JOURNAL OF CRITICAL REVIEWS

ISSN- 2394-5125 VOL 09, ISSUE 03, 2022

NUMERICAL SIMULATION FOR GAS-LIQUID TWO-PHASE FREE TURBULENT FLOW BASED ON VORTEX IN CELL METHOD

SANTOSH CHERIPALLY,MOUNIKA VELPULA
Dept of Mech, Sree Dattha Group of Institutions, Hyderabad, Telangana, India

This paper proposes a two-dimensional vortex method, based on Vortex in Cell method, for gas-liquid two-phase free turbulent flow. The behavior of vortex element and the bubble motion are calculated through the Lagrangian approach, while the change in the vorticity due to the bubble is analyzed in the computational grids resolving the flow field. Therefore, the numerical procedure corresponds to the Lagrangian-Eulerian method. The present method is applied to simulate the air-water bubbly flow around a square-section cylinder. The simulation demonstrates that the bubble entrainment into the Karman vortex and the resultant reduction for the strength of vortex are successfully captured by the method. It is also confirmed that the vortex shedding frequency and the pressure distribution on the cylinder are favorably compared with the measured results.

Key Words: Multiphase Flow, Numerical Analysis, Vortex Method, Bubbly Flow, Wake

1. Introduction

Free turbulent flows loaded with small bubbles are observed in various engineering applications including chemical reactors, heat exchangers and waste treatment systems. For the fundamental flows, such as plane mixing layers(1), (2), jet(3) and wake flows behind an obtuse body(4) – (6), the turbulence modulation of the liquid-phase due to the bubble and the relation between the large-scale vortical structure and the bubble motion have been experimentally investigated. Some numerical analyses have also been carried out. Sun and Faeth(7) simulated the jet, issuing from a round nozzle, by using a k-ε turbulence model based on the steady and axisymmetrical assumptions. They reported that the velocity and the gas volumetric fraction are favorably predicted by the model. Sugiyama et al.(8) developed a finite difference method employing a number density model for bubble, and they analyzed the bubbly flow around a circular cylinder to investigate the phase distribution and the behavior of the Karman vortex. To make clear the flow field in detail, direct numerical simulations on mixing layers have been performed. Ruetsch and Meiburg(9) reported that the accumulation of bubble on the higher vorticity region, called the preferential concentration of bubble, reduces the vorticity and the pressure gradient. Druzhinin and Elghobashi(10) clarified the bubble accumulation caused by the merging of the large-scale eddies.

Recently, vortex methods have been usefully applied to analyze single-phase free turbulent flows. This is because the methods can simulate directly the development of vortical structure, such as the formation and deformation of vortices, through the Lagrangian calculation for the behavior of the vortex elements discretizing the vor- ticity field. To extend the applicability of vortex methods, one of the authors(11), (12) has proposed the vortex meth- ods for gas-particle two-phase free turbulent flow. The methods were applied to simulate various free turbulent flows(13) – (17). Uchiyama and Naruse(18) proposed another two-dimensional vortex method for gas-particle free tur- bulent flow. The method is based on the Vortex in Cell method, abbreviated to VIC method, presented for the single-phase flow analysis. It can calculate the convec- tion velocity of vortex element with less CPU time than the former vortex method.

Since the free turbulent flow entraining small bub- bles is chiefly governed by the large-scale eddies of the liquid-phase, the vortex method promises to be applica- ble to simulate the flow. Such two-phase vortex method has been rarely presented except for few studies, in which the flow of liquid-phase is simulated by vortex methods and the bubble motion is computed by the Lagrangian ap- proach. Sene et al.(19) conducted the two-dimensional sim- ulation of the air bubble motion in a plane mixing layer by assuming that the water flow is not affected by the bub- bles. By using such one-way scheme, Uchiyama(20) per- formed the three-dimensional simulation of a bubbly jet to search for the possibility to control the bubble disper- sion. Yang et al.(21) proposed a two-dimensional two-way vortex method, which can take account for the interaction between the two phases, to simulate a plane mixing layer loaded with bubbles. But the volumetric fraction is not considered in the conservation equations for the liquid- phase. Thus, the method seems to be unreasonable.

