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Experimental and Numerical Investigation of Two-Phase Flow through Enlarging Singularity

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ABSTRACT

Gas-liquid flow is extensively used in industrial systems such as power generation units, cooling and heating systems (i.e. condensers, evaporators and manifolds), safety valves, etc. These systems generally have complex geometries composed by singularities like expansion, contraction, bends and orifices. Thus two-phase flow characteristics through these singularities should be identified in order to be used in designing of the systems.

In this study, experimental and numerical investigations on characteristics of adiabatic air-water flow through a horizontal channel having smooth expansion are performed. Internal diameter of the channel expands from 40 mm to 50 mm with an angle (δ) of 9º. Flow rate for water is constant at 3 l/s while that for air is taken as 30, 50 and 60 l/min. In the experiments, effects of air flow rate, thus the volumetric void fraction, and internal diameter of the channel on hydrodynamic characteristics of two-phase flow (i.e. local void fraction) are examined. Measurements are carried out by dual optical probe at different axial positions upstream and downstream the singularity. In addition to the measurements, the flow is numerically modeled via commercial software, GAMBIT (v. 2.3.16) and ANSYS FLUENT (v. 12). Eulerian (Dispersed) model is employed in the simulations. According to the comparison between the numerical results and the experimental data, good agreement is obtained.

1. INTRODUCTION

Gas-liquid two-phase flow takes the leading role in applications including evaporation and/or condensation, flow through cross-sectional area change (i.e. nozzle, diffuser) and sudden pressure drop (i.e. flashing). These systems normally have complex geometries composed by singularities like expansion, contraction, bends, orifices, etc. Thus two-phase flow characteristics, such as distribution of local void fraction and phase velocities, pressure drop and two-phase pattern, through these singularities should be identified in order to be used in designing of the system. Some of the studies dealing with the two-phase flow characteristics through cross-sectional area change are as follows. Ching-Yi H. et al. (1997) studied the flow of two-phase oil/water mixtures through sudden expansions and contractions from 41.2 mm to 20.3 mm and vice versa. They found good agreement with the literature and concluded that conventional correlations can be used for the case investigated. Fossa and Guglielmini (1998) experimentally investigated the void fraction distribution in horizontal pipes with sudden area contraction. They measured the instantaneous electrical impedance of air-water mixture in order to obtain the cross-sectional average of void fraction along the test pipes. Bertola (2002, 2004) used single-fiber optical probes to investigate the time-averaged structure of gas–liquid horizontal flow through a sharp-edged sudden area contraction. It is stated that the distribution of the gas and the liquid close to the pipe contraction is quite different from that of a homogeneous flow, so that the commonly used void fraction and pressure drop correlations are unable to predict the flow behavior near a singularity. It is also concluded that the sudden contraction considerably affects the gas distribution in both upstream and downstream pipes, and its effect grows more and more as the flow approaches the singularity. Ahmed et al. (2007) investigated two-phase flow through a horizontal sudden expansion, experimentally. They used air and oil as fluids, two different area ratios and concluded that upstream flow pattern and area ratio are dominant on phase distribution and developing length after expansion. Delgado-Tardâguila (2008) studied on channel having divergence and convergence type singularities and proposed a modified correlation for static pressure change. Water and air at atmospheric conditions are used as fluids and effects of liquid and gas flow rate, volume fraction of the gas and distance from the singularity, on pressure change are investigated. A comparison of experimental and numerical profiles with handbook solution is found to be in good agreement.

Once literature is surveyed, it can be seen that the studies investigating two-phase flow characteristics through singularities commonly considered sudden changes. In this study, adiabatic air-water flow through horizontal channel having smooth expansion is researched experimentally and numerically. Dual optical probe measuring local void fraction (α) is employed to evaluate the hydrodynamic characteristics of the flow. Experimental data is also compared with the results of numerical modeling performed via commercial software, GAMBIT (v. 2.3.16) and ANSYS FLUENT (v. 12).

