# The variation of ventilation performance in relation to change in workstation location in a ventilated room

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## ABSTRACT

This paper considers the predictions obtained using a recently developed ventilation parameter (VP) for evaluating the ventilation performance which combines the indices for indoor air quality and thermal comfort. This ventilation parameter is used to analyse the changes in ventilation performance with changes in the position of workstation in a room ventilated using mixing ventilation.

Measurements and CFD simulations for different workstation positions have been carried out at different air change rates. The four indices: the removal effectiveness of contaminant and heat, the predicted percentage of dissatisfied for thermal comfort (*PPD*) and the percentage of dissatisfied (*PD*) for air quality were obtained and then used to calculate the value of the ventilation parameter (VP). The results show that VP is a comprehensive index for assessing the changes in ventilation performance due to variations of workstation position. In this study, it was found that the optimum position of a workstation is achieved when the workstation is positioned at a zone adjacent to the air exhaust point.

## INDEX TERMS

Ventilation parameter; Personalized zone; Coanda effect; Jet interaction with plume

## INTRODUCTION

Indoor air quality and thermal comfort are the main concerns of the occupants of a building. However, even when the air quality indices are achieved, this does not always guarantee good thermal comfort. It is therefore necessary to couple these two parameters when analysing the indoor environment. Recently, a *Ventilation Parameter* (*VP*) that combines a thermal comfort and air quality indices was developed and applied to analyse the performance of four different ventilation systems (Cho *et al.*, 2002).

In a mixing ventilation system in which case the air supply terminals are close to the ceiling, the flow in the plume from heat source could interact with the jet flow along the ceiling. Depending on the heat sources locations, the jet entrainment of each plume flow occurs at different points and different air flow patterns can occur in the room (Cho and Awbi, 2002). This effect of interaction between jet and plume on occupants' comfort around a workstation has not been thoroughly studied.

Xing *et al.* (2001) found that for displacement ventilation, the air quality at the breathing zone is quite different from that in the occupied zone as a whole. The ventilation parameters obtained from breathing zone and the relatively global value from the occupied zone cannot explain a whole human body's response in a workstation. It then becomes necessary to explore a *personalized zone* (breathing zone < personalized zone < occupied zone) that include a direct and indirect impact to a sedentary person in a workstation. In this study, the effect of change in workstation's position on ventilation performance is studied using CFD and experiments on three zones (breathing zone, personalized zone, occupied zone). The results are compared for the ventilation performances on three different workstation positions using *ventilation parameter* (*VP*) index.

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## EXPERIMENTAL SET-UP AND CFD CALCULATIONS

The experiments were carried out in the environmental chamber with the dimensions of 2.78 m × 2.78 m × 2.3 m (ceiling height) at the University of Reading. Tests with the three different positions of workstation (*MXL, MXR* and *MXE*) were carried out with two different flow rates (15 and 21 l/s) at the same conditions: the heat loads –35 W/m$^2$, the inlet temperature 13°C.

In order to prevent the cold jet from dropping into the occupied zone, a single air inlet slot (20 mm × 400 mm) was placed at the height above the floor of 2.18 m, corresponding to $H \leq 6\sqrt{A}$ (Awbi, 1991), where *A* is the area of opening, and projecting the air jet at an angle of 36°. Sixty-five four-wire Platinum Resistance Thermometer (PRT) sensors (accuracy = ±0.15 K) were used to measure air temperature and the inside and outside surface temperatures of the chamber. Other measuring devices used in the tests were a Watt meter, DANTEC omni-directional velocity sensors and a Brüel and Kjäer $SF_6$ gas sampling system. To provide a realistic workstation, a computer box (a 400 mm cube with a 200 W light bulb fitted inside), a desk and a chair were placed in the chamber. A heated mannequin (see Figure 1) was made from 1 mm aluminium sheet with the overall surface area of 1.60 m$^2$ and its emissivity is approximately 0.9. Heating elements inside the body, head and legs of the mannequin were controlled to provide a surface temperature equal to that of a typical naked human (Olesen, 1982). A polyurethane tube was attached to a copper tube inside the head and fed through the torso and out to the gas sampler. This location represented the sampling point for the breathing zone (i.e. $C_B$).

