CFD Calculation for Two-Phase Flow in Concentric Annulus with Rotating Inner Cylinder

Yoichi Shiomi, Shigeyasu Nakanishi and Hiroaki Kutsuna

Department of Mechanical and System Engineering,

Faculty of Science and Technology, Ryukoku University

Seta, Otsu 520-2194, Japan

Tel: +81-77-543-7458

Fax: +81-77-543-7457

E-mail: shiomi@rins.ryukoku.ac.jp

Abstract

Calculations have been carried out using the "PHOENICS" for two-phase flow in a concentric annulus with a rotating inner cylinder. The flow in such system for the single-phase flow is well known as the Taylor-vortex flow. The two-phase Taylor-vortex flow has quite interesting characteristics in experiments. With increasing of the rotating inner cylinder, bubbles agglomerate and make spirals or rings owing to the Taylor-vortex. According to the flow visualization of a cross section in the annulus, the bubbles of spirals or rings locate at very close to the rotating inner cylinder and at out-flow region. Calculations carried out to confirm these characteristics and investigate in detail.

Two-phase Taylor-vortex flow was calculated in two dimensional cylindrical coordinate with IPSA method. The original k-ε and k-ε RNG models are used as the turbulent model. It is confirmed that the Taylor-vortex is obtained in this calculation by the vector of liquid phase. From the void fraction distribution, bubbles exist close to the inner cylinder and locate at out-flow region as same as the experimental results. The calculated results agree with the experimental results qualitatively but we do not obtain the quantitative agreements.

1. Introduction

The flow in a concentric annulus with a rotating inner cylinder for the single-phase flow is well known as the Taylor-vortex flow. Experiments in such system for the two-phase flow were carried out and found very interesting phenomena. With increasing of the rotating inner cylinder, bubbles agglomerate and make spirals or rings owing to the Taylor-vortex. According to the flow visualization of a cross section in the annulus, the bubbles of spirals or rings locate at very close to the rotating inner cylinder and at out-flow region. Calculations carried out to confirm these characteristics and investigate in detail.

2. Description of phenomenon simulated

Taylor first investigated the instability in the concentric annulus and found the Taylor-vortex, i.e. there appear pairs of counter-rotating toroidal vortices above a certain critical Taylor number[1]. This flow is very important for cooling of bearings in rotating machineries and/or heat and mass transfer in chemical reactors. Authors have investigated
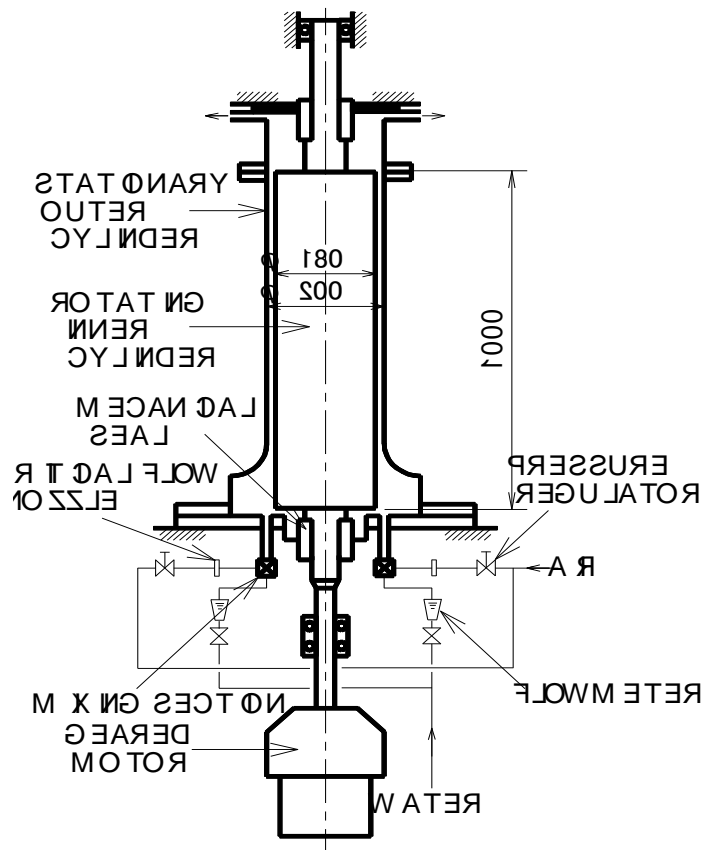
Fig.1 Experimental apparatus

