnitudes in the projection of inlet opening is obtained with increasing air change rates. The part of the air jet profile before the upward deflection gains a thinner structure as the inlet velocity increases. Although the main flow structure preserves its form independently of the air velocity, minor changes in the orientations and higher velocity values in other regions are observed.

Figure 4. Velocity contours and streamlines.
The normalized concentration contours in the center plane are illustrated in Fig. 5. For the lowest inlet velocity, the particles are accumulated in the upper and left sides of the room where relatively low air velocities exist. As the air change rate increases, a better dilution is noticed and particle concentration distribution is mainly limited with air jet profile. Simulation results also reveal that deposition is about 0.1 % in all air change rates examined, which means that nearly all the particles leave the flow domain without any contact with the walls.

Figure 5. Normalized particle concentration contours.

3.3 Concentration values at the outlet and of the room
Figure 6 depicts the change in concentration values at the outlet and of the room regarding to the increasing of inlet air velocity. As it is seen, average concentration of the room is higher than the outlet concentration for the lowest air velocity, which is related with particle accumulation in the flow domain. As the air velocity, therefore the air change rate, increases, the concentration values decrease as a result of dilution of constant particle flow rate. Additionally, the difference between outlet concentration and room concentration values decreases as the air change rate increases because of the elimination of accumulation regions. For the highest two values of air inlet velocities, it can be stated that both concentration values are nearly equal, which means that all the particles leave the domain without any accumulation. Moreover, it should also be noted that the general reduction behavior draws an asymptotic character, indicating that the reduction rate in concentrations may have limits.

Figure 6. Change in concentration values of room and at the outlet opening.

4. Conclusions
In this study, the effect of air change rate on particle distribution is investigated for the case of particle release by incoming air with constant particle flow rate. Main findings are summarized as follows:
- Minor differences are obtained in the air flow pattern by increasing the air change rates.
For $ACH = 1.73$ and $1.88$, the difference between average room and outlet concentration values is due to the accumulation of particles.

As the air velocity increases, the average room concentration and the outlet concentrations get similar values with the removal of the accumulation.

The reduction in concentration values resemble an asymptotic function which indicates that further increasing the air change rate can provide a very limited contribution to obtain a cleaner indoor environment.

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