Numerical Particle Transport in Partitioned Room

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Abstract: - In this work, we solved particle transport in a two-zone enclosure numerically with different airflow patterns, particle properties and also source positions. A discrete trajectory was employed for the particle movement. Five isotropic line sources which are all taken at different positions of the same zone were tested. It was observed that for all airflow patterns, residence time increases with decreasing size of particles. Increase in size and mass increases the chance of particles to get deposited onto the floor. Source locations should be chosen in the main stream of the flow so that particles convect fast through and not contribute indoor pollutant concentration. Conclusions were drawn for every numerical experiment in order to show tendencies of particle dynamics within the enclosure.

Key-Words: - Aerosol Particles, Transport, Deposition, Ventilation, Source, Indoor

1 Introduction

In modern society, people spend most of their time indoor and are constantly exposed to particles. Indoor particles have multiple origins from outdoor soil dust, building materials, to occupants and their activities. Knowledge of transport and deposition of these particles in indoor environments is important in addressing questions concerning occupational exposure, associated health risks and also implementing cleaning strategies [1, 2].

Aerosol particle movements and deposition are investigated by many researchers. Among them, Miguel and Silva experimentally studied particle deposition on a flat plate with various slopes [3]. Lu et al. calculated aerosol particle migration and deposition in a two zone chamber and compared their predictions with corresponding experimental measurements [4]. Lee and Awbi investigated the effect of internal partitioning on the room air quality and ventilation [5]. Zhao et al. studied air movement and aerosol particle concentration and deposition in displacement and mixing ventilation rooms numerically [6]. Aydin et al. obtained equilibrium particle distribution in a cavity and also a ventilated room [7, 8]. Recently, Miguel et al. studied effects of air humidity and currents and electrical charges upon indoor particle deposition experimentally [9].

In this work, the movement of particles is investigated considering airflow patterns, particle properties and source positions in a model room. Airflow pattern is changed by altering the location of the outlet (exhaust). Three different locations were tested. The particles used in the study vary from 1 to 100 μm with two different densities of (ρ_p=240 kg/m^3) and (ρ_p=2300 kg/m^3) representing light and heavy materials. Five line sources are considered in one zone of the enclosure. Particles are all released homogenously and isotropically with the same initial conditions

2 Computational Fluid Dynamics

A square cavity with dimensions of 2.5 m in length and 2.5m in height is considered here. At the middle of the cavity a partition half way down to its height is used, which divides it into two connected zones. In each configuration air is supplied through the same location while exhaust (outlet) location is changed (see Fig. 1).

The steady state flow field is defined by the Navier-Stokes equations together with the standard k-ε two-equation model of turbulence and solved numerically with the finite volume method [10]. The airflow is assumed to be incompressible. The non-slip boundary conditions are set along walls of the enclosure and also surfaces of the partition. The flat velocity profile is prescribed at the inlet while pressure outlet boundary conditions are set at the outlet.

A homogenously distributed nodded grid was employed at first run and then, the cell size of the grid where high gradients of velocities exist has been varied gradually to ensure a grid independent solution. The final form of the grid for outlet V1 can be seen in Fig. 2.

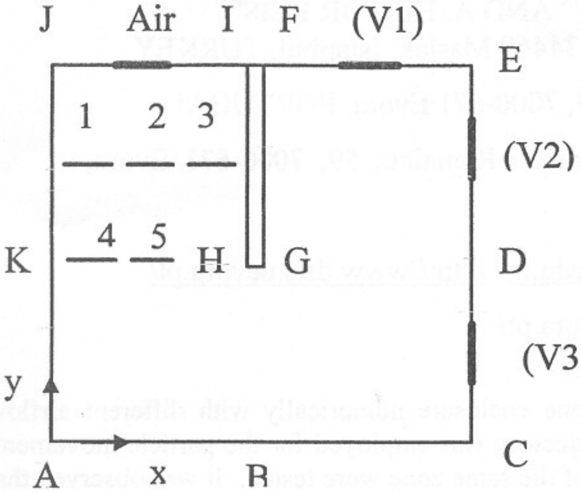


Fig.1 Geometrical configuration: 1-5 show source positions and V1-V3 represent outlet positions

The grid with 18092 quadrilateral cells and 19080 nodes are found to be appropriate for this study.

