Motion of Small Particles due to a Pulsatile Flow in a Chamber*

Hiroataka SUZUKI**, Eiji HASEGAWA***
and Hisayoshi MATSUFUJI**

The unsteady motion of small particles, which are uniformly distributed at first, in a square chamber with a pulsating inlet velocity is studied numerically. The force between particle and fluid is assumed to be proportional to the relative velocity. The problem considered is governed by four parameters, the Reynolds number, the dimension ratio (which characterizes the particles as coarse or fine), the period and the amplitude of the pulsating inlet velocity (which are made dimensionless). The motion of the particles is classified into three types: the exhaust type, in which the particles are exhausted through the outlet; the circulation type, in which the particles circulate in the chamber; and the adhesion type, in which the particles adhere to the wall of the chamber. The effects of the period and the amplitude of the inlet velocity on the ratio of the number of particles of each type to the total number of particles are examined taking the Reynolds number and the dimension ratio as parameters. The suitable ranges of the period and the amplitude of the inlet velocity, in which the number of exhausted particles becomes large, and the number of circulating particles becomes small, are found, taking the dimension ratio as a parameter. The mechanism of the exhausting of the particle is qualitatively clarified on the basis of the relationship between the streamline and the trajectory of the particles.

Key Words: Fluid Mechanics, Multiphase Flow, Unsteady Flow, Pulsatile Flow, Numerical Analysis, Trajectory of Particle, Exhausting of Particle

1. Introduction

In clean rooms, which are the manufacturing environment of precision devices such as semiconductors, it is important to decrease dust floating in the air and to prevent it from adhering to these devices in order to obtain large yields. Accordingly, it is necessary to control the motion of small particles by understanding their behavior in air.

Many studies⁽¹⁾⁻⁽⁶⁾ have been conducted on the analysis of the concentration distribution of particles in a gas stream using the distribution equation, in which suspended particles are regarded as a continuous phase. However, because the information which is ultimately required as the design data of clean rooms is each motion of the few remaining particles in the chamber, namely, which particle has the greatest possibility of adhering to devices, it is more important to treat the motion of particles which are regarded as

discrete.

As a basic attempt towards this aim, the authors studied the motion of discrete particles for the case where the ventilation of a two-dimensional square region suddenly commenced with a constant inlet velocity, which indicated that the number of particles suspended in fluid can be decreased by controlling the inlet velocity properly⁽⁷⁾. Furthermore, in a succeeding paper⁽⁸⁾, the motion of particles was studied for the case in which the inlet velocity increased in proportion to time from zero to a constant value, because the flow feature in actual ventilation is that the inlet velocity initially increases during the course of time and becomes constant after a start-up time. It was also indicated that there is a suitable start-up time in which the number of particles suspended in fluid can be made small.

Another feature of the actual inlet velocity is that the inlet velocity is not necessarily constant but pulsates even after the fluid field becomes roughly constant. Therefore the motion of particles becomes very complicated. Because the unsteadiness of the flow changes the motion of particles greatly, there is a possibility that the amount of particles suspended in

* Received 13th March, 1992. Paper No. 90-0876 A

** Sanki Engineering Co., Ltd., Sanshin Bldg., 1-4-1 Yuraku-cho, Chiyoda-ku, Tokyo 100, Japan

*** Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223, Japan

fluid can be decreased if the pulsatile flow is suitably adopted. Normally, the inlet velocity is controlled by dumpers in the duct system or the rotation speed of fans, so it is easy to alter the flow with time so that suitable control of particle motion can be carried out.

In this paper, a pulsating flow with a constant period and amplitude of the inlet velocity is assumed, and the motion of particles in a square chamber which has an inlet at the center of the upper wall and an outlet at the lower part of one of the side walls, is studied. The influence of the period and the amplitude of the inlet velocity on the motion of particles is examined numerically, and the conditions under which particles are efficiently exhausted from the chamber are clarified to obtain the basic condition for the most suitable operation of clean rooms.

2. Basic Equation System

2.1 Modeling

The chamber considered is square with the side length $9L$. The chamber has an inlet with the width L at the center of the upper wall and an outlet with the width L at the lower part of the right wall, as shown in Fig. 1. The origin of coordinates is taken at the lower corner on the left-side wall and x and y axes are taken along the lower wall and the left-side wall, respectively. The time-dependent velocity $U(t)$ at the inlet and the outlet has the period T^* , the mean velocity $\bar{U}$, and the amplitude u_m and pulsates according to $U(t) = \bar{U} - u_m \cos(2\pi t/T^*)$, as shown in Fig. 2.