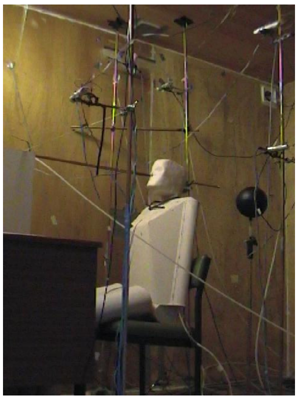

**Figure 0** Example of workstation.

As shown in Figure 2, the room is subdivided into the occupied zone and the primary zone (3.92 m$^3$), which has the supply air and extract air openings. The occupied zone has the four fictive zones with equal volume (3.48 m$^3$). In order to investigate the effect of changing workstation position on the indoor environment of the zone, the workstation was located at each of the three fictive zones (i.e. Z11, Z12 and Z22), which is defined as the personalized zone of the cases *MXR, MXL* and *MXE*, respectively, in Figure 3. Table 1 shows the

**Table 1** Measuring points for zones

| Zone | Location | Height (Y) 1.8m | 1.2m | 0.1m |
|---|---|---|---|---|
| Occupied zone | Stand A (0.25X, 0.5Z) | P1 C1 | P6 | P11 |
| | Stand B (0.5X, 0.25Z) | P2 | P7 | P12 C12 |
| | Stand C (0.5X, 0.5Z) | P3 | P8 | P13 |
| | Stand D (0.5X, 0.75Z) | P4 | P9 | P14 C14 |
| | Stand E (0.75X, 0.5Z) | P5 C5 | P10 | P15 |
| Personalized zone | *MXR* (Zone Z11) | P1,2,3 C1 | *$P_B$6, P7, 8 $C_B$ | P11,12,13 C12 |
| | *MXL* (ZONE Z12) | P1,3,4 C1 | *$P_B$6, P8, 9 $C_B$ | P11,13,14 C14 |
| | *MXE* (ZONE Z22) | P3,4,5 C5 | P8,9, *$P_B$10 $C_B$ | P13,14,15 C14 |

