PERGAMON

Building and Environment 34 (1999) 275–284

BUILDING AND ENVIRONMENT

Approaches for improving airflow uniformity in unidirectional flow cleanrooms

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Received 19 January 1998; accepted in revised form 22 May 1998

Abstract

Airflow behavior inside a cleanroom with vertical unidirectional flow has been investigated. The design parameters, such as porosity and height of raised floor, width of cleanroom and inlet velocity profile, which affect the uniformity of air velocity distribution inside the cleanroom have been studied computationally. The Reynolds-averaged Navier–Stokes equations governing the flow are solved using a finite-volume code STAR-CD. The standard k-ε turbulence model has been used. Approaches for improving airflow uniformity have been proposed and quantitatively examined based on intensive case studies. The present results show that the uniformity increases along with the height of raised floor. Alternatively, better airflow uniformity can also be achieved through a proper allocation of floor porosity or by controlling the distribution of inlet velocity profile. Suggestions on how to design unidirectional cleanrooms with desired airflow uniformity under practical constraints have been given.

1. Introduction

Contamination control is a key factor in assuring product reliability in many high technology industries, such as biotechnology, material engineering, high-density storage technology, microelectronics and semiconductor industries, because the contamination of even submicron size particles can lead to a total failure of a complete production process. Different industries require different levels of cleanliness, which can be achieved in a cleanroom of a certain class. The cleanliness level in a cleanroom depends on both the quality of air introduced into the room and the efficiency of exhausting the particles generated within the room. In a unidirectional flow cleanroom, air is introduced evenly through filters mounted on one entire surface of the room, such as the ceiling or a wall. The filtered air flows at a unidirectional constant velocity across the room and is removed through the entire area of the opposite surface [1]. In recent years, there have been significant developments in filtration and contamination prevention techniques. Consequently, the quantity and size range of airborne particles in cleanroom inlet air have greatly decreased. However, large concentrations of these submicron particles can be generated by process equipment and cause many severe problems. A unidirectional flow at a proper velocity must be used to carry away the particles constantly generated by equipment within the room. It has been found by experimentation that at air velocities below 0.34 ms^{-1}, the contamination will generally diffuse, while air velocities above 0.56 ms^{-1} contribute little in contamination removal and may generate turbulence on obstructions. High contamination concentrations are often observed in the turbulent area [2]. In order to exhaust air borne particles effectively, it is essential to have a uniform air velocity distribution inside cleanrooms. Therefore, controlling airflow inside the room to maximize the uniformity of air velocity distribution poses a big challenge in the cleanroom design and operation. Many engineers and researchers in the field have been interested in finding effective methods to control the airflow velocity distribution in order to improve and optimize the cleaning process.

Several numerical and experimental studies on the uniformity of air velocity distribution in a vertical unidirectional flow cleanroom have been conducted. The velocity profile across the HEPA filter at the ceiling was investigated by Takahashi et al. [3] under various flow velocities and the heights of the supply chamber. The supply plenum and air velocity uniformity in cleanrooms was simulated numerically by Sadjadi et al. [4]. Nishioka

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S0360-1323/99/$—see front matter
PII: S0360-1323(98)00028-6

and Xie [5] made an experimental examination of the influence on the uniformity of air velocity distribution in a cleanroom generated by the heights of the supply chamber, the height of supply nozzle and the resistance characteristic of filter, using one-tenth-scale model. The influence of supply outlet shape on the air velocity distribution in a line type cleanroom system was studied by Fujita et al. by means of numerical simulation and experiments [6]. Airflow turbulence behind a pleated air filter was investigated by Suwa et al. [7], and a generation mechanism of turbulent fluctuation behind pleated air filter is discussed. Free shear caused by a velocity non-uniformity makes vortex streets behind the filter ends. These vortex streets interfere with neighboring streets and a spanwise synchronized fluctuation is generated. Similar experiment work was carried out by Fujii et al. [8]. More recently, a numerical simulation was done by Nishioka and Xie [9] to calculate the flow field in a unidirectional flow cleanroom and to examine the influence of plenum geometry on the uniformity of the air velocity distribution. Their calculation has been conducted over the whole room system including both HEPA filters and floor gratings (from the inlet of the plenum chamber in the ceiling to the outlet of the return chamber under the floor). The calculated pressure loss distribution between the HEPA filter agrees with the calculation and the experiment in their investigation. They also found disagreements between the calculation and experiment when the flow rate increases.

Although the influence of filter and chamber configurations on the uniformity of air velocity distribution in cleanrooms had been considered [3–9], little attention has been drawn to other design parameters such as raised floor and inlet velocity profile on the uniformity. These parameters also have significant effects on the uniformity, especially, when the room is wide. Recently, more and more high-class and large cleanrooms have been built for microelectronics industries. MEGA bit device fabrication needs a large supply and return plenums to circulate the large amount of air required for high level cleanliness. On the other hand, the plenums or the raised floor space may be limited when the cleanroom is constructed within an existing building. Difficulties in achieving the uniformity of air velocity distribution inside a cleanroom will certainly arise due to the limitation on space.

