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# Numerical Assessment of Room Air Distribution Strategies

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**SYNOPSIS**

The air distribution in a room is investigated using computational fluid dynamics. Four common methods of supplying air to a room are compared. The effect of air change rate on the ventilation effectiveness for contamination is small, however the effect of room heating or cooling load can be very significant. It was found that air turbulence has a major influence on the air movement, air velocity and dispersion of contaminants in the room.

## 1. INTRODUCTION

Numerous studies have been carried out during the last few years to determine what effect the method of supplying air to a room has on the air quality in the occupied zone. The traditional method of supplying the air at high level, representing mixing or dilution ventilation, is generally considered less effective in reducing the contaminant concentration in the occupied zone in comparison with a floor displacement system, eg Kim and Homma (1,2). Nielsen (3) has also shown that mixing ventilation has a lower effectiveness than displacement ventilation because this method produces large contaminant concentration in the occupied zone. However, there are many other parameters that can influence the air movement in a room: such as the position and strength of the heat sources/sinks; the physical properties of air supply, eg temperature, velocity and turbulence; the position of the air extract, obstructions, etc. Because all these factors can influence room air movement, it is almost impossible to establish 'rules of thumb' in designing air distribution systems.

In the investigation of the performance of different ventilation methods the emphasis has invariably been on the effectiveness of the system in removing contaminants, ie to maximise the ventilation effectiveness for contaminant removal, $\varepsilon_c$. However, there are other factors which must be included in evaluating the overall performance of the air distribution system such as the thermal comfort level and the effectiveness of heat removal, $\varepsilon_t$. Using computational fluid dynamics (CFD) for predicting the room air movement, Awbi et al (4,5) have shown that some methods of air distribution may produce a large value of $\varepsilon_c$ but may have a low value of $\varepsilon_t$ and vice versa. Whereas a high $\varepsilon_c$ can mean a reduction in fresh air supply, thus saving energy, a low $\varepsilon_t$ could cancel any energy saving accrued. An efficient air distribution system is one that is capable of producing the highest values of $\varepsilon_c$ and $\varepsilon_t$ under all operating conditions.

In this paper a CFD code called VORTEX has been applied to assess four methods of supplying air to a room containing a $CO_2$ source under isothermal and non-isothermal conditions. The effectiveness of each method is investigated for different air change rates.

## 2. METHOD

### 2.1 Ventilation Effectiveness

The overall effectiveness for contaminant removal ($\bar{\varepsilon}_c$) and heat removal ($\bar{\varepsilon}_t$) from the occupied zone represent the ability of the air distribution system to maintain average values of concentration and temperature in the occupied zone as a whole. These are defined as follows:

$$\bar{\varepsilon}_c = \frac{c_e - c_i}{c_{oz} - c_i} \times 100 \quad \% \tag{1}$$

$$\bar{\varepsilon}_t = \frac{t_e - t_i}{t_{oz} - t_i} \times 100 \quad \% \tag{2}$$

where $c_{oz}$ and $t_{oz}$ are the occupied zone average of the contaminant concentration (ppm) and temperature respectively; c and t with subscripts i and e refer to the values at the inlet and exit positions respectively.

Similarly, a local effectiveness for contamination removal ($\varepsilon_c$) and heat removal ($\varepsilon_t$) can be defined to evaluate the performance of the air distribution system at specified positions in the room such as the breathing zone of an occupant. These are then defined as follows:

$$\varepsilon_c = \frac{c_e - c_i}{c_p - c_i} \times 100 \quad \% \tag{3}$$

$$\varepsilon_t = \frac{t_e - t_i}{t_p - t_i} \times 100 \quad \% \tag{4}$$

where $c_p$ and $t_p$ represent the concentration and temperature at the required point in the room.