2. EXPERIMENTAL FACILITY AND CONDITIONS

Schematic of the experimental facility is given in Figure 1. Water at atmospheric conditions is taken from a tank of 300 liters by a pump having maximum capacity of 18 m^3/h. Outlet of the pump, water is filtered up to 5 µm and sent to the electro-magnetic type flow meter for flow rate (i.e. 3 l/s) measurement. Meanwhile, air is compressed to 4 bar absolute pressure, filtered from the moisture and the particles and measured by a rotameter to determine the flow rate (i.e. 30, 50 and 60 l/min). Compressed air is then injected to the water flow by an immersed injector at where the two-phase flow is obtained. Injector has 16 holes with 2 mm diameter. Air-water flow through the test section is subject to the measurements by means of dual optical probe. Measurement principles of the optical probe can be found in François et al. (2003). All pipes in the facility are made of transparent acrylic in order to observe the flow.

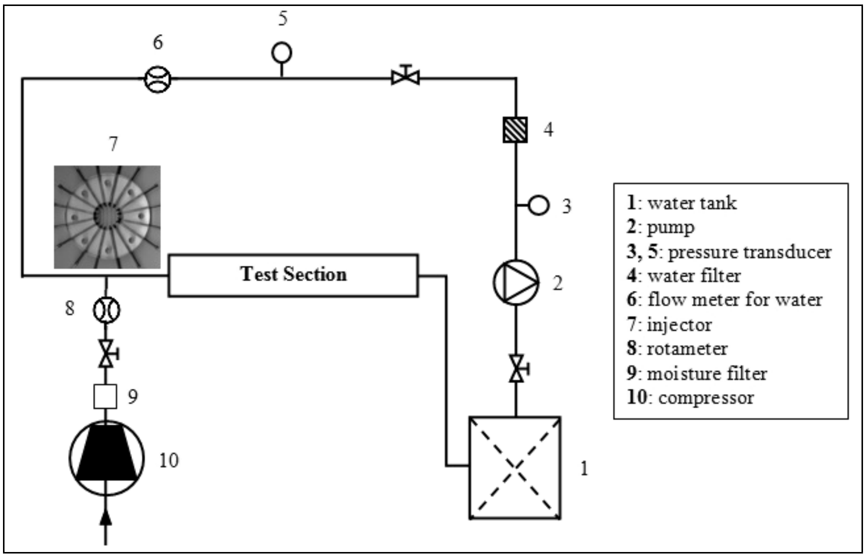

Figure 1: Schematic of the facility

Test section is given in details in Figure 2. It consists of three pipes named upstream pipe, singularity pipe and downstream pipe with prescribed lengths and diameters. Black bars stand for the measurement positions thus there are four and three positions at upstream and downstream pipes, respectively.

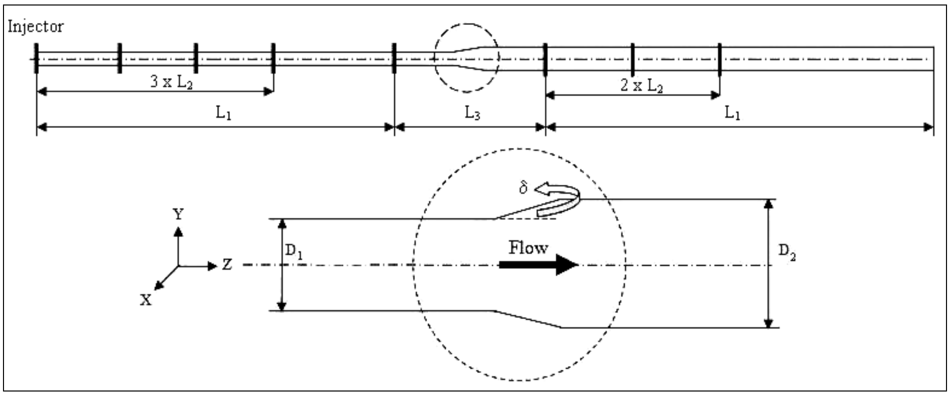

Figure 2: Detailed scheme of the test section

During the experiments, flow rate for water is kept constant at 3 l/s while that for air is taken as 30, 50 and 60 l/min. Thus volumetric void fraction ($\beta = \dot{Q}_{air} / \dot{Q}_{total}$) of the cases are estimated to be 13.87 %, 21.74 % and 25.31 %, respectively. Expansion angle (δ) is also kept constant at 9° for all cases. Operational conditions and the geometrical details of the test section can be seen in Table 1.

