Exploration of CFD models for personalized ventilation air terminal devices

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ABSTRACT
Whilst Computational Fluid Dynamics (CFD) has been popularly applied in indoor air and ventilation research, most Personalized Ventilation (PV) research is based on experiments. This study is an attempt to seek validation of PV experimental data with results from numerical models of Air Terminal Device (ATD), since the ATD is crucial in the simulation of PV system.

The CFD study involves a systemic study and comparison of various simulation methods of PV ATD, aimed to develop PV ATD models for future whole room PV system simulation. Boundary Conditions (BC) are obtained from an elaborate set of measurements obtained with a PV ATD at one workstation. In this study, PV ATD is simulated and validated by direct description method and box method. It is found that both methods cannot accurately predict PV air velocity. The method proposed out of this study is a development of direct description method and it substantially improves simulation accuracy, and has acceptable agreement with the measurement.

INDEX TERMS
Personal control; CFD; Diffuser; Ventilation system

INTRODUCTION
Being a robust and powerful research tool, CFD has been popularly applied in indoor air and ventilation research. However, numerical simulation of PV system has been seldom conducted. Hiwatashi *et al.* (2000) simulated fresh air supply in a PV system. To simplify the model in their study, the PV ATD was simulated as a simple square opening. The simple ATD model may not produce similar PV airflow pattern as that of the real PV system.

The model of ATD is crucial in the simulation of the PV system. It is because air supply from a terminal device strongly influences airflow in a room, and the PV ATD is usually close to occupants. It is, therefore, likely to have a more direct influence on human perception of indoor environment. However, as far as known, there is no air supply openings simulation particularly designed for a PV system. There are some investigations on model of supply openings. Nielsen (1992) summarized four simulation methods of BC at supply openings: Direct description, Box method, Prescribed velocity method and Computer-generated inlet supply conditions. Srebric and Chen (2001) developed a Method of Test (MOT) to obtain the needed parameters for simulations, which is a kind of direct description method.

This study involves a systemic investigation and comparison of various simulation methods of PV ATD, aimed at developing PV ATD models for future whole room PV system simulation.

METHODS
The experiments are conducted in the Indoor Air Quality (IAQ) chamber (Figure 1) in the Department of Building, National University of Singapore. For the simulation of PV ATD, the measured and simulated space is Workstation 2 in the chamber with the dimension of 2.0 m (L) × 1.0 m (W) × 1.5 m (H) (Figure 2).

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PV air parameters (velocity, temperature, turbulence, etc.) are measured in Workstation 2, and the measured points at position A, B, C, D, E, F, G, H, I are shown in Figure 3, which is used for validation.

The simulated PV ATD in this study is about a rectangular shaped box shown in Figure 4 with the dimension 260 × 100 × 100 mm^3. The structure of the ATD is: a short air duct from which PV air enters the ATD and an indefinitely shaped cloth air bag covering the short duct inside the ATD. The air bag has a certain resistance to convert the air dynamic pressure into static pressure. Therefore, PV air could change its initial velocity direction and distribute more uniformly along the panel. There is also a layer of thin gauze closely attached on the perforated panel. This gauze also assists in developing a uniform air distribution.

The experiment is conducted under isothermal condition of 23°C, with only the PV system in operation, and the ambient secondary air-conditioning system being turned off. There are no human subjects; both lights and PCs are off during the experiment. Table 1 is the summary of simulation model and the BC used. The computer simulation includes the box method and the direct description method. In the direct description method, three sub-methods are adopted: MOT, Momentum method and Real slots method.

RESULTS

The velocity distribution of the PV air at the PV panel is shown in Table 2. The velocity distribution is quite non-uniform. The mean value (2 m/s) of the velocities at 0.5 cm from the ATD will be used for MOT simulation.

The measured velocity data along the PV airflow is shown in Figure 5. Stronger airflow is observed at the region near points 3 and 4 rather than the region near points 1, 2 and 5. The increased airflow at locations of points 3 and 4 is verified by smoke visualization, which is conducted after the velocity measurement.

In the comparison of measured and simulated result, the velocity data considered is only after the distance of 20 cm from PV ATD since most subjects usually adjusted the PV ATD at a distance of 20 cm or more from the breathing zone in our recent PV pilot study and Danish studies (Kaczmarczyk *et al.*, 2002).

The simulations are done for BOX, MOT, Momentum and Real slots methods. Viewing the velocity data after 20 cm, similar features are observed for all methods, i.e. the predicted value of locations 3 and 4 is lower than the measured data, while predicted data of locations 1, 2 and 5 are all higher than measured data. For example, mean difference between measured and predicted value of real slot method for location 1 is –0.26 m/s, for location 3 it is 0.30 m/s. It has also been observed that all the methods cannot accurately predict PV air velocity.