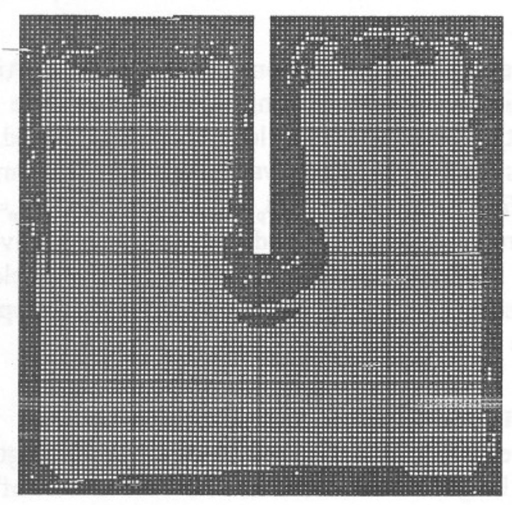


Fig.2 Grid of the domain for outlet V1

Reynolds number Re is calculated according to $\rho u D_h / \mu$, where ρ is density of air, u is velocity at the supply, μ is dynamic viscosity of air, D_h is the hydraulic diameter of the room, which was 2.5 m. Under relaxation factors were arranged to ensure convergence in the solution. Airflow pattern is changed by shifting the location of the outlet. Three different locations were tested. Contours of stream function at Re=170000 are shown in Fig. 3. This shows four asymmetric slowly re-circulating regions located at the corners

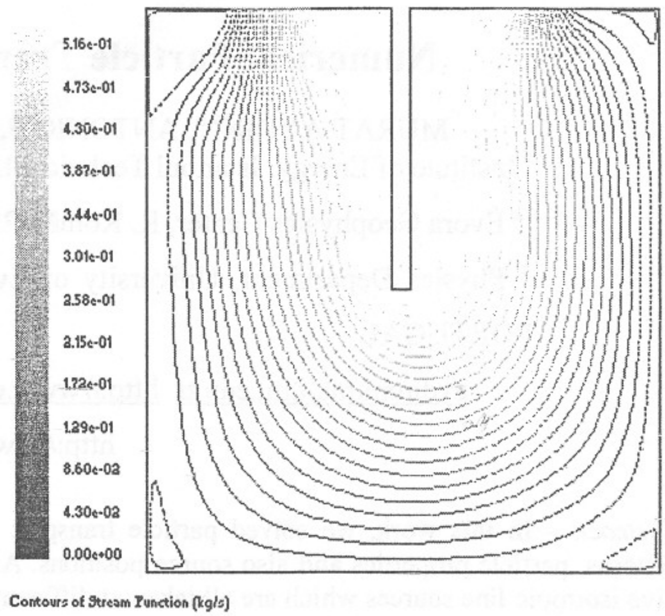


Fig.3 Contours of Stream Function for V1

3 Particle Dynamics

Once the solution of air flow has been obtained, each particle trajectory was then calculated. A fixed continuous phase flow field was assumed, in other words, the particles do not modify significantly the air flow (uncoupled approach). All particles are assumed to be spherical. The trajectory of a particle is predicted by integrating the force balance on the particle. This force balance equates the particle inertia with forces acting on the particle and can be written as

$$d\vec{u}_p / dt = \vec{F}_a - F_D\left(\vec{u} - \vec{u}_p\right) + \frac{\vec{g}\left(\rho_p - \rho\right)}{\rho_p} \tag{1}$$

where $\vec{F}_a$ represents additional forces such as lift force due to shear, the force due to the pressure gradient in air and the Brownian force [11], and $F_D\left(\vec{u} - \vec{u}_p\right)$ is the drag force per unit mass and

$$F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D \, Re}{24} \tag{2}$$

Here u is the air velocity, u_p is the particle velocity, μ is the viscosity of air, ρ is the air density, ρ_p is the density of the particle, and d_p is the particle diameter. The last term in Eq.1 stands for the buoyancy force.

In the case of larger particles, Eq.1 becomes an ordinary deterministic differential equation due to the exclusion of Brownian term, which brings stochastic character to it. Therefore, its solution is straightforward as long as initial conditions are given.

The trajectory equations are solved by stepwise integration over time steps. The integration time step is computed based on a specified length scale (L) and the velocity of the particle and of the continuous phase as $\Delta t = \dfrac{L}{u_p + u}$. Integration in time of Eq.1 yields the velocity of the particle at each point along the trajectory, with the trajectory itself predicted by

$$\frac{d\vec{r}}{dt} = \vec{u}_p \qquad (3)$$

Equations (1) and (3) are solved to predict the trajectories of particles.