Table 1: Operational conditions and geometrical details of the test section

Geometry	L_1 = 1500 mm L_2 = 330 mm L_3 = 382 mm D_1 = 40 mm D_2 = 50 mm $\delta = 9°$	**Gas phase / Liquid phase**	Air / Water
		Mass flow rate for gas ($\dot{m}_{air}$)	0.0006125, 0.001021 and 0.001245 kg/s
		Mass flow rate for liquid ($\dot{m}_{water}$)	2.99 kg/s
		Volumetric void fraction (β)	13.87 %, 21.74 % and 25.31 %

3. NUMERICAL MODELING

Theoretical modeling of the two-phase flow under consideration is also done in this study. Construction of the numerical domain and calculation is performed by GAMBIT (v. 2.3.16) and ANSYS FLUENT (v. 12), respectively. Since air-water flow is obtained by injecting air to the water flow via an injector in the experiments, as shown in Figure 1, it can be stated that the inlet conditions of two-phase flow through the test section (i.e. upstream, singularity and downstream pipes) are determined by the outlet conditions of the injector. Therefore numerical analysis of the flow will be performed in two steps including modeling of the flow through the injector and, then through the test section. Shape and diameter of the bubbles in the flow are affected by design of the injector and forces (i.e. drag and lift) between the phases. Break-up and/or coalescence between the bubbles also modify the diameter, instantly. In this study, a constant diameter value is estimated for the bubbles at the injector outlet via correlation written in the literature (Kunii, 1991). Also, it is assumed that there is no break up/coalescence between the bubbles in the flow.

$$V_{bubble} = 1.138 \frac{(\upsilon / N)^{6/5}}{g^{3/5}} \tag{1}$$

Here, V_{bubble} is the volume of an individual bubble, υ is the total volumetric flow rate of air through the injector, N is number of the holes in the injector and g is the gravitational acceleration. Diameter is then extracted from the bubble volume, assuming that the bubble is spherical.

3.1 Modeling of the Flow through the Injector

Injector used in the experiments and numerical geometry constructed for the injector is given in Figure 3. Here, holes of the injector are represented by means of rods with 100 mm length which inserted to a pipe created in 3D. In order to ease to have structural mesh, rods are constructed with square cross-section having 2 mm of hydraulic diameter. According to the simulation, air flows through these rods while water enters the pipe from the remaining cross-section of the inlet and, two-phase flow to be considered is obtained just after the outlet of the rods where the phases infiltrate each other. At the end of each simulation for different air flow rates, phase velocity and void fraction profiles obtained at that location are extracted from the simulation in order to be introduced as the inlet condition for the analysis of the flow through the test section.

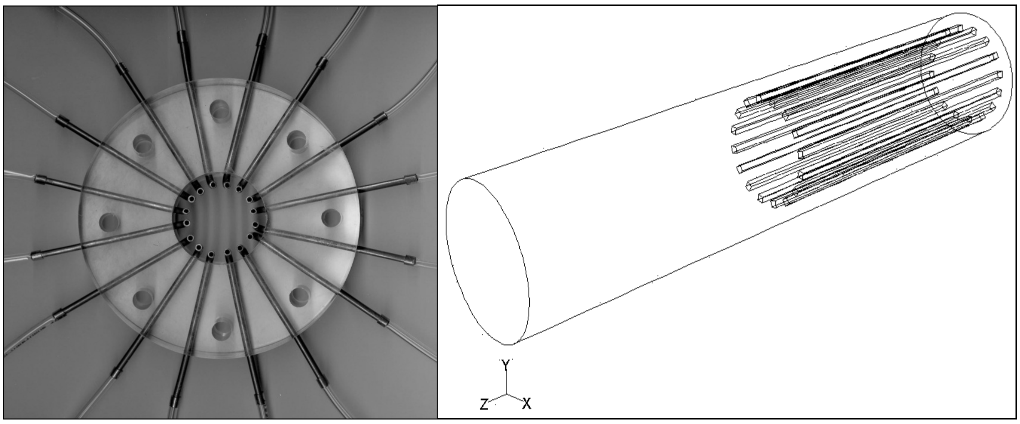

Figure 3: Experimental and numerical injector

94,969 nodes are considered to be adequate for the injector simulation according to the grid independency examination performed by testing several domains with different node densities. Mesh structure of the domain is given with the water-inlet region shown in Figure 4. In ANSYS FLUENT (v.12), boundary conditions like “velocity inlet” is taken as the inlet condition for water and air, while “interior” and “outflow” are employed as the outlet conditions for the rods and the pipe, respectively. Eulerian (Dispersed) multiphase model is used for the analysis. Reynolds Stress Model is utilized to model the turbulent flow. Standard Wall Functions are operated for near wall treatment. Phase Coupled SIMPLE scheme for pressure-velocity coupling, Green-Gauss Cell Based option for gradients and Second Order Upwind for spatial discretization are chosen.