This study proposes a two-dimensional two-way vor- tex method, based on the VIC method, for gas-liquid two-phase free turbulent flow. In the method, the bub- ble motion and the behavior of vortex element are traced, while the change in the vorticity due to the bubble is computed in the computational grids resolving the flow field. Therefore, the numerical procedure corresponds to the Lagrangian-Eulerian method. This study also applies the vortex method to simulate the air-water bubbly flow around a square-section cylinder. It is confirmed that the simulated flow fields are favorably compared with the cor- responding experiments and the existing numerical results on bubble-laden free turbulent flows

2.Basic Equations

2. 1 Assumptions

The following assumptions are employed for the sim- ulation.

(1) The mixture is a bubbly flow entraining small bubbles.

(2) Both phases are incompressible and no phase changes occur.

(3) The mass and momentum of the gas-phase are very small and negligible compared with those of the liquid-phase.

(4) The bubbles maintain their spherical shape, and neither fragmentation nor coalescence occurs.

2. 2 Conservation equations for bubbly flow

The conservation equations for the mass and momen- tum of the bubbly flow are expressed by the following equations under the assumptions (1) – (3).

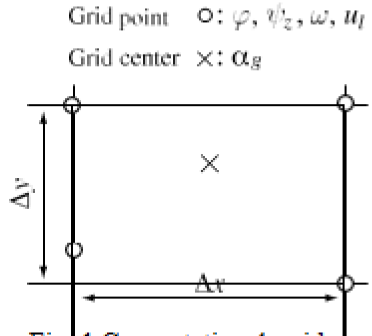


Fig. 1 Computational grid

3. Application to Bubbly Flow Analysis around a Cylinder

3. 1 Simulation conditions

The present method is applied to simulate the air- water bubbly flow around a square-section cylinder. The flow was experimentally investigated by Shakouchi et al.(5), (6). The square-section cylinder, of which side length s is 30 mm, is mounted in a channel with 90 mm 45 mm cross-sectional area. The flow direction is vertically up- ward. The Reynolds number Re, based on s and the water velocity ul0 upstream of the cylinder, is 15 000.

Figure 2 shows the computational domain. The inlet and outlet boundaries, B0 and B3, are located 3s upstream and 10.3s downstream of the cylinder, respectively. The domain is resolved into 18 80 square grids.

The vorticity field is generated by the bubble motion and the velocity shear layer originating from the cylin- der surface. The vorticity field due to the velocity shear layer is simulated by a method presented by Kamemoto and Miyasaka(25) for single-phase flow analysis.