In this paper, airflow behavior inside a cleanroom with vertical unidirectional flow will be simulated numerically. The design parameters, such as porosity and height of raised floor, width of cleanroom and inlet velocity profile, which affect the uniformity of air velocity distribution inside the cleanroom are studied. The Reynolds-averaged Navier–Stokes equations governing the airflow are solved using the finite-volume code STAR-CD, a general computer code for fluid and heat transfer computations. The standard k-ε turbulence model is employed in the simulation. It is focused on the development of new approaches to achieve airflow uniformity at a desired work station level in cleanrooms. The present simulation will throw some light on the effects of the raised floor and the inlet velocity profile on the airflow distribution in the room. The simulation carried out in this work gives an insight into the details of the airflow behavior in a model cleanroom, and helps to understand the influence of raised floor and inlet velocity profile on the uniformity of air velocity distribution. Consequently, some practical approaches will be proposed to improve the airflow uniformity in a cleanroom. These approaches are applicable for designing new cleanrooms as well as to improve the airflow uniformity of the existing cleanrooms.

2. Numerical method

A typical cleanroom is shown schematically in Fig. 1. The fundamental equations governing steady, incompressible, adiabatic, turbulent flows are the Reynolds-averaged Navier–Stokes and continuity equations. They can be written in Cartesian coordinates as

$$\frac{\partial U_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial}{\partial x_i}(\rho U_i U_j) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(2\mu S_{ij} - \rho\overline{u_i u_j}), \tag{2}$$

$$S_{ij} = \tfrac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right), \tag{3}$$

$$-\rho\overline{u_i u_j} = 2\mu_t S_{ij} - \tfrac{2}{3}\rho k \delta_{ij}, \tag{4}$$

where x_i is the spatial coordinates, $(x_1, x_2, x_3) = (x, y, z)$, U_i is the mean field velocity component, $(U_1, U_2, U_3) = (U, V, W)$, u_i is the velocity fluctuation, ρ is the mass density, S_{ij} is the strain rate of mean, μ and μ_t are the molecular and eddy viscosities.

For turbulent closure the standard k-ε model is adopted:

$$\frac{\partial}{\partial x_j}(\rho U_j k) = \frac{\partial}{\partial x_j}\left(\frac{\mu+\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + 2\mu_t S_{ij}\frac{\partial U_i}{\partial x_j} - \rho\varepsilon, \tag{5}$$

$$\frac{\partial}{\partial x_j}(\rho U_j \varepsilon) = \frac{\partial}{\partial x_j}\left(\frac{\mu+\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) + 2C_{\varepsilon 1}\mu_t S_{ij}\frac{\varepsilon}{k}\frac{\partial U_i}{\partial x_j} - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}, \tag{6}$$

$$\mu_t = f_\mu C_\mu^{1/4} \rho k^{1/2} l, \tag{7}$$

$$l = C_\mu^{3/4}\frac{k^{3/2}}{\varepsilon}, \tag{8}$$

where f_μ, σ_k, σ_ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ and C_μ are empirical coefficients, and their values are 1.0, 1.0, 1.22, 1.44, 1.92 and 0.09, respectively [11].

The boundary conditions for the above equations are

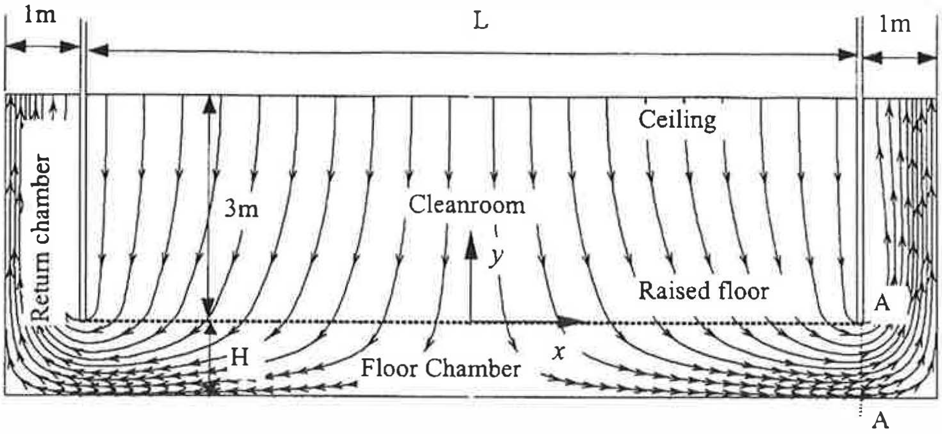

Fig. 1. Schematic sketch of a cleanroom with vertical unidirectional flow.

Inlet boundary:

$$U = W = 0, V = V_{inlet}, k = \frac{3}{2} I^2 \bar{V}^2_{inlet}, \varepsilon = C_{\mu}^{3/4} \frac{k^{3/2}}{l}, \quad (9)$$

Outlet boundary:

$$\partial V/\partial y = \partial k/\partial y = \partial \varepsilon/\partial y = 0, \quad (10)$$

Symmetry boundary:

$$\partial \phi/\partial x = 0, \quad (11)$$

Wall boundary:

$$U_i = 0 \text{ on the walls}, \quad (12)$$

and the logarithm law is adopted near the walls, where ϕ represents all variables, V_{inlet} is the velocity distribution specified over the inlet boundary, $\bar{V}_{inlet}$ is the mean value of inlet velocity, I is the turbulence intensity and l is the turbulence length scale.