DISCUSSION

Since the predicted value of all simulation methods is lower at location 3 and 4 in comparison, and higher at location 1, 2 and 5, it is possible that the momentum in the region near locations 3 and 4 may be underestimated, while the momentum at locations 1, 2 and 5 are overestimated. For the direct description methods, i.e. Momentum, MOT and Real Slot, the velocity used as BC is the mean value of velocity, which could be a possible reason causing inaccurate estimation of momentum distribution along the PV ATD. Therefore, this study will discuss how to improve the direct description method by proper distribution of momentum along the PV ATD.

For the MOT method, directly using the measured data at each position on the ATD instead of using mean value could more accurately reflect the real momentum distribution. In the PV ATD model of modified MOT, the supply opening is divided into 10 parts, which corresponds with the measured 10 locations, and the measured velocity data are assigned accordingly. So the difference between modified and original MOT is the use of local velocity instead of mean velocity in the modified MOT.

For modified momentum and real slot method, the effective supply area is divided into three parts, and a different airflow rate is assigned to different parts. The area ratio of the three parts is 1:2:2, which corresponds, respectively, to the region of location 5, locations 3 and 4, locations 1 and 2. By trial and error to match the prediction and measurement, the boundary velocity at each part is determined with higher value in the region of locations 3 and 4, lower value in the region of locations 1 and 2 and the region of location 5. Although the velocity at each part is varied, the mean velocity is kept the same as that of the original model. This flow rate assignment, i.e. increased airflow rate at locations 3 and 4, and less at locations 1, 2 and 5, is identical with smoke visualization results.

The comparison between simulated results and measurements at the five points along the PV panel is shown in Figures 6(a) and (b) for the modified real slot method. The aim is to show the same improved simulation feature for all modified methods. From the figures, it could be seen that the simulated velocity at location 3 and 4 areas matches well with the measurement, while there are some deviations at locations 1, 2 and 5 compared with measured data, but not significant. For example, the mean difference between measured and predicted values of the modified real slot method in locations 1–5 are –0.17, –0.1, 0.01, 0.08, and –0.17 m/s, respectively.

There are some deviations between the measurement and predictions at locations 1, 2 and 5 for the modified MOT, Momentum and Real Slot methods. But all the deviations are less than those of the original models. At locations 3 and 4 the prediction matches with the measurement quite well. Since the flow rate in the region of locations 3 and 4 occupies 68% of the entire airflow rate (calculated from the assumption that each measured value as a mean value corresponding to equal section area of flow field), it could be argued that the prediction is accurate for most airflow supplied from ATD. Therefore, it could lead to the conclusion that the predictions of three modified methods have acceptable agreement with the measurement. Also, the simulation results show that modified real slot method is better for accuracy, followed by modified momentum method and modified MOT in descending order.

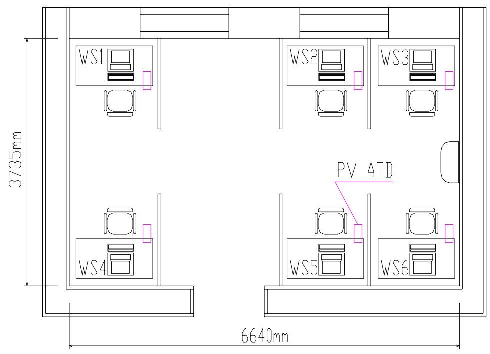

Figure 1 Indoor air quality chamber.

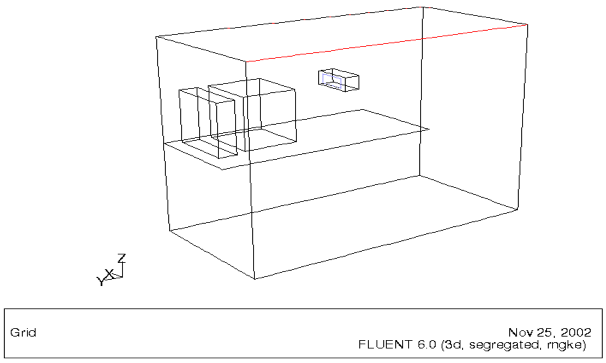

Figure 2 Simulation space of ATD model.

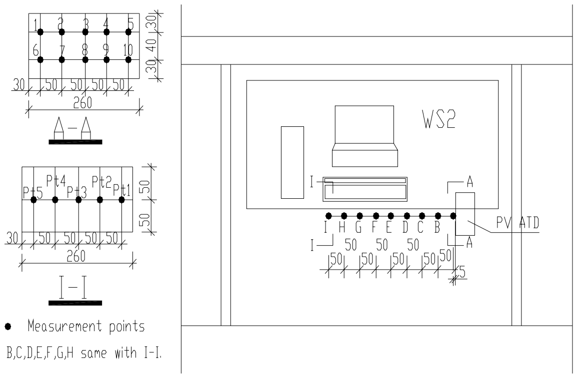

Figure 3 Measurement points for simulation. **Figure 4** PV ATD used in the study.