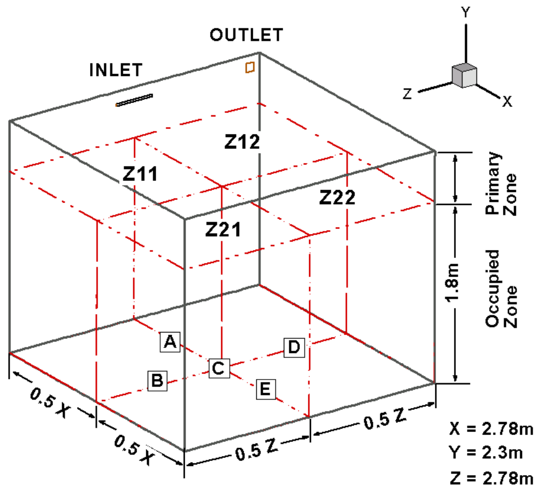


**Figure 1** Room configuration.

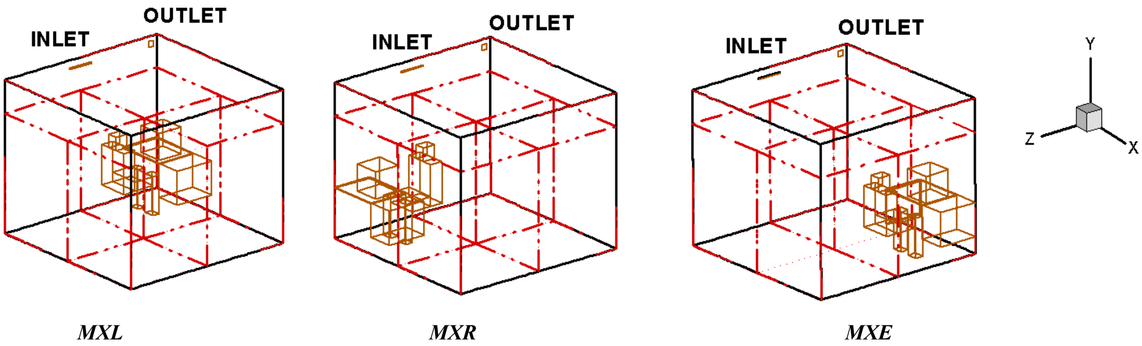


**Figure 2** Three different positions of workstation.

measuring points for the occupied zone and the personalized zone. As a example, the point located at 0.46 m on *X*-axis, 1.8 m on *Y*-axis and 1.39 m on *Z*-axis, can be expressed by P1 (0.25X, 1.8 m, 0.5Z). The measuring points for the velocity and temperature sensors (P1–P15, Table.1) were positioned vertically at heights 0.1, 1.2 and 1.8 m above the floor on the stands (A, B, C, D, E in Figure 2) that located at the centre of interfaces between the zones. The points for breathing zone, $P_B6$, $P_B10$ and $C_B$ of Table1, are positioned at the head region. Four concentration measuring points along with $C_B$ are used for measuring mean concentration for the occupied zone. The preliminary mapping for concentration sampling points was determined using the factorial design concepts (see AIVC34, 1991). Using the tracer decay technique, a small amount of SF6 gas is emitted from a ping-pong ball placed just above the computer box.

The CFD program VORTEX (Gan and Awbi, 1994) with a non-uniform grid size of 70 × 63 × 70 has been used to predict the air flow, heat transfer and mean age distribution in the chamber. This is a three dimensional program which solves, using a Cartesian grid, the continuity equation, the Navier–Strokes equation, the thermal energy equation, the concentration of species equation, the two equations for k and $\varepsilon$ in the $k$–$\varepsilon$ turbulence model and room surface radiation. The calculated velocity, air temperature and radiant temperature at each computational cell were used in Fanger's comfort equation (Fanger, 1972) for calculating the PPD at the cell.

In a post-processing analysis of CFD results, the mean *Ventilation Parameter* indices for the breathing zone, the personalized zone and the occupied zone are obtained by the zone method (volume weighted mean of cells in a zone, CFD-z) and by the point method (the arithmetic mean of the points, CFD-p). The mean values for the breathing zone in CFD-z were obtained from the five section areas close to the head of mannequin.

## VENTLATION PARAMETER (VP)

To assess the effectiveness of ventilation on a workstation using both measurement and CFD simulation, the effectiveness for heat removal ($\varepsilon_t$) and contaminant removal ($\varepsilon_c$) are used together with the predicted percentage of dissatisfied (*PPD*) for thermal comfort and percentage of dissatisfied (*PD*) for air quality. $\varepsilon_t$ and $\varepsilon_c$ are defined by:

$$\varepsilon_t = \frac{T_o - T_i}{T_x - T_i}, \quad \varepsilon_c = \frac{C_o - C_i}{C_x - C_i} \qquad (1)$$

In Eqns (1), $T$ is temperature (°C), $C$ is the contaminant concentration (ppm), subscripts o, i denote outlet, inlet and $x$ denotes characteristic values for the breathing zone, the personalized zone and occupied zone (to a height of 1.8 m). $\varepsilon_t$ is similar to a heat exchanger effectiveness and is a measure of the heat removing ability of the system. $E_c$ is a measure of how effectively the contaminant is removed. The values for $\varepsilon_t$ and $\varepsilon_c$ are determined by heat and contaminant sources, the method of room air distribution, room characteristics, etc.

However, high values do not always give a good indication of the thermal comfort and air quality in a certain zone (e.g. occupied zone, personalized zone and breathing zone).

Fanger (1972) has developed the expressions for the percentage of dissatisfied (*PD*) with the indoor air quality and the predicted percentage of dissatisfied (*PPD*) with the thermal environment given by Eqns (2) and (3).

$$PD = 395 \cdot \exp(-1.83\ \dot{v}^{0.25}) \qquad (2)$$

$$PPD = 100 - 95 \exp -\{0.03353\ (PMV)^4 + 0.2179\ (PMV)^2\} \qquad (3)$$

where $\dot{v}$ is the ventilation rate (l $s^{-1}$) and PMV is the Predicted Mean Vote as defined in ISO 7730 (1994) and the recommended PPD limit for ideal thermal environment is 10%, corresponding to $-0.5 \leq \text{PMV} \leq 0.5$. Thus, low values for both indices guarantee a good indoor air quality and thermal comfort.

