INFLUENCE OF FURNITURE LAYOUT AND VENTILATION DESIGN ON AIR QUALITY AND THERMAL COMFORT

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ABSTRACT
This paper describes the development of design charts to determine the influence of diffuser's layout on the air quality and thermal comfort conditions based on three diffuser's layouts and two office's layouts over a range of air change rates. Layout A, with a ceiling supply diffusers and a wall extract grille, was studied as the base case. The measurements of air velocity, temperature and pollutant were conducted in an environmental test facility. Computational Fluid Dynamics simulations were carried out to predict the air velocity, temperature and pollutant profiles. These simulated results were validated against the empirical measurements to ensure that the subsequent simulations for Layouts B and C were accurate. Air quality and thermal comfort parameters, such as pollutant removal efficiency, predicted mean vote and predicted percentage of dissatisfied, were computed for all layouts over a range of air change rates and presented in the form of design charts.

INDEX TERMS
Design Charts, Diffuser, Thermal Comfort, Indoor Air Quality, CFD Modelling.

INTRODUCTION
The behaviour of airflow influences the propagation of airborne pollutants, the thermal environment and general comfort conditions. Airflow pattern in indoor environment is affected by parameters such as velocity and momentum flux at the supply diffuser; type of supply diffuser; location of supply and extract terminals; geometry of the room; movement of objects; stationary or intermittent load; obstacles and furniture. Investigation of the collective effect of all these parameters on the airflow pattern in indoor environment can become very complex. In the preliminary study, it is more appropriate to assess the effect of individual parameter on the indoor airflow pattern since each of these parameters has varying degree of impact on the airflow pattern. A specific interactive study of two or more parameters can be pursuit to determine the insight of the complex flow pattern following the preliminary evaluation.

Research on the effect of partitions on air movement in rooms is of increasing importance with the growing number of commercial buildings adopting the open-plan workspace. In 1998, Nielsen et al. (1998) investigated the influence of office furniture on the air movement in a room with mixing ventilation, and found that the furniture affected the air movement only at the lower portion of the room. In recent years, Lee and Awbi (1999) conducted scale-model tests and Computational Fluid Dynamics (CFD) simulations to investigate the effect of partition configuration on the airflow and contaminant movement, including its location in the room and the gap between the partition and the floor. The results implied that optimal

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configurations existed for the partition location, the gap height and the contaminant source location for maximum ventilation performance. In a recent research, Cheong et al. (2000) conducted empirical and numerical studies on the influence of office layout on the ventilation and temperature distribution in an environmental chamber. It was concluded that the office layout has significant impact on the air velocity and air temperature distributions. This research has led to development of design charts to determine the influence of diffuser layout on air quality and thermal comfort as discussed in this paper. The main objective of the design chart is to assist ACMV designer in the formulation of optimum design to provide good ventilation performance and comfort conditions.

DEVELOPMENT PROCESS OF THE DESIGN CHARTS

The sequence of development of the diffuser's layout charts for the air quality and thermal comfort parameters in an office environment is illustrated in Figure 1.

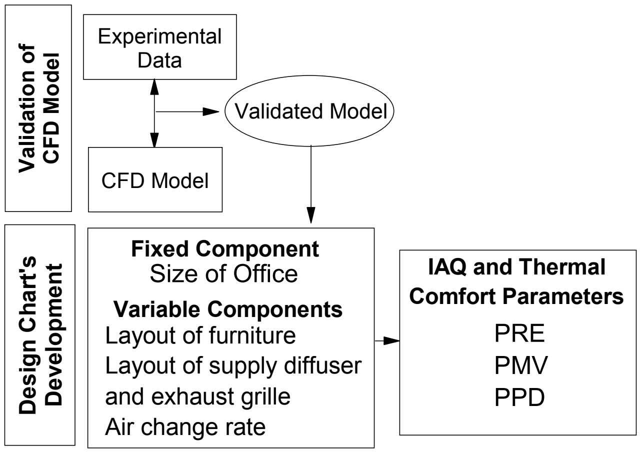

Figure 1. Development process.

