An Experimental Study of In-Situ Phase Fraction in Jet Pump Using Electrical Resistance Tomography Technique *

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We perform the experiments to investigate in-situ phase fraction in a jet pump using the electrical resistance tomography (ERT) technique. A new jet pump with ERT sensors is designed to measure in-situ phase fraction and flow regime. The study is based on laboratory experiments that are carried out on a 50-mm vertical flow rig for various gas and liquid phase superficial velocities. The different flow patterns of gas liquid in the jet pump and vertical pipe are studied using the ERT technique. The results suggest that the ERT system can be used to successfully produce images of gas–liquid flow patterns with frames rates of 58 fps and the in-situ phase fraction with frame rates of 5 fps can be obtained. The visualizations of a rapid mixing process in the throat of a jet pump obtained in this work provide a reliable basis for theoretical study and optimal design of jet pumps.

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A jet pump can transfer energy from a liquid or gas primary fluid to a secondary fluid. The latter may be a liquid, a gas, a two-phase gas-in-liquid mixture, or solid particles transported in a gas or a liquid. All these combinations occur in a wide range of practical applications in the chemical, oil and process industries. The main components of a jet pump, as shown in Fig. 1, are a primary nozzle, secondary fluid injectors, a mixing chamber, a throat, and a diffuser. Due to the high reliability of these devices which have no moving parts, considerable interest has been concentrated on theoretical and experimental studies of jet pump.[1−3] These studies, in general, are similar in the aspect of applying momentum-continuity modelling of the throat process. With the development of particle image velocimetry (PIV), some authors have also used the PIV technique to study the flow field of jet pump.[4] However it is of difficulty to accurately measure the in-situ phase fraction and flow pattern in a jet pump by PIV alone. Due to the characteristics of its structure, the jet pump should have an important influence on flow patterns when it is used to transport multi-phase flows, especially for liquid–liquid flows.[5] Electrical resistance tomography (ERT) has been successfully applied to predict gas concentration, disperse phase velocity and flow regimes in both vertical and horizontal flows.[6,7] To understand the performance of a two-phase jet pump which influences on the flow pattern, in this work we experimentally investigate the in-situ phase fraction and flow patterns in a jet pump on a vertical pipe using the ERT technique.

The experimental setup reported here has a gas-liquid flow loop of about 12 m length with an inner diameter of 50 mm. The experimental investigations are conducted in the setup shown in Fig. 2. The flow loop can run at a maximum superficial liquid velocity of 1 m/s and a superficial gas velocity greater than

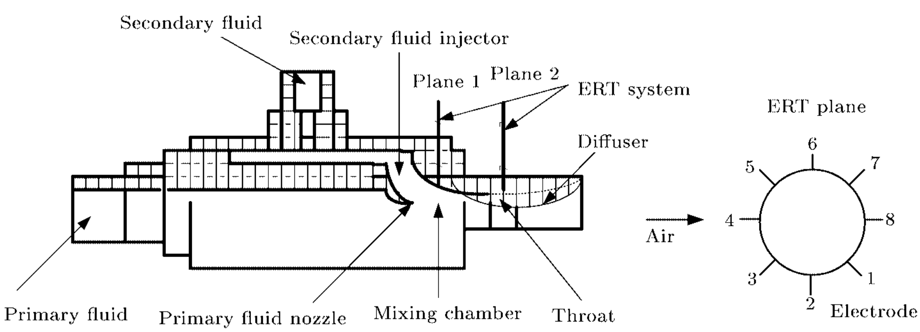

Fig. 1. Schematic of a new jet pump with ERT sensors.

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40 m/s. Tomographic sensors with four sensing planes were installed in the flow loop to obtain the in-situ phase fraction and flow patterns. Tap-water (conductivity 0.284 mS/cm and temperature $21 \pm 0.3^\circ$C) was used as the liquid phase which was scaled with an accumulating tank during the experiments to obtain the water flow rate and superficial velocity, and air was introduced into the flow loop, which was measured by a gas flow meter. Liquid phase and gas phase were fed into the pipeline via the jet pump with dual-plane ERT sensors. In this work, we concentrate our attention on a particular jet pump, the liquid-jet-gas pump (LJGP). This device uses a liquid as the primary fluid and will use compressed air as a secondary fluid. The schematic of the new jet pump with ERT sensors is shown in Fig. 1. Photographs were recorded as visual presentations of these different flow patterns.

