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A model of particulate matter dispersion from unfiltered air conditioner indoor

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Abstract. The air conditioner is used not only for indoor temperature control but also as a particulate filtering system. However, bad maintenance of the air conditioner would lead to the damage of the filtering system. The result is a bad indoor air quality due to particulate matters depositing from outdoor. By the fact that a room with an air conditioner system is isolated, the risk of the human to be exposed is high. In this research, we built a model to simulate the particulate dispersion from air conditioner without active filtering system to find the effective range of the exposure. The research is purposely to model particulate matters, especially for PM$_{2.5}$ and PM$_{0.1}$. The model was built in the Navier-Stokes equation for incompressible fluids by using a Lagrangian approach in the grid system. The model simulated the dispersion of particulate matters in an 8 x 8 x 3 m room with a single air conditioner. The temperature of the room was settled at 24$^\circ$C without any external particulate source. The speed of the airflow was set at 3 m/s while the concentration of the PM was set by change the air conditioner temperature setting. In the simulation, we found the increase of the effective range of particulate matters in the function of time. In the initial condition, the particulate matters are dispersed into the ceiling with the highest concentration. In the less than 5 minutes, our simulation shows the particulates dispersing in the whole room in the varied concentration. In the minute 50th, the concentration is similar to the air conditioner exposure. Our measurement in real condition showed a similar condition by a maximum different of 15% than the simulation both in the dispersion time and 2.5% in the concentration. These results were achieved after we compared the simulation in t time concentration with the real particulate dispersion in the identical room dimension with the simulation. In conclusion, the model can be performed to simulate an indoor PM dispersion from non-filtering air conditioner well.

1. Introduction
Particulate matters (PMs) may reduce the air quality [1], increase the mortality, and morbidity especially for the human [2]. PMs can be formed in various ways: natural and unnatural. In nature, PMs are generated as the result of the natural phenomenon such as volcanoes or forest fire [3]. On the other hand, the unnatural ways are mostly caused by the human activity, for example, the vehicles or factory process [4]. Both types of particulates have been known to induce several health problems, especially for the respiratory systems [5] due to their penetration ability and the human inhalation rate [6]. Smaller particulate matters can penetrate into the deeper human body [7]. The PMs toxic property triggers an inflammation, resulting in the tissues damage [8]. There have been identified the evidence of the human health problem [9]. By the fact that there is no an effective procedure to avoid the particulate exposures, the study of particulate distribution may be an alternative method to estimate the exposure effect. A PMs distribution contains very important information such as how far the
particulate distributed in the space, the speed of the particulates and the direction. The study about the particulate distribution model has been used to determine and predict the particulate attentiveness in the space [10]. For example, the distribution of the vehicle particulate emission in an urban area [11], etc. By understanding about the particulate motion in the air, the effective exposure zone may be able to be predicted in order to prevent the further effects on human.

The air conditioner technology has been used commonly in the modern building or indoor [12]. The air conditioner works to flow the cold air into the indoor through the thermodynamic mechanism and removes the particulate [13]. The latest technology of air conditioner system used a particulate filter that was known to reduce the particulate concentration [14]. However, the old or unfiltered air conditioner may deposit PMs especially PM0.1[15]. The particles spread widely in the ambient together with the airflow due to their size. The particulates remain in the air for a long time. Numerical modes to approach the particulate motion in the air has been built in the previous study for a domestic residence to improve comfort in the summer[16]. In this study, we simulate the air condition particulate distribution indoor to investigate the particulate distribution for an unfiltered air conditioner.

2. Numerical Methods

2.1.1. Fluid Model

In indoor, particulate matters have a similar behave with the air. Based on this information, we model the distribution based on the incompressible Navier-Stokes equation [17]. The model is built by assuming that particulate matters are incompressible in the indoor. This assumption is taken by the fact that there is no compressible factor in the room.

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} + \nabla p = \frac{1}{Re} \Delta \mathbf{u} + \mathbf{g}
\]  

(1)

Equation 1 is the general form of the Navier-Stokes equation. The left hand of the eq. (1) presents the velocity. The right hand defines the force/unit volume. Equation 1 is rewritten into a new form;

\[
\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = \frac{1}{Re} \frac{\partial^2 u_i}{\partial x^2_j} + \frac{\partial^2 u_i}{\partial y^2} - \frac{\partial (u_i u_j)}{\partial x_j} + \frac{\partial (u_i u_j)}{\partial y} + g_x
\]

(2)

That is also the form of momentum equation. The discretization of the Navier-Stokes equation is used to find the numerical form of the equation 2. The difference is used in this step forward. The result is the discrete form of the Navier-Stokes equation for numerical form as presented in Eq.3.

\[
\frac{\partial (u_i^2)}{\partial x} = \frac{u_{i+1,j} + u_{i-1,j}}{2} - \frac{(u_{i-1,j} + u_{i+1,j})^2}{2} + \frac{u_{i,j} + u_{i+1,j}}{2} \left( \frac{|u_{i,j} - u_{i+1,j}|}{\delta x} - \frac{|u_{i,j} - u_{i-1,j}|}{\delta x} \right)
\]

(3)

And

\[
\frac{\partial (u^2)}{\partial x} = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{\delta x^2}
\]

(4)

And for the pressure;

\[
\frac{\partial p}{\partial x} = \frac{p_{i+1,j} - p_{i,j}}{\delta x}
\]

(5)

The discretization is done for the speed for y and z axis that resulted in the

\[
\frac{\partial (u_i j)}{\partial x_j} + \frac{\partial (u_i j)}{\partial x_j} + \frac{\partial (u_i j)}{\partial y} + \frac{\partial (u_i j)}{\partial y} = \frac{\partial (u_i j)}{\partial x_j} + \frac{\partial (u_i j)}{\partial x_j} + \frac{\partial (u_i j)}{\partial y} + \frac{\partial (u_i j)}{\partial y} \]

The u, v, and w presents the velocity of the fluid in x, y, and z respectively.

The simulation is built using a C++ language program and Cuda graphical language as visualization. The model was tested in as three dimensions virtual room with the shape as present in Fig 1. The geometrical property of the virtual room was constructed in identical dimension with the real
dimension. The scale of the room was 1 grid = 0.25 meters in real condition. The total grid was 64 x 64 x 24 grid represented 8 x 8 x 3 meter in real condition.

2.1.2. Experimental Approach

The measurement procedure was done by using the Kanomax 8552 indoor particle counter. The air conditioner was set to release the air at 24° C (Room temperature), spread horizontal direction, 45° at the vertical direction and medium fan speed. The measurement was conducted by measuring the particle concentration in the determined point after the air conditioner was activated for 5 minutes. The measurement point is shown in Fig.1. The measurement of the PM$_{0.1}$ was separated into two main processes. First, we measured the concentration of the particle in the small room labeled Rs. The dimension of Rs was measured of 3 x 3 x 2.5 m$^3$ respectively for width, length, and height. The grid size was determined at 1 x 1 meter. The measurement point was settled at the center of the grid with a height of 1 meter above the floor. The second procedure was executed in the large room (Rl) by using the similar procedure as in Rs. The measurement point is present in Fig.2.

![Figure 1. The virtual room in 3 dimension form](image1)

![Figure 2. Measurement point on the experimental room and simulation](image2)

3. Results and Discussion

3.1.1. Experimental Result

The experimental data show the distribution of the particulates in the indoor. We observed the PM$_{0.1}$ concentration was low in the area under the air condition. The concentration was found an increase in the distances of 1.5 meter from the air condition. The concentration gradually reduced by the longer of the distance. For example, in Rl, we measured the concentration of the PM$_{0.1}$ of 8.1 x 10$^3$ particles/cm$^3$ in the position 1. In the position 2, we calculated the PM$_{0.1}$ concentration increases of 0.1 x 10$^3$ particle/cm$^3$ into 8.2 x 10$^3$ particles/cm$^3$. In the point 8 and 9, the concentration of the particle was observed of 7.8 x 10$^3$ particles/cm$^3$ and 7.7 x 10$^3$ particles/cm$^3$ respectively. In the point 10, the concentration was dropped to 6.3 x 10$^3$ particles/cm$^3$. The similar result was found in the Rs. In the position C, we recorded the PM$_{0.1}$ concentration of 7.5 x 10$^3$ particles/cm$^3$. The concentration was increased in the position F that was quantified of 8.9 x 10$^3$ particles/cm$^3$. In the Rl, we found the average concentration was lower than the Rs. In the Rs, we calculated the average concentration of 9.0 x 10$^3$ particles/cm$^3$ while in the Rl was quantified of 7.8 x 10$^3$ particles/cm$^3$. 
Table 1. The experimental and simulation result for PM$_{0.1}$ concentration distribution in various position and room PM$_{0.1}$ x 10$^3$ particles/cm$^3$

| Position | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|----------|----|----|----|----|----|----|----|----|----|----|
| Experiment | 8.1 | 8.2 | 7.8 | 7.7 | 7.6 | 7.4 | 7.2 | 7.8 | 7.7 | 6.3 |
| Simulation  | 7.9 | 8.0 | 7.5 | 7.4 | 7.3 | 7.1 | 7.0 | 7.4 | 7.4 | 6.0 |

| Position | A  | B  | C  | D  | E  | F  | G  | H  | I  |
|----------|----|----|----|----|----|----|----|----|----|
| Experiment | 7.2 | 7.3 | 7.5 | 9.2 | 9.2 | 8.9 | 9.2 | 9.3 | 9.3 |
| Simulation  | 7.1 | 7.2 | 7.4 | 8.6 | 8.6 | 7.9 | 8.5 | 8.7 | 8.6 |

3.1.2. Simulation and data validation

The numerical simulation was executed at the similar condition setting to the experimental practice. In the result, we observed the concentration of PM$_{0.1}$ was similar to the real measurement. The measurement of PM$_{0.1}$ concentration in the direct exposure zone in the R/ was detected at a higher level. The concentration under the air condition was found lower than the exposure zone. However, we observed the numerical result was lower than the experimental result. The different between the experimental and numerical was calculated at 2%-5%. The numerical data trend is similar to the experiment. As seen in table 1, the PM$_{0.1}$ concentration is 7.9 x 10$^3$ particles/cm$^3$ in the point 1. In the point 2 and 3, the concentration increases to 8.0 x 10$^3$ particles/cm$^3$ and 7.5 x 10$^3$ particles/cm$^3$, respectively. The concentration reduces in the point 4 to 7 from 7.4 particles/cm$^3$ to 7.0 x 10$^3$ particles/cm$^3$. In the Rs, the concentration is higher than in the R/. The concentration of the Rs raises up to 9.3 x 10$^3$ particles/cm$^3$. In the point C, the concentration was measured at 7.5 x 10$^3$ particles/cm$^3$ while the concentration of 8.9 x 10$^3$ particles/cm$^3$ at the point F. The concentration distribution shows a similar trend in the R/. The higher particle concentration measured in the G is 9.3 x 10$^3$ particles/cm$^3$. In the point D, and A, the concentration reduces to 8.9 x 10$^3$ particles/cm$^3$ and 7.1 x 10$^3$ particles/cm$^3$.

Figure 3. Visualization of the particle movement in the virtual room with a fan speed of 1.6 m/s and 45° exposure angle.

Fig 3 visualizes the particle movement in the rooms. The figure shows the motion of the particle in 1 minute, 2 minutes, 3 minutes, 4 minutes, and 5 minutes. The particle movement is focused in the certain area. The particle concentration is found lower in a longer distance. The green area in the figure shows the lower concentration in a certain point. The direction analysis of the fig.2 leads to the movement prediction as presented in Fig 4. In the Fig, it can be seen the particle flow directs to the room corner. As a result, we obtain the increase concentration in the corner. A similarity trend is obtained for the simulation and experimental data. We calculate the different between the simulation
and the experimental data is less than 2.0% (Fig.5). For example, the calculated particle concentration was $8.0 \times 10^3$ particles/cm$^3$ for the simulation meanwhile the measured concentration is $8.0 \times 10^3$ particles/cm$^3$. In the point 3, the PM$_{0.1}$ concentration is of $7.5 \times 10^3$ particles/cm$^3$ and $7.8 \times 10^3$ particles/cm$^3$ for the simulation and experiment respectively. This result is validates our simulation.

In result, we find the air conditioner system exposing particulate matters especially PM$_{0.1}$. Before the air conditioner is activated, we measure the concentration of the PM$_{0.1}$ of $6.5 \times 10^3$ particles/cm$^3$ - $7.0 \times 10^3$ particles/cm$^3$. After the air conditioner is on, the concentration of PM$_{0.1}$ increases up to $9.0 \times 10^3$ particles/cm$^3$. The higher particle concentration is found in the certain position that is affected by the air condition wind flow that is stated as the effective zone. The area $R > 1$ meter is measured in the higher concentration. However, in the $R < 2.5$ meter, the concentration of PM$_{0.1}$ reduces. In the simulation, we succeed to visualize the distribution of the particulate matters. The simulation output shows that the particulate matters emitted by the air conditioner exposes effectively in the range $R > 1$ m when it places at the height of 3 meters with the flow direction of $45^\circ$. The area covered under the air condition is more affected. The air flow direction seems a responsible to the particle distribution [18]. The room geometric influences the effective zone. As shown in the simulation, the concentration of the particulate matter is found higher in the Rs. In the Rl, the concentration of the PM$_{0.1}$ is found lower. The large dispersion area is also responsible for this outcome. The particulate concentration reduces due to the effect of the particulate adhesion in the floor or the wall [19]. The flow direction observation from the simulation shows the PM$_{0.1}$ is concentrated at the corner of the wall. This result explains the increases in the PM$_{0.1}$ concentration in the corner of the room as stated in the measurement result. The different of the PM$_{0.1}$ concentration between the simulations and experimental may cause by the wakes of the particulates caused by the wind flow [20]. The airflow from the air condition blows the particles as a consequence is to increase the concentration. The difference between the calculated and experimental data is of 2.0%.

![Figure 4](image-url) The particulate movement in upper view after the simulation run for 50 minute

![Figure 5](image-url) The trend of experimental and simulation show similarly.
4. Conclusion
The unfiltered air condition system is found to release the PM$_{0.1}$ concentration up to 2.0 x $10^3$ particles/cm$^3$. The simulation model is successes to predict the particulate distribution in the indoor. The different between the experimental and the data is found at 2.0 %. The visualization of the air conditioner system particulate matters shows the particulate distribution indoor.

5. References

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