EULERIAN-LAGRANGIAN SIMULATION OF BUBBLY TWO-PHASE WAKE STRUCTURE INDUCED BY A CYLINDER

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ABSTRACT

When a solid object is inserted in a flow field containing many buoyant rising bubbles, a variety of two-phase flow patterns appear around the object due to interaction between the rising bubbles and surrounding liquid flow. A quite unique flow pattern similar to a shock wave is observed in the case of high void fraction and large bubbles suspended. However, the detailed mechanism of the affection of such object on its ambient flow pattern has not been elucidated. The present paper is concerned with the numerical investigation on various wake structure downstream of a cylinder which is fixed in a rising bubbly flow. The Eulerian-Lagrangian model is adopted to predict the two-phase wake structure interacting the cylinder and shows two-kinds of interesting phenomena. One is the generation of negative force acting on the cylinder against bubble-rising direction because of formulating a large liquid single-phase region downstream of the cylinder. The bubble distribution pattern agrees with experimental results. Second one is the vanishing of Karman vortex shedding in an upward flow owing to a thin bubble layer near the cylinder surface.

INTRODUCTION

In a uniform rising bubbly two-phase flow, a large wake structure is caused by inserting a solid object whose size is larger than the bubble size. Especially, a quite quick separation of many bubbles from a cylinder, which resembles with an oblique shock wave, is found in the case of high void fraction and large bubble size. Then, the downstream of the cylinder is covered with liquid single-phase as shown in Fig.1 and pushes the cylinder in the upstream direction. The authors found this phenomenon in our experimental observation and named "two-phase wake structure." The two-phase wake structure consists of dispersed phase wake and continuous phase wake motions, and there is a great difference between the velocity fields of the two phases. Therefore, the translational motion of bubbles is the key phenomenon governing the whole flow behavior. Of course, this phenomenon is related to many sites of engineering design handling the bubbly liquid media, such as boilers, chemical devices, bioreactors, and so forth, so that comprehensive research is required from the point of view for avoiding the flow instability and optimizing the system efficiency.

Related investigations to the present interest in the past were divided into two parts by characteristic spatial scale, i.e., behavior of single bubble interacting with solid surface, and effect of many bubbles' inclusion on the flow field around an object or near solid wall. The former problem was already studied by a great number of researchers as the cavitation errosion researchers. However, recently, a bouncing phenomenon which is independent on compressibility of the gas inside the bubble is reported by Tsao & Koch (1997). According to their experiment, the bouncing of the bubble at a solid plate is explained by the transient surface tension due to bubble's rapid deformation and the wake. Yamada & Kataoka, et al. (1996) also found such bouncing on a cylinder surface and considered it in their one-way Lagraingian numerical method for simulating the bubbly flow through tube bundles. Takagi & Matsumoto (1997) tried to calculate directly the single bubble's bouncing on an inclined plate using Front-tracking method which was developed by Esmaeeli & Tryggvason (1996). On the other hand, the later problem, especially focusing on shear layer control, was a quite attractive investigation and tried to be solved by many turbulent flow researchers. For instance, Madavan et al. (1985) reported a numerical method for frictional drag reduction due to microbubble inclusion. Yoshida et al. (1998) predicted bubble motion in turbulent boundary layer. For study of an external flow, the experimental measurement of void fraction for co-current bubbly two-phase flow around a blade was reported by Ichikawa et al. (1991), and that around a cylinder was also by Ichikawa & Matsumoto (1998). The effect of bubble inclusion on the vortex shedding flow structure around a cylinder was calculated by Bayly & Rielly (1994) for counter-current flow, and Sugiyama & Matsumoto (1997) for co-current flow.

However, when the flow speed of bubbly mixture against the object is not fast, the relative motion of bubble against liquid phase becomes a dominant factor to govern the flow structure near the object. In that case, bubble's collision to the object surface is impotant. Futhermore the shading effect of rising bubbles due to the object can cause complicated natural convection in the downstream region. Such the flow has not been investigated yet.

In the present investigation, detailed mechanism of generating the large two-phase wake structure around a cylinder has been made clear by a parametric study based on full two-way coupled Eulerian-Lagrangian model. After confirming a good analogy of the flow pattern with the experiment, possibility of controling the wake structure inlcuding a strong vortex shedding was examined by this model. The predicted results showed that a drastic alternation of the wake pattern from Karman vortex shedding flow to non-vortex shedding flow could be realized by injecting bubbles into the boundary layer region of the cylinder.