The above equations are solved using the STAR-CD code, based on a finite volume discretization method. The estimation of diffusion fluxes at the cell faces is obtained by a centered approximation while a first-order upwind approximation is adopted for the advective fluxes. The pressure–velocity linkage is solved via the SIMPLE algorithm of Patankar and Spalding [10]. In this algorithm the convective fluxes per unit mass through cell faces are evaluated from so-called guessed velocity components. Furthermore, a guessed pressure field is used to solve the momentum equations and a pressure correction equation derived from the continuity equation, is solved to obtain a pressure correction field which is in turn used to update the velocity and pressure fields. The process is iterated until convergence of the velocity and pressure fields. More details on the computational code can be found in [11].

3. Results and discussion

In the present study, several design parameters are of significance on air velocity distribution inside a unidirectional flow cleanroom. They are L, the width of the room, H, the height of the raised floor, C the porosity of the perforated floor (the ratio of the total area of the holes to the floor area), and V_{inlet} the velocity profile across the HEPA filter at the ceiling. The uniformity of airflow, λ, is defined as

$$\lambda = (1 - \sigma/\bar{V})100\% \quad (13)$$

where σ is the standard deviation of the velocity distribution and $\bar{V}$ is the mean velocity.

Since the flow is symmetrical about y–z plane only one half of the room was simulated. The computational domain is divided into 33400 cells, which are used as control volumes as shown in Fig. 2. The turbulence of 1% at the inlet is adopted for all the subsequent computations. A linear under-relaxation is applied to the pressure during the iterative resolution. The convergence criterion is set to 0.1% for the summation of the residuals. The numerical simulation is carried out on a Silicon Graphics workstation. For each case, about 1000 iterations (or 1 h in CPU time) are needed to reach a convergent result.

3.1. Width of the room

The velocity vectors at different room width L are shown in Fig. 3. Where, it is assumed that the uniform inlet velocity, floor height and a uniform porosity are 0.45 ms^{-1}, 0.6 m and 25%, respectively. When $L = 4$ m, the airflow basically approaches a uniform velocity distribution inside the room, except that it is slightly higher at the corner than that at other places. This agrees

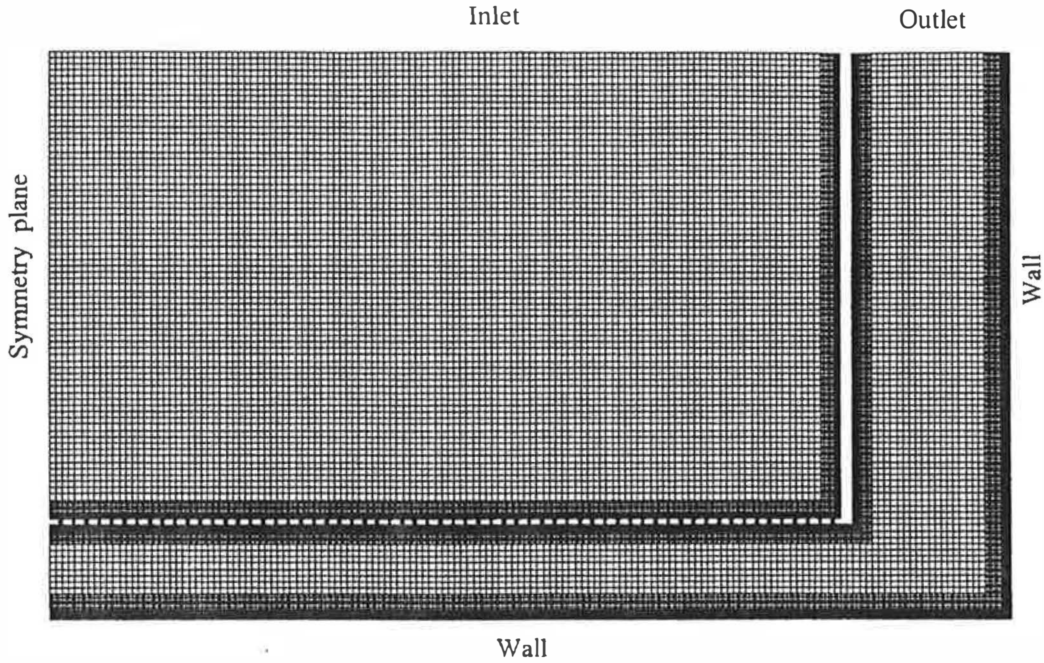

Fig. 2. Mesh structure in a half domain.