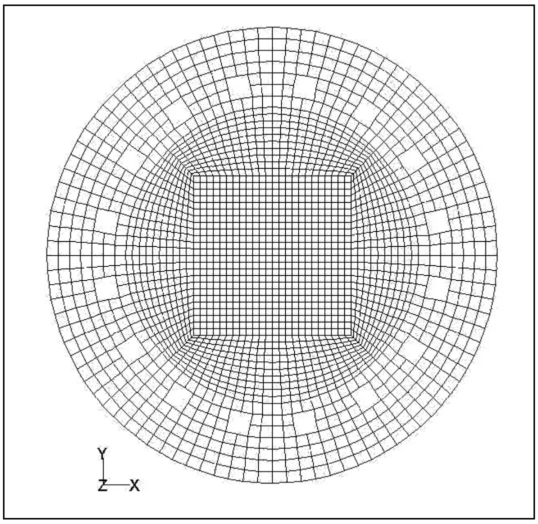

Figure 4: Mesh structure at water-inlet of the injector

3.2 Modeling of the Flow through the Test Section

Second step of the analysis is modeling of two-phase flow through the test section having three regions called upstream, singularity and downstream pipes. It is performed separately by taking the outlet conditions of the former pipe as the inlet conditions of the following. Numerical domain of the system is constructed in 3D and symmetrical with respect to y-axis. Node density at cross-section of the pipes are adjusted to be equal to that of the injector in order to avoid numerical errors due to interpolation thus 348,558 nodes are used for upstream and downstream pipes while 119,274 for those of the singularity pipe. y-directional node density of the upstream pipe and mesh structure for the enlarging section are illustrated in Figure 5.

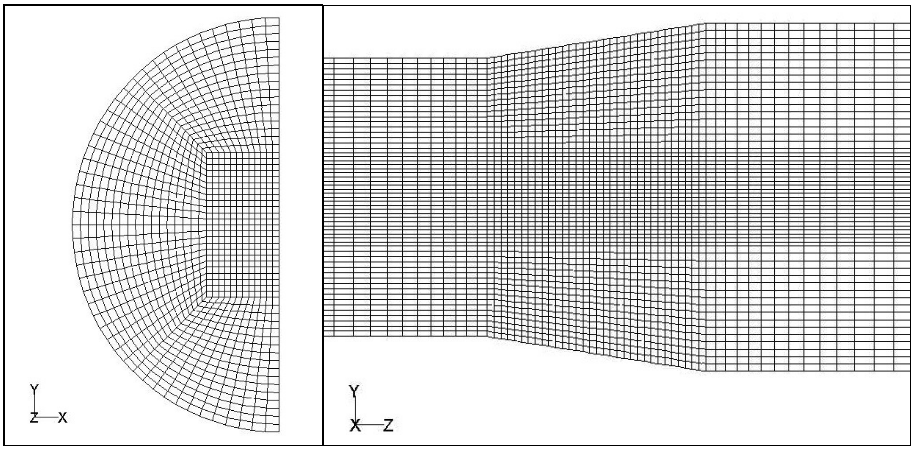

Figure 5: Mesh structure for upstream-inlet and enlarging section

Referring to the study in the literature (Deniz and Eskin, 2011), Reynolds Stress Model is chosen to model turbulence. As in the injector simulation, Eulerian (Dispersed) multiphase model is used for the analysis. Standard Wall Functions are utilized for near wall treatment. Phase Coupled SIMPLE scheme for pressure-velocity coupling, Green-Gauss Cell Based option for gradients and Second Order Upwind for spatial discretization are chosen.

4. RESULTS AND DISCUSSIONS

Experimental results and comparison of them with those of numerical are given discretely in this section. In the following figures, location of the measurement positions along axial direction, shown in Figure 2, will be defined in terms of γ which is expressed as the distance of the position from the injector divided by the total length of the test section, i.e. 3.382m. Consequently, γ takes the values between 0.1-0.44 at upstream pipe and 0.55-0.75 at downstream pipe. Furthermore, y-axis of the figures denotes the position at radial direction which is given by non-dimensional parameter of *y/D* where *D* is internal diameter of the related pipe. Thus, *y/D* varies between zero and the unity representing the bottom and top of the pipe, respectively.