2.2 Governing equations of fluid motion

Since it is reasonable to assume that the size of the particle and the number of mixed particles are small, the effect of mixed particles on fluid motion is neglected. Fluid with the density ρ and the kinematic viscosity ν is assumed to be incompressible and viscous. Making the length, velocity, time and pressure dimensionless with the width L of the inlet, the velocity $\bar{U}$ of the fluid at the inlet, the time $L/\bar{U}$ and the pressure $\rho\bar{U}^2$, respectively, the equations governing unsteady fluid motion are written as

Fig. 1 Coordinate system

$$\frac{\partial u}{\partial t} = -\frac{\partial u^2}{\partial x} - \frac{\partial uv}{\partial y} - \frac{\partial p}{\partial x} + \frac{1}{R} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (1)$$

$$\frac{\partial v}{\partial t} = -\frac{\partial uv}{\partial x} - \frac{\partial v^2}{\partial y} - \frac{\partial p}{\partial y} + \frac{1}{R} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \quad (3)$$

Here R denotes the Reynolds number $L\bar{U}/\nu$, u and v denote the x and y velocity components, and p and t denote the pressure and the time. The boundary conditions for Eqs. (1)–(3) are nonslip conditions on the walls and the conditions at the inlet and the outlet,

$$y=0, 0 \leq x \leq 9: u=v=0 \quad (4)$$

$$x=9, 0 < y < 1: u=U(t), v=0 \quad (5)$$

$$x=9, 1 \leq y \leq 9: u=v=0 \quad (6)$$

$$y=9, 0 \leq x \leq 4, 5 \leq x \leq 9: u=v=0 \quad (7)$$

$$y=9, 4 < x < 5: u=0, v=-U(t) \quad (8)$$

$$x=0, 0 \leq y \leq 9: u=v=0. \quad (9)$$

Here the inlet velocity $U(t)$ is written, through assumption, as

$$U(t) = 1 - \beta \cos(2\pi t/T^*). \quad (10)$$

Here β and T denote the dimensionless amplitude $u_m/\bar{U}$ and period $T^*\bar{U}/L$, respectively. Next, since it is assumed that fluid is initially at rest in the chamber, the initial conditions become

$$t=0, 0 \leq x \leq 9, 0 \leq y \leq 9: u=v=0. \quad (11)$$

As the fluid motion is assumed to be unaffected by the presence of particles, the governing equations, Eqs. (1)–(11), are first solved numerically by the MAC method⁽⁹⁾ with 28×28 mesh arrays and the time step of 0.05.

2.3 Governing equations of particle motion

In this paper, the following assumptions for particle motion are introduced. The particle-particle interaction is neglected since the size and the number of mixed particles are small. The particles are spherical. The interaction between the particle and the fluid is described by Stokes' drag law. The influence of the gravitational force is neglected since the particles are fine. Denoting the velocity components of a particle with u_p and v_p , the equations of motion of a particle with the radius a and the density ρ_p are given by

$$\frac{3}{4} \pi a^3 \rho_p \frac{du_p}{dt} = 6 \pi \rho \nu a (u - u_p) \quad (12)$$

Fig. 2 Time-dependent inlet velocity

$$\frac{3}{4}\pi a^3 \rho_p \frac{dv_p}{dt} = 6\pi \rho \nu a (v - v_p). \quad (13)$$

If the position of the particle is denoted by the coordinates x and y , the velocities of the particle are defined by the time derivative of these coordinates. When coordinates are made dimensionless by the same procedure as for fluid motion, the equations of motion for a particle are represented in the dimensionless form as

$$\frac{d^2x}{dt^2} = \frac{N}{R} \left(u - \frac{dx}{dt} \right) \quad (14)$$

$$\frac{d^2y}{dt^2} = \frac{N}{R} \left(v - \frac{dy}{dt} \right). \quad (15)$$

Here N is a nondimensional parameter called the dimension ratio, which corresponds to the mass ratio of one particle to the fluid in the chamber, defined as

$$N = \frac{9}{2} \frac{\rho L^2}{\rho_p a^2}. \quad (16)$$

Then the motion of a particle is governed by the dimension ratio N , the Reynolds number R , the amplitude β and the period T . As particles are assumed to be initially at rest, the initial conditions for these equations are written as

$$t=0, 0 \leq x \leq 9, 0 \leq y \leq 9: u_p = v_p = 0. \quad (17)$$

These equations governing the particle motion are solved numerically using the Runge-Kutta method with the time step of 0.05. The calculation of particle motion is performed until $t=1000$. Furthermore, it is assumed that once a particle collides with the wall of the chamber during the calculation, the particle

remains adhered to the wall.