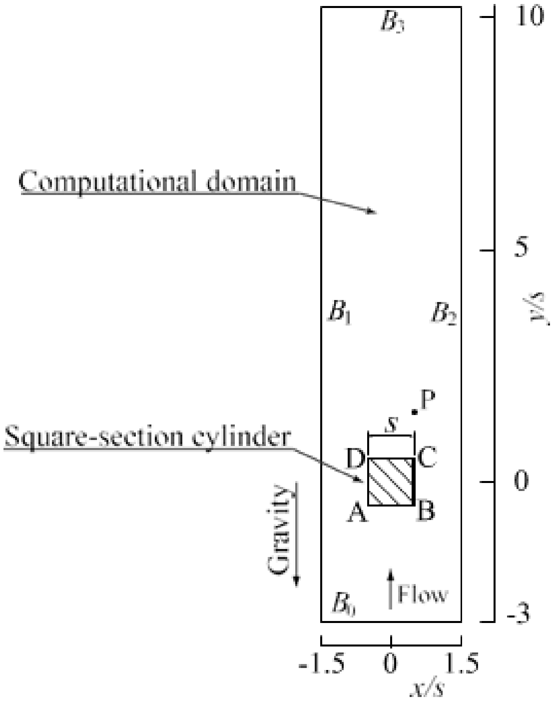


Fig. 2 Computational domain

is released from each segment into the flow field at a time interval Δt. In this simulation, the number of segments is 96, and the height of vorticity layer h is set at 5/Re1/2 with reference to the single-phase flow analysis(25). When releasing the vortex element, the strength is equivalent to the vorticity in the segment and the core radius σ0 is de- termined from the relation πσ2 = lh. The σ0 value for the vortex element used to represent the vorticity field caused by the bubble motion is the grid size Δx in the x-direction. The vortex element leaving the outlet boundary B3 is ex- cluded from the calculation. To consider the exclusion, a region with a length 3s is added downstream of B3 and the vortex elements are made to convect in the region with their velocity kept constant. The vorticity layer on the channel wall can also be represented through the same method applied on the cylinder surface. Assuming that the vorticity layer scarcely affects the wake of the cylinder, it is ignored and the slip condition for velocity is imposed on the channel wall.

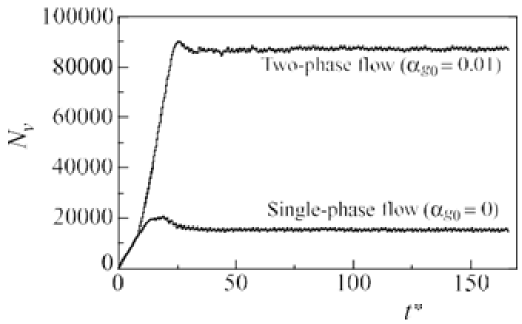
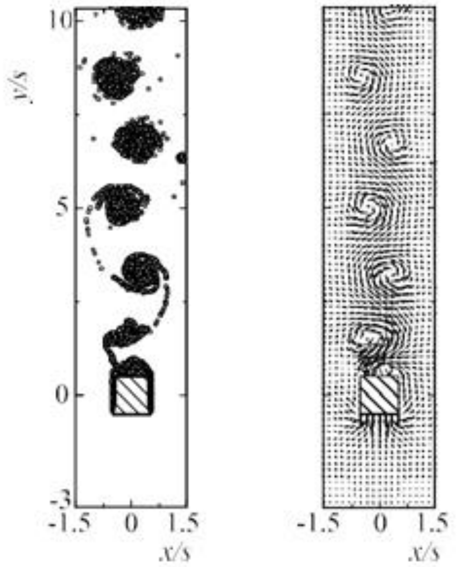


Fig. 3 Time variation for number of vortex elements



(a) Vortex element (b) Velocity

Fig. 4 Water single-phase flow field at $t^{=}$ = 100

Results for bubbly flow

The time variation for the number of vortex elements Nv for the bubbly flow is superimposed in Fig. 3. The air volumetric fraction αg0 at the inlet boundary is 0.01. The bubbles are released when t∗ ≥ 7.5. Nv varies periodically around 86 500 at t∗ ≥ 40, demonstrating the appearance of a fully developed bubly flow. The Nv value for the bubbly flow is about 5.6 times larger than that for the water single- phase flow. This is because a number of vortex elements are introduced to represent the vorticity field induced by

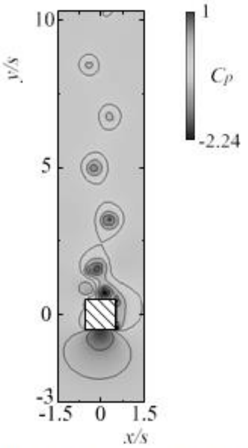
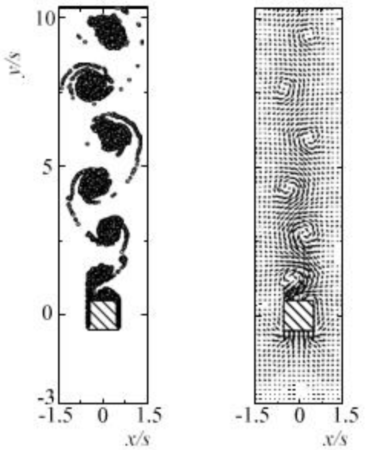


Fig. 5 Pressure distribution for water single-phase flow at $t^{=}$ = 100



(a) Vortex element (b) Water velocity

Fig. 6 Two-phase flow field at $t^{=}$ = 84 in case of α_{g0} = 0.01

The pressure distribution at the same instant as Figs. 6 and 7 is shown in Fig. 8. The distribution in the region up- stream of the cylinder is nearly the same as that for the single-phase flow presented in Fig. 5. But the minimum pressure at the center of Karman vortex is higher. The re- duction for the strength of Karman vortex found in Fig.