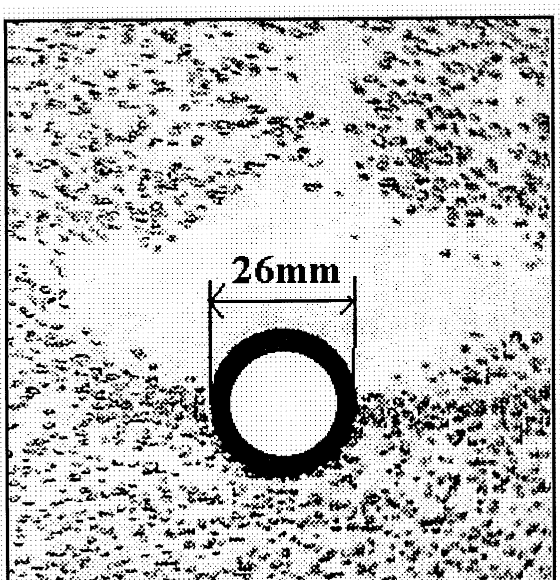

Fig.1 Quick Bubble Separation from a Cylinder (Experiment, void fraction =4.5 %, Bubble radius =1.2mm)

NUMERICAL PREDICTION METHOD

The following assumptions are employed for formulating the governing equations of bubbly flow.

Assumptions

1) Bubble size is smaller than the characteristic length of the flow. Local bubble motion in a control-volume is described by the volumetric and translational motion equations. 2) Coalescence and fragmentation of the bubbles are neglected since void fraction in the bubbly flow is not over 0.1 for the present simulation. 3) Gas inside the bubble is non-condensable and obeys the perfect gas law. There is no mass diffusion of gas near bubble interface.

Governing Equations

Conservation laws for bubbly two-phase flow are described by Eulerian-type equations. The translational motion and volumetric change of each bubble are described by Lagrangian-type equations.

$$\frac{\partial f_L \rho_L}{\partial t} + \nabla f_L \rho_L \boldsymbol{u}_L = 0. \quad (1) \qquad f_L + f_G = 1. \quad (2)$$

$$f_G = \frac{1}{V}\int f_{G local} dV. \quad (3) \qquad \boldsymbol{x}_G = \boldsymbol{x}_{G0} + \int_0^t \boldsymbol{u}_G(t)dt. \quad (4)$$

$$\frac{\partial f_L \rho_L \boldsymbol{u}_L}{\partial t} + \nabla \cdot f_L \boldsymbol{u}_L \boldsymbol{u}_L + \frac{f_G \rho_G \boldsymbol{u}_G}{\partial t} + \nabla \cdot f_G \rho_G \boldsymbol{u}_G \boldsymbol{u}_G$$
$$= -\nabla p - (f_L \rho_L + f_G \rho_G)\boldsymbol{g} + (\boldsymbol{F}_{LL} + \boldsymbol{F}_{GG}), \quad (5)$$

$$\boldsymbol{F}_{LL} = \nabla \cdot \mu\{\nabla \boldsymbol{u}_L + (\nabla \boldsymbol{u}_L)^T - \frac{2}{3}(\nabla \cdot \boldsymbol{u}_L)\boldsymbol{I}\}, \quad \mu = (1 + f_G)\mu_L \quad (6)$$

$$\frac{d}{dt}(\rho_G V_G \boldsymbol{u}_G) + \frac{d}{dt}(\beta \rho_L V_G \boldsymbol{u}_G) - \frac{D_L}{Dt}(\beta \rho_L V_G \boldsymbol{u}_L) + \rho_G V_G g$$
$$+ V_G \nabla p - V_G \mu\{\nabla^2 \boldsymbol{u}_L + \frac{1}{3}\nabla(\nabla \cdot \boldsymbol{u}_L)\}$$
$$+ \frac{1}{2}\rho_L \pi r_G{}^2 C_D |\boldsymbol{u}_S| \boldsymbol{u}_S + \frac{1}{2}\rho_L V_G \boldsymbol{u}_S \times (\nabla \times \boldsymbol{u}_L) = 0, \quad (7)$$

$$\beta = \frac{1}{2}, \quad (8) \qquad \frac{D_L}{Dt} = \frac{\partial}{\partial t} + \boldsymbol{u}_L \cdot \nabla, \quad (9) \qquad V_G = V_{G0}. \quad (10)$$

$$C_D = \frac{24}{Re} + \frac{4}{\sqrt{Re}} + 0.4, \quad (11) \qquad Re = \frac{2 r_G \rho_L |\boldsymbol{u}_S|}{\mu_L}. \quad (12)$$