two-phase flow in the Taylor-vortex flow experimentally[2]-[5]. The experimental apparatus used in the two-phase Taylor-vortex flow is shown in Fig.1.

When the rotational speed of the inner cylinder was at relatively low level, the buoyancy effect of bubbles played a dominant role in the flow field, and then the dispersed bubbly flow appeared as shown in Fig.2. On the other hand, when the rotational speed was at high level, the vortex motion dominated the flow field, and ring and/or spirals consisted of small bubbles were formed as shown in Fig.3. To understand the flow structure in such two-phase Taylor-vortex flow, it is necessary to pay attention to each bubble behavior and the interaction with the Taylor-vortex.

The water flow rates were Q_L= 0 - 1.6x10^{-3} m^3/s, the air flow rates Q_G=0 - 3.86x10^{-4} m^3/s, and the rotational speeds of the inner cylinder n=0 - 800 rpm in the experiments. Then the respective axial volumetric fluxes were j_L= 0 - 0.268 m/s and j_G=0 - 0.0647 m/s. The tangential velocities of the inner cylinder were u_{T0}=0 - 7.54 m/s. The corresponding Taylor
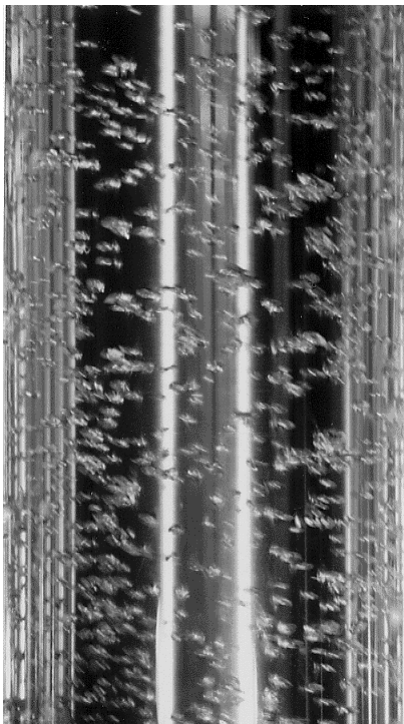

Fig. 2   Bubbly flow
(j_G=0.0163m/s, j_L=0.067m/s,
Ta=9.86x10^6)
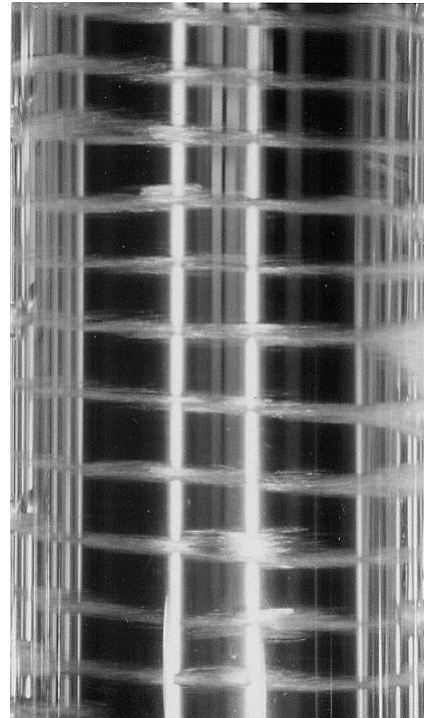
Fig. 3   Bubble-ring flow
(j_G=0.0163m/s, j_L=0.067m/s,
Ta=6.31x10^8)

number, which was defined by

$$Ta = \frac{R_1 \Omega_1^2 d^3}{v^2}$$ (1)

where R_1 was the radius of the inner cylinder, Ω_1 was the angular velocity of the inner cylinder, d was the gap of the concentric annulus and v was the kinematic viscosity of water, was in the range $Ta = 0 - 6.31 \times 10^8$.