6 is also confirmed from the pressure distribution. Such re- laxation of pressure gradient and reduction for strength of large-scale eddies due to the bubble entrainment were also reported by Ruetsch and Meiburg(9) performing the DNS of a plane mixing layer

4.Conclusions

A two-dimensional vortex method for gas-liquid two- phase free turbulent flow is proposed. It is based on the Vortex in Cell method, in which the scalar potential and the vector potential are solved to calculate the liquid veloc- ity. The behavior of vortex element and the bubble motion are calculated through the Lagrangian approach, while the change in the vorticity due to the bubble is analyzed in the computational grids resolving the flow field.The vortex method is also applied to simulate the air-water bubbly flow around a square-section cylinder. The flow direction is vertically upward, and the air volumet- ric fraction αg0 upstream of the cylinder ranges from 0 to The simulated flow features, such as the preferential concentration of bubble in the Karman vortex, the resul- tant reduction for the strength of vortex and the relaxation for the pressure gradient, are favorably compared with the existing numerical results on the bubble-laden free turbu- lent flows. It is also confirmed that the shedding frequency for Karman vortex and the pressure distribution on the cylinder agree well with the measurement. These indicate the validity of the present method.

References

(1) Roig, V., Suzanne, C. and Masbernat, L., Experimental Investigation of a Turbulent Bubbly Mixing Layer, Int.
J. Multiphase Flow, Vol.24, No.1 (1998), pp.35–54.

(2) Rightley, P.M. and Lasheras, J.C., Bubble Dispersion and Interphase Coupling in a Free-Shear Flow, J. Fluid Mech., Vol.412 (2000), pp.21–59.

(3) Sun, T.Y. and Faeth, G.M., Structure of Turbulent Bub- bly Jets-I. Methods and Centerline Properties, Int. J. Multiphase Flow, Vol.12, No.1 (1986), pp.99–114.

(4) Inoue, A., Kozawa, Y., Yokosawa, M. and Aoki, S., Studies on Two-Phase Cross Flow, Part I: Flow Char- acteristics around a Cylinder, Int. J. Multiphase Flow, Vol.12, No.2 (1986), pp.149–167.

(5) Shakouchi, T., Tian, D. and Ida, T., Behavior of Verti- cal Upward Gas-Liquid Bubbly Flow Past Obstacle in Rectangular Channel (Effect of Blockage Ratio), JSME Int. J., Ser.B, Vol.45, No.3 (2002), pp.686–6932.

(6) Shakouchi, T., Tian, D., Ida, T. and Nakamura, T., Be- havior of Flow around Obstacle in Vertical Gas-Liquid, Bubbly Two-Phase Flow (Effects of Geometry and As- pect Ratio of Obstacle), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol.68, No.672, B (2002), pp.2240– 2246.

(7) Sun, T.Y. and Faeth, G.M., Structure of Turbulent Bub- bly Jets-II. Phase Property Profiles, Int. J. Multiphase Flow, Vol.12, No.1 (1986), pp.115–126.

(8) Sugiyama, K., Takagi, S. and Matsumoto, Y., Three Di- mensional Numerical Analysis for Bubbly Flow around a Circular Cylinder, JSME Int. J., Ser.B, Vol.44, No.3 (2001), pp.319–327.

(9) Ruetsch, G.R. and Meiburg, E., Two-Way Coupling in Shear Layers with Dilute Bubble Concentrations, Phys. Fluids, Vol.6, No.8 (1994), pp.2656–2670.