Eq. (1) is the conservation equation of liquid mass. Eq. (2) is kinematic restriction condition of total volume fraction. Eq (3) is definition of local gas volume fraction. Eq. (4) denotes position of bubble's center of gravity. Eq. (5) is the conservation equation for total momentum of bubbly mixture, where viscosity term is represented by eq. (6). Eq. (7) is the equation of bubble's translational motion. The lift force is considered according to Auton (1987). Added mass coefficient and substantial derivative are given by Eqs. (8), and (9). In this analysis, compressibility of two-phase media due to volume change of the bubble is ignored so that the bubble volume is constant as shown in Eq. (10). Drag coefficient of the bubble is given by that of solid particle, as a function of bubble Reynolds number, as described by Eq. (11) and Eq. (12), because of assuming the bubble interface covered with surfactant.

Numerical Procedure

The governing equations are solved by a semi-implicit method based on the HSMAC algorithm (Hirt & Cook ,1972) because the HSMAC method is available for calculating simultaneously both single phase and two-phase flows. The calculation procedures are as follows:

[1] Calculation of new translational velocity of bubble by Eqs. (7), (8), (9) ,and (12).
[2] Calculation of new center of gravity of bubbles by using the translational velocity by Eq. (4)
[3] Calculation of liquid velocity by Eqs. (5) and (6).
[4] Calculation of new gas volume fraction by Eq. (3).
[5] Calculation of new liquid volume fraction by Eq. (1)
[6] Calculation of the over-estimated volume fraction and pressure correction value which are derived by the principle of the HSMAC algorithm.
[7] Going to the next time step if the over-estimated volume fraction is enough converged to zero.

Differential Schemes and Boundary Conditions

The two-dimensional CIP (Cubic Interpolated pseudo-Particle) scheme (Takewaki & Yabe, 1987) is employed to descritize the convection terms. Second order central differencing scheme is used for other spatial derivative terms. For accurate calculation of local interaction between two phases, the TD (Template Delivery) method is adopted for conversion of Lagrangian variables to Eulerian variables, which was developed by authors (Murai et al., (1997))

Boundary conditions are as follows. 1) Uniform bubble injection is set at the bottom plane (upstream) at the same bubble size, rising velocity and number density. Liquid does not inflow at the bottom. 2) Side boundaries are free-slip wall. 3) Top boundary (downstream) of the calculation domain is set by free-outflow convective condition. 4) Perfect non-elastic collision is used for bubble behavior on the cylinder surface because of only predicting low bubble Reynolds number condition under 50.

Table 1. Numerical Conditions for Uniform Bubbly Flow

Physical Domain Calculation Domain	210 mm x 420 mm 60 x 120 grids		
Kinematic Viscosity and Density of Liquid	$1.0 \times 10^{-5} m^2/s$ (10cSt) $960 kg/m^3$		
Gravitational Acceleration Average Void Fraction	$981 m/s^2$ 0.00 to 0.05 (max)		
Cylinder Diameter	42mm		
Bubble Radius (mm)	0.2	0.5	1.0
Terminal Velocity (mm/s)	7.9	39.1	103.6
Bubble Reynolds number	0.32	3.91	20.72
Injection Frequency (1/s)	2.3	11.8	33.3

BUBBLY FLOW AROUND A CYLINDER

Numerical prediction of buoyant bubbly flow around a cylinder is carried out using the above-mentioned method. Detailed simulation conditions are denoted in Table 1. The bubble configuration pattern in the initial region is controlled as a square grid pattern to ensure the isotropic bubbly flow.

