# Numerical Simulation of Effects of Moving Operator on the Removal of Particles in Cleanroom

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The motions of the airflow and particles induced by a moving operator in a cleanroom were studied numerically. This situation is classified as a kind of moving boundary problem, and a Galerkin finite element formulation with an arbitrary Lagrangian-Eulerian kinematic description method is adopted to analyze this problem. Two different moving speeds of the operator under Reynolds number $Re = 500$ and Schmidt number $Sc = 1.0$ are taken into consideration. The results show that circulation zones, which are disadvantageous to remove the particles, are observed around the operator and near the worktable and that the operator usually prevents the removal of the particles. The relatively slow moving speed of the operator is beneficial to remove the particles. These phenomena are quite different from those regarding the moving operator as stationary in the cleanroom.

**Keywords:** cleanroom, airflow, particles, ALE, moving boundary problem

## 1. Introduction

Recently, the cleanroom has become an indispensable environment for the semiconductor industry to produce high quality and precision products. To maintain the cleanliness of the cleanroom, the external air entering the cleanroom needs to be filtered by a high efficiency particulate air filter bank. Consequently, the particles detected in the cleanroom are mainly generated by the contaminative sources of the operators and operating equipment in the cleanroom, and most particles are continuously removed by the airflow. However, some residual particles, which are suspended within circulation zones or deposited on the products and equipment by the effects of gravity, diffusion, collision, and electrostatic attraction, etc., are extremely difficult to sweep away. Besides, the movement of the operator in the cleanroom also prevents the removal of the particles.

For removing the particles in the cleanroom efficiently, several researchers have investigated the motions of the particles in the airflow. Ermak and Buckholz (1980) adopted a Monte Carlo method to simulate the effect of the airflow on the characteristics of the particles, and the results showed that the characteristics of the particles were dominated by the airflow. Kuehn (1988), Yamamoto et al. (1988a, 1988b), Yamamoto (1990), Busnaina et al. (1988), and Lemaire and Luscuere (1991) adopted the computational

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methods to investigate the airflow patterns and contaminant diffusion in the cleanroom. Settles and Via (1988) utilized Schlieren observations to observe the flow paths of the particles in the cleanroom. In addition, Liu and Ahn (1987) used the analogy between the mass and heat transfers to determine the particle deposition rates by diffusion. Donovan (1990) reviewed and summarized the development of particle control for semiconductor manufacturing.

However, the operator is also a serious contaminant source, and the motions of the particle generated by the operator have also become an important issue. To facilitate the analysis, most of the studies mentioned above regarded the moving operator as stationary when they investigated the effects of the airflow on the particle diffusion induced by the moving operator in the cleanroom. But the motions of the operator regarded as stationary are quite different from those when he is regarded as a moving object.

Furthermore, the diameter of most particles is smaller than $0.1\,\mu m$ in the high quality semiconductor cleanroom at present, and diffusion has been the main effect on the movement of the small particles. For convenience of analysis, the motion of the particles in the cleanroom is reasonably assumed as the mass transfer model of gas.

Consequently, the aim of this paper is to investigate the motions of the airflow and particles induced by the movement of the operator in the cleanroom numerically. An appropriate kinematic description method of the arbitrary Lagrangian-Eulerian (ALE) method (Noh 1964) is adopted to describe the phenomena related to the above object. A Galerkin finite element method with moving mesh and a backward difference scheme dealing with the time terms is used to solve the governing equations.

## 2. Physical Model

A two-dimensional cleanroom under vertical laminar flow as sketched in Fig. 1 is used. The width and height of the cleanroom are $w\,(= w_1 + w_2)$ and $h$, respectively. A rectangular block with height $h_1$ and width $w_4$ is used to simulate an operator in the cleanroom. The distance from the outlet of the cleanroom to the bottom surface of the operator is $h_3$. A worktable with height $h_2$ and width $w_1$ is set on the left side of the cleanroom. Two different inlet air velocities, $v_1$ and $v_2$, separately flow at the inlet sections of $\overline{AB}$ and $\overline{BC}$, which are employed as an energy conservation measure. Initially ($t = 0$), the operator is stationary and the air flows steadily, and the distance from the worktable to the operator is $w_3$. At time $t > 0$, the operator moves to the worktable with a constant velocity $u_b$, stays beside the worktable, and finally leaves the worktable. Therefore, the motions of the particles induced by the operator are affected by the airflow and the movement of the operator mutually, and the problem becomes time-dependent. As a result, the ALE method is properly utilized to analyze this problem. The detail of the ALE kinematic description method is delineated in Hirt et al. (1974), Hughes et al. (1981), Ramaswamy (1990), and Fu and Yang (2000).