The theoretical critical Taylor number without an axial flow, at which the Couette flow instability occurs, is 1920. Although this critical Taylor number increased, in general, with the increase in the axial Reynolds number, the Taylor number was far beyond this critical value, i.e. $Ta = 2.47 \times 10^6$ even at the lower limit of the rotation n=50 rpm.

The Rossby number, Ro, which is the ratio of the centrifugal force to the inertial force, also represents important characteristics in the Taylor-vortex flow with an axial flow. In these experiments, Rossby number defined by

$$Ro = \frac{R_1 \Omega_1}{j_L} = \frac{R\omega}{Re}$$ (2)

where $R\omega$ was the rotational Reynolds number and Re was the axial Reynolds number, was greater than unity. Then the centrifugal force was larger than the inertial force in the present range of experiment. That is, the centrifugal force caused by the rotation of the inner cylinder is dominant factor relative to the inertial force caused by the axial flow.
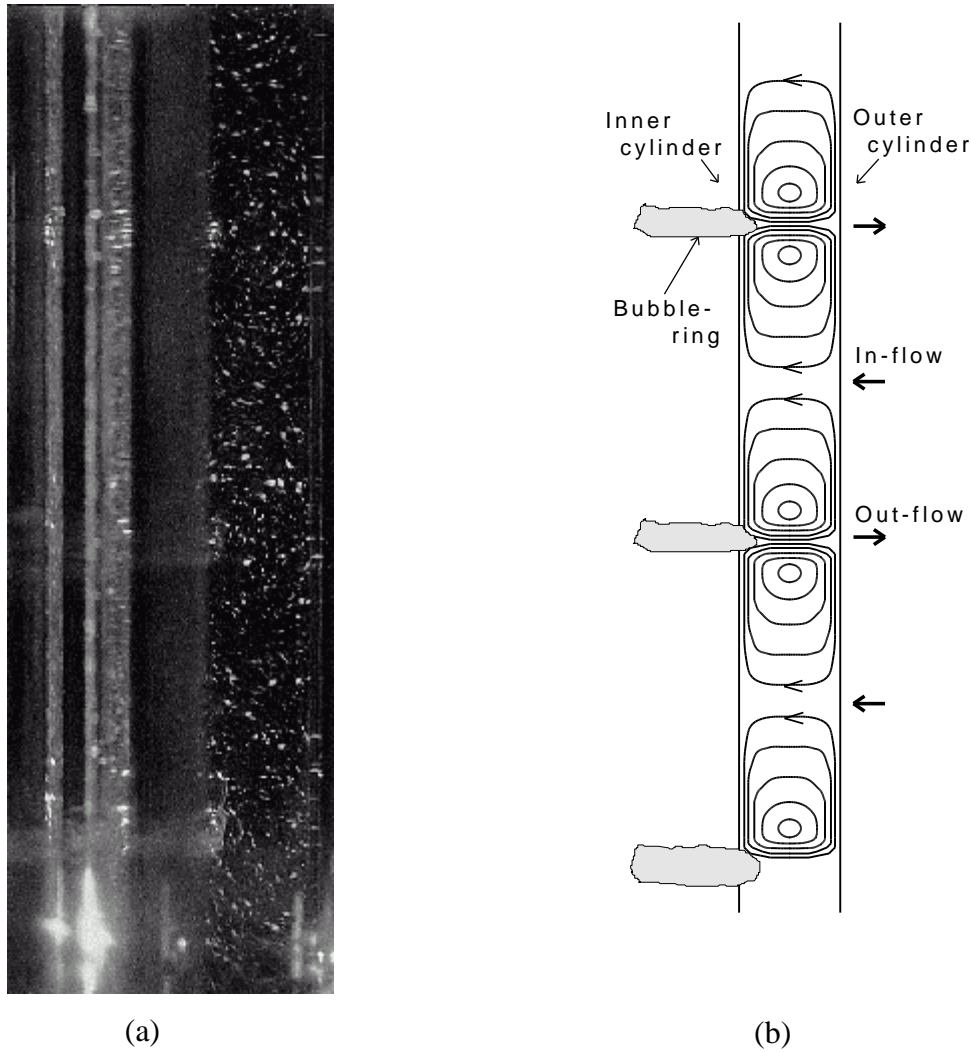
<div align="center">(a)   (b)</div>