The *comfort number*, $N_t$, and the *air quality number*, $N_c$ (Awbi, 1998) combined with PPD and PD, respectively, are useful to examine the quality of a ventilation system.

These are defined as:

$$N_t = \frac{\varepsilon_t}{PPD}, \quad N_c = \frac{\varepsilon_c}{PD} \qquad (4)$$

These two numbers can be combined into a single parameter which determines the effectiveness of an air distribution system in providing air quality and thermal comfort in the form of a Ventilation Parameter defined as:

$$VP = \sqrt{N_t \times N_c} \qquad (5)$$

## RESULTS AND DISCUSSION

Table1 summarizes the results obtained from the tests and the CFD simulations at the same conditions. The cases I, II are classified by two different flow rates, i.e. 15 and 21 l/s and the results of CFD-p and CFD-z are obtained by the point method and by the zone method

**Table 2** Data for experiments and CFD

| Case | | | | | Breathing zone | | | Personalized zone | | | Occupied zone | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Voc | Toc | PD | $\varepsilon_t$ | PPD | $E_c$ | $\varepsilon_t$ | PPD | $E_c$ | $\varepsilon_t$ | PPD | $\varepsilon_c$ |
| I | 15l/s | | | | | | | | | | | | |
| *MXL-I* | EXP | 0.07 | 25.1 | 11.4 | 113 | – | 113 | 112 | – | 114 | 112 | – | 114 |
| | CFD-p | 0.06 | 24.6 | | 110 | 9.5 | 114 | 112 | 8.5 | 114 | 112 | 8.7 | 114 |
| | CFD-z | 0.05 | 25 | | 99 | 9.1 | 114 | 99 | 9.2 | 127 | 107 | 9.4 | 117 |
| *MXR-I* | EXP | 0.07 | 26.6 | 10.9 | 116 | – | 100 | 102 | – | 102 | 102 | – | 97 |
| | CFD-p | 0.06 | 26.1 | | 114 | 18.1 | 100 | 103 | 19.0 | 102 | 104 | 18.3 | 97 |
| | CFD-z | 0.05 | 26.3 | | 99 | 24.1 | 113 | 95 | 18.9 | 109 | 102 | 18.2 | 102 |
| *MXE-I* | EXP | 0.07 | 25.5 | 11.1 | 110 | – | 112 | 111 | – | 102 | 106 | – | 105 |
| | CFD-p | 0.06 | 25.1 | | 113 | 6.4 | 114 | 109 | 9.5 | 106 | 108 | 10.1 | 105 |
| | CFD-z | 0.05 | 25.5 | | 102 | 10.4 | 118 | 97 | 10.7 | 116 | 104 | 11.1 | 108 |
| II | 21 l/s | | | | | | | | | | | | |
| *MXL II* | EXP | 0.08 | 24.3 | 7.7 | 116 | – | 132 | 114 | – | 131 | 114 | – | 134 |
| | CFD-p | 0.07 | 23.6 | | 111 | 5.7 | 143 | 111 | 5.9 | 140 | 112 | 5.7 | 131 |
| | CFD-z | 0.06 | 23.8 | | 94 | 8.7 | 155 | 99 | 6.0 | 135 | 109 | 8.7 | 133 |
| *MXR II* | EXP | 0.09 | 25.4 | 7.9 | 110 | – | 102 | 98 | – | 92 | 98 | – | 90 |
| | CFD-p | 0.07 | 24.8 | | 113 | 9.8 | 98 | 100 | 10.4 | 97 | 101 | 10.0 | 83 |
| | CFD-z | 0.07 | 25.1 | | 95 | 13.3 | 107 | 89 | 11.9 | 98 | 99 | 10.3 | 89 |
| *MXE II* | EXP | 0.09 | 24.8 | 7.8 | 98 | – | 131 | 104 | – | 131 | 105 | – | 118 |
| | CFD-p | 0.07 | 24.4 | | 94 | 10.5 | 128 | 102 | 7.9 | 124 | 103 | 7.7 | 117 |
| | CFD-z | 0.07 | 24.6 | | 94 | 12.2 | 139 | 100 | 7.8 | 128 | 109 | 8.0 | 124 |

respectively. The overall agreement between the measured and predicted (CFD) are generally good. The discrepancies between the measured and CFD can be due to a limited number of measuring points and/or poor accuracy in measuring velocities <0.1 m/s. On the other hand, when two flow elements (plume and jet) meet, the limited points may not guarantee to show as representative values for whole regions (e.g. velocity decay region, the extent of jet interaction with plume, the region where maximum velocity of return flow occurs). Therefore, for the CFD to provide the additional information to that obtainable using point measurement, the cell volume weighted average was used to calculate the mean value for each zone.