3. Time-Dependent Variations of Flow Field

The time-dependent variations of flow field after a sufficient length of time are shown in Figs. 3(a)-(d) in the case of $R=50$, $T=10$ and $\beta=1.0$. The representative values of stream functions are shown in Fig. 3. Here the difference between the values of stream functions of every two adjacent streamlines is $\Delta\psi=0.05$.

At the time $t=300$ in Fig. 3(a), the inlet velocity is zero and thus the fluid does not flow in or out at the inlet and the outlet. There are two large vortexes arising at either side of the streamline of $\psi=0.0$. Then the inlet velocity gradually increases and its magnitude becomes 1 at the time $t=300 + T/4$ in Fig. 3(b). Here the two vortexes stated above become small, depressed by the fluid flowing into the chamber, and move downward. Calling the flow which flows directly from the inlet to the outlet, the main flow, the value of the stream functions in the main flow region is, at this time, $0.0 < \psi < 1.0$, and this region spreads to the right and left at the top of the chamber. When the inlet velocity becomes maximum at the time $t=300 + T/2$ in Fig. 3(c), two vortexes newly arise on both sides of the inlet, and the two vortexes at the lower side of the chamber become smaller. Furthermore, the main flow region having the value $0.0 < \psi < 2.0$ of the stream function spreads to the right and left between these vortexes. Conversely when the inlet velocity decreases

Fig. 3 Time-dependent variations of fluid field ($R=50$, $T=10$, $\beta=1.0$)

at the time $t=300+3T/4$ in Fig. 3(d), two-vortex pairs at the upper and lower sides fuse. Then the flow field returns to the state shown in Fig. 3(a). Hereafter, the two vortices arising one after another on both sides of the inlet in Figs. 3(a)-(d) are called the primary vortices, and the vortices arising at the corners of the chamber are called the secondary vortices.

4. Ratio of Exhaust, Circulation and Adhesion Particles

The representative trajectories of particles in the case of $R=50$ and $N=100$ are shown in Figs. 4(a) and (b). Here, Fig. 4(a) is the case of constant inlet velocity and Fig. 4(b) is the case of the pulsatile flow of $T=10$ and $\beta=1.0$. In Fig. 4, the initial positions of particles are shown by the symbol $\bullet$, and the positions at time $t=1\,000$ are shown by the symbol $\circ$. The final states of the particles are found from Fig. 4(a) to be classified into the following three types: the exhaust type in which the particles are exhausted through the outlet, the circulation type in which the particles circulate in the chamber, and the adhesion type in which the particles adhere to the walls of the chamber⁽⁷⁾. Hereafter, they are referred to as the exhaust particle, the circulation particle and the adhesion particle, respectively. It is evident from Fig. 4(b) that the trajectories of particles are greatly affected by the pulsatile flow, and that circulation particles in

the left primary vortex in Fig. 4(a) become either exhaust particles, adhesion particles or circulation particles in the right primary vortex in Fig. 4(b).

Next, the influence of the parameters R , N , T and β on the motion of particles is examined using the ratios defined below. Namely, the ratios of the numbers n_e , n_c and n_a of the exhaust, circulation and adhesion particles to the total number n of particles which are uniformly distributed throughout the chamber at $t=0$, denoted by ϕ_e , ϕ_c and ϕ_a , respectively, are defined as

$$\left. \begin{aligned} \phi_e &= n_e/n \\ \phi_c &= n_c/n \\ \phi_a &= n_a/n \\ n &= n_e + n_c + n_a \end{aligned} \right\} \quad (18)$$

These ratios are numerically obtained on the basis of the 289 (17×17) particles distributed uniformly in the chamber.