3 Results

Particles are tracked until they hit surfaces. Five source locations for the particles are considered in the volume of the left zone (see Table 1). Note that all locations were given in dimensionless coordinates ($x^* = x/D_h$, $y^* = y/D_h$). For each calculation and at every source location, 100 particles homogenously distributed in each source location are released exactly with the same initial conditions. Injected particles were all tracked down until they leave the domain or hit surfaces of the enclosure. Rebounding was not considered. Cork (ρ_p=240 kg/m^3) and concrete materials (ρ_p=2300 kg/m^3) of sizes 1, 10 and 100 μm were considered. This lets the range of densities, which most of solid indoor contaminants fall in between.

Table 1 Source Locations

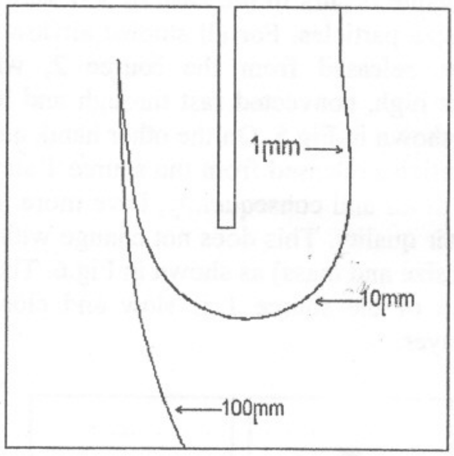
Source No	x^*_{min}	x^*_{max}	y^*
1	0.04	0.08	0.88
2	0.22	0.26	0.88
3	0.40	0.44	0.88
4	0.04	0.08	0.50
5	0.22	0.26	0.50

2.1 Effect of Particle Sizes

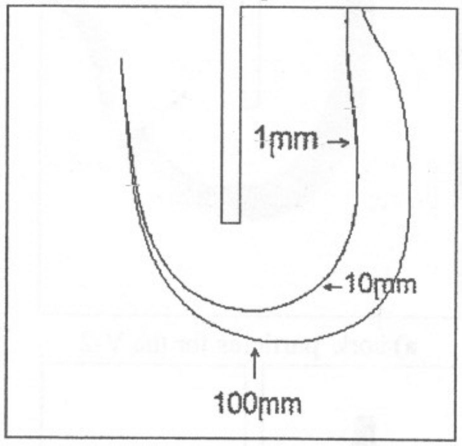
The typical trajectories of 3 particles of sizes 1, 10 and 100 μm placed initially at the same place (x^*=0.25 and y^*=0.88) for V-1 (i.e. outlet location in V-1) are shown in Fig. 4. Among them, the concrete particle with the size of 100 μm deposits on the floor due to gravity while all others leave the room. Particles with 1 μm size follow air streamline. However, they are affected by Brownian motion and this effect as small deviations from streamline is visible.

2.2 Effect of Airflow Patterns

A maximum number of 10^6 time steps is used as to prevent the possibility of a particle being caught in a re-circulating region of the flow field and being tracked infinitely.



a) concrete particles



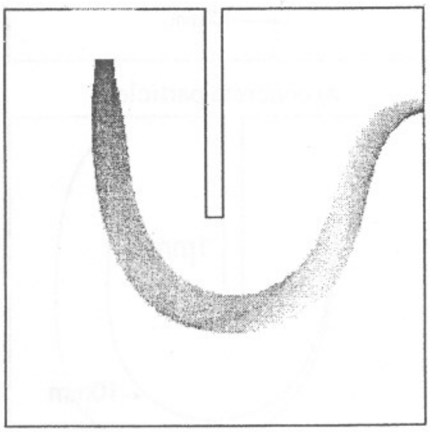
b) cork particles

Fig.4 Typical trajectories of 3 particles of sizes 1, 10 and 10 mm placed initially at the same place for V-1

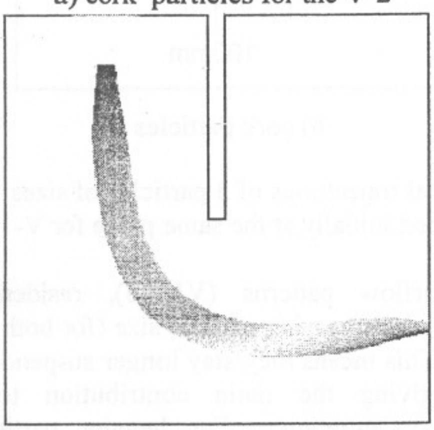
For all airflow patterns (V1-V3), residence time increases with decreasing particle size (for both concrete and cork). This means they stay longer suspended in air, therefore giving the main contribution to indoor pollutant concentration. For heavier particles, the deposition probability is high due to gravity. The chance that small size particles get deposited onto the ceiling is high. This chance becomes higher for lighter particles. For all airflow patterns, while particle deposition probability is the highest for the outlet V-1 whereas the V-2 is found to be the most efficient in terms of particle escaping probability. The V-3 is close to the recirculation region at the corner. This increases the possibility of a particle being caught in this region. As a result, it is wise to choose outlets on sidewalls. Most of deposition occurs on floor surfaces. Therefore, it would be more efficient for filters for collecting deposited particles if positioned on sidewalls close to floor surface.