### 2.2 CFD Code

The CFD code VORTEX (**V**entilation **O**f **R**ooms with **T**urbulence and **E**nergy e**X**change) has been used to simulate the airflow, heat transfer and contaminant diffusion in a room. Although there are two and three dimensional versions of this code the two-dimensional program has been used in this study to enable better assessment be made of the large amount of data that is generated. The Navier-Stokes equation, the continuity equation, the thermal energy equation, the concentration of species equation and the two equations for the kinetic energy of turbulence (k) and its dissipation rate ($\varepsilon$) are solved using a finite volume method and a structured cartesian grid. Further details of VORTEX are found in references (5) and (6).

### 2.3 Numerical Test Room

Measurements in environmental chambers are often tedious, time consuming and the results can be influenced by scaling. A validated CFD code should be able to produce accurate prediction of the flow providing that a suitable grid is used with realistic boundary conditions. However, experience in this area has shown that there are certain limitations to the application of the k-ε turbulence model in room air flow because this is an isotropic model which can predict fully turbulent flows more accurately than flows where there may be non-isotropy of turbulence. The latter occurs in a room where the flow may not be fully developed or where the flow experiences separation or reattachment such as the flow over obstructions. In the absence of these situations a CFD simulation should produce reliable results (6).

The numerical test room selected for this study is a two-dimensional box of length 6m and height 3m with a contaminant source producing $5 \times 10^{-3}$ l/s of $CO_2$ (rate produced by a sedentary person) at a height of 1m above the centre of the floor. Simulations where carried out for the cases shown in Fig 1 (a to d), ie a single air supply over the ceiling representing mixing ventilation, a single air supply over the floor representing floor displacement ventilation, four air supplies from the floor representing upward displacement ventilation, and four air supplies from the ceiling representing downward displacement ventilation.

Simulations have been carried out for isothermal flow, cooling and heating. In the cooling mode a heat gain of 60 W $m^{-2}$ has been assumed over a curtain (east) wall and 20 W $m^{-2}$ over the floor giving a total cooling load for the room of 300 W, ie 50 W per $m^2$ of floor area. In the heating mode the heat loss from the curtain wall was -60 W $m^{-2}$ giving a room heating load of -180 W or -30 W per $m^2$ of floor area. Four air change rates were used for the room, ie 2, 4, 6 and 8 $h^{-1}$.

## 3. RESULTS AND DISCUSSION

A total of 24 simulations were carried out, 16 for isothermal conditions covering an air change rate from 2 to 8 $h^{-1}$, 4 cooling simulations for an air change rate 8 $h^{-1}$ and 4 heating simulations for an air change rate of 8 $h^{-1}$ also. Other simulations have also been carried out which will be described later. The key input data and the main results are given in Table 1.

### 3.1 Effect of Air Change Rate

Figure 2 shows the effect of increasing the air change rate on the average concentration of $CO_2$ in the occupied zone for the four methods of air supply which have been studied. These results are for isothermal flows. As would be expected there is a reduction in the concentration with increasing the flow rate but this reduction is lower at higher change rates than it is at