The influence of the period of the inlet velocity on these ratios when $\beta=0.1$ is shown in Figs. 5(a) and (b) for the case of $N=100$ and $N=2\,000$, respectively. The values of R/N which correspond to the relaxation time of the particles are shown in Fig. 5. In the case of $N=100$ of Fig. 5(a), the ratio of the circulation particle decreases in the range $3 < T < 150$, and becomes minimum near $T=10$. Its value is about 2%, which is one-twentieth of the value 40% in the ranges $T \leq 3$ and $T \geq 150$, in which the value is the same as in

the case of constant inlet velocity. On the contrary, in the same range of the period, in which the ratio of the circulation particle is affected by the period, the ratio of the adhesion particle increases and becomes maximum near $T=5$. Its value is about 62%, which is about twice the value 32% in the ranges $T \leq 3$ and $T \geq 150$. But the influence of the pulsatile flow on the ratio of the exhaust particles appears only in the narrower range of $4 < T < 60$, not in $3 < T < 150$ of the circulation and adhesion particles. The ratio of the exhaust particles becomes a maximum of 44% near $T=9$, to which the ratio in the ranges $T \leq 4$ and $T \geq 60$ increases from 29%. In this way, the influence of the period of the pulsatile flow on the ratio of the particle is easily appears for the circulation and adhesion particles, but not for the exhaust particle. Therefore, if the value of the period is set in the range $3 < T < 150$ in the case of $N=100$ and $\beta=0.1$, the circulation particles in the chamber can be decreased, and the suitable value of the period is about $T=10$. In the case of $N=2000$ of Fig. 5(b), the influence of the period on each ratio is rather small compared to that in Fig. 5(a). The ratio of the circulation particle decreases in the range $3 < T < 200$, and becomes minimum near $T=20$. Its value is about 11%, about one-fourth of the value 49% in the ranges $T \leq 3$ and $T \geq 200$. On the other hand, the ratio of the adhesion particle increases and becomes maximum near $T=20$. Its value is about 54%, more than twice the value 22% in the ranges $T \leq 3$ and $T \geq 200$. In the same manner as in Fig. 5(a), the influence of the period to the ratio of the exhaust particle appears only in the narrower range of $5 < T < 50$. The ratio of the exhaust particle becomes a maximum of 36% near $T=10$, to which the ratio in the ranges $T \leq 5$ and $T \geq 50$ increases from 28%. Accordingly, in the case of $\beta=0.1$, the circulation particles in the chamber can be decreased even in the case of $N=2000$ in which the particle is relatively fine and light, if the value of the period is set within the range $3 < T < 200$. A suitable value of the period is about $T=20$. In this way, the

influence of the pulsatile flow on the motion of the particle appears in the same manner, even if the dimension ratio alters greatly, such as from $N=100$ to $N=2000$.

It is concluded from the above discussion that it is necessary to set the value of the period within a specific range so as to decrease the circulation particles and to increase the exhaust and adhesion particles. If the value of the period is not in the range stated above, there is no effect of the pulsatile flow. In particular, to increase the exhaust particles, it is necessary to set the value of the period in the center of that range. But the influence of the pulsatile flow on the motion of the particle appears in the range of period much greater than the relaxation time of the particle. It indicates that the influence is not caused by the simple difference between the motions of the fluid and the particles.

The influence of the amplitude of the inlet velocity of $T=10$ on the ratio of the particle is shown in Figs. 6(a) and (b) for the case of $N=100$ and $N=2000$, respectively. For $N=100$ of Fig. 6(a), the ratio of circulation particles greatly decreases near $\beta=0.1$, becomes minimum near $\beta=0.3$, and increases gradually in the range $\beta \geq 0.3$. The reason for the increase in the range $\beta \geq 0.3$ is that the number of particles caught by the right primary vortex increases, as shown in Fig. 4(b). Conversely, the ratio of adhesion particles greatly increases, becomes maximum near $\beta=0.1$, and gradually decreases in the range $\beta \geq 0.1$. The ratio of exhaust particles increases with increasing amplitude, becomes maximum near $\beta=0.5$, and decreases in the range $\beta \geq 0.5$ according to the increase of circulation particles. Thus it is clear that the suitable value of the amplitude to decrease circulation particles in the chamber for the case of $T=10$ and $N=100$ is about $\beta=0.3$. In the case of $N=2000$ of Fig. 6(b), the ratio of circulation particles greatly decreases with increasing amplitude, becomes minimum near $\beta=0.6$, increases slightly in the range $0.6 \leq \beta \leq 0.7$, and then becomes almost constant in the range $\beta > 0.7$. The

Fig. 6 Influence of β on the ratios of particles of three types ($R=50$, $T=10$, $t=1000$)

ratio of adhesion particles becomes maximum near $\beta = 0.2$, and then gradually decreases. The ratio of exhaust particles monotonously increases with increasing amplitude and reaches 75%. It is clear that the suitable value of the amplitude to decrease circulation particles in the chamber for the case of $T=10$ and $N=2000$ is in the range $\beta \geq 0.6$.