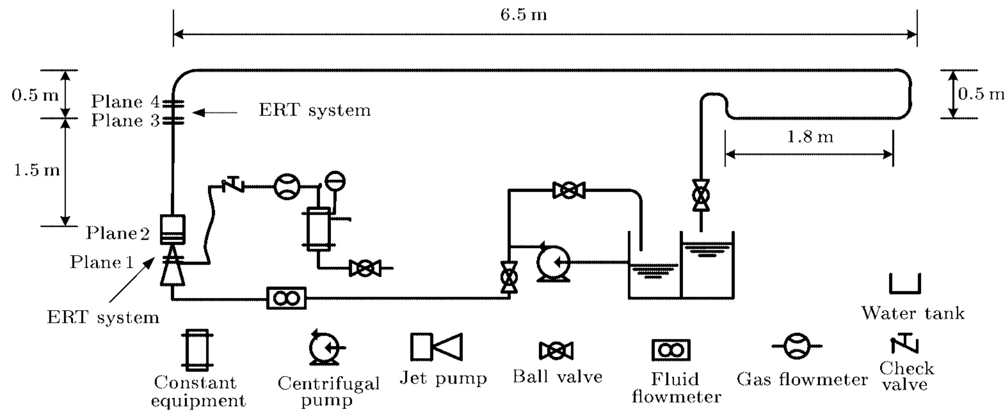

Fig. 2. Schematic of the test flow loop.

Experimental results presented here were obtained from an ITS 2000 ERT system (Industrial Tomography Systems Ltd. P2000) in monitoring gas–liquid flow in the jet pump and vertical pipes at various superficial velocities. In each plane, eight stainless steel electrodes are mounted flush to the surface at equal intervals. Since the current data collection speed was still limited, we set the distance between the two sensing planes in the vertical pipe to be 50 mm and the distance between the two sensing planes in the jet pump to be 30 mm. The voltage potential differences for tomography images were collected by using the normal adjacent protocol, with a data collection speed of 58 frames per second at an ac current injection frequency of 38400 Hz and a current value of 15 mA for flow pattern recognition, and with a 5 frames per second at the signal frequency of 9600 Hz for average fraction calculation. With the development of the image technology, some authors adopted different methods to study the image reconstruction and obtained some preferable results.[8–11] In this work the reconstruction of the image was carried out by using the linear back protection (LBP) algorithm to product the image fast and truly. The average void fraction was determined from Maxwell equations.[12,13] The concentration profile obtained using ERT could be erroneous to a certain level due to the highly sensitivity of factors, such as the accuracy of the electrical measurement made at the system boundary and image reconstruction algorithm used. Reference measurement error of 1% could lead to conductivity error of up to 10% depending on the magnitude of the conductivity charge.[14] In this work, prior to collecting data we calibrated the ERT system and took the reference frame when the sensor was full of liquid only so that the reference measurement error could be controlled within 1%.

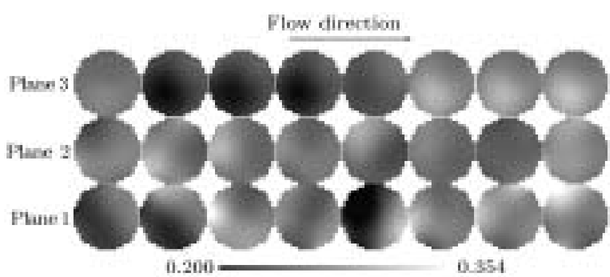

Fig. 3. Reconstructed two-dimensional images in terms of typical in-situ phase fraction in the jet pump and the vertical pipes, respectively, at superficial water velocity 0.008 m/s and superficial gas velocity 0.170–0.212 m/s, with the water-gas conductivity in the range from 0.200 to 0.354 mS/cm.

Two-dimensional (2-D) slice images were sequentially reconstructed using an ITS 2000 ERT system. Figure 3 shows that typical in-situ air fraction in jet pump and the vertical pipe under slug flow regime. Here the dark areas represent the air cavities or low conductivity regions, and the bright areas represent the water or high conductivity regions. These slice images were accumulated to show the flow patterns. It can be seen from plane 3 in Fig. 3 that a long series of bubbles are moving through the vertical test section. Furthermore, it can be also observed from a comparison between planes 1 and 2 that the flow of gas-phase in the jet pump may be rotational round the axes. This will be investigated in detail in a future study using a new fast ERT system.