Fig.2 shows the time evolution of bubble distribution around a circular cylinder after starting the bubble injection. At first, bubble rising motion is shaded by the cylinder, and a pair of bubble plume is generated beside the cylinder. After the bubble plumes rapidly rise up, a closed domain where there is no bubble, is formed just above the cylinder. The bubbles are reattached at a downstream region and continue to rise up with fluctuation. Area of the "single-phase wake region" just above the cylinder is much larger than the cross-section area of the cylinder. This bubble distribution agrees well with experiment. The reason why such phenomenon occurs is considered as follows.

Wake-Enhancement Mechanism

The wake-enhancement mechanism in this two-phase flow is considered by liquid flow pattern around the cylinder. This is so because the liquid flow has a quite different velocity field from the bubble motion as mentioned below. At first, liquid flow is induced by buoyancy of many rising bubbles beside the cylinder. Then, slow downward flow is generated at the bubble-shaded region above the cylinder. When the downward flow reaches cylinder surface, the bubbles which slide up along the cylinder surface from bottom are quickly ejected by the counter-current liquid flow. This bubble separation can happan easily because of very small inertia of the bubbles. By this separation, larger singe-phase wake region is formed and stronger downward liquid flow is enhanced. This is newly recognized two-phase flow instability in the case of external flow, and must be investigated in detail.

Fig.3 shows the bubble distribution in which magnitude of each force component acting on individual bubble is simultaneously represented by gray scale level. Here, inertia (including added inertia), pressure, drag, and lift forces are shown. As seen in the figures, the inertia force is weak in the upstream region and strong in the downstream region.

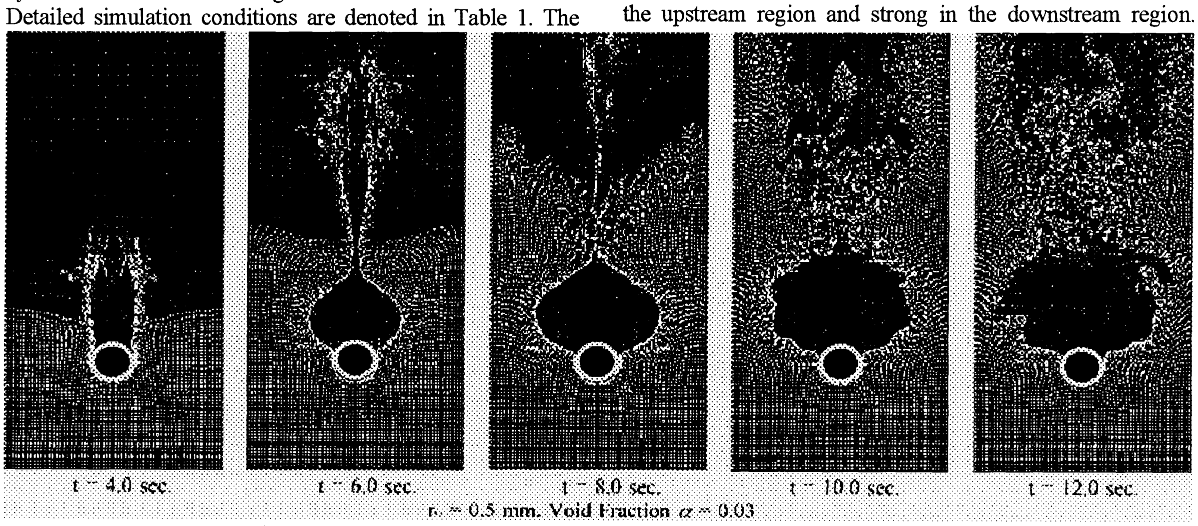

Fig.2 Time Evolution of Bubble Distribution around a Circular Cylinder.