It is concluded from the above discussion that the adhesion particles tend to increase in small amplitude and the exhaust particles tend to increase in large amplitude in both Fig. 6(a) and Fig. 6(b).

5. Streamlines and Trajectories of Particles

5.1 Shapes of main flow and vortex

It is expected that if the flow field alters in time for the particles to easily enter the region of the main flow, the particles entering that region are carried to the outlet by the flow and easily exhausted. Hence hereafter, the time-dependent variations of the streamlines of the main flow and the vortex region near the main flow are examined.

Now, denoting the values of the stream functions on the walls right and left of the inlet ψ_{LW} and ψ_{RW} , respectively, the value of the stream functions of the main flow region falls in the interval $\psi_{LW} \leq \psi \leq \psi_{RW}$. Then the time-dependent variations of the two

streamlines, $\psi = \psi_{LW}$ and $\psi = \psi_{RW}$, are examined. They are shown in Figs. 7(a) and (b). In the case of $\beta = 0.1$ in Fig. 7(a), there is no great change in the structure of the main flow, but the width of the main flow in the upper part of the chamber varies relatively greatly. In the case of $\beta = 1.0$ in Fig. 7(b), the structure of the main flow varies complicatedly. In particular, at times $T=300+T/4$ and $300+T/2$, the region of the main flow even reaches the right and left walls. It is expected that particles are easily exhausted in such flow fields.

Next, the time-dependent variation of a streamline, having the value of $\psi = \psi_{LW} - 0.05$, of a left primary vortex near the main flow is shown in Figs. 8(a) and (b). In the case of $\beta = 0.1$ in Fig. 8(a), the upper half of the streamline of the primary vortex varies slightly, and it is concave where it is tangent to the main flow at the center and the top of the chamber, and is convex at other places. In such a flow, particles have a tendency to move out of the vortex, due to the centrifugal force, where the streamline is convex, and to move again into the vortex, accelerated by the main flow, where the streamline is concave. In the case of $\beta = 1.0$ in Fig. 8(b), the streamline varies greatly to the right and left directions where it is tangent to the main flow. Moreover, the shape of the

Fig. 7 Time-dependent variations of the main flow ($R=50$, $T=10$)
(①: $t=300$, ②: $t=300+T/4$, ③: $t=300+T/2$, ④: $t=300+3T/4$)

Fig. 8 Time-dependent variations of a streamline of the left primary vortex
($R=50$, $T=10$)(①: $t=300$, ②: $t=300+T/4$, ③: $t=300+T/2$, ④: $t=300+3T/4$)

primary vortex is convex everywhere in the circuit of the streamline at the time $t = 300 + T/4$ and $300 + T/2$. It is expected from the discussions above that the number of particles circulating in the vortex is decreased by the effects of the spreading region of the main flow and of the convex shape of the vortex which are caused by the time-dependant variation in flow.

5.2 Particle trajectory and amplitude

The representative particle trajectory in the case of $R=50$ and $N=100$ with a constant inlet velocity is shown in Fig. 9(a). The effects of the amplitude in $T=10$ on the trajectories of the particles which have the same initial position as that in Fig. 9(a) are shown in Fig. 9(b) and Fig. 9(c) for the case of $\beta=0.1$ and 1.0, respectively. Moreover, the cases of the same parameters as Fig. 9(c) and of other initial positions of the particle are shown in Figs. 10(a) and (b). In Fig. 9 and Fig. 10, the positions of particles when the inlet velocity becomes minimum are shown by $\times$ with the time interval of $\Delta t = T$. In the case of constant inlet velocity in Fig. 9(a), the particle moves gradually toward a circulating orbit turning in the left primary vortex and finally becomes a circulation particle. In the case of $\beta=0.1$ in Fig. 9(b), the trajectory slightly varies at the top of the chamber, and the particle leaves the left primary vortex and enters the main flow while the inlet velocity gradually increases