<div align="center">Fig. 4 Flow visualization of two-phase Taylor vortex flow(Ta=6.31x10^8)</div>

Figure 4 shows the flow visualization of the two-phase Taylor-vortex flow at Ta=6.31x10^8. The schematic diagram at the right side is drawn based on the visual images of the photograph and VTR. It can be seen from the photograph and VTR images that the bubble-rings exist close to the inner cylinder. The visual image also indicates that the bubble-rings are located at the out-flow regions as shown in the diagram.

In order to confirm the above discussion, the void fraction was measured at various radial positions by using a conductance probe, and the results are shown in Fig.5. When a bubble attacked the conductance probe, the signal indicated a peak. The zero-line in Fig.5 corresponds to the liquid phase. At the radial position r=92mm apart 2mm from the inner cylinder, there are many bubbles, i.e. the void fraction is high. On the other hand, there is no

bubble at r=98mm close to the outer cylinder. Namely, the void fraction decreases along with the traverse in the radial direction, i.e. void fraction has the inner wall-peak distribution.

3. Numerical Method

Two-phase Taylor-vortex flow is calculated in two dimensional cylindrical coordinate with IPSA method. The original k-ε and k-ε RNG models are used as the turbulent model.

The mesh region containing fluid is composed of 10 cells in the r direction, labeled with the index y, and 400 cells in z direction, labeled with the index z shown in Fig.6.

The boundary condition at the inner cylinder was set to the tangential velocity of the inner cylinder and at the outer cylinder was set to the no-slip condition. The boundary condition at the upper and bottom boundaries were continuative out- and in-flow conditions, respectively.

Calculation was conducted using same geometrical configurations as the experiment [2]. The Taylor number was in the range Ta=0 - 6.31×10^8. The calculated conditions are listed
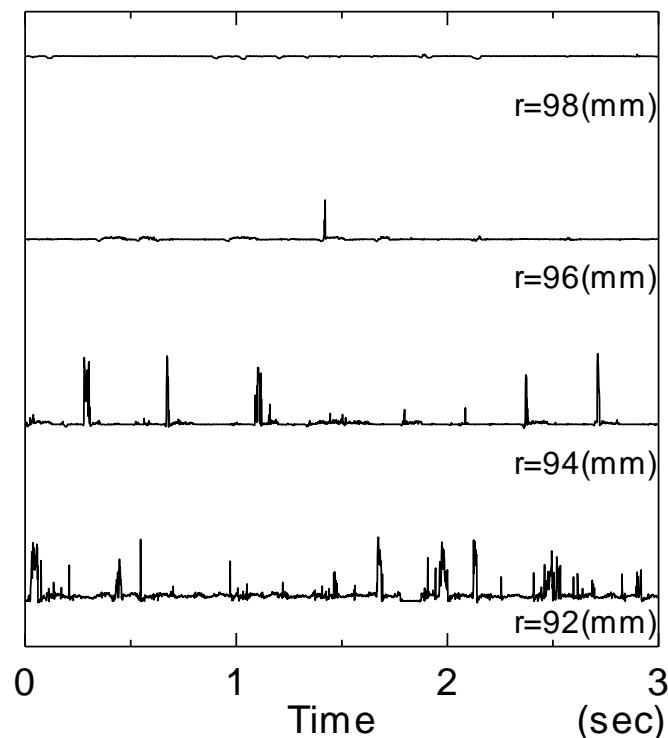

Fig. 5   Void fraction
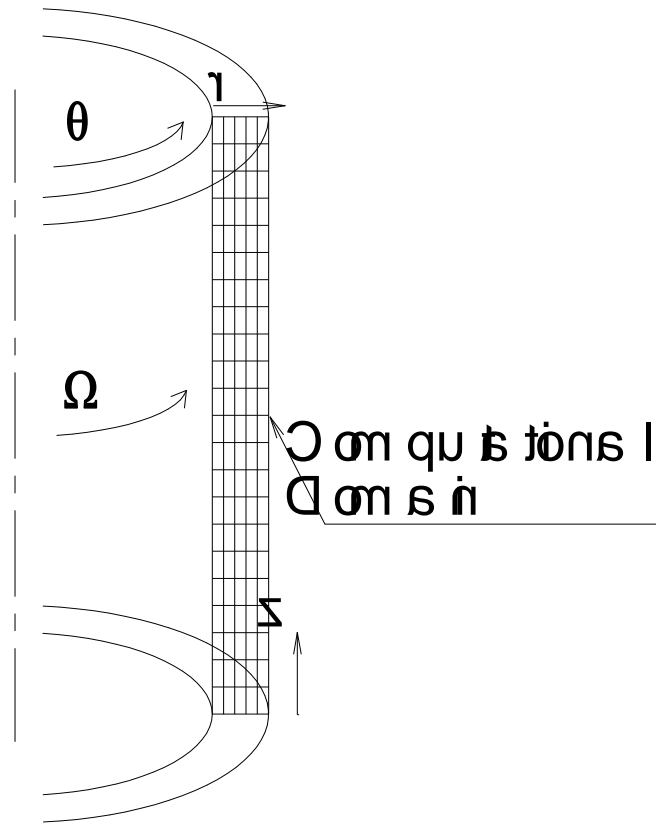
(j_G=0.0214m/s, j_L=0.0628m/s, Ta=6.31×10^8)

Fig. 6   Physical model

Table 1   Calculated conditions

Radius of Inner Cylinder	0.09 [m]
Radius of Outer Cylinder	0.10 [m]
Taylor number	0 - 6.31×10^{8}
Density of liquid	998.2 [kg/m^3]
Density of gas	1.205 [kg/m^3]
Inlet	j_T=0.0833 [m/s], $\alpha = \beta = 0.05$
Bubble diameter	1.0×10^{-3} [m]
Turbulence model	k-ε , k-ε RNG

in Table 1.

The two-phase flow comes into the annulus from the bottom and goes out at the top. If the outlet at the top sets to the pressure boundary condition, p=0 as the normal outlet boundary condition, the two-phase flow does not flow out at the top because of the pressure distribution of the annulus owing to the rotation. Then, the outlet boundary condition at the
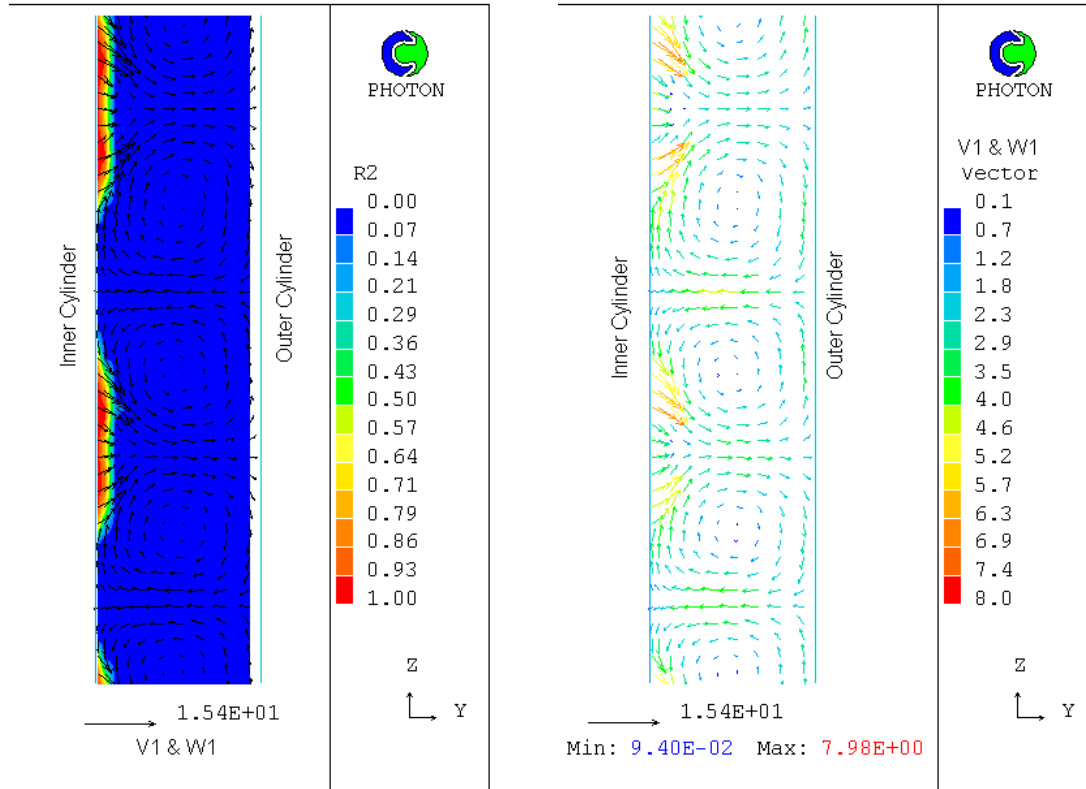
Fig. 7   Void fraction and vectors of liquid phase

top is set to the minus value of the inlet boundary condition at the bottom. Using these boundary conditions, the nett sources of R1 and R2 balance at the top and the bottom. The total volumetric flux, j_T and the void fraction, α, which is same with the volumetric fraction, β in the two-phase homogeneous model, are set at the inlet boundary condition of the bottom.

4. Results and Discussion

Before the discussion of the two-phase flow, the existence of the Taylor-vortex in the liquid single-phase flow was confirmed.

Figure 7 shows the results of the void fraction distribution and vectors of liquid phase in the case of k-ε RNG model. It can be seen that the Taylor-vortex is also obtained in this calculation from the vectors of liquid phase. And from the void distribution, bubbles which correspond to red region exist close to the inner cylinder and locate at out-flow region. These features are same with the experimental results as mentioned above. In the case of original k-ε model, almost same results obtained. Therefore there is no remarkable difference between original k-ε model and k-ε RNG model in this calculation.
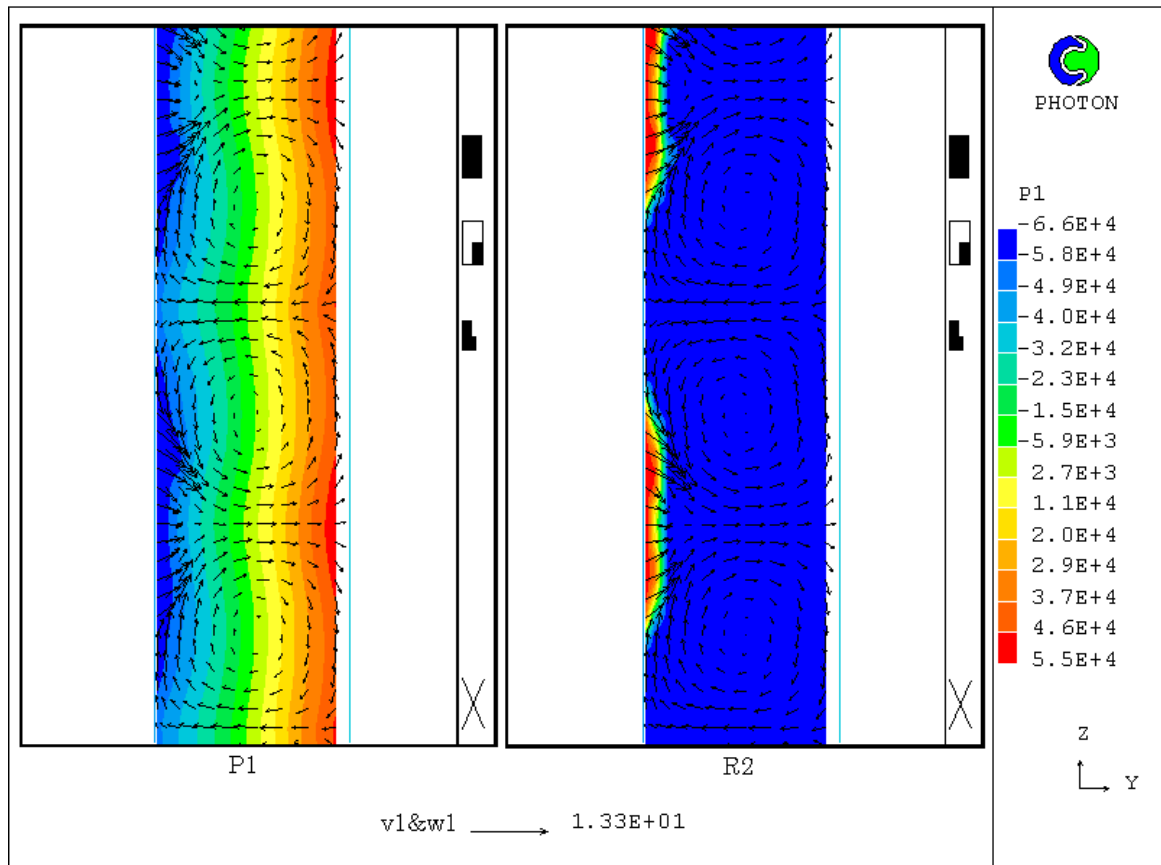
Fig. 8   Pressure distribution, void distribution and velocity vector

Owing to the rotation of the inner cylinder, the annulus has the interesting pressure distribution. The pressure increases with increasing the radial position and its distribution is wavy. In other words, the pressure close to the outer cylinder is higher than that close to the inner cylinder. It has the positive higher region where the flow is the out-flow, i.e. the flow from the inner cylinder to the outer one, close to the outer cylinder. On the other hand, it has the lower region close to the inner cylinder. The negative pressure region corresponds to the high void fraction region. Therefore the bubbles are trapped in the negative pressure region.

The calculation results agree with the experimental results qualitatively but do not have the quantitative agreement. For example, bubbles locate in the wide range and liquid velocity was calculated largely where it must be zero.

These errors might come from numerical errors during the iteration. Though the void fraction must be zero in practice, the calculated void fraction has the very small finite value. Therefore, the liquid velocity was calculated largely. Figure 9 shows the modified liquid
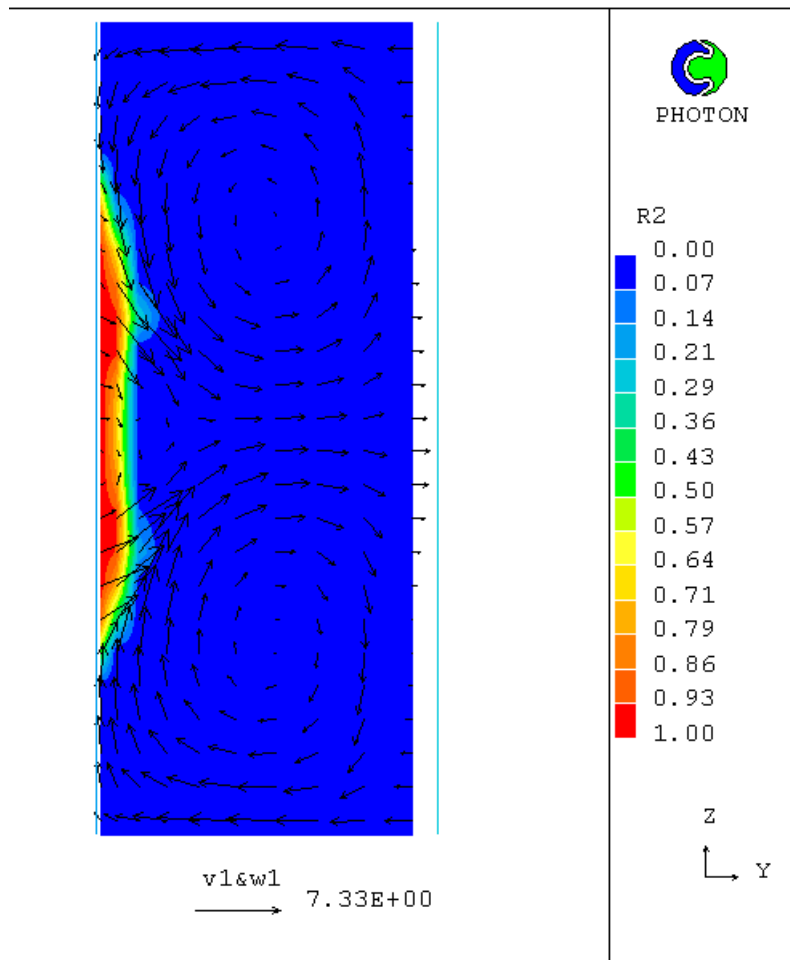
Fig. 9 Modified liquid velocity

velocity, the product of the original liquid velocity and the void fraction. The modified liquid velocity close to the inner cylinder becomes very small and seems to be reasonable.

5.Conclusions

Calculations have been carried out for the two-phase Taylor-vortex flow in the concentric annulus with the rotating inner cylinder. The calculation results agreed with the experimental results qualitatively that the bubbles exist at the out-flow region close to the inner cylinder. The pressure distribution in the two-phase Taylor-vortex flow is deeply related to the void fraction distribution.

Acknowledgement

References

1. G.I.Taylor, Stability of a Viscous Liquid Contained between Two Rotating Cylinders, Phil. Trans. Roy. Soc. Ser.A, 223(1923), 289-343.

2. Y.Shiomi, H.Kutsuna, K.Akagawa and M.Ozawa, Two-Phase Flow in an Annulus with a Rotating Inner Cylinder(Flow Pattern in Bubbly Flow Region), Nuclear Engineering and Design, 141(1993), 27-34.

3. Y.Shiomi, H.Kutsuna, K.Akagawa and M.Ozawa, Bubble and Particle Behavior in Taylor- and Spiral-Vortex Flows, Advances in Multiphase Flow, (1995), 17-26.

4. Y.Shiomi, H.Kutsuna, K.Akagawa and M.Ozawa, Two-Phase Flow in an Annulus with a Rotating Inner Cylinder, Proc. The International Conference on Multiphase Flows '91-Tsukuba, (1991), 179-182.

5. Y.Shiomi, M.Ozawa, H.Kutsuna, S.Nakanishi and K.Akagawa, Void Fraction of Two-Phase Flow in Concentric Annulus with Rotating Inner Cylinder, Proc. The Japan-U.S. Seminar on Two-Phase Flow Dynamics, (1996), 259-263.