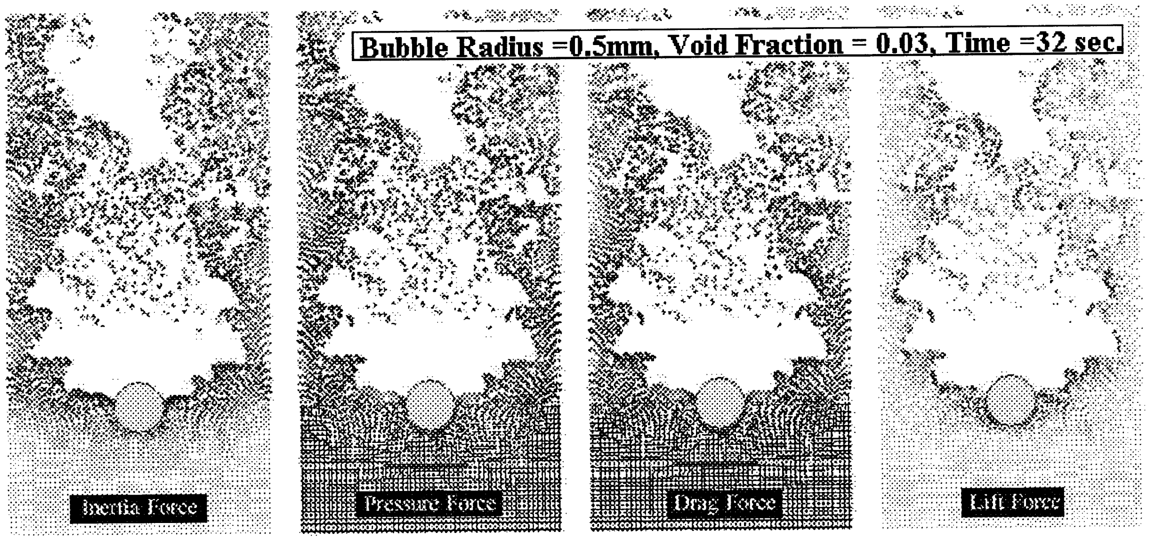

Fig.3 Distribution of Magnitude of Force Components acting on each Bubbles (Black: strong, while: weak)

This means the bubble rising motion is affected by local fluctuation of liquid flow which is generated in the region downstream of the cylinder. The magnitudes of pressure gradient force and drag force do not depend remarkably on position because they always acts on rising bubbles. The magnitude of lift force increases at near the cylinder surface and boundary layer between single-phase wake region and two-phase region in the downstream region. This is because shear or rotational velocity of liquid phase is strong in their region. The lift force is thought to be a trigger of generating the periodical fluctuation of bubble distribution in the wake region.

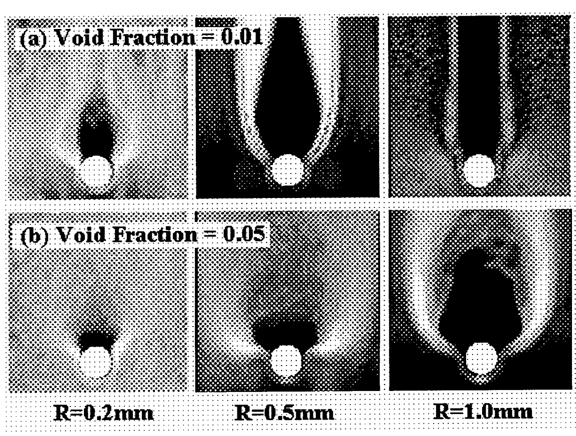

Fig.4 Distribution of Time Averaged Void Fraction (white: high void fraction, black: low void fraction)

Dependency on Bubble Size and Void Fraction

Fig.4 shows time averaged distribution of void fraction around the cylinder for six cases. The averaging period is 30 seconds after the flow is sufficiently developed. In the case of small bubbles, the single-phase wake region is small because bubble-shading effect is low, i.e., the slip velocity of bubbles against liquid is restricted by viscosity. When high void fraction is given in the small bubble case, the wake area decreases more owing to the mixing effect of bubbles due to strong local interaction. To the contrary, quite a long shading region appears when large bubble (R=1.0mm) and low void fraction. This is a simple phenomenon that all the bubbles rise up straightly except around the cylinder surface. In the case of high void fraction containing large bubbles, a pair of highly concentrated bubble layers appear from the cylinder surface like an oblique shock wave in a supersonic gas flow.