**Table 1 Input and Output Data for the Air Distributions Simulated**

| supply type | inlet width mm | $V_i$ m/s | $t_i$ °C | ach | Re x $10^{-3}$ (*) | Ar x 103 (*) | load W/m | $V_{oz}$ m/s | $t_{oz}$ °C | $C_{oz}$ ppm | $\bar{\varepsilon}_c$ % | $\bar{\varepsilon}_t$ % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ceiling | 10 | 1 | 21 | 2 | 0.66 | - | - | 0.044 | 21 | 986 | 78.9 | - |
| ceiling | 10 | 2 | 21 | 4 | 1.32 | - | - | 0.098 | 21 | 664 | 80.4 | - |
| ceiling | 10 | 3 | 21 | 6 | 1.98 | - | - | 0.152 | 21 | 560 | 80.5 | - |
| ceiling | 10 | 4 | 21 | 8 | 2.63 | - | - | 0.207 | 21 | 510 | 79.5 | - |
| ceiling | 10 | 4 | 16 | 8 | 2.63 | 0.15 | 300 | 0.218 | 21.9 | 491 | 87.4 | 116.9 |
| ceiling | 10 | 4 | 25 | 8 | 2.63 | 0.12 | -180 | 0.183 | 21.7 | 505 | 81.3 | 127.3 |
| floor | 40 | 0.25 | 21 | 2 | 0.66 | - | - | 0.027 | 21 | 1169 | 61.4 | - |
| floor | 40 | 0.5 | 21 | 4 | 1.32 | - | - | 0.057 | 21 | 754 | 62.2 | - |
| floor | 40 | 0.75 | 21 | 6 | 1.98 | - | - | 0.088 | 21 | 616 | 63.1 | - |
| floor | 40 | 1.0 | 21 | 8 | 2.63 | - | - | 0.119 | 21 | 549 | 63.4 | - |
| floor | 40 | 1.0 | 18 | 8 | 2.63 | 7.57 | 300 | 0.085 | 21.5 | 512 | 75.4 | 158 |
| floor | 40 | 1.0 | 25 | 8 | 2.63 | 5.27 | -180 | 0.113 | 20.5 | 468 | 108.8 | 100 |
| upward | 10 | 0.25 | 21 | 2 | 0.17 | - | - | 0.013 | 21 | 835 | 102.3 | - |
| upward | 10 | 0.5 | 21 | 4 | 0.33 | - | - | 0.027 | 21 | 603 | 98.5 | - |
| upward | 10 | 0.75 | 21 | 6 | 0.5 | - | - | 0.041 | 21 | 519 | 91 | - |
| upward | 10 | 1.0 | 21 | 8 | 0.67 | - | - | 0.055 | 21 | 478 | 88.8 | - |
| upward | 10 | 1.0 | 18 | 8 | 0.67 | 2.57 | 300 | 0.081 | 23.9 | 454 | 86.3 | 122 |
| upward | 10 | 1.0 | 25 | 8 | 0.67 | 1.38 | -180 | 0.073 | 21.5 | 482 | 93.1 | 102.8 |
| downward | 10 | 0.25 | 21 | 2 | 0.17 | - | - | 0.009 | 21 | 1488 | 45.5 | - |
| downward | 10 | 0.5 | 21 | 4 | 0.33 | - | - | 0.02 | 21 | 801 | 47.6 | - |
| downward | 10 | 0.75 | 21 | 6 | 0.5 | - | - | 0.037 | 21 | 636 | 51.5 | - |
| downward | 10 | 1.0 | 21 | 8 | 0.67 | - | - | 0.04 | 21 | 637 | 49.5 | - |
| downward | 10 | 1.0 | 16 | 8 | 0.67 | 2.03 | 300 | 0.119 | 21.4 | 497 | 93.1 | 125.9 |
| downward | 10 | 1.0 | 25 | 8 | 0.67 | 1.55 | -180 | 0.028 | 22.1 | 512 | 79.2 | 68.8 |

(*) Re and Ar refer to supply jet

lower rates. This is probably due to the increased mixing of the contaminant with room air as a result of higher turbulence.

The lowest concentrations are produced by the upward displacement system whereas the highest are those from the downward displacement. If 1000 ppm of $CO_2$ is considered an acceptable limit then all supply methods are capable of achieving lower than this for an air change rate in excess of 4 $h^{-1}$.

The overall contaminant effectiveness as defined by equation (1) is plotted in Fig 3. The upward displacement gives the highest effectiveness. The floor displacement gives only slightly higher effectiveness than the downward displacement. This is because such a system is most effective in the presence of thermal loads in the room. There is only a small influence of air change rate on the effectiveness.

### 3.2 Effect of Room Load

Simulations have been carried for 8 air changes per hour to examine the effect of room load on the contamination effectiveness. The results of the overall effectiveness are shown in Fig 4. The same heating or cooling load is used in each air distribution method, however the ceiling supply and the upward displacement show only a small room load effect on $\bar{\varepsilon}_c$. Velocity vector plots show that in the case of the ceiling supply the room air movement under cooling, heating and isothermal flows is similar and is primarily influenced by the air jet. This is also confirmed by the vertical distribution of the mean concentration in a horizontal plane which shown in Fig 5(a). A slightly higher value of $\bar{\varepsilon}_t$ is achieved in the cooling mode, Table 1.