with the results obtained by experimentation [2]. When L increases to 6 m, it is observed in Fig. 3b that the velocity from the ceiling to the floor increases near the side-wall and decreases in the center area of the room. As a result, a non-uniform velocity distribution on the horizontal plane appears in the zone from the floor to 1m above the floor. This tendency becomes increasingly remarkable as the width L increases (see Fig. 3c). When $L = 8$ m and at 1 m above the floor (usually, the position at 1 m above the floor is very crucial as product operations are normally carried out around this level), the velocity near the side-wall of the room is double that at the center of the room, and the zone of the non-uniform velocity distribution becomes larger. The reason for causing this flow pattern can be given as follows. According to the continuity condition, when $L > H$, the mean velocity at section A-A (see Fig. 1) should be higher than the fixed inlet velocity, and the mean velocity at section A-A should increase with the increase of L. The higher the mean velocity at section A-A, the greater the pressure gradient along the x-direction. Moreover, when the flow separates on the corner in the return chamber, the flow with a recirculation zone appears around the corner, and a low-pressure zone is formed around the corner. The flow separation also increases the pressure gradient. The flow inside the room is affected by this pressure distribution under the raised floor. Therefore, when flow approaches the floor the velocity component V decreases in the center area of the room, and increases near the side-wall of the room. When the width of the room is beyond 8 m, the velocity in the center area of the roo is below 0.35 ms^{-1} which is recommended as the minima standard design velocity for cleanrooms of unidirectiona flow.

A comparison of velocity profiles at 1 m above th floor for different L is summarized in Fig. 4. When $L = 4$ 6, 8 and 10 m the uniformity λ at 1 m above the floor i 98, 89, 82 and 75%, respectively. The results show a important fact that when the inlet velocity is kept at constant the uniformity of the air velocity distributio decreases with the increase of the room width.

3.2. Height of floor chamber

To increase the uniformity of the air velocity in a cleanroom, one approach is to increase the height of the floor chamber. Computational investigations are, therefore, carried out to examine quantitatively the effects of the height of the floor chamber. Figure 5 shows the variation of the streamline patterns with the different heights for $C = 25\%$ and $L = 10$ m. It is evident that the recirculation zone generated by the flow separation around the corner in the return chamber decreases with the increase of H. As the total mass flow rate is unchanged through the floor, the horizontal velocity component at A-A section in the floor chamber decreases with the increase of H, which leads to a reduction of the recirculation zone generated by flow separation around the corner and the pressure gradient along the x-direction in the floor chamber. It means that the velocity difference