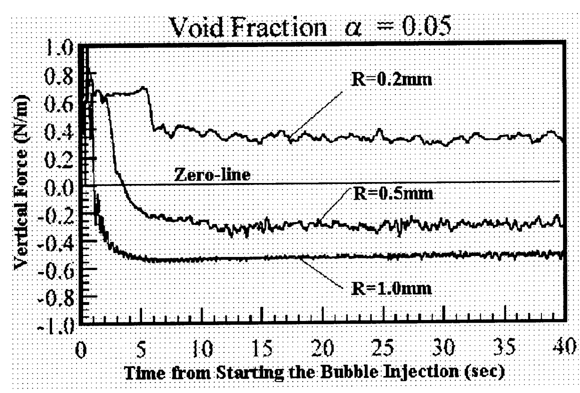

Fig. 5 Time History of Vertical Force Acting on Cylinder

Fluid Dynamical Force Acting on the Cylinder

The vertical component of fluid dynamical force acting on the cylinder is obtained by integrating the stress tensor on the cylinder surface. Here, the flow direction is defined as positive of force. The time history is shown in Fig.5. At the starting stage, the vertical force increases in the positive direction impulsively in all the cases. Then, it converges to an almost constant value. In the case of small bubble

(R=0.2mm), the vertical force acts in the positive direction because of shear stress on the cylinder surface. The force contains a time-dependent fluctuation due to the bubble-generated turbulence in the region upstream of the cylinder. The bubble-generated turbulence in a uniform rising buoyant bubbles was already calculated by a number of researchers (Tryggvason et al.,1997, Murai et al.,1997). In the cases of large bubble (R=0.5mm, R=1.0mm), the vertical force becomes negative value but contains small fluctuation. It is considered that the negative force is caused by two factors. The first one is that there is downward liquid flow induced in the single-phase wake region, so that the cylinder surface receives the dynamic pressure from the downward flow. The second factor is the effect of gravity, i.e., the static pressure increases at the cylinder surface because of the single-phase wake region.

SHEAR CONTROL BY THE BUBBLE LAYER

Possibilities of shear control and wake alternation due to injection of many buoyant bubbles are discussed in this chapter. As an example, the influence of bubble injection in a Karman vortex shedding flow around a cylinder is shown in Fig.6. The numerical method is the same as the previous interest. In this example, upward liquid inflow is given by uniform flow with a speed of 0.1m/s. Reynolds number of the cylinder is 210. As shown in the figure, the Karman vortex shedding is vanished by a little inclusion of bubbles whose injection point is set at the center axis of the cylinder. The vanishing of the Karman vortex is realized by momentum supply of liquid flow from the buoyant bubbles in the region downstream of the cylinder. The key phenomenon of this alternation is that the vorticity generation on the side parts of the cylinder drastically decreases due to the bubble inclusion into the boundary layer. The influence of bubble inclusion is larger for large bubble case than for small bubble case. It is expected that the phenomenon similar to this example happens when the bubbles are injected or generated from the object surface.