In order to facilitate the analysis, the following assumptions are made.

(1) The fluid is air and the flow field is two-dimensional, incompressible and laminar.

(2) The fluid properties are constant and the effect of the gravity is neglected.

(3) The no-slip condition is held on the interface between the airflow and operator.

(4) The concentration of particles on the operator surface is constant and equal to $c_0$.

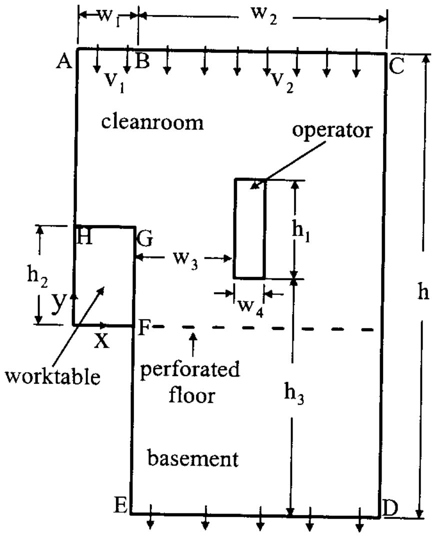


**Fig.1** Physical model

(5) The effect of the perforated floor of the cleanroom is neglected.

Based on the characteristic scales of $w_4$, $v_2$, $\rho v_2^2$ and $c_0$, the dimensionless variables are lefined as follows:

$$X=\frac{x}{w_4},\quad Y=\frac{y}{w_4},\quad U=\frac{u}{v_2},\quad V=\frac{v}{v_2},$$
$$\hat{U}=\frac{\hat{u}}{v_2},\quad U_b=\frac{u_b}{v_2},\quad P=\frac{p-p_\infty}{\rho v_2^2},\quad \tau=\frac{tv_2}{w_4},\qquad (1)$$
$$C=\frac{c}{c_0},\qquad Re=\frac{v_2 w_4}{\nu},\qquad Sc=\frac{\nu}{D}.$$

According to the above assumptions and limensionless variables, the dimensionless ALE ;overning equations are expressed as the ollowing equations:

ontinuity equation

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \qquad (2)$$

nomentum equations

$$\frac{\partial U}{\partial \tau}+(U-\hat{U})\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \qquad (3)$$

$$\frac{\partial V}{\partial \tau}+(U-\hat{U})\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right) \qquad (4)$$

concentration diffusion equation

$$\frac{\partial C}{\partial \tau}+(U-\hat{U})\frac{\partial C}{\partial X}+V\frac{\partial C}{\partial Y}=\frac{1}{Re\,Sc}\left(\frac{\partial^2 C}{\partial X^2}+\frac{\partial^2 C}{\partial Y^2}\right) \qquad (5)$$

At time $\tau>0$, the boundary conditions are as follows:

on the wall surfaces of $\overline{CD}$, $\overline{EG}$, $\overline{AH}$

$$U=V=0,\qquad \partial C/\partial X=0 \qquad (6)$$

on the wall surface of $\overline{GH}$

$$U=V=0,\qquad \partial C/\partial Y=0 \qquad (7)$$

on the airflow inlet section of $\overline{AB}$

$$U=0,\qquad V=V_1,\qquad C=0 \qquad (8)$$

on the airflow inlet section of $\overline{BC}$

$$U=0,\qquad V=-1,\qquad C=0 \qquad (9)$$

on the airflow outlet section of $\overline{DE}$

$$\partial U/\partial Y=\partial V/\partial Y=\partial C/\partial Y=0 \qquad (10)$$

on the interface of the operator and airflow

$$U=U_b,\qquad V=0,\qquad C=1 \qquad (11)$$

## 3. Numerical Method

A Galerkin finite element method with moving meshes and a backward scheme dealing with the time terms is adopted to solve the governing equations (2)-(5). A penalty function and Newton-Raphson iteration algorithm are utilized to reduce the pressure and nonlinear terms in the momentum equations, respectively. The velocity and concentration terms are expressed as quadrilateral and nine-node quadratic isoparametric elements. The discretization process of the governing equations is similar to the one used in Fu et al. (1990). The detail of the solution procedure is delineated in Fu and Yang (2000).