Validation of CFD Model

The simulated air velocities, temperature and pollutant profiles generated by the CFD model were validated by the empirical measurements. This is to ensure reliable and reasonable predicted results.

Empirical measurements

Empirical measurements were carried out in an environmental test facility, 6.6m (L) x 3.7m (W) x 2.6m (H), with the mock-up of two typical office layouts. Figures 2a and 2b show the mock-up of office layouts 1and 2 respectively. In Furniture Layout 1 (FL1), the two workstations are located in the middle of the room and separated by a low-level partition. In Furniture Layout No. 2 (FL2), a low-level partition separates the room into two halves with one workstation at each corner. The test facility is ventilated at 7 air changes per hour (ACH) via a 600mm x 600mm square supply air diffuser located at the ceiling and a 645mm x 290mm rectangular return air grille at the end wall close to workstation 1(WS1). The room is illuminated by 6 sets of twin double-battens fluorescent lights, consuming a total of 6x120 Watts of electricity energy.

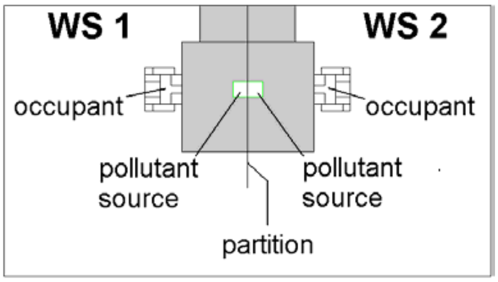

Figure 2a. Plan of layout 1

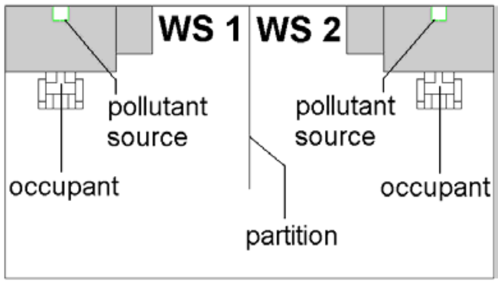

Figure 2b. Plan of layout 2

These empirical data were to establish boundary condition values for the simulation. The types of boundary condition include airflow rates of the supply diffuser and return grille; air temperatures of supply and return grille; and surface temperatures of the walls and furniture. In the validation exercise, air velocity and temperature were measured at thirty-five locations in the room and these were compared against the predicted values. For each location, the air velocity and temperature were taken at 4 different heights, i.e. 0.1m, 0.6m, 1.1m, and 1.7m from the floor level respectively. In the pollutant study, a constant emission of sulphur hexafluoride (SF_6) was to simulate the pollutant source and measurements were made at the breathing level of the occupants.

Numerical simulation

In the simulation process, the pre-processor generated the test facility model with two pollutant sources using unstructured grid meshes for the mock-up of two office layouts. The source, representing a typical computer monitor, was modelled as a box with dimension of 0.2m x 0.2m x 0.2m. These two sources are located at the head's level at 0.9m from the front of the human. Different part of the model had different grid coarseness. The face of the diffuser had mesh size of 30mm while the partition and furniture had mesh size of 100mm. The entire space in the room had volume mesh size of 150mm. The finer meshes at the diffuser and furniture were to capture airflow details that were critical to this study. In order to ensure that these simulated cases were independent of the spacing between two grid points, a grid dependency test was carried out by reducing the grid size of the partition, furniture and the room to 75mm and with the grid size of the diffuser remains unchanged. It was found that there was no difference with different mesh coarseness, and hence the case was grid independent. The boundary conditions specified for the model were based on data obtained from the field measurements. The heat generated from the human body and artificial lightings was modelled as 42 W/m^2 and 166.7 W/m^2 respectively. All other walls were assumed to be 24 °C. The air was supplied to the room at 18 °C with a total air change rate of 7 ACH (1.35 ACH as outdoor air change rate). The resulting models have around 160,000 cells. RNG k-ε was selected as the turbulence model and the non-equilibrium wall function was used. The computational process needed around 1500 iterations before convergence. The total Central Processing Unit (CPU) time taken was about 40 hours.