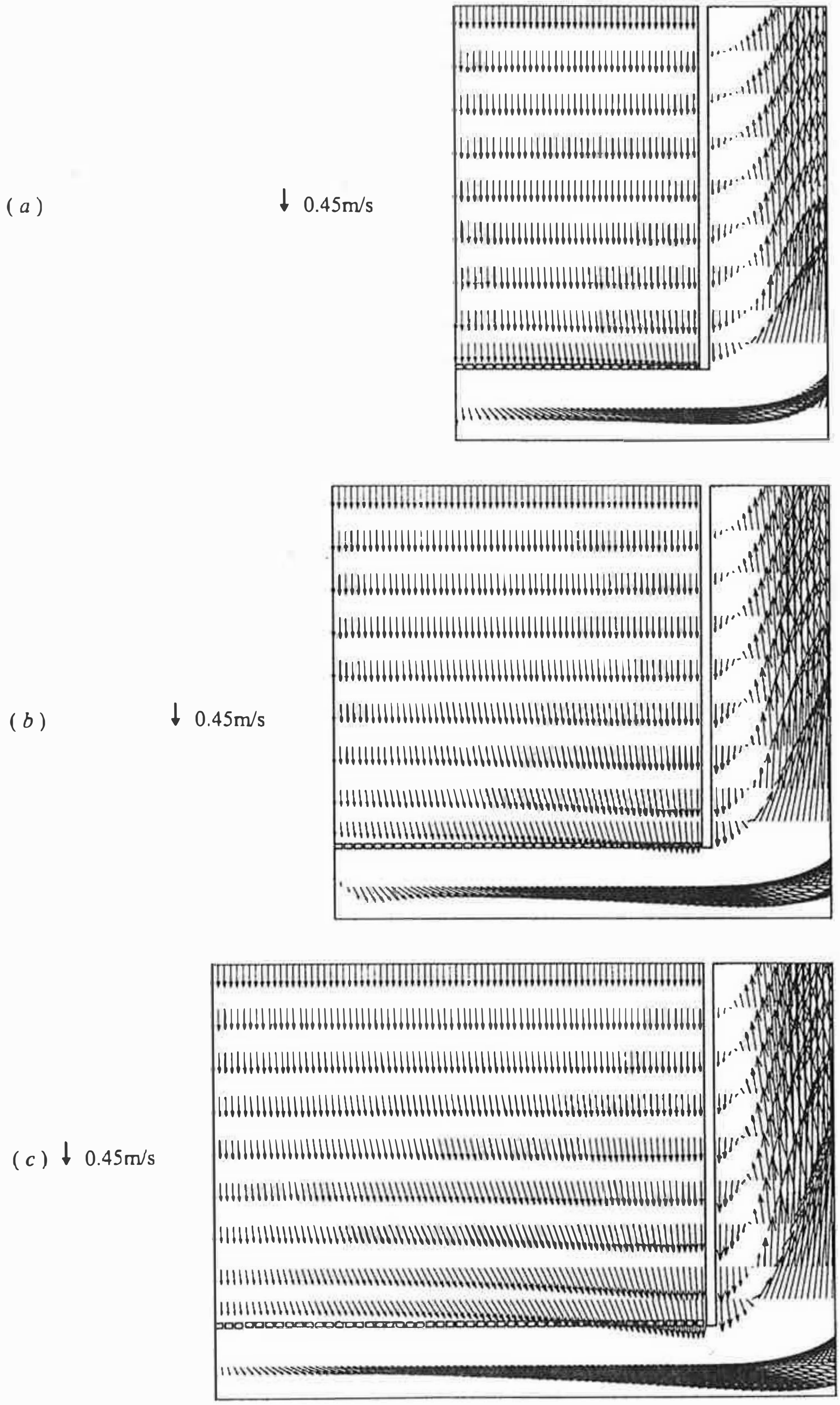

Fig. 3. Velocity vector for $C = 25\%$, $H = 0.6$ m and different values of L. (a) $L = 4$ m, (b) $L = 6$ m, (c) $L = 8$ m.

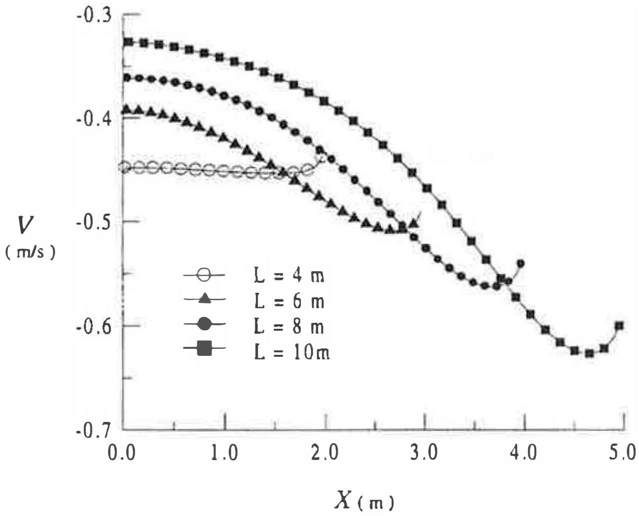

Fig. 4. Comparison of velocity distribution at 1 m above floor for different values of L.

between the center and the corner of the room decreases with the increase of H. The variation of the velocity profiles with H at 1 m above the floor is shown in Fig. 6 for $C = 25\%$ and $L = 10$ m. When $H = 0.6$, 1 and 1.5 m, the uniformity λ at 1 m above the floor is 75, 86 and 92%, respectively. Results in Fig. 6 clearly show that the higher the floor chamber, the more uniform the air velocity distribution in the room will be, and that increasing the height is really an effective way to obtain a uniform airflow. However, this is a very expensive way if not impossible. In many practical cases, it is impossible to raise the floor due to the limitation on space, especially, when the cleanroom is installed in an existing building.

3.3. *Porosity of the floor*

An alternative way proposed here to increase the uniformity is simply to change the porosity of the floor across the floor area. To examine the effectiveness of this approach, an intensive computation has been carried out. The velocity vectors for $H = 0.6$ m, $L = 10$ m and different porosity C distributions on the floor are shown in Fig. 7. It is observed that the velocity distribution in the zone from the floor to 1 m above the floor varies with the distribution of the floor porosity. When the porosity is uniform and $C = 50\%$ (see Fig. 7a), the velocity component V increases along the x-direction, and the trend is increasely remarkable as the airflow moves from the ceiling to floor in the room. When $C = 25\%$ uniformly, the flow pattern in the room is found to be basically the same as for $C = 50\%$. This indicates that the uniform distribution of the floor porosity has very little effect on the uniformity of air velocity distribution. When a work station is located in the center area of the room, particles drawn into this region can have a very high chance of depositing on the upper surface of the work station. When the porosity of the floor is non-uniform, as shown in Fig. 7c and d, the velocity distribution is changed. When $C_1 = 25\%$, $l_1 = L/2$, $C_2 = 5\%$ and $l_2 = L/2$ (where l_1 is the width of the floor with a porosity of C_1 and l_2 is the width of the floor with a porosity of C_2), the velocity component V in the center area of the room is higher than that near the side-wall of the room. Velocity distributions for $C_1 = 25\%$, $l_1 = L/2$, $C_2 = 10\%$ and $l_2 = L/2$ are shown in Fig. 7d. It is seen that the velocity distribution is similar but the velocity distribution is more uniform. This means that a proper porosity distribution can improve the uniformity of airflow in the room. The comparison of the velocity profiles at 1 m above the floor and different porosity of the floor is shown in Fig. 8 for $H = 0.6$ m, $L = 10$ m, $l_1 = L/2$ and $l_2 = L/2$. The uniformity λ at 1 m above the floor is 97% for $C_1 = 25\%$ and $C_2 = 10\%$, which is the best in these cases. The present results show clearly that when the width is beyond 8 m and the height of the raised floor is limited the desired airflow uniformity can be achieved by adjusting the distribution of the floor porosity. This approach can be much cheaper than raising the floor.