Concerning the mesh velocity $\hat{U}$, it is a linear distribution and is in inverse proportion to the distance between the node of the computational meshes and the moving operator in this study. The mesh velocity near the operator is faster than that near the boundary of the computational domain. In addition, the boundary layer thickness on the surface of the operator is extremely thin and can be approximately estimated by $Re^{-1/2}$ (Schlichting 1979). To keep the computational nodes in the vicinity of the operator from slipping away from the boundary layer, the meshes velocities adjacent to the operator are expediently assigned equal to the velocity of the operator.

## 4. Results and Discussion

For convenience of analysis, the dimensionless parameters are adopted in this study. At time $\tau = 0.0$, the distance from the worktable to the operator is $W_3 = 4.5$. For satisfying the boundary condition at the outlet of the airflow, the dimensionless length $H_3 (= \frac{h_3}{w_4})$ is determined by numerical tests and equal to 28.0.

Concerning the diffusion coefficient D of the particles, the diffusion coefficient decreases as the diameter of the particle increases (Hinds 1982), and Schmidt number Sc is in inverse ratio to the diameter of the particles. To facilitate the analysis, the value of Sc is assumed to be 1.0 which is an appropriate value for most gases.

Two different moving speeds, 2.0 and 0.75, of the operator are taken into consideration under $V_1 = -1.25$, $Re = 500$ and $Sc = 1.0$ situation. To obtain the optimal computational meshes and time step, a series of numerical tests is executed. The nonuniform distribution of 5,732 elements corresponding to 23,332 nodes and time step $\Delta\tau = 1 \times 10^{-2}$ are chosen.

The dimensionless stream function $\Psi$ is defined as:

$$U = \frac{\partial \Psi}{\partial Y} \quad \text{and} \quad V = -\frac{\partial \Psi}{\partial X} \tag{12}$$

To illustrate the flow and concentration fields more clearly, only the phenomenon in the work region of the cleanroom is presented.

The transient developments of the streamlines and constant concentration lines of particle distributions when the moving speed of the operator is equal to 2.0 are shown in Fig. 2. At the time $\tau = 0.0$, as shown in Fig. 2(a), the operator is stationary and the air flows steadily. Several circulation zones, in which particles may suspend, are found near the top and lateral surfaces of the worktable. At time $\tau > 0.0$, the operator starts to move toward the worktable with a constant moving velocity $U_b = -2.0$ and the variations of the flow and concentration fields become a transient state. Shown in Fig. 2(b), the space between the worktable and operator is contracted gradually which results in the airflow beginning to flow to the rear region of the operator. The airflow from the inlet is remarkably affected by the movement of the operator. As the time increases, as shown in Figs. 2(c)-(d), the space between the worktable and operator becomes narrow and then most inlet air flows through the rear region of the operator. In this duration, new airflow induced by the moving operator is forced to flow over the worktable and sweeps away the original circulation zones formed on the worktable. Afterward, the new airflow joins with the airflow from the inlet and