Design Charts' Development

In the development of the design charts, the size of the office was the only fixed component while the layout of supply diffuser and return grille, layout of furniture and air exchange rate are variable components. From the simulated results, air velocity, air temperature and pollutant concentration around the occupants were recorded. In addition, the concentrations of pollutant at the exhaust grille and supply diffuser were measured. The values of predicted mean vote **(**PMV), predicted percentage of dissatisfied (PPD) and pollutant removal efficiency (PRE) were computed based on these results. The PMV and PPD indices were calculated using the standard method described in ISO Standard 7730 (1994) and ASHRAE

Standard 55 (1992). PRE was computed by dividing the time-average concentration of pollutants in the exhaust air by the time-average concentration of pollutants in the breathing zone. It is a more direct indicator of the effectiveness of the ventilation system in removing the indoor-generated pollutants. The performance removal efficiency is a function of the locations of the pollutant sources and the pollutant emission momentum and the indoor airflow pattern (Faulkner et al 1999).

The previous validated CFD model was used for a series of numerical experiments with the same furniture layouts. The design charts were developed for three layouts of supply diffuser and return grille. Layout A has a square diffuser mounted at the ceiling and an exhaust grille at one of the end walls as shown in Figure 3a. This arrangement of the supply diffuser and exhaust grille is the same as the previous validated model. It is to note that WS 1 is located nearer to the exhaust grille in this layout. Layout B comprises of two diffusers located symmetrically at the ceiling of the room. The exhaust grille is located at the ceiling near the wall as shown in Figure 3b. The grille is above the partition that divides the room to form two workstations. In Layout C, there is only one diffuser and one exhaust as shown in Figure 3c. The supply diffuser is located at the ceiling above WS 2 and the exhaust grille is located at the ceiling above WS 1. The arrangement of the furniture layout for both workstations is symmetrical.

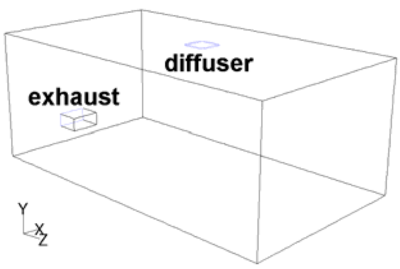

Figure 3a. Layout A

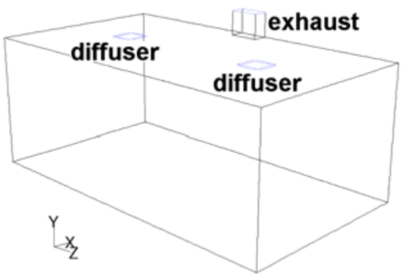

Figure 3b. Layout B

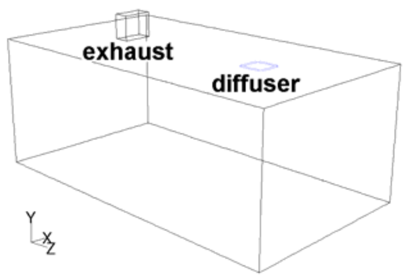

Figure 3c. Layout C

A total of six cases were studied based on the various combinations of layouts of diffuser and furniture. Cases 1, 2 and 3 are furniture layout 1 with diffuser layouts A, B and C respectively. Cases 4, 5 and 6 are furniture layout 2 with diffuser layouts A, B and C respectively. They were modelled at 5 different air change rates, i.e. 5, 7.5, 10, 12.5, 15 ACH. The fresh air provision was assumed to be 20% of the supplied air. All the boundary conditions and simulation parameters were the same as the validated model. The pollutant source was assumed to emit 8.35×10^{-7} m^3/sec of SF_6.