from the minimum velocity, namely, at the time of acceleration of the main flow. But the particle cannot get near the center of the main flow, so it becomes an adhesion particle, adhering to the lower wall. In the case of $\beta=1.0$ in Fig. 9(c), as expected from the variations of the streamlines in Figs. 3(a)-(d), the particle trajectory varies greatly, moves with a spiral trajectory in the left primary vortex, nears the center of the main flow at the time of acceleration of the main flow after turning especially greatly at the top of the chamber, is exhausted from the outlet, and becomes an exhaust particle. The reason why the particles enter the main flow at the top of the chamber in Figs. 9(a) and (b) is assumed to be due to the effect of the variations of the streamline at the top of the left primary vortex shown in Fig. 8, and to the main flow region spreading to the right and left, shown in Fig. 7, respectively. Also, another reason is that the shape of the left primary vortex is convex everywhere in Fig. 8(b), as indicated by the particle entering the main flow at the center of the chamber in Fig. 10(a). When the variations of the field are complicated as in the case of $\beta=1.0$, particles which travel across the main flow, enter the right primary vortex, and become circulation particles also exist.

It is concluded from the above discussion that when the amplitude is small, mainly adhesion particles

Fig. 9 Influence of β on the trajectory of a particle ($R=50, N=100, 0 \leq t \leq 1000$)

Fig. 10 Influence of the initial position of a particle on its trajectory ($T=10, \beta=1.0, R=50, N=100, 0 \leq t \leq 1000$)

Fig. 11 Influence of T on a particle trajectory ($R=50$, $N=100$, $\beta=0.1$, $0 \leq t \leq 1000$)

are increased by the variations of the streamlines of the top of the left primary vortex to allow the particles to enter the main flow at the time of acceleration of the main flow. Also, when the amplitude is large, mainly exhaust particles are increased by the effect of the main flow region spreading to the right and left and of the convex shape of the left primary vortex, to enable the particles to enter deeply into the main flow at the time of acceleration of the main flow.

5.3 Particle trajectory and period

The influence of the period in $R=50$, $N=100$ and $\beta=0.1$ on the trajectories of the particles is shown in Figs. 11(a)-(c) in the case of $T=3$, 10, and 200, respectively. In the case of $T=3$ of Fig. 11(a), because of the too rapid variations of the inlet velocity, the variations in the chamber, mainly those of the streamline of the top of the left primary vortex, are restricted to small magnitude, and the trajectory of the particle is almost the same as the case of the constant inlet velocity shown in Fig. 9(a). In the case of $T=10$ of Fig. 11(b), the influence of the variations of the inlet velocity affects the flow field of the chamber and the period is relatively small. Hence the particle cannot follow the fluid motion. Consequently, the trajectory of the particle varies at the top of the chamber, and the particle leaves the left primary vortex and adheres to the lower wall. In the case of $T=200$ of Fig. 11(c), although the variations of the inlet velocity greatly affect the fluid field of the chamber, because of the relatively long period, the particle can easily follow the motion of the fluid, and the trajectory becomes the same as that of Fig. 11(a) in the case of $T=3$.

It is concluded from the above discussion that the period must be set in a range long enough for the influence of the variations of the inlet velocity to sufficiently affect the fluid field of the chamber, and short enough for the particle not to follow the fluid motion. Moreover, the fact that the particular range of the period is, as known from Figs. 5(a) and (b), sufficiently greater than the relaxation time R/N ,

indicates that the influence of the pulsating flow on particle motion has a characteristic of accumulating a gap between the motions of the fluid field and the particle.

6. Conclusions

The motion of small particles due to a flow field in a square chamber with an inlet and an outlet in which the inlet and outlet velocities have time-dependent periodic variations was solved numerically by applying Stokes' drag law to the interaction force between a particle and fluid. The following results were obtained.

(1) The influence of pulsating flow appears in the range of period much greater than the relaxation time of the particle, and the width of the range does not depend on the dimension ratio.

(2) In particular, to increase exhaust particles, it is necessary to set the range of the period in the center of the range stated above.

(3) When the amplitude is small, the adhesion particles increase with increasing amplitude, and when the amplitude is large, the exhaust particles increase with increasing amplitude.

(4) The mechanisms of the variety of motions of particles are qualitatively clarified relative to, among other factors, the size and shape of the primary vortex which arises on the right and left of the inlet, and the periodic variations of the shape of the main flow which flows from the inlet to the outlet.

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