3.4. *Velocity distribution of inlet*

To provide sufficient air motion to prevent the settling of particles in the center area of the room, one can also change the inlet velocity distribution, using, for example, individually controlled filter-fan units. It provides another alternative approach aiming to achieve a uniform airflow. Airflow uniformity has been investigated for

(1) linear inlet velocity distribution

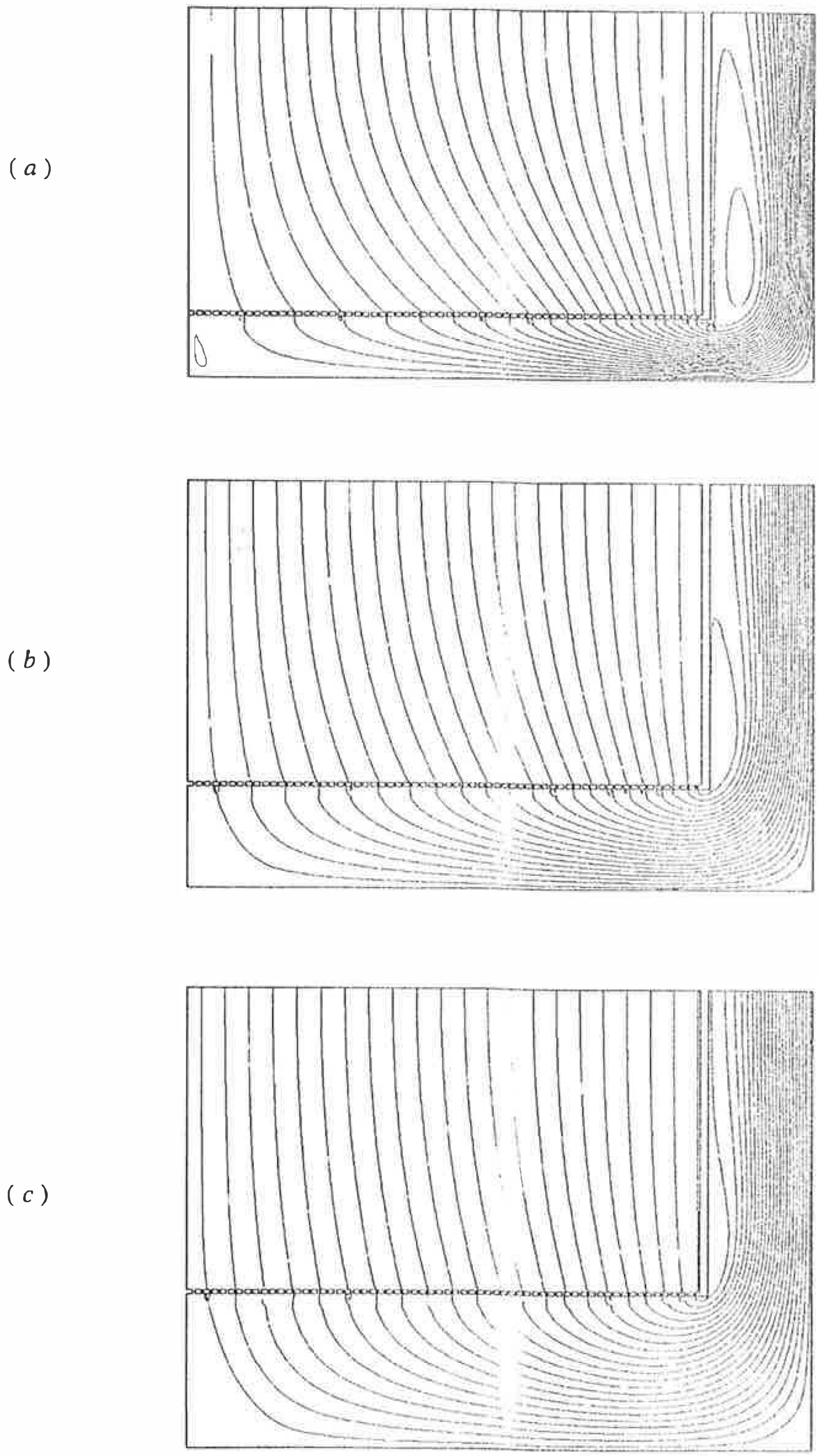

Fig. 5. Streamline patterns for $C = 25\%$. $L = 10$ m and different values of H. (a) $H = 0.6$ m. (b) $H = 1$ m. (c) $H = 1.5$ m.