(10) Druzhinin, O.A. and Elghobashi, S.E., Direct Numer- ical Simulation of a Three-Dimensional Spatially De- veloping Bubble-Laden Mixing Layer with Two-Way Coupling, J. Fluid Mech., Vol.429 (2001), pp.23–61.

(11) Uchiyama, T. and Naruse, M., A Numerical Method for Gas-Solid Two-Phase Free Turbulent Flow Using a Vortex Method, Powder Technol., Vol.119 (2001), pp.206–214.

(12) Uchiyama, T. and Fukase, A., Three-Dimensional Vor- tex Method for Gas-Particle Two-Phase Compound Round Jet, Trans. ASME, J. Fluid Eng., Vol.127 (2005), pp.32–40.

(13) Uchiyama, T. and Naruse, M., Numerical Simulation of Gas-Particle Two-Phase Mixing Layer by Vortex Method, Powder Technol., Vol.125 (2002), pp.111– 121.

(14) Uchiyama, T. and Naruse, M., Vortex Simulation of Slit Nozzle Gas-Particle Two-Phase Jet, Powder Technol., Vol.131 (2003), pp.156–165.

(15) Uchiyama, T. and Yagami, H., Numerical Analysis of Gas-Particle Two-Phase Wake Flow by Vortex Method, Powder Technol., Vol.149 (2005), pp.112–120.

(16) Uchiyama, T. and Naruse, M., Three-Dimensional Vor- tex Simulation for Particulate Jet Generated by Free Falling Particles, Chem. Eng. Sci., Vol.61 (2006), pp.1913–1921.

(17) Uchiyama, T. and Fukase, A., Three-Dimensional Vor- tex Simulation of Particle-Laden Air Jet, Chem. Eng. Sci., Vol.61 (2006), pp.1767–1778.

(18) Uchiyama, T. and Naruse, M., Numerical Simulation of Gas-Particle Two-Phase Free Turbulent Flow Based on Vortex in Cell Method, Powder Technol., Vol.142 (2004), pp.192–208.

(19) Sene, K.J., Hunt, J.C.R. and Thomas, N.H., The Role of Coherent Structures in Bubble Transport by Tur- bulent Shear Flows, J. Fluid Mech., Vol.259 (1994), pp.219–240.

(20) Uchiyama, T., Three-Dimensional Vortex Simulation of Bubble Dispersion in Excited Round Jet, Chem. Eng. Sci., Vol.59 (2004), pp.1403–1413.

(21) Yang, X., Thomas, N.H., Guo, L.J. and Hou, Y., Two- Way Coupled Bubble Laden Mixing Layer, Chem. Eng. Sci., Vol.57 (2002), pp.555–564.

(22) Schiller, L. and Naumann, A.Z., U¨ ber die Grundlegenden Berechungen bei der Schwerkraftaufbereitung, Zeit. Vereines Inge., Vol.77 (1933), pp.318–321.

(23) Hirasaki, G.J. and Hellums, J.D., Boundary Con- ditions on the Vector and Scalar Potentials in Vis- cous Three-Dimensional Hydrodynamics, Quart. Appl. Math., Vol.28, No.2 (1970), pp.293–296.

(24) Leonard, A., Vortex Methods for Flow Simulation, J. Comput. Phys., Vol.37 (1980), pp.289–335.

(25) Kamemoto, K. and Miyasaka, T., Development of a Vortex and Heat Elements Method and Its Application to Analysis of Unsteady Heat Transfer around a Circu- lar Cylinder in a Uniform Flow, VORTEX METHODS, Edited by Kamemoto, K. and Tsutahara, M., (2000), pp.135–144, World Scientific.

(26) Ishii, M., One-Dimensional Drift-Flux Model and Constitutive Equations for Relative Motions between Phases in Various Two Phase Flow Regimes, ANL Re- port, ANL-77–47, (1977).

(27) Kawakami, K., Nishida, H. and Satofuka, N., An Open Boundary Condition for the Numerical Anal- ysis of Unsteady Incompressible Flow Using the Vorticity-Streamfunction Formulation, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol.68, No.574, B (1994), pp.1891–1896.