RESULTS AND DISCUSSION

Validation of Predicted Results Against Measured Results

Fair agreement was found between the predicted and measured results for air velocity, temperature and pollutant concentration. The percentage difference between the measured and simulated air velocity ranged between 5.8 and –6.5. The difference between the measured and simulated temperatures ranged between 0.2 ^oC and -0.3^oC. The percentage difference between the measured and predicted pollutant's concentration ranged between –3 and –5.4.

Multi-factorial Design Charts for the Effect of Diffuser Layout on PMV, PPD and PRE

Figures 4a - c show the design charts for PMV, PPD and PRE respectively. Figure 4a shows that all the cases have PMV values of less than 1, except for WS 1 with DL C in FL 2 at 5 ACH. However in FL 1, most of the cases have PMV values between 0.5 and 1. It is to note that PMV values between 0.5 and 1 are still considered acceptable. However, the desired value is to be within 0.0 ± 0.5. FL 2 is observed to have more instances where PMV values are within the desired range when the air change rate exceeds 7.5 ACH. However, it is to note that WS 1 with DL C has PMV values exceeding 0.5 for almost all air change rates. In summary, there is only marginal difference in the PMV values between the diffusers' layout except for DL C. It is observed for DL C that there is a difference in PMV profiles between the two workstations. The occupants seated at WS 1, which is located near to the exhaust grille, will experience relatively warmer sensation as compared to occupants seated at WS 2, which is located near to the diffuser. In general, the occupants seated at the workstations in FL2 will be thermally more comfortable as compared to FL1 for the three layouts of diffuser.