In the case of upward ventilation vector plots show that the air movement in the cooling mode is largely influenced by an anti-clockwise circulation due to natural convection from the east wall causing a purge of the contaminant. An opposite circulation but a similar effect is produced in the heating mode, Fig 5(c). These profiles show large gradients in the lower part of the room for both cooling and heating but almost a uniform gradient for the isothermal flow. However, the overall contamination effectiveness for the three cases is almost the same. The value of $\bar{\varepsilon}_t$ for cooling is higher than that for heating, Table 1.

The overall contamination effectiveness for the downward displacement air supply is much higher for the cooling and heating modes than it is for isothermal flow, Fig 4. The isothermal flow shows almost uniform distribution of $\varepsilon_c$ with marginally higher values in the upper part of the room as would be expected, see Fig 5(d). However, the heating mode produces a large stratification of the contaminant with much higher concentrations (low $\varepsilon_c$) in the lower part of the room and lower concentrations (high $\varepsilon_c$) in the upper part. This is caused by the buoyancy force counteracting the effect of supply jet momentum. The cooling mode produces similar effect but it is caused by the considerable air movement due to the convection from the heated east wall. Furthermore, the value of $\bar{\varepsilon}_t$ for cooling is almost double that for heating which makes the downward displacement method more effective for cooling than it is for heating.

The floor supply method produces a larger contamination effectiveness for the cooling mode than that for the isothermal flow because of the greater mixing caused by convection from the east wall. However, $\bar{\varepsilon}_c$ is much higher for the heating mode than for the two other cases, Fig 4. This is a result of the supply jet separation from the floor just below the contamination source causing it to disperse throughout the room, hence more uniform distribution of the contaminant and $\varepsilon_c$, see Fig 5(b). The value of $\varepsilon_t$ for cooling is the highest of all the four air distribution methods, Table 1.

### 3.3 Effect of Turbulence

It can be seen from Fig 3 that $\bar{\varepsilon}_c$ is almost independent of the air change rate. These simulations have been carried out using the k-$\varepsilon$ turbulence model in VORTEX. It was important therefore to establish if there is a Reynolds number effect on the contamination distribution as predicted by the CFD model.
Figure 6 shows the resultant velocity profile for the isothermal ceiling supply where the air change rate is between 2 and 12 $h^{-1}$, giving a Reynolds number, based on the supply opening, in the range 658 to 7900. Here, v is the average velocity in a horizontal plane and $V_i$ is the supply velocity. These results show a slight variation of the normalised velocity with Re but the effect is lower for Re>1320.

A further investigation to ascertain the effect of flow turbulence was carried out by running the same case using the k-$\varepsilon$ turbulence model and by assuming a laminar flow. The influence of turbulence on the flow was significant as illustrated in Fig 7. The results shown here are for the isothermal and cooling ceiling supply cases corresponding to Re=2630. The laminar flow simulations produce much higher velocities close to the floor than the turbulent flow simulations. In addition, the laminar boundary layer is much thinner than the corresponding turbulent boundary layer. However, the mean velocity in the room is considerably higher for the turbulent flow cases than the laminar flow ones, eg in the case of isothermal flow $v_{oz}/V_i$ (where $v_{oz}$ is the mean velocity in the occupied zone) is 0.036 for the laminar simulation against 0.062 for the turbulent case with the difference even greater for the cooling case. It is clear therefore that turbulence has a major influence on the air movement in a room and to obtain accurate CFD simulations reliable turbulence models together with accurate boundary conditions must be used.

## 4. CONCLUSIONS

Using the k-$\varepsilon$ turbulence model for predicting the air movement and contaminant distribution in a room produces realistic results and can be used to explain the influence of heat sources and sinks on the air flow pattern in a room and the ventilation effectiveness of the air distribution method. Although air turbulence has been shown to greatly influence the air movement in the room, the effect of air change rate on the ventilation effectiveness for contaminant removal has been found to be small. However, the ventilation effectiveness is not only influenced by the air supply position but it is also greatly affected by the room load.