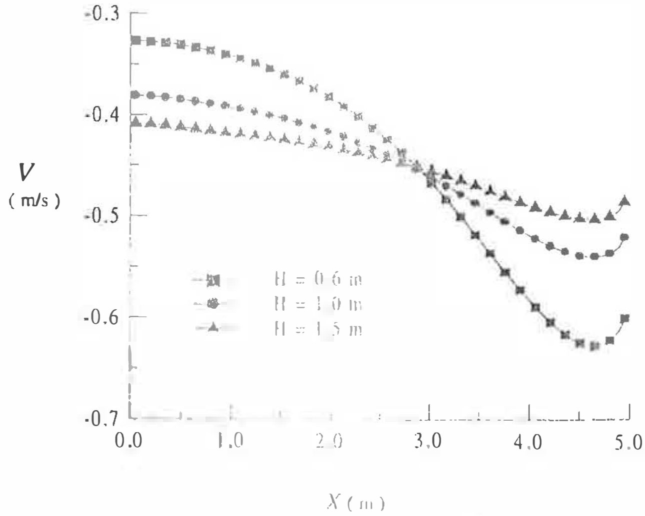

Fig. 6. Comparison of velocity distribution at 1 m above floor for different values of values of H.

$$V_{inlet} = 3x/50 - 0.6\,(ms^{-1}), \tag{14}$$

(2) step inlet velocity distribution

$$V_{inlet} = \begin{cases} -0.6\,(0 \leqslant x < 1.2) \\ -0.5\,(1.2 \leqslant x < 2) \\ -0.45\,(2 \leqslant x < 3) \quad (ms^{-1}) \\ -0.4\,(3 \leqslant x < 4.8) \\ -0.3\,(4.8 \leqslant x \leqslant 5) \end{cases} \tag{15}$$

(3) uniform velocity distribution

$$V_{inlet} = -0.45\,(ms^{-1}). \tag{16}$$

Figure 9 shows the velocity profiles at 1 m above the floor for these three velocity distributions for $H = 0.6$ m, $C = 25\%$ and $L = 10$ m. It is clear that owing to the effect of the inlet velocity, the velocity increases in the center area of the room and decreases near the side-wall of the room. As a result, the uniformity of the velocity distribution increases. For uniform, linear and step inlet velocity distributions, the uniformity of the air velocity distribution at 1 m above floor is 75, 88 and 89%, respectively. The linear distribution and step distribution give almost the same uniformity, and they are far better than that of the uniform inlet velocity. In practice, it is easier to implement the step distribution velocity at the inlet.

It can be expected that the combination of different porosity C and inlet velocity distributions can further improve the uniformity of the airflow in a cleanroom.

4. Summary and conclusions

An intensive computational simulation has been conducted to investigate the flow in vertical unidirectional flow cleanrooms. In the present work, the influence of the inlet velocity profile, the width of the room, the height and the porosity of the raised floor on the uniformity of air velocity distribution have been studied. It has focused on the development of new approaches to achieve airflow uniformity at a desired work station level in cleanrooms. It was found that the uniformity of the airflow distribution in the cleanroom significantly depends on the inlet velocity distribution, the height and porosity of the raised floor, in particular, when the width of the room is large. For a given constant velocity, the uniformity of the air velocity distribution decreases with the increase of the room width. The uniformity increases with the increase of the height of the raised floor. A desired airflow uniformity can also be achieved by the following approaches:

(1) By increasing the height of the floor chamber. This obvious, but expensive, approach may or may not be possible.
(2) By changing the porosity distribution of the perforated floor across the floor area. This approach is cheap, efficient, and is therefore recommended.
(3) By changing the velocity distribution of the inlet across the ceiling. This can be done by using duct filter or fan filter units, where velocity of airflow out of the units can be controlled individually.