2.3 Effect of Source Locations

For all airflow patterns, source 1 (see Fig.1) gives the highest contribution in deposition on the ceiling. The maximum value occurs in the case of V-1 and for light and small size particles. For all studied airflow patterns all particles released from the source 2, where air velocities is high, convected fast through and leave the domain as shown in Fig.5. On the other hand, among the sources, particles released from the source 1 stay longer suspended in air and consequently, have more influence on indoor air quality. This does not change with particle properties (size and mass) as shown in Fig.6. The flow at the location of the source 1 is slow and close to the boundary layer.



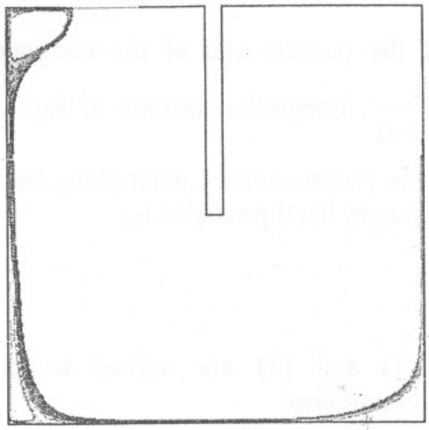
a) cork particles for the V-2



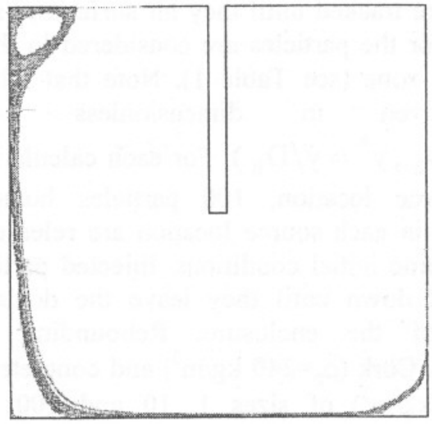
b) concrete particles for theV-3

Fig.5 Trajectories of particles of size 100 μm released from Source 2

Whatever mass and size of the particles are, particles released from sources 4 and 5 for both V2 and V3 leave the room without deposition.



a) 10 μm concrete particles for the V-2



b) 1 μm cork particles for the V-3

Fig.6 Trajectories of particles released from Source 1

For all airflow patterns, the effect of the partitioning on deposition is more significant when particles are released from source 3 as shown in Fig.7. Increase in size and mass increases the chance of particles to get deposited on the floor.

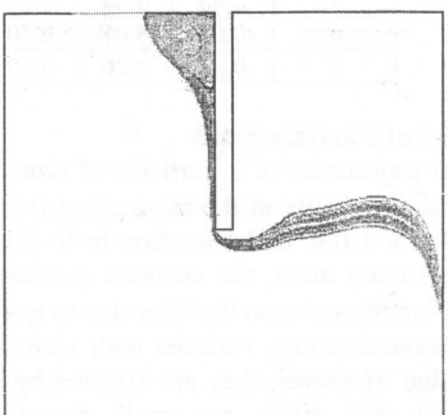


Fig.7 Trajectories of 1 μm concrete particles released from Source 3 for V-3

4 Conclusion

Movement of particles is investigated considering the factors of airflow patterns, particle characteristics and source positions in a model room. For all airflow patterns, residence time increases with decreasing size (for both heavy and light particles). This means they stay longer suspended in air and therefore, contributing significantly to indoor pollutant concentration, which confirms the findings of Lu et al [4]. For larger particles, the probability to get deposited is higher due to gravity. Increase in size and mass increases the chance of particles to get deposited onto the floor. This is in agreement with the literature [4, 6]. Airflow pattern and source locations have important influences upon indoor air quality. Particles entrained in main flow stream easily convect and leave the room. Particles captured in a re-circulating region of the flow field have more residence times in the room and consequently, contribute significantly indoor pollutant concentration.

Finally, the approach presented in this paper can be extended to more interesting indoor cases and three-dimensional deposition problems.

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