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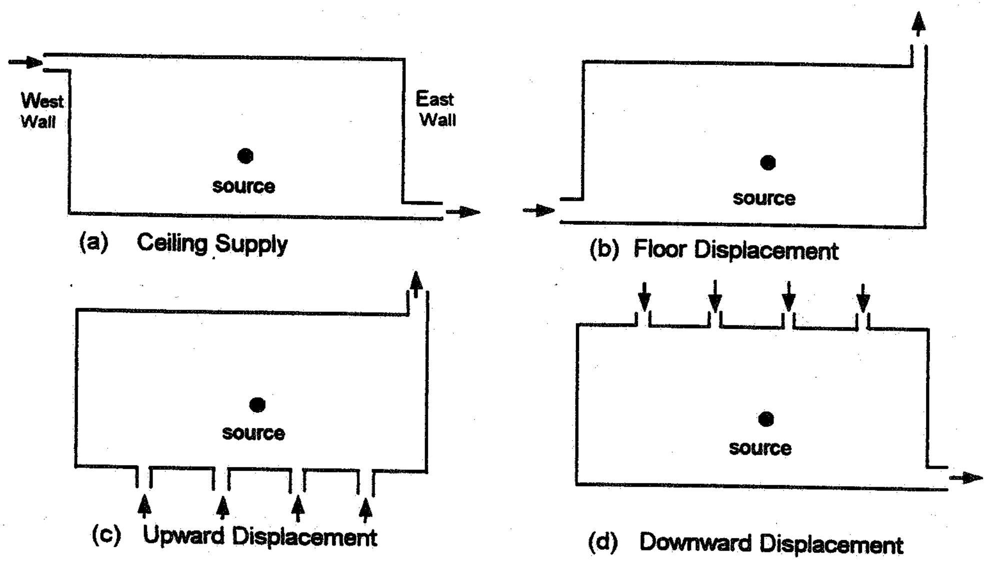