As can be seen Figure4, temperature contours and velocity iso-surface plots were used to illustrate the change in air flow pattern due to interaction between jet and plume. The velocity iso-surface plots represent the velocities more than 0.15 m/s for case I and the velocities more than 0.25 m/s for case II. The location of workstation for the *MXR* cases is a mirror image of the *MXL* cases with respect to air supply and room geometry. For the *MXR* cases, the plume from the computer box (convection load 100W) is travelling along the wall due to the Coanda effect and merged with the unequal plume from the mannequin on the ceiling. When the plumes meet the jet, the plume causes meandering of jet, which is distributed onto the corner of room. Also, the plumes interact each other and entrained inside the personalized zone. Thus, as shown in Figure5, the *Ventilation Parameter* (*VP*) indices of the *MXR* cases are lowest in respect to thermal comfort and indoor air quality.

However, for the MXL cases, the plume from computer box progresses to outlet hence the degrees of jet deflection from the inlet centreline are smaller than those of *MXR* cases. Therefore, the removal of heat and contaminant, as well as the human comfort are better than other positions. Especially, in the case of *MXL II*, the efficient ventilation performance is obtained because VP indices of the personalized zone are better than that of the occupied zone (see Figure5).

For the case *MXE I*, the jet momentum is not strong enough to reach the wall opposite the inlet thus the cold jet is dropping onto the mannequin's head region but it does not spread over