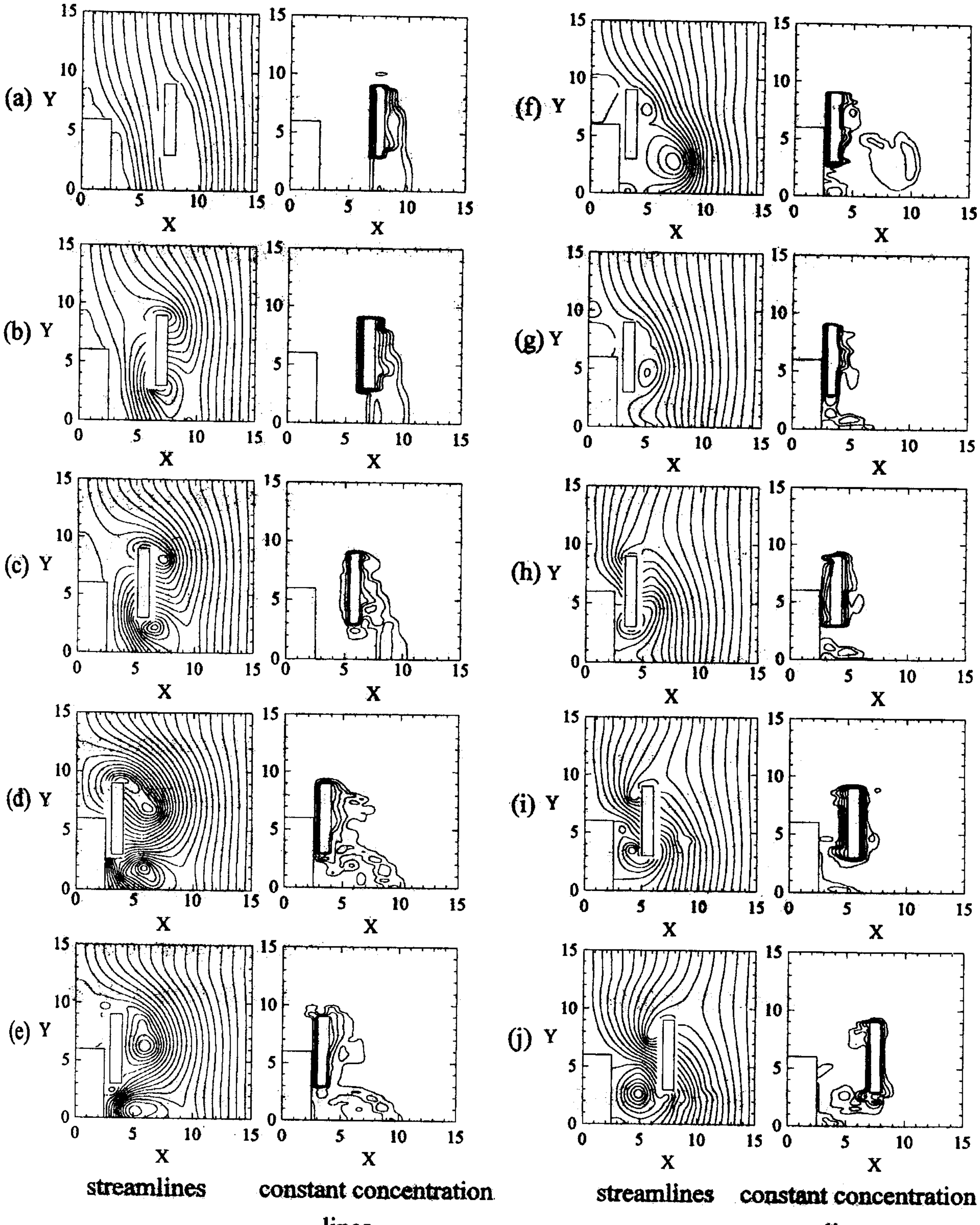


Fig. 2 The transient developments of the streamlines and constant concentration lines of particles distributions around the work region of the cleanroom for the operator moving speed equal to 2.0 case **(a)** $\tau = 0.0$, $U_b = 0.0$, **(b)** $\tau = 0.25$, $U_b = -2.0$, **(c)** $\tau = 1.0$, $U_b = -2.0$, **(d)** $\tau = 2.0$, $U_b = -2.0$, **(e)** $\tau = 2.5$, $U_b = 0.0$, **(f)** $\tau = 7.0$, $U_b = 0.0$, **(g)** $\tau = 12.0$, $U_b = 0.0$, **(h)** $\tau = 12.2$, $U_b = 2.0$, **(i)** $\tau = 13.0$, $U_b = 2.0$, **(j)** $\tau = 14.0$, $U_b = 2.0$.