Flow patterns in three different planes in both the vertical test section (plane 3) and jet pump (plane 1 and 2), namely bubble, bubbly and slug, are shown in Fig. 4. The flow patterns were stacked within three different planes with 10 continuous images from a data set of 400 images for bubble and bubbly flow, and 20 continuous images from 500 images for slug flow. Different flow patterns between the jet pump and the vertical section can be clearly imaged by ERT using the conductive ring sensing strategy under the same superficial velocities. It is shown from the comparison between planes 1 and 2 in Figs. 4 that the liquid jet leaves the nozzle at the position of plane 1 simultaneously with the air phase. It is clear that gas phase is continuous, most of the air is moving along the boundary near the injector. After entering the throat, the phases start to mix strongly as can be seen on plane 2 in Fig. 4. In the mixing process in the throat region, in which the liquid jet entrains, accelerates and compresses the gas, the transfer of momentum from the liquid serves largely to compress the gas in which significant momentum transfer is involved in increasing the kinetic energy of air phase. It can be seen that both gas- and liquid-phase distributions and their dynamical varying processes (flow processes) in the jet pump and in the vertical pipe can be clearly demonstrated using the ERT technique. Furthermore, we can also acquire from plane 2 in Figs. 3 and 4 that for the design of the jet pump, the accustomed assumption of the two-phase flows at the throat consisting of homogeneous bubble mixtures of a gas in a continuous liquid is incorrectness under some conditions in which gas phase may also be continuous.

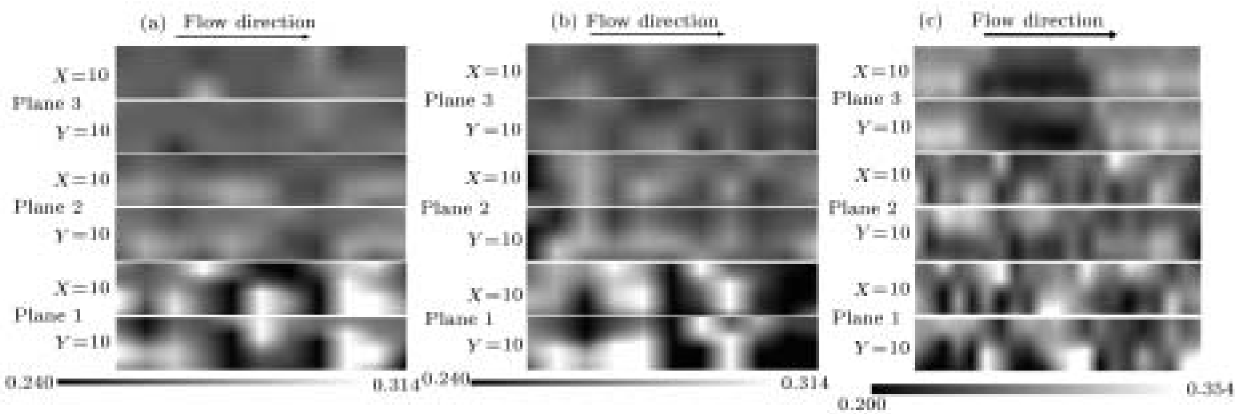

Fig. 4. Flow pattern recognitions in three different planes with a mixture of water and gas (water conductivity 0.284 mS/cm). (a) Bubble flow: frames from 250 to 260 at superficial water velocity 0.395 m/s and superficial gas velocity 0.008–0.024 m/s with the water-gas conductivity in the range 0.240–0.314 mS/cm. (b) Bubble flow: frames from 250 to 260 at superficial water velocity 0.785 m/s and superficial gas velocity 0.127–0.153 m/s. (c) Slug flow: frames from 240 to 260 at superficial water velocity 0.008 m/s and superficial gas velocity 0.170–0.212 m/s with the water–gas conductivity in the range 0.200–0.354 mS/cm.

For each superficial velocity, 350 images were collected for all the loading concentrations. The images were averaged and merged over the recorded voltage values. From the merged images produced for each plane, the concentration profile can be obtained from the Maxwell equation. The mean concentration can be calculated from

$$\bar{C}_V = \frac{\sum_{i=1,j=1}^{i=n,J=n}(C_{i,j}, A_{\rm pixel})}{A_{\rm total}},$$

where $A_{\rm pixel}$, $A_{\rm total}$ $C_{i,j}$ and n are the area of pixel, the area of pipe, the in-situ phase fraction and the grid number, respectively. Since there are 316 pixels in the linear back projection algorithm, and the area of each pixel is $6.2\,\rm mm^2$, the area of the pipe is $1963\,\rm mm^2$ according to the diameter 50 mm. Table 1 lists the mean concentrations of three different planes under bubble flow, bubbly flow and slug flow, respectively. It can be found that from the obtained concentration data, the mean concentration of gas phase at the position of plane 2 (i.e. the throat) is smaller than those at positions of planes 1 and 3 due to the compressible characteristics of gas phase. Furthermore, owing to the effect of the slip velocity and gas condensability on phase fraction, the mean concentration