4.1 Experimental Results of Local Void Fraction

Radial distribution of local void fraction along upstream pipe is given for different volumetric void fraction (β) values in Figure 6.

Development of the void fraction distribution and thus the stratification of the flow can be observed from the plots in Figure 6. At $\gamma = 0.1$, bubbles are still dominated by the jet effect due to being injected out from the injector rods, but as they move forward to $\gamma = 0.2$, they decelerate as a consequence of drag force between the water. Thus void fraction values increase at that position. Then gravitation and lift forces between water and air affect the bubbles and shift them up ($\gamma = 0.3$). Since most of the bubbles gathered at top of the pipe, local void fraction value decreases at the other levels indicating that the stratification has developed ($\gamma = 0.44$).

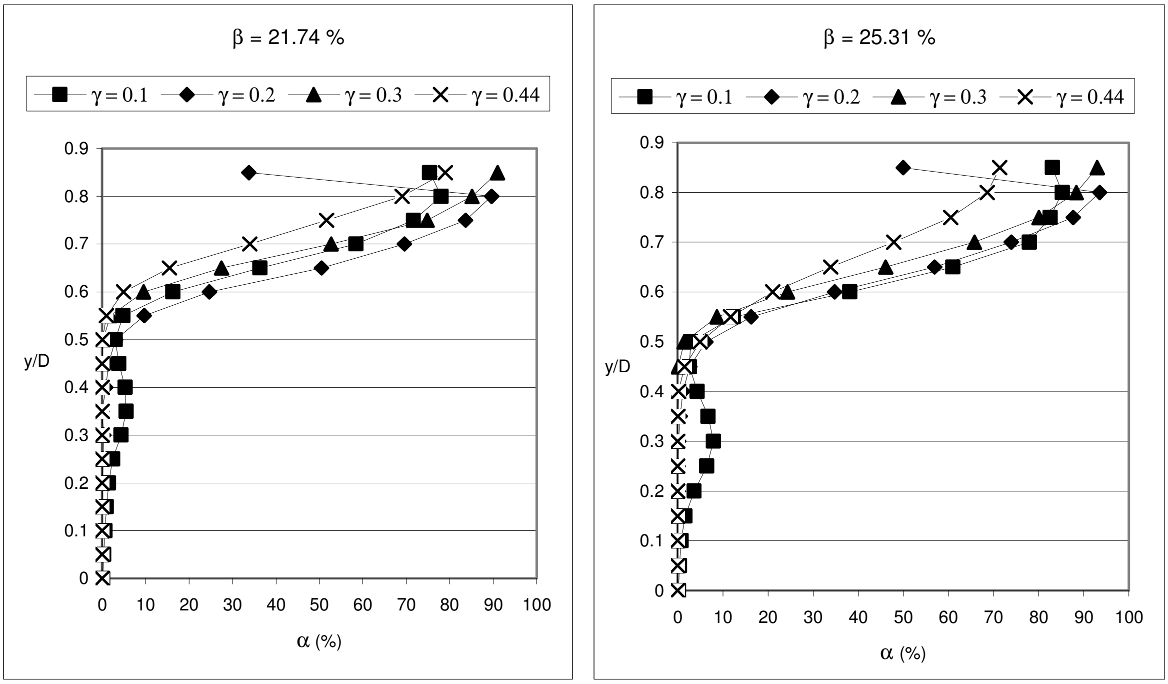

Figure 6: Radial distribution of local void fraction with respect to volumetric void fraction along upstream pipe

Local void fraction distribution with respect to volumetric void fraction can be seen in Figure 7. It can be stated that the local void fraction values increase with increasing flow rate of air, as expected.