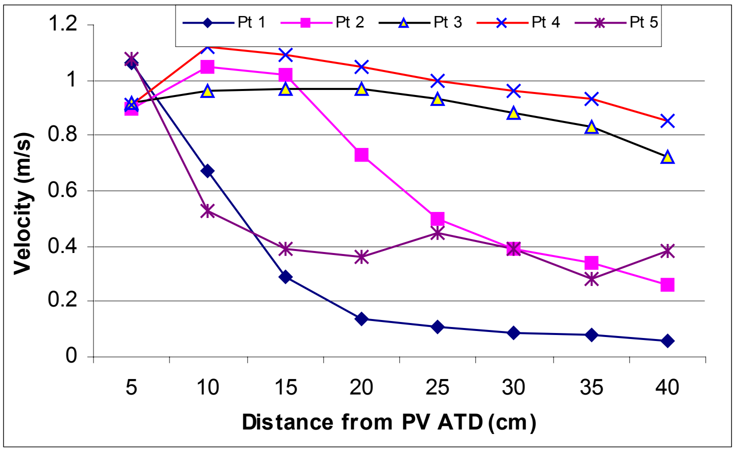

Figure 5 Measured PV air velocity.

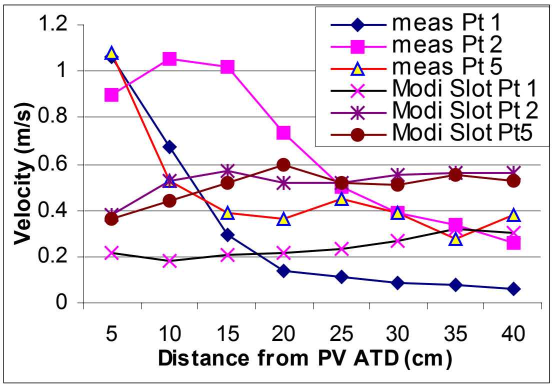

Figure 6a Velocity comparison for Pt 1, 2, 5.

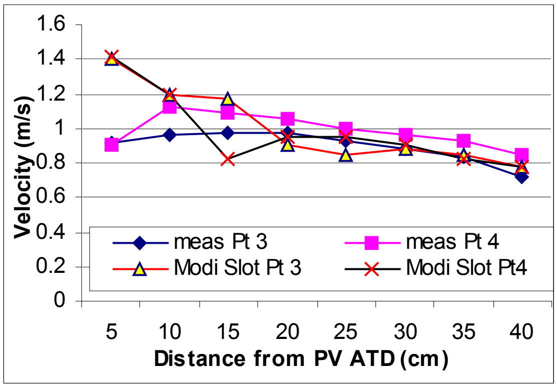

Figure 6b Velocity comparison for Pt 3, 4.

Table 1 Simulation model and boundary condition

Turbulence model	Meshed Cell	Human heat	PC	Lights	Wall	Furniture
RNG k–ε	166×10^3	N/A	Off	Off	Constant temp	
Method	MOT	Momentum	Real slot	Box		
Supply BC	2 m/s	1.25 m/s	1.25 m/s	Measured data 10 cm from ATD		
Exhaust BC	Top and one side air surface $P_s = 0$					

The initial velocity at the PV panel for MOT, Momentum and Real Slot methods are obtained as follows: MOT—measured mean velocity at 0.5 mm from the PV panel; Momentum and Real Slot—v = airflow rate (15 l/s)/effective area of panel (0.012 m^2); Box Method—measured velocity at 100 mm from PV panel.

Table 2 Measured PV air velocity distribution at PV panel

PV air velocity distribution at 0.5 cm from ATD (m/s)						
Position	Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	MEAN
0.5 cm top	3.21	1.19	2.33	3.33	1.59	
0.5 cm bottom	2.27	1.39	1.2	1.69	2.05	2.00

For the location of the measured points, please refer to Figure 3, I–I sectional view.

CONCLUSION

The CFD study, presented in this paper, involves a systemic study and comparison of various simulation methods of PV ATD, aimed to develop PV ATD models for future whole room PV system simulation. In this study, PV ATD is simulated and validated by direct description method and box method. It is found that:

- Direct description and box method cannot accurately predict PV air velocity of PV ATD. As a development of the direct description method, this study proposes modified MOT, real slot and momentum methods, which properly distribute momentum along ATD outlet surface.
- The modified methods could substantially improve simulation accuracy compared with original methods, and have acceptable agreement with the measurement. Among the three methods, modified real slot method is good to be taken for accuracy, followed by modified momentum method and modified MOT in descending order.

ACKNOWLEDGEMENTS

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