Fig 1 Air Distribution Methods

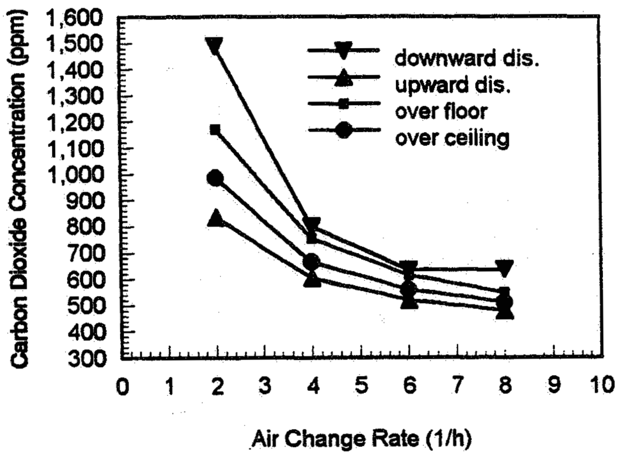



Fig 2 $CO_2$ Concentration in Occupied Zone with Air Change Rate

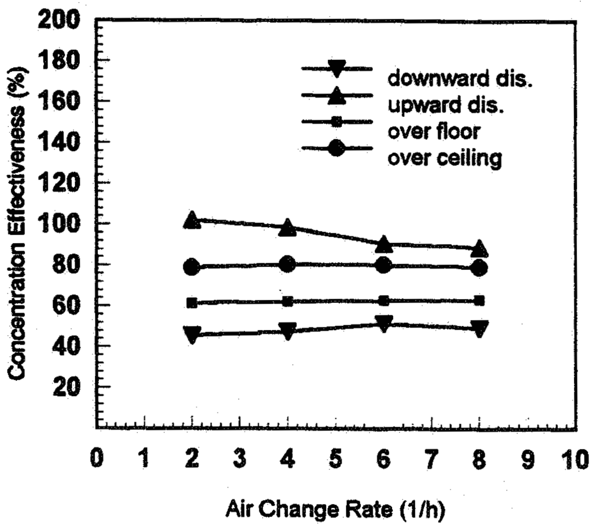



Fig 3 Overall Concentration Effectiveness with Air Change Rate

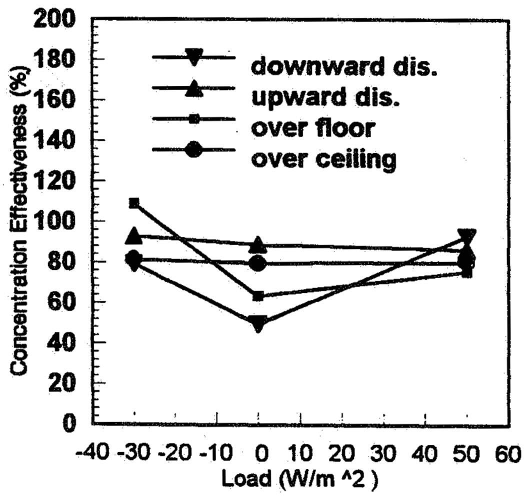
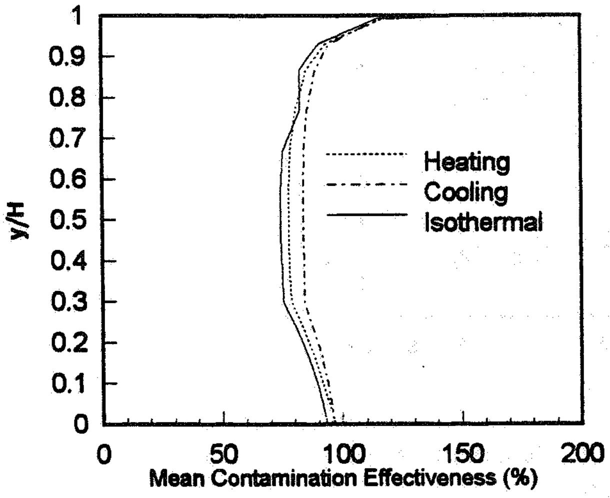
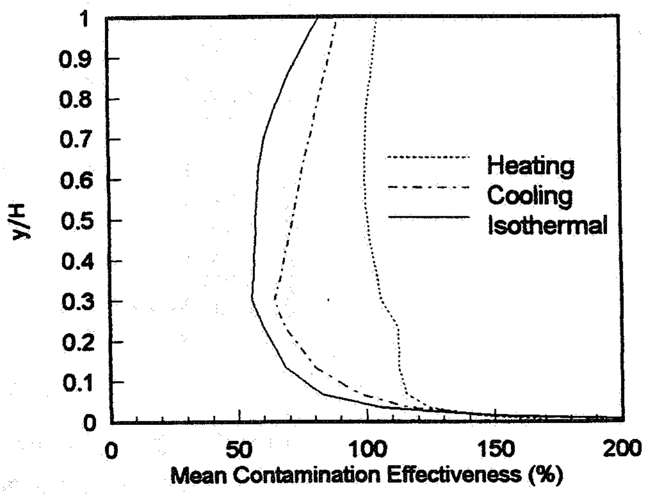