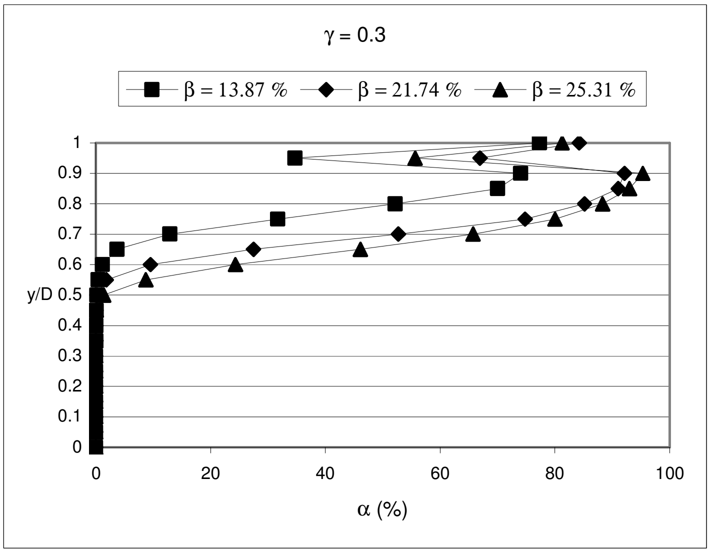

Figure 7: Radial distribution of local void fraction with respect to volumetric void fraction

Effect of smooth expansion on local void fraction distribution is shown for different volumetric void fraction values in Figure 8. It is seen that local void fraction increases after the smooth expansion due to deceleration of the phases caused by enlarging cross-section and, to flow separation occurred just after the singularity region. It is also concluded that the liquid phase (water) is pressed downwards with increasing volumetric void fraction after the singularity.

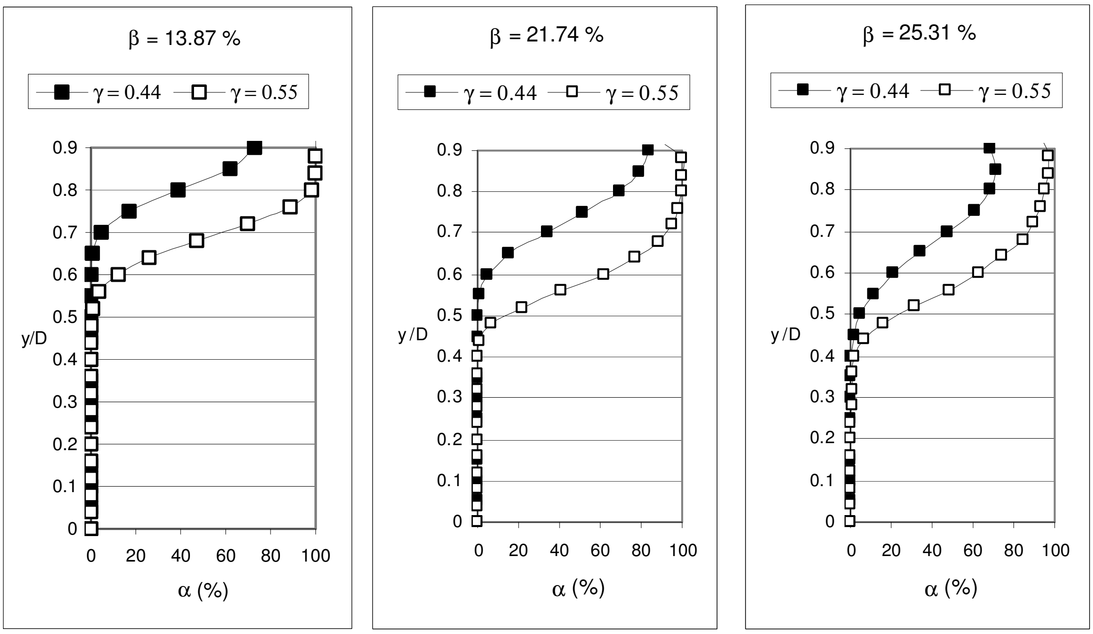

Figure 8: Local void fraction distribution before ($\gamma = 0.44$) and after ($\gamma = 0.55$) the singularity

Development of the stratification, thus the local void fraction allocation, along downstream pipe is illustrated in Figure 9.