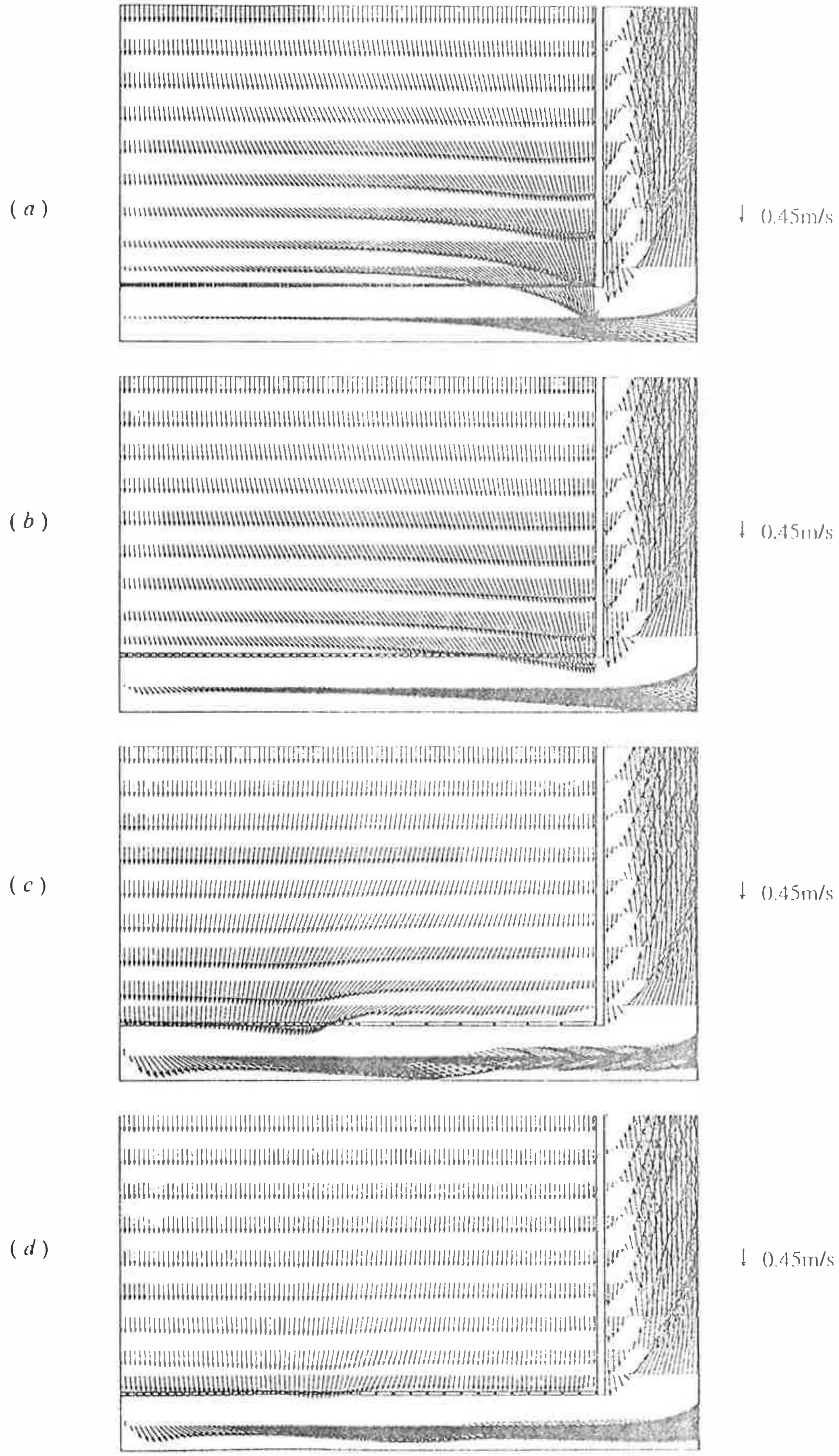

Fig. 7. Velocity vector for $L = 10$ m, $H = 0.6$ m and different values of porosity C. (a) $C = 50\%$, $l = L$, (b) $C = 25\%$, $l = L$, (c) $C_1 = 25\%$, $l_1 = L/2$, $C_2 = 5\%$, $l_2 = L/2$, (d) $C_1 = 25\%$, $l_1 = L/2$, $C_2 = 10\%$, $l_2 = L/2$.

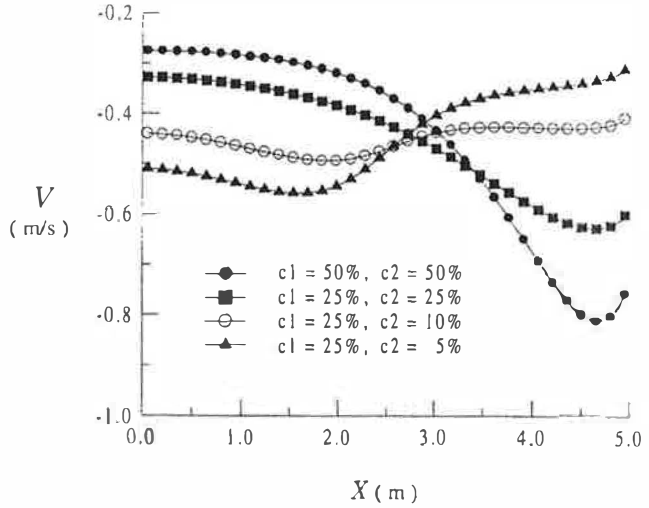

Fig. 8. Comparison of velocity distribution at 1 m above floor for different *C*.

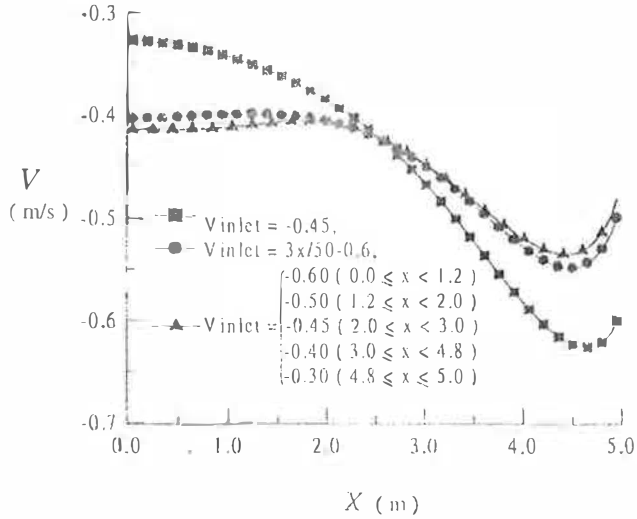

Fig. 9. Comparison of velocity distribution at 1 m above floor for different inlet velocity profiles.

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