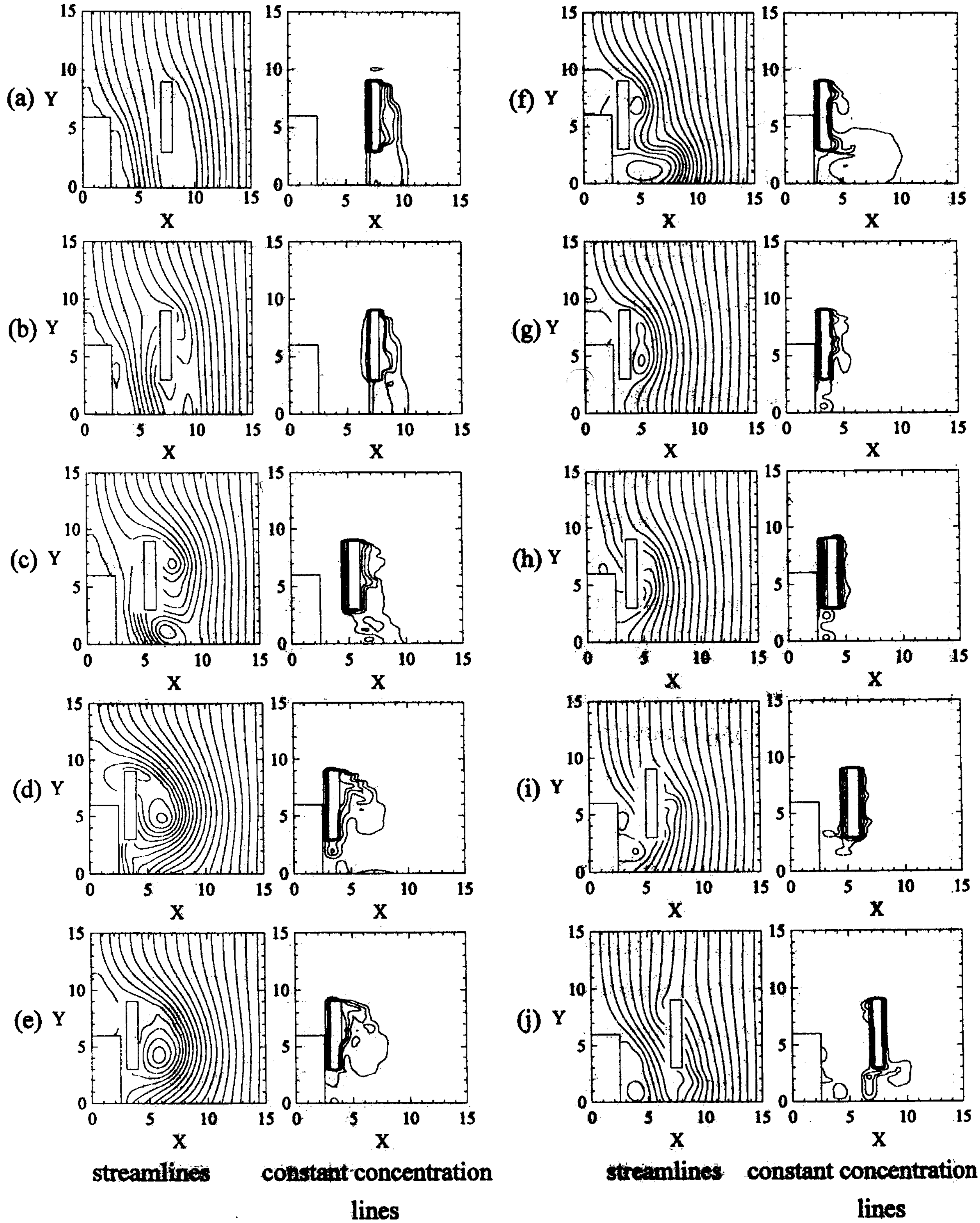


**Fig. 3** The transient developments of the streamlines and constant concentration lines of particles distributions around the work region of the cleanroom for the operator moving speed equal to 0.75 case **(a)** $\tau = 0.0$, $U_b = 0.0$, **(b)** $\tau = 0.25$, $U_b = -0.75$, **(c)** $\tau = 2.67$, $U_b = -0.75$, **(d)** $\tau = 5.33$, $U_b = -0.75$, **(e)** $\tau = 6.33$, $U_b = 0.0$, **(f)** $\tau = 10.33$, $U_b = 0.0$, **(g)** $\tau = 15.33$, $U_b = 0.0$, **(h)** $\tau = 15.6$, $U_b = 0.75$, **(i)** $\tau = 18.0$, $U_b = 0.75$, **(j)** $\tau = 20.66$, $U_b = 0.75$.