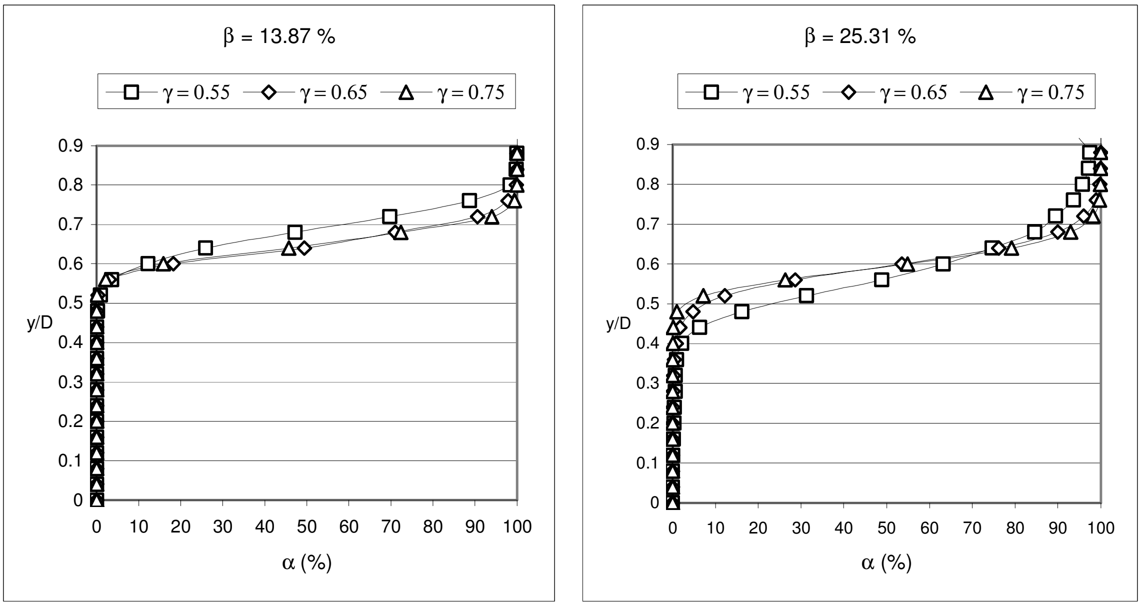

Figure 9: Radial distribution of local void fraction with respect to volumetric void fraction along downstream pipe

4.2 Validation of Numerical Modeling

Theoretical analysis performed in the study will be validated by comparing numerical results with the related experimental data obtained. Experimental and numerical values of α for $\beta = 21.74\ \%$ and $\beta = 25.31\ \%$ before the smooth expansion are plotted in Figure 10, while effect of the singularity on α for $\beta = 21.74\ \%$ in Figure 11.

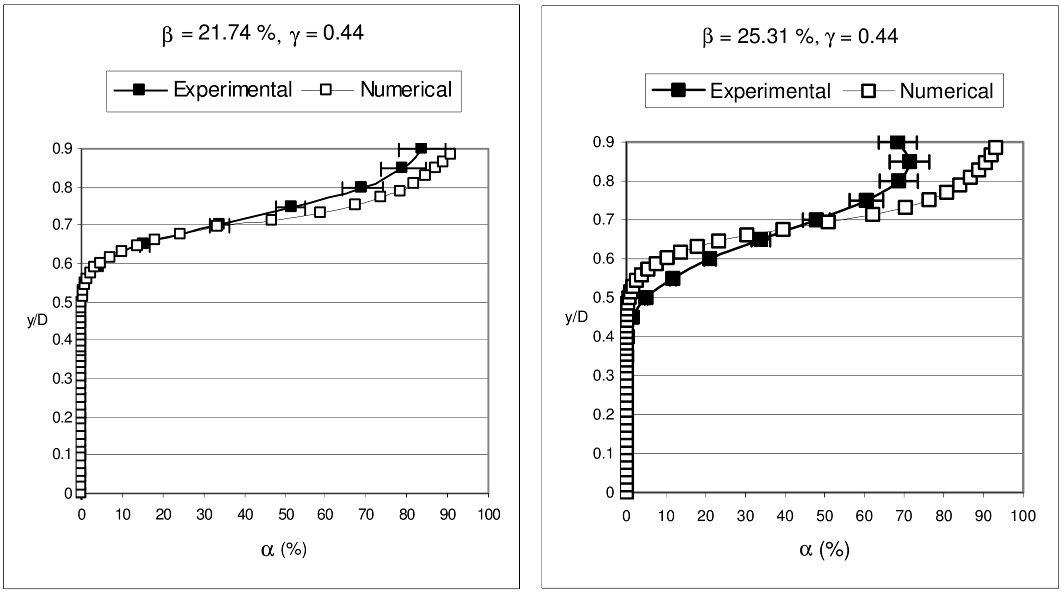

Figure 10: Comparison of experimental and numerical results before the singularity