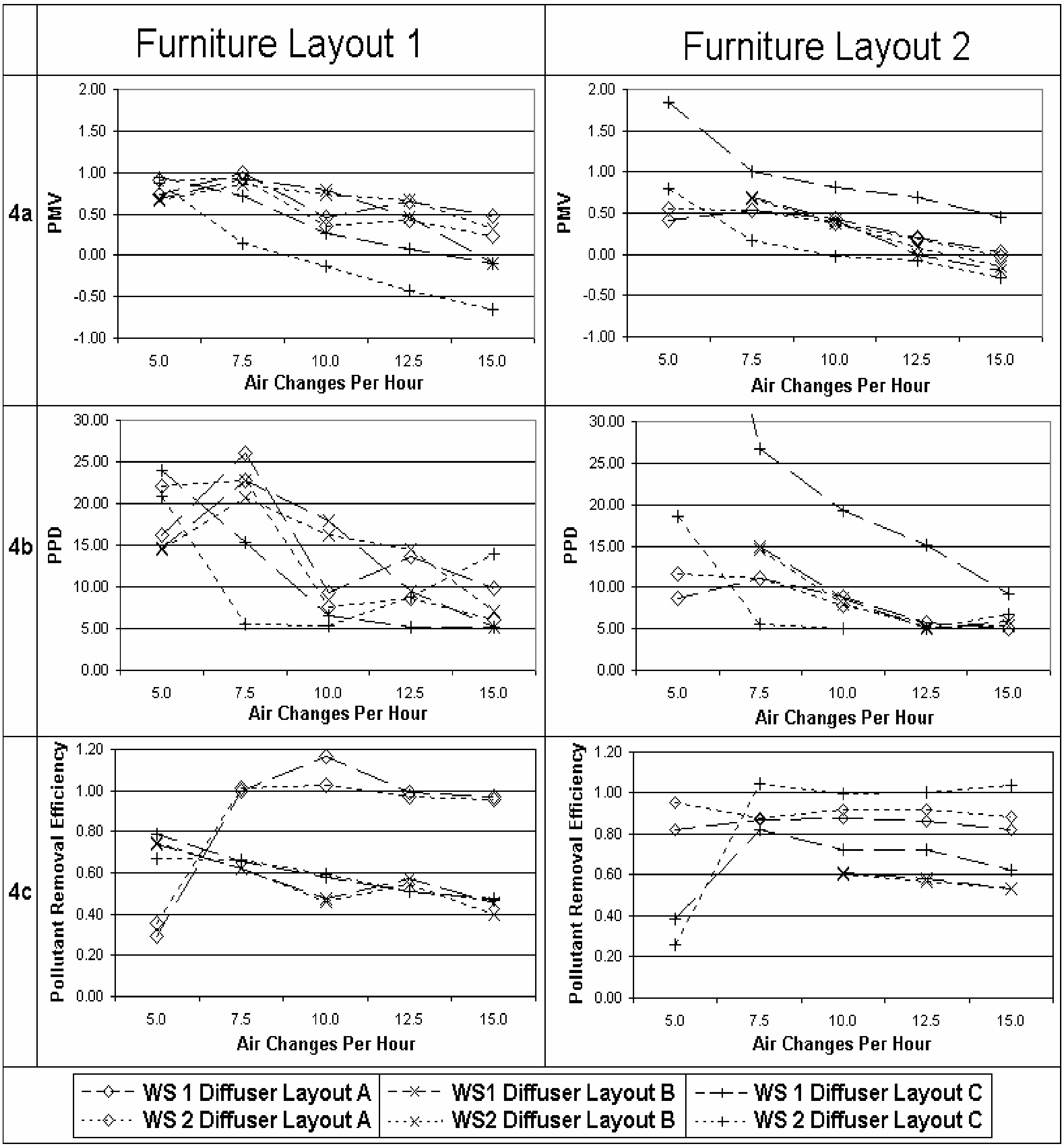

Figure 4a - c. Effect of diffuser layout on PMV, PPD and PRE.

Figure 4b shows the effect of diffuser layout on PPD. In FL 1, the PPD values have marginally exceeded 20% in some instances for all diffusers' layout. In FL 2, most of the cases have PPD less than 20% except for WS 1 with DL C. It is observed from the other results not presented in this paper that occupants become dissatisfied when air velocity is less than 0.06m/s with temperature exceeding 26^{o}C and relative humidity at 60%.

Figure 4c shows the effect of diffuser layout on PRE. In FL 1, DL A shows that with the air change rate exceeds 7.5 ACH, the PRE value is closed to 1. This suggests that DL A is more effective in removing pollutant at the occupant's level as compared to DL B and DL C with lower PRE. In FL 2, DL A has an almost constant PRE profile of about 0.86 over all the air change rates. DL B has the lowest PRE values. However, the PRE values vary depending on the location of the workstation in DL C. The workstation, WS2, closer to the diffuser has higher PRE values. This may imply that the air from the diffuser is able to dilute and prevent any build-up of pollutant's concentration at the occupant level in WS 2.

CONCLUSION

The design charts on the effects of diffuser layout on PMV, PPD and PRE have been successfully established for an office environment over a range of air change rates. The CFD model was well validated with reasonable correlation between the measured and predicted results. The influence of diffuser's layout on PMV and PPD was found to be minimal. There was only marginal difference in the PMV values for the different layouts of diffusers except for DL C. It was observed in DL C that occupants seated at the workstation near to the exhaust grille would experience relatively warmer sensation as compared to occupants seated at the workstation near to the diffuser. The PPD value of more than 27% was found at 7.5 ACH in FL 2 at WS 1. The influence of diffuser's layout on PRE is found to be more significant as compared to PMV and PPD. DL B has the lowest PRE values as compared to DL A and DL C. However, it was observed that the PRE values vary depending on the location of the workstation in DL C. With these multi-factorial design charts, the ACMV Designer could construe from these charts to formulate the design of the air distribution system. It is hoped that these multi-factorial models could guide them to achieve better air quality and comfort for the occupants.

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