flows to the back region of the operator. In the meanwhile, the circulation zones in the rear region of the operator enlarges gradually, which is disadvantageous to the removal of the particles. As for the distributions of the constant concentration lines, most particles are removed by the airflow, and the residual particles usually suspend within the circulation zones. As shown in Figs. 2(c)-(d), as the operator moves to the worktable, the space between the worktable and the operator becomes narrow. Consequently, the effect of the airflow from the inlet on the removal of the particles is reduced, and the particles suspending in this space now diffuse gradually to the worktable.

During time $\tau$ from 2.0 to 12.0, the operator stays beside the worktable ($U_b = 0.0$), as shown in Figs. 2(e)-(g). New circulation zones are formed near the worktable and operator, and the airflow from the inlet passing through the space mentioned above is slight. As a result, the particles easily suspend in these circulation zones, those damaging the product on the worktable.

At time $\tau > 12.0$, as shown in Figs. 2(h)-(j), the operator leaves the worktable with a constant velocity $U_b = 2.0$. Since the operator moves to the right, the airflow from the inlet is affected by the operator and also flows to right. The space mentioned above gradually becomes broad, and the inlet airflow easily passes through this space, causing the circulation zones near the worktable and operator to be destroyed gradually. But new circulation zones also appear in the low region beside the worktable.

Concerning the distributions of the particles that accompany the variations of the airflow mentioned above, the particles distributed around the worktable are gradually swept by the airflow from the inlet. As the time increases, most particles are observed distributing around the operator only.

Fig. 3 shows the transient developments of the streamlines and constant concentration lines of particle distributions for the moving speed of the operator being equal to 0.75 case. At time $\tau > 0$, the operator starts to move toward the worktable with a constant velocity $U_b = -0.75$. The moving speed of the operator is smaller than the air inlet velocity from the ceiling, so that the air flows easily through the space between the worktable and operator (Fig. 3(c)) until the operator is very close to the worktable (Fig. 3(d)). These phenomena shown in Fig. 3 are different from those shown in Fig. 2. Besides, the new airflow induced by the operator is not so remarkable due to the slower moving speed of the operator, and the variations of the flow fields are relatively simple. The circulation zones are still observed around the operator, but the strength of the circulation zones is smaller than that of the above case. Consequently, the particles suspending in these circulation zones are possibly removed by the airflow. For the same reason, the constant concentration lines of particles can not diffuse so broadly as they do in the above case (Fig. 2).

During time $\tau$ from 5.33 to 15.33, the operator stays beside the worktable ($U_b = 0.0$). As shown in Figs. 3(e)-(g), the circulation zones around the operator have shrunk gradually with the time increase, and most particles can be swept away by the airflow in the cleanroom.

At time $\tau > 15.33$, the operator leaves the worktable with a constant moving velocity $U_b = 0.75$. As shown in Figs. 3(h)-(j), the circulation zones are formed around the bottom surface of the operator and the lateral surface of the worktable due to the movement of the operator. Since the airflow from the inlet dominates the flow field mentioned earlier, the variations of the airflow are simple and are beneficial to remove the particles.

## 5. Conclusions

The motions of the airflow and particles induced by an operator in the cleanroom are investigated numerically. The results can be summarized as follows:

1. The airflow and particle transports in the cleanroom are deeply influenced by the movement of the operator. These phenomena are quite different from those of regarding the moving operator as stationary as was done in previous studies.
2. The effects of the moving speed of the operator on the motions of the airflow and particles are remarkable. From the viewpoint of removing the particles, the relatively smaller moving velocity of the operator and the relatively higher velocity of the inlet airflow are recommended.

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