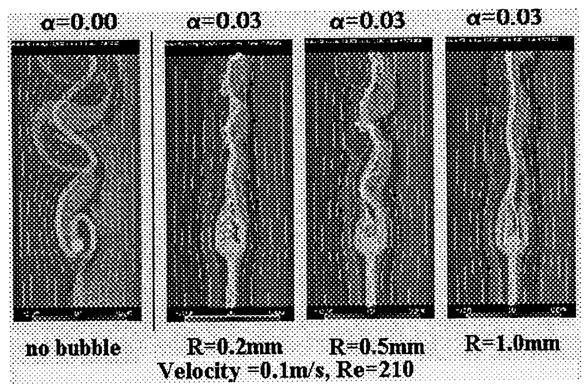

Fig.6 Vanishing of Karman Vortex due to Bubbles

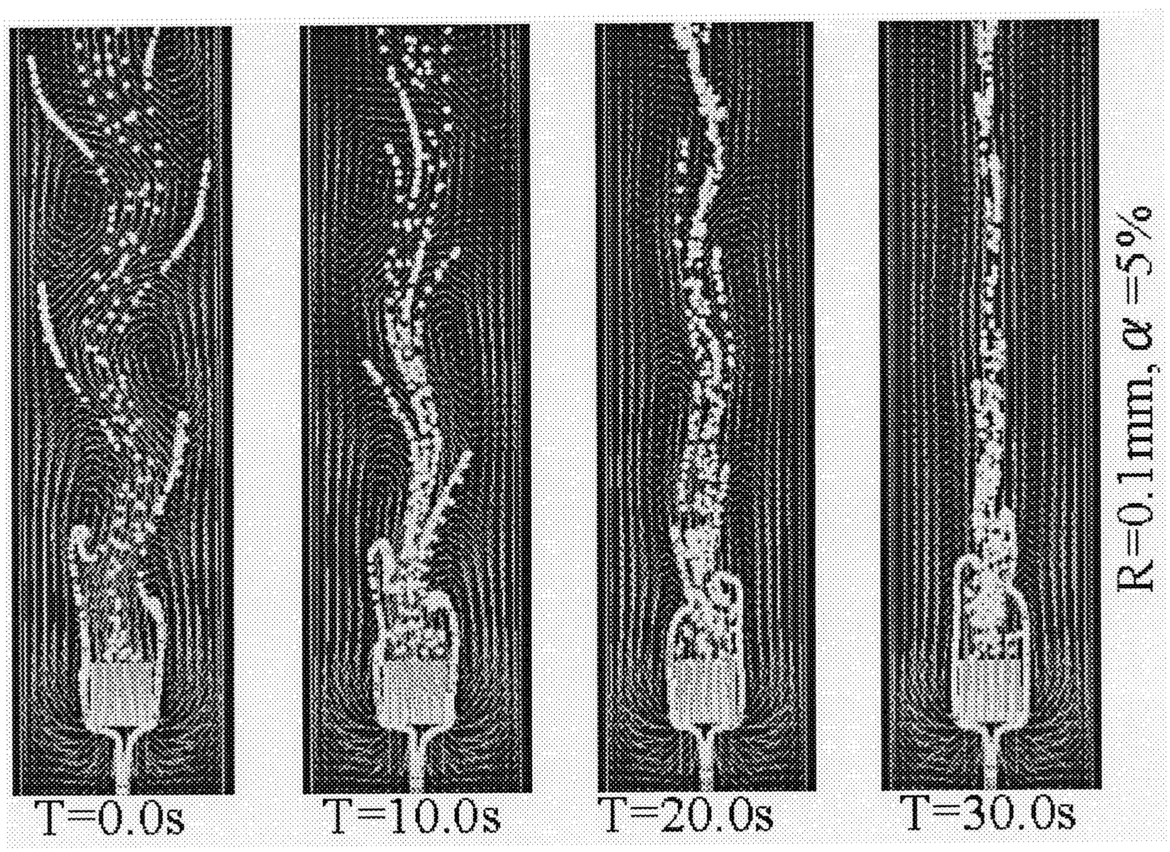

Fig.7 Time Evolution of Karman Vortex Vanishing

Another example of Karman vortex vanishing is shown in Fig.7, where time evolution of flow field around a square cylinder is represented after starting the bubble injection. In the figures, the distribution of bubbles and velocity vectors of liquid phase are depicted. When T=0 s., bubbles are transported by Karman vortex of liquid phase. So that, periodical concentration of the bubbles appears in the region downstream of the object. However, this flow pattern is very unstable because the liquid flow direction is opposite to the bubble rising direction in the region downstream of the object. Therefore, local downward liquid flow in the Karman vortex is slowly damped by the bubble buoyancy at T=10 s. When such interaction between the bubbles and liquid motion achieves an equilibrium state, there is no vortex shedding from the object, and just a thin bubbly two-phase layer remains in the center axis region as shown in the figure of T=30s. This phenomenon indicates the possibility of shear layer control near the object based on the bubbly mixture.

CONCLUDING REMARKS

The Eulerian-Lagrangian model is applied for numerical prediction of bubbly two-phase flow around a cylinder. The model is formulated with emphasis on the translational motion of bubbles. A high resolution scheme and the adequate numerical precesure are employed to calculate accurately the local two-way interaction. By using the present numerical method, the various interesting flow patterns due to two-way interaction between rising bubbles and liquid motion around a cylinder are predicted. A singe-phase wake structure which is much larger than the cylinder size is predicted in the case of uniform rising bubbly flow, and it is confirmed that this structure has a good analogy with experimental results. In this flow, a negative force against the bubble rising direction acts on the cylinder in the case of large bubble. Two factors to generate the negative force are explained, i.e., the dynamic pressure from downward liquid flow in the single-phase wake region, and static pressure increases due to weight of the single-phase region. Furthermore, two kinds of applied calculation are introduced as a discussion of future possibility for shear and wake control around an object. As a result, a typical example of the vanishing of Karman vortex shedding is shown. In future, the detailed mechanism of bubble-vorticity interaction inside the bubbly boundary layer is expected to be investigated.

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