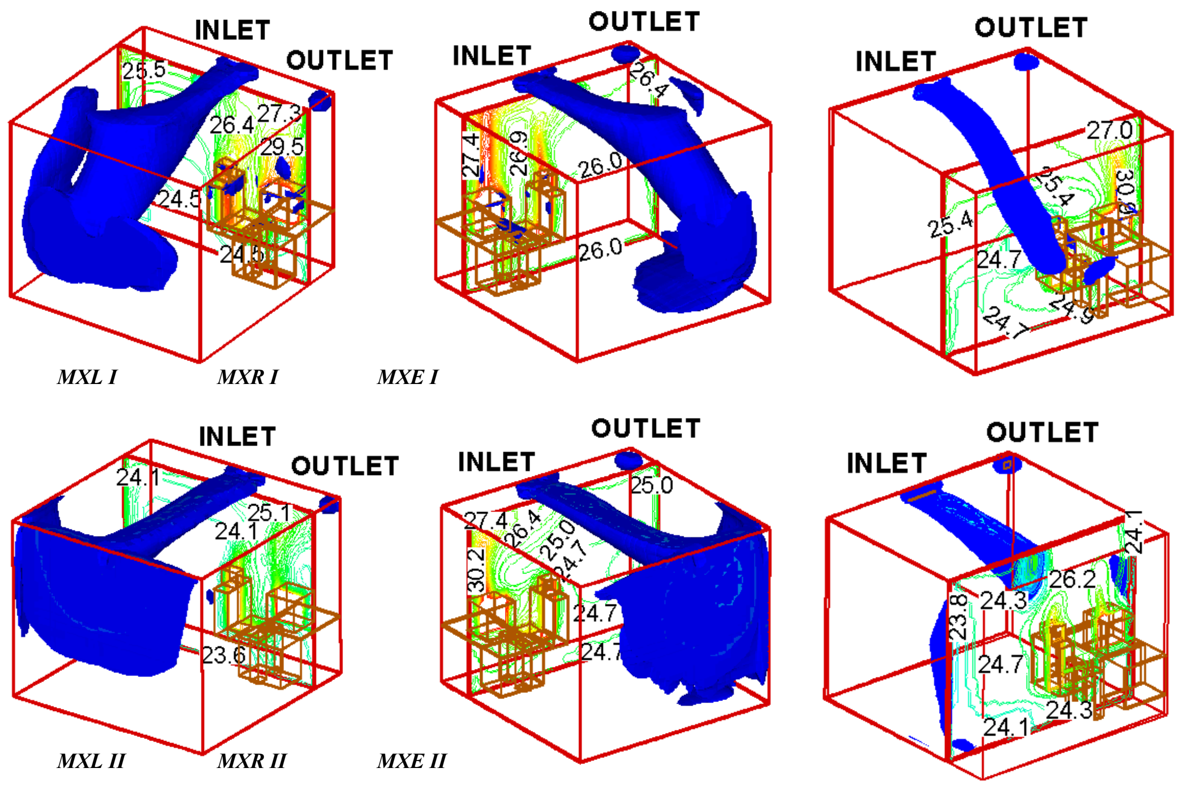


**Figure 3** Airflow patterns for different workstation's location.

the personalized zone. As a result, the *ventilation parameter* indices for the personalized zone are lower than those for the case *MXL I*.

In the case of *MXE II*, the interaction between the plume and the jet causes the jet to reach the back of the mannequin. Thus, the *comfort number* ($N_t$) for the personalized zone is lower than that of the occupied zone, unlike the case *MXLII*.

Overall, in the cases of *MXE*, the contaminant from the computer is entrained by the plume which travels along the adjacent wall and then directly towards the outlet. Therefore, the *air quality number* ($N_c$) for *MXE* cases is generally good but the *comfort number* ($N_t$) depends on the jet momentum and cooling capacity. Thus, this unstable location would not be recommended.

The local values of *PPD* and $\varepsilon_t$ may not be significant in describing local conditions as these are directly influenced by local values of the temperature and velocity, etc. This is particularly true close to the mannequin where the heat convection influences the local temperature, hence giving a higher value of *PPD*. Therefore, local values should only be considered for determining the local air quality and local $\varepsilon_c$ and not *PPD* or $\varepsilon_t$.

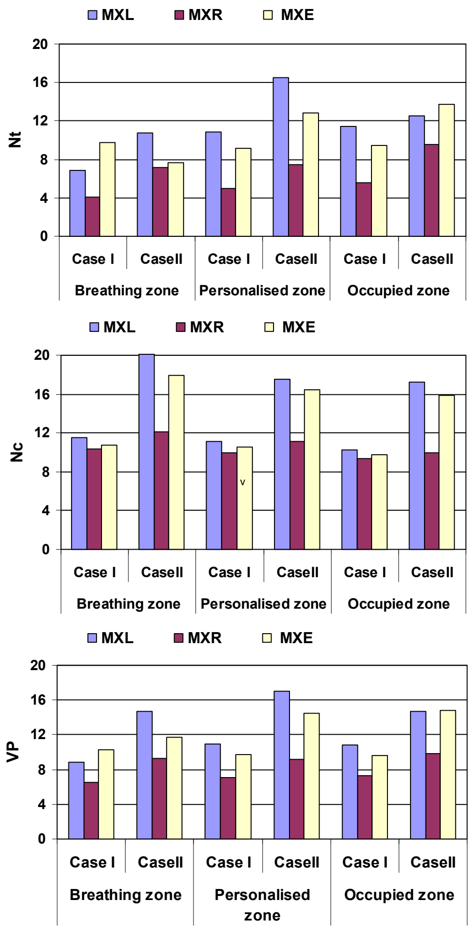


**Figure 3** Comfort Number ($N_t$) , Quality Number ($N_c$) and Ventilation Parameter (*VP*).

## CONCLUSIONS AND IMPLICATIONS

*Ventilation Parameter*(*VP*) that combines the decoupled indices for indoor air quality and thermal comfort is a comprehensive index to study the effect of change in position of workstation.

The use of personalized zone can give additional information because sedentary person's response to thermal comfort and indoor air quality varies with the location of the work place.

This study shows that when the workstation is located close to the zone containing the exhaust opening, then good ventilation performance can be obtained in the breathing zone, personalized zone and in the occupied zone as a whole.

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