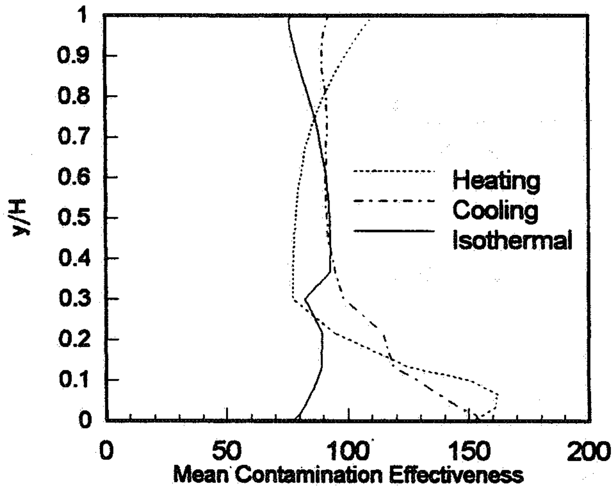

Fig 4 Overall Concentration Effectiveness with Room Load



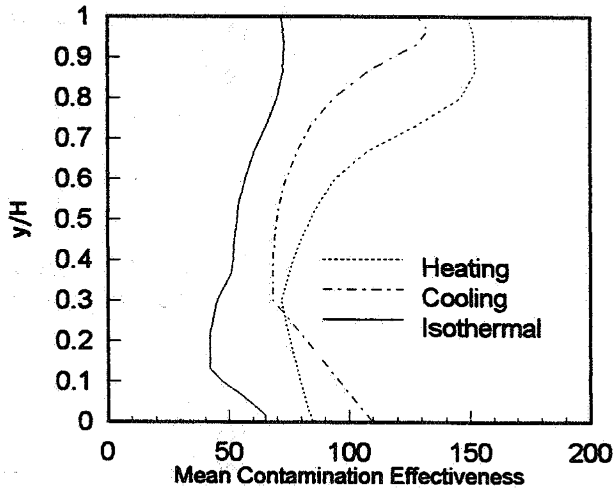

(a) Ceiling Supply




(b) Floor Supply




(c) Upward Displacemennt




(d) Downward Displacement

Fig 5 Vertical Distribution of Contamination Effectiveness

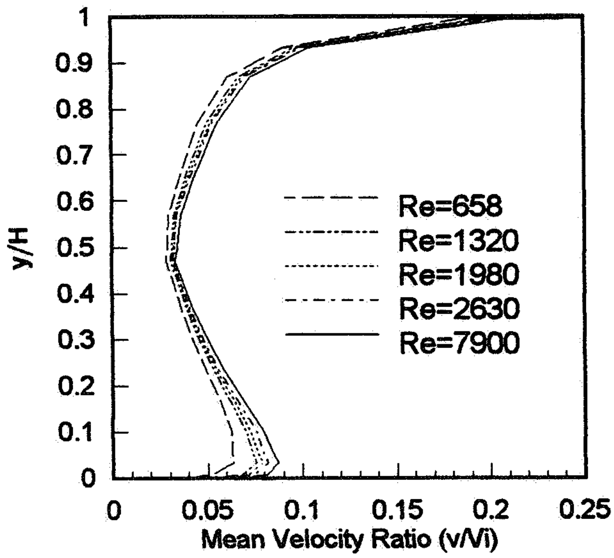



Fig 6 Effect of Reynolds Number on the Mean Velocity Distribution (Ceiling Supply)

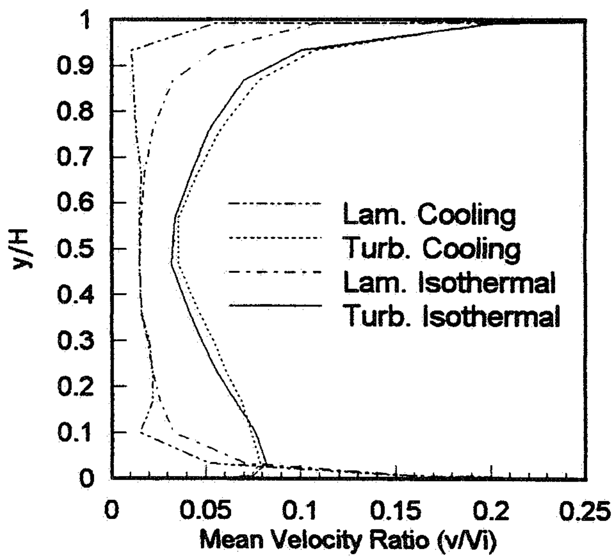



Fig 7 Mean Velocity Distribution for Laminar and Turbulent Flows (Ceiling Supply)