From Figure 10, it can be concluded that numerical and experimental values are close to each other at low β values. Discrepancy increases with increasing β . Referring to Figure 11, one can state that the results are in good agreement before the singularity rather than the after. Blockage effect caused by the probe in the experiments and the constant bubble diameter assumption made in the modeling are the main reasons for these consequences. Dual optical probe is an intrusive device which may shift or gather the bubbles in the flow with its handle. Therefore it measures the α values within an error of 7 %. On the other hand, higher β raises the interaction between the bubbles (break-up/coalescence) and bubbles decelerating after the expansion are subject to coalescence resulting larger bubbles. However it seems that the numerical model considering constant bubble diameter is not able to evaluate the effects caused by the former phenomenon, properly. As a result, it can be concluded that a model taking diameter variation into account would give more reasonable values.

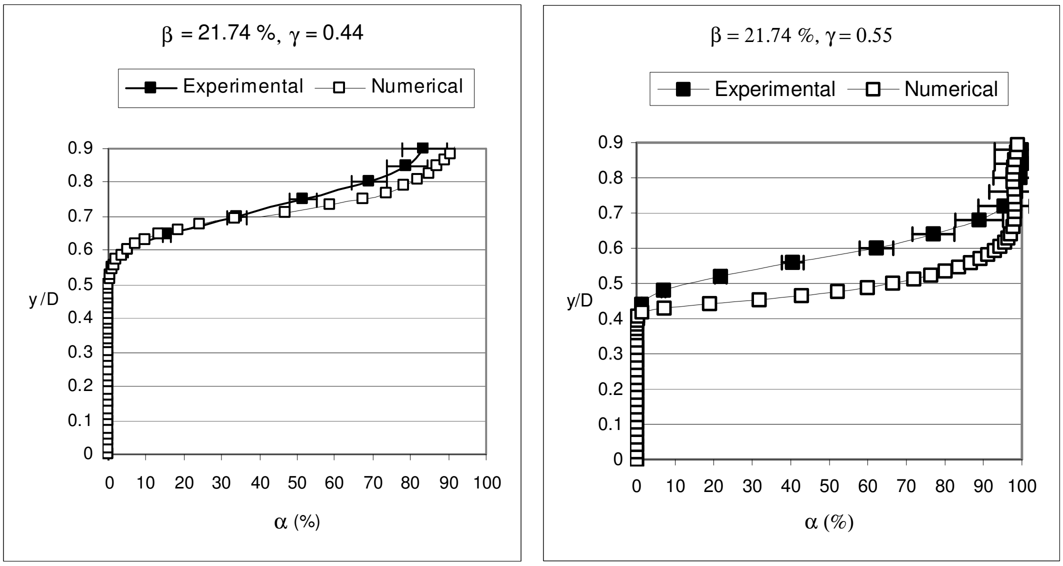

Figure 11: Effect of smooth expansion on local void fraction distribution

5. CONCLUSIONS

Local void fraction distribution of adiabatic air-water flow through horizontal pipe with smooth expansion is investigated experimentally in this study. Experimental results are also compared with those obtained via a numerical modeling performed under certain assumptions. Conclusions can be listed as follows.

- Design characteristics of the injector, such as diameter and distribution of the holes, are critical since they determine the initial conditions of the air-water flow through the test section.
- Local void fraction increases with increasing values of volumetric void fraction for both experimental and numerical considerations.
- Local void fraction rises downstream the singularity due to deceleration of the phases caused by enlarging cross-section and flow separation occurred.
- Effect of the enlarging section on local void fraction becomes evident as volumetric void fraction increases.
- Numerical and experimental values are close to each other at low β values. Discrepancy gets higher as β increases.
- Numerical model considering constant bubble diameter is not able to evaluate the phenomenon caused by interaction of the bubbles (i.e. break-up and/or coalescence). A model taking diameter variation into account can be taken as the future work of the study.

NOMENCLATURE

D	diameter of the pipe	(mm)
L	length of the pipe	(mm)
V	volume	(cm^3)
$\dot{m}$	mass flow rate	(kg/s)
$\dot{Q}$	volumetric flow rate	(m^3/s)
υ	volumetric flow rat	(cm^3/s)
N	number of the injector holes	(–)
g	gravitational acceleration	(cm/s^2)
y	distance along radial direction	(mm)
δ	expansion angle	(°)
γ	non-dimensional location	(–)

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