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MODELLING OF PARTICLE TRANSMISSION IN LAMINAR FLOW USING COMSOL MULTIPHYSICS

Ismail Abdul Rahman[1], Jouvan Chandra Pratama Putra[2] and Ade Asmi[2]
[1]Department of Civil and Environmental Engineering, Universiti Tun Hussein Onn, Malaysia
[2]Department of Civil Engineering, Bakrie University, Indonesia
E-Mail: ismailar@uthm.edu.my

ABSTRACT

Modelling and simulation is one of approaches to study the airflow movement and its effect to particle transmission within the room. This presents a study on the effect of laminar flow on particle transmission in an air condition room. The measured supply air velocity was taken using Davis Anemometer. While, the transmitted particulate matter of diameter ≥ 0.3 μm was using Particle Counter GT-521. Both of the measured values were used as an input in simulating particle transmission using COMSOL Multiphysics software. The simulation process comprise of constructing geometry space of the room, selecting physics module, assigning values and defining boundary, meshing and finally executing and computing the simulation. The results from simulation indicated that the air velocities at the occupant's area are 22.5 % to 43 % below than ASHRAE standard but the airflow distribution at working area meet with the standard. The simulation results are validated with the measured value and found that the percentage differences between the simulated and measured values are within the range of 0.4 % to 8.45 % which is in the tolerable range of 10 %.

Keywords: laminar flow, particle transmission, air condition room, COMSOL multiphysics.

INTRODUCTION

Indoor air pollutant is associated with the emission and accumulation of pollutants which generally attributed to poor ventilation and air exchange (Pepper and Carrington, 2009). Effective approach to assess the performance of ventilation and its effect to the particle dispersion is by using modelling and simulation (Abadie and Limam, 2007). Where modelling is process of emulating a real system (Robinson, 2007) and simulation is the process of manipulating of the model for the purpose of understanding behaviour of the system or for evaluating various strategies for the operation of the system (Shannon, 1975). The advantage of the modelling is that it able to combine several physics phenomena into a single entity (COMSOL AB, 2007) and simulation will carry out analysis using several approaches for getting solution (Pryor, 2011).

Several studies on particle distribution in mechanically ventilated room were carried out either by using experiment or modelling. Matson (2005), used a dynamic method for estimating numbers of Ultra-Fine Particles (UFP) concentration (particles' diameter range of 0.01 μm to 1 μm). He found that lower air changes rate could be resulted to the increase of the numbers of particles. Zhong and Yang (2010), studied the prediction of aerosol dispersion in indoor spaces using computer model and found that the particle removal performance strongly depends on the ventilation efficiency and the position of air supply in the room. Chang *et al.*. (2013), had improved the simulation method of investigating particle residence time in indoor environment by using Lagrangian model. The new method improves by adding convection to the previous method which only confine to advection-diffusion approach.

In Tian *et al.* (2006), they employed turbulence models which are standard k-ε and re-normalization group (RNG) - based Large Eddy Simulation (LES) to assess the contaminant particle concentration as affected to turbulence airflow. They found that the RNG-based LES is a proper model for simulate particle concentration in unsteady condition as compared to other two turbulence models. Subsequently, to identify the influencing factors on particle deposition, Zhao and Wu (2007) have employed analytical model and three dimensional numerical simulation models.

On other hand, Lin *et al.*. (2005) used Computational Fluid Dynamic (CFD) to investigate the effect of the air supply location towards thermal comfort and Indoor Air Quality (IAQ). They found that the air supply location should be located at centre of the room near, to provide better thermal condition in the room. Zhao and Wu (2009) used experimental test and simulation to study the effect of particle spatial distribution on particle (0.5 μm to 1 μm) deposition in ventilation rooms and found that the particle deposition is strongly influenced by the location of the inlets, outles and particle source. These studies of indoor particle modelling and simulation had motivated the authors to study and evaluate the particle transmission in laminar flow by using COMSOL Multipysics software.

MEASUREMENT OF AIR VELOCITY AND PARTICULATE MATTER (PM) ≥ 0.3 μm

This study was carried out in office rooms at Universiti Tun Hussein Onn Malaysia (UTHM). These rooms are mechanically ventilated by using split unit air-conditioning system. Air velocity samples were measured using Davis anemometer while the number of Particulate Matter (PM) ≥ 0.3 μm was using particle counter GT-521. Prior to that, the particle counter was calibrated according to GT-521-9800 REV. D standard (Met One Instruments Inc. 2001). The measurements were carried out for duration of eight (8) hours within five (5) days consecutively.

MODELLING AND SIMULATION

COMSOL Multiphysics software used in this study is a tool for modelling and solving all kinds of scientific and engineering issues based on Partial Differential Equations (PDE) (COMSOL AB, 2007). These PDEs are solved using Finite Element Method (FEM) and runs it together with adaptive meshing and a variety of error control numerical solvers. Since the COMSOL Software is able to interrelate with different kinds of physics phenomena into single entity (COMSOL AB, 2007), thus this flexibility not only simplifies the modelling process but also decreases the computational time.

Modelling

Modelling process involved several steps which include building up space geometry, selection of physics module, assigning values and defining boundaries, and meshing.

Space geometry

In space geometry, the required inputs for models are as in Figures-1, 2 and 3.

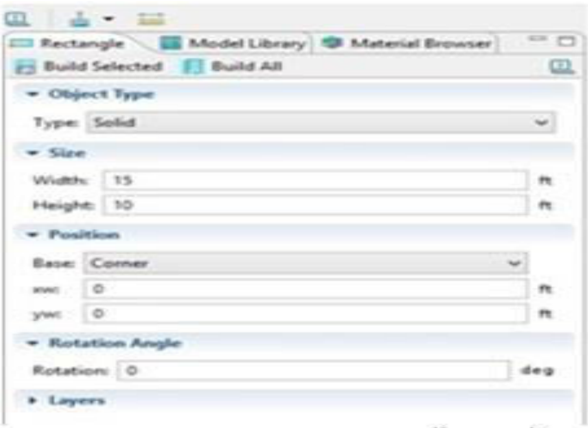

Figure-1. Room dimension.

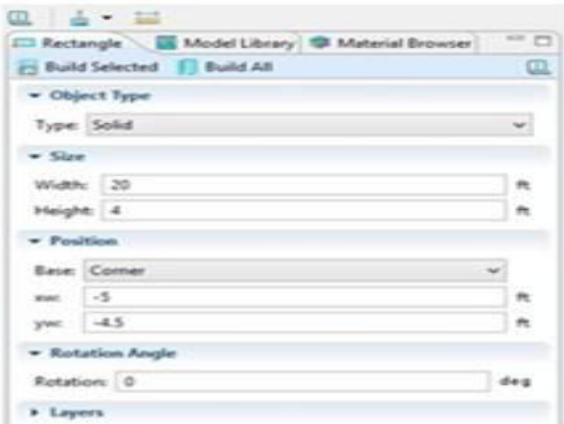

Figure-2. Dimension of hallway.

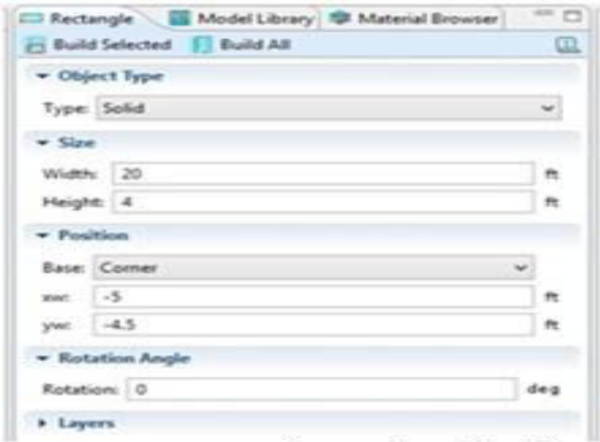

Figure-3. Dimension of hallway 2.

The figures indicated the input parameters for the room and the hallway. Once the input process completed then the 2D geometry models of room and hallway are developed as in Figure-4.

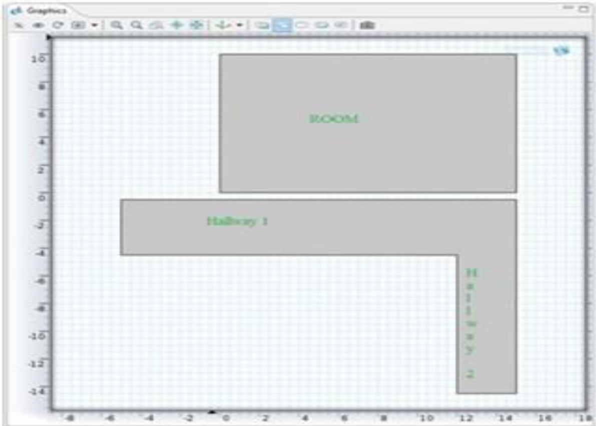

Figure-4. 2D geometry models of room and its hallway

Subsequently, a 3D geometry is needed to get the model as close as the real condition. This is achieved by extrude the geometry and assign it with the door and inlet air supply dimensions as in Figures-5 and 6.

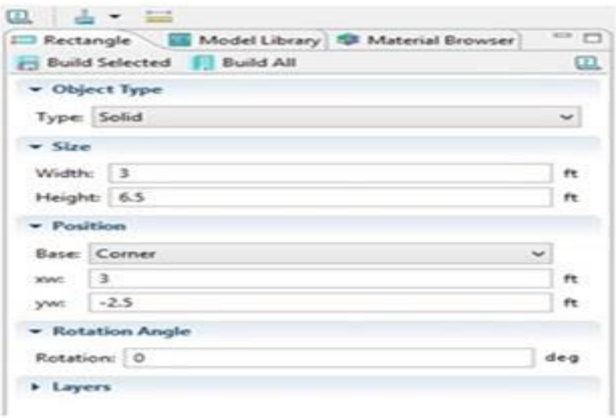

Figure-5. Door dimension.

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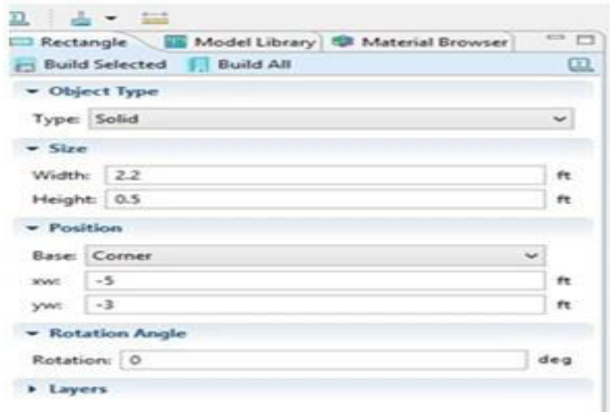

Figure-6. Inlet air supply dimension.

Figures-5 and 6 indicate the dimensions of door and inlet air supply which is used in 3D model and the output is depicted as in Figure-7.

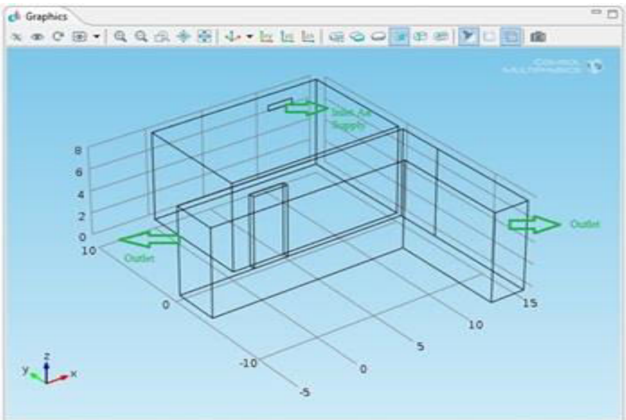

Figure-7. 3D geometry models.

Selection of physics module

Prior to modelling the particle transmission, it needs to model the air velocity as a medium for the particle transmission (Pepper & Carrington, 2009). Then, to select the proper physics module to model the air velocity distribution, first Re number of measured air velocity was calculated using the following equation:

$$Re = \frac{\rho.vs.L}{\mu} \quad (1)$$

Where:
Re = Reynold Number (Dimensionless)
ρ = The density of air (kg/m^3)
vs = Velocity of air (m/s)
L = Characteristic of length (m)
μ = The viscosity of air

Since the Re number is below than 2000, then it flow is categorized as laminar flow. Based on this result, the proper selection of physics module in COMSOL Multiphysics is laminar flow module. Subsequently, this module is coupled with the particle tracing module to model particle transmission.

Assigning values and defining boundary

In assigning the input values for laminar airflow module, the parameters required are air velocity (inlet air supply) and air temperature. While defining the boundary, it involves the selection of wall, inlet air supply and outlet of the room. For particle tracing module, the assigning value involved numbers of particle release. The input values are gained from the critical measurement in which the numbers of particulate matter is quite extreme. Those input values are tabulated as in Table-1.

Table-1. Input values of laminar flow and particle tracing module.

No. of Models	Inlet Air Supply Velocity (m/s)	Air Temperature(°C)	PM ≥ 0.3 µm (particle/m³)
1	1	29.1	101,229,070
2	1	29.1	101,406,006
3	1.5	29	101,791,035
4	1.5	28.9	102,602,549
5	1.5	28.8	103,302,868
6	1	29	104,193,599

Beside inlet air supply velocity and air temperature, laminar flow module also requires air properties such as air density, viscosity and kinematic of air. These required values were generated in software as default using the input values of air velocity and air temperature.

Meshing

Meshing is making partitions of space model geometry into smaller shape or area. If the mesh is too coarse then it will generate a low of element quality, which can cause large error in the simulation results. Conversely, if mesh is too fine the solution time for nonlinear system of equation will take longer computational time. Thus, it is appropriate to decide the proper types of mesh model which are finer, normal, coarse and extra coarse size. For this study, normal size and unstructured 3D mesh was used as is shown in Figure-8.

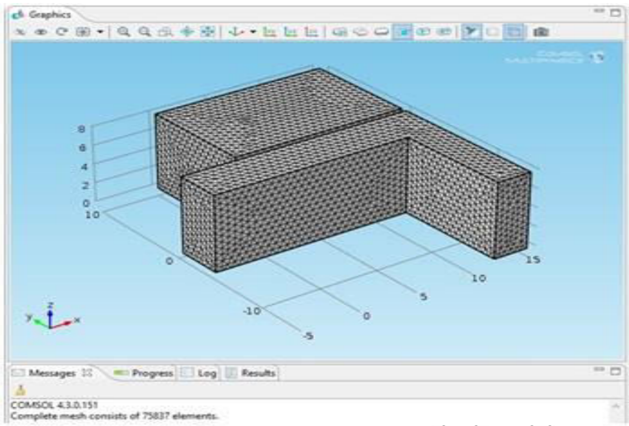

Figure-8. Geometry meshed model.

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Figure-8 shows the numbers of elements involved in this geometry meshed model which are 75,837 elements. The same approach was adopted for the other five models in determining meshing process and the number of elements involved in each of the model. Since the shape and the boundary position are same for all the six models, thus it has resulted to the same number of element involved in the meshing process.

Simulation process

Once the modelling process are completed, the simulation stage can be executed. The simulation process comprises of two stages, where the first stage is regarding of computing the air velocity distribution using laminar flow module and the second stage is computing particle transmission using particle flow module.

Simulation for airflow distribution applied laminar flow module which required the degree of freedom (DoF) and computational time for all the six models are as in Table-2.

Table-2. DoF & computational time for airflow.

No. of Models	Degrees of Freedom(DoF)	Computational Time
1	80,520	538 sec
2	80,520	538 sec
3	80,520	770 sec
4	80,520	770 sec
5	80,520	770 sec
6	80,520	538 sec

Similarly, simulation for particle transmission applied tracing module which required the degree of freedom and computational time for all the six models are as in Table-3.

Table-3. DoF & computational time for particle transmission.

No. of Models	Degrees of Freedom(DoF)	Computational Time
1	303,687,210	78,480 sec
2	304,218,018	80,640 sec
3	305,373,105	82,080 sec
4	307,807,647	84,960 sec
5	309,908,604	92,160 sec
6	312,908,604	96,480 sec

From Tables-2 and 3, it indicate that the degree of freedom values for airflow simulation are constant but for particle transmission, the values are not constant. In particle transmission simulation the degree of freedom depends on numbers of particle input, while its computational time based on the degree of freedom.

RESULTS AND DISCUSSION

Air velocity distribution

The simulation outputs for all the models are visualized in air velocity mode as Figures-9 to 14. Based on colour range displayed outside the model, maximum air supply velocity of the model can be determined. Air velocity at the occupant can be identified by clicking points around the occupant location and the system will pop-up the value. Airflow rate at occupant can be estimated by multiplying the air velocity at the occupant's location with its working area. Thus, for ventilation rate at working area, the determined airflow is divided with the number of occupants.

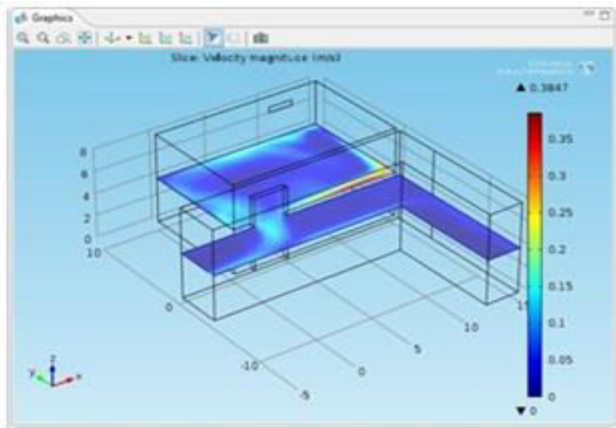

Figure-9. Air velocity distribution of model 1.

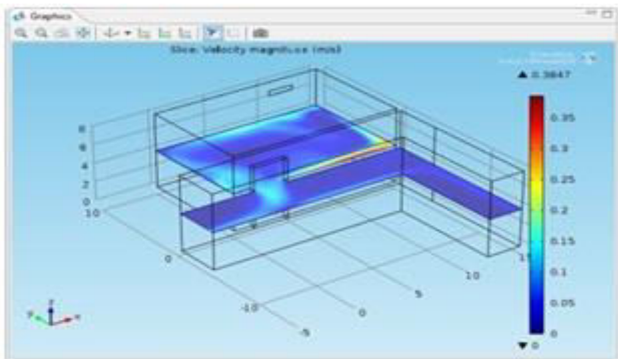

Figure-10. Air velocity distribution of model 2.

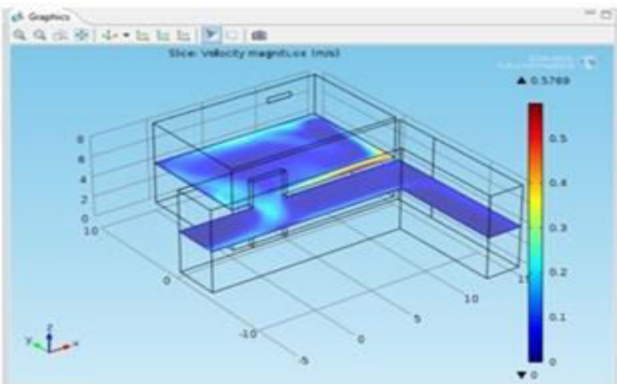

Figure-11. Air velocity distribution of model 3.

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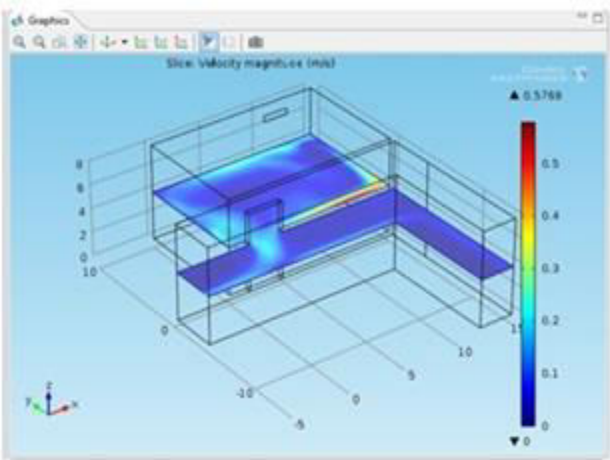

Figure-12. Air velocity distribution of model 4.

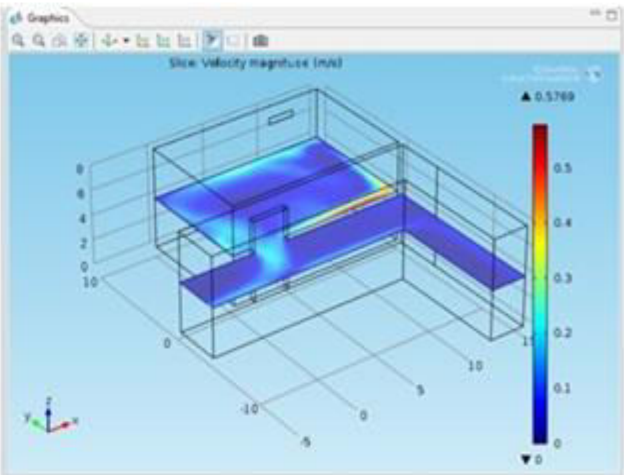

Figure-13. Air velocity distribution of model 5.

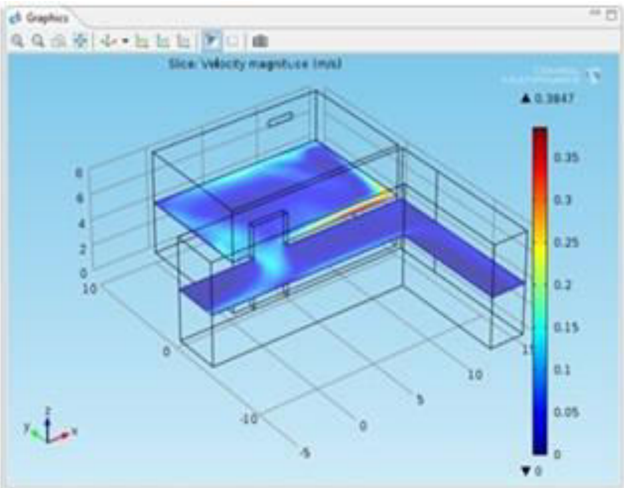

Figure-14. Air velocity distribution of model 6.

The maximum inlet air supply velocity, air velocity at occupant and also ventilation at working area for all the six (6) models are presented as in Table-4.

Table-4. Simulation results.

No. of Models	Maximum Inlet Air Supply (m/s)	Air Velocity at Occupant (m/s)	Ventilation at Working Area (l/s/p)
1	0.3614	0.028 to 0.09	33.6 to 108
2	0.3614	0.028 to 0.09	33.6 to 108
3	0.5428	0.043 to 0.135	51.6 to 162
4	0.5428	0.043 to 0.135	51.6 to 162
5	0.5428	0.043 to 0.135	51.6 to 162
6	0.3614	0.028 to 0.09	33.6 to 108

Table-4 shows that the air velocities at occupant are 22.5 % to 43 % below than ASHRAE standard which should be between 0.1 to 0.4 m/s. This implies that the occupant does not feel comfort to the lacking of circulating air.

Particle transmission

The particles movement is influenced by the pattern of supply and extraction of the air. In this case, the air movement in the room and the hallway is governed by air conditioning system where the supply air is coming from the diffuser located in the room and the extractor located in the hallway to extract the air out. All the six (6) models are assigned with 600 sec simulation time to estimate the amount of particle transmitted from the room to the hallway. The results of the simulation are presented in Figures-15 to 20 which visualise the trajectories of the particle from the room to the hallway of all the models.

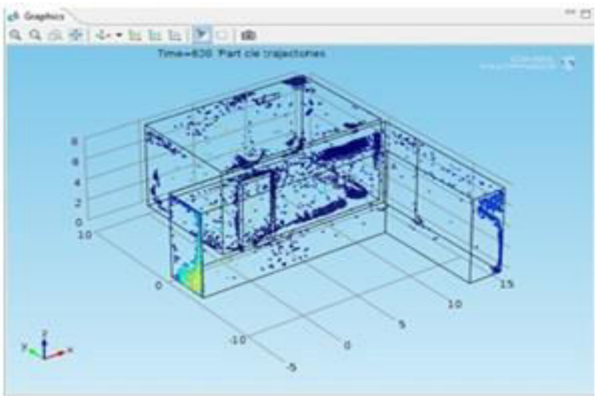

Figure-15. Particle transmission of model 1.

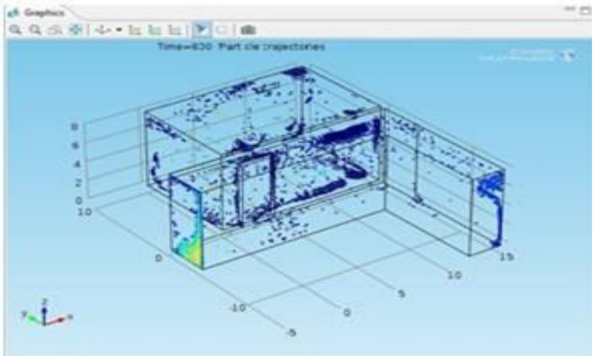

Figure-16. Particle transmission of model 2.

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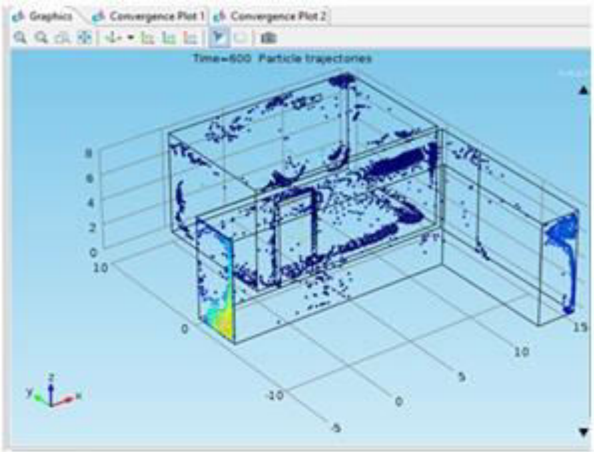

Figure-17. Particle transmission of model 3.

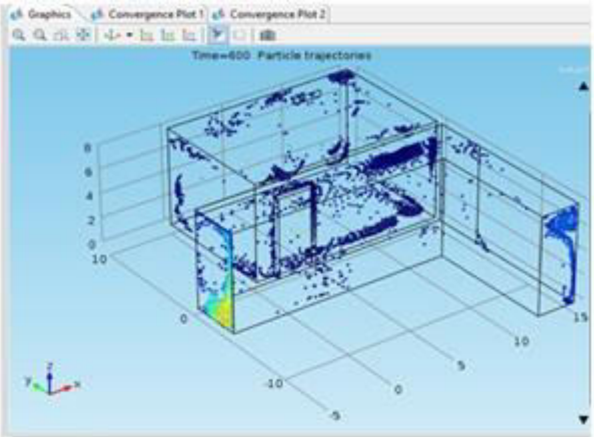

Figure-18. Particle transmission of model 4.

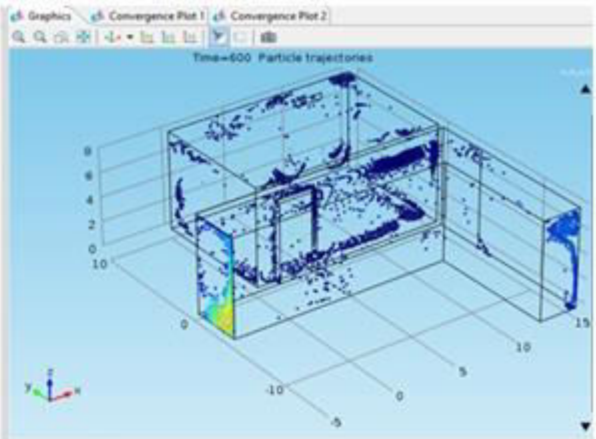

Figure-19. Particle transmission of model.

By using transmission probability function in particle tracing module, it will able to estimates the numbers of particle. These numbers of particles are manually calculated for deciding the percentage of the particle transmitted from the room to the hallway in 600 sec simulation time. The results of particle transmission for all the models are tabulated as in Table-5.

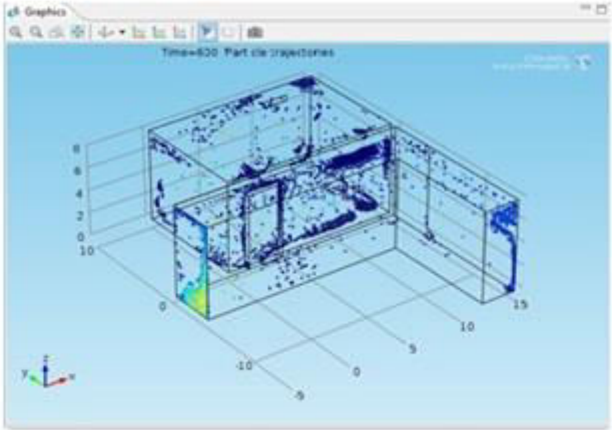

Figure-20. Particle transmission of model 6.

Table-5. Particle transmission.

No. of Models	% of Particle Retained in Room (m/s)	% of Particle Transmitted to the Hallway	Air Velocity at Occupant (m/s)
1	55.82	44.18	59.767
2	55.79	44.21	60.153
3	56.17	43.83	59.878
4	56.73	43.27	59.896
5	56.89	43.11	59.85
6	55.79	44.21	59.764

From the Table-5 describes the percentage of particle retained in the room is in the range of 55.79 % to 56.89 %, while the transmitted particle to the hallway is in the range of 43.11 % to 44.21 %. This indicates that performance of inlet air supply velocity to the room is almost constant.

VALIDATION

Particle transmission and dispersion is basically governed by the air velocity and according to Pepper and Carrington (2007), it is enough to validate the air velocity movement which also be representing the particle transmission and dispersion. As suggested earlier, the validation for this study was carried out between the measured and simulated air velocity values. The values of the two velocities and their percentages difference are in Table-6.

Table-6. Percentage difference.

No. of Models	Measured Velocity (m/s)	Simulated Velocity (m/s)	% Difference
1	0.5	0.54227	8.45
2	0.5	0.54227	8.45
3	0.78	0.81857	4.94
4	0.76	0.81857	7.71
5	0.76	0.81857	7.71
6	0.54	0.54227	0.42

The percentages difference of the two velocities are in the range of 0.42 % to 8.45 %, it is considered accepted as many researchers suggested the tolerable accepted percentage is below 10 % (Judkoff *et al*.. 2008). However, Maamari *et al*.. (2006) suggested a wider tolerance where the acceptable percentage difference between measured and simulated results should not be more than 15 %. Beside the percentage difference, the correlation between the measured and simulated velocity is checked using the R2 value. The correlation between the two velocities is presented as in Figure-21.

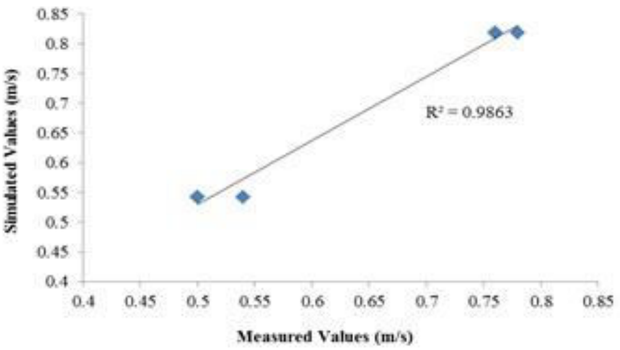

Figure-21. The correlation between the measured and simulated velocity.

The simulated velocity for all the six (6) models is strongly correlated with the measured velocity as represented with the R2 value of 0.9863 in the Figure-21. With the acceptable percentage difference and strong correlation, it can justify that all the models are validated as representation of the actual condition. Thus, the simulated particles transmission that was determined earlier is reasonably.

CONCLUSIONS

Modelling and Simulation in this study was carried out using Comsol Multiphysics software to assess and demonstrate the particle transmission as affected by laminar flow. Essentially, the results of this simulation cannot resemble 100% of the actual circumstances and this cause to the discrepancy of the simulated value. However, for this study the discrepancy between the simulated value and measured value is in the range of 0.4 % to 8.45 % which is in the tolerable limits of 10% as quoted by many researchers (Judkoff *et al*.. 2008). In addition, the correlation between simulated value and measured value are strongly correlated as indicated through R2 value of 0.9863. This study found that the air velocity at occupant's location is below than ASHRAE standard (0.1 m/s to 0.4 m/s), which will affect to the occupant's health and work performance and the particle transmitted from the room to the hallway is about 44%. This means that either increment or decrement of air supply velocity in the same location of inlet did not impacted significantly for lessening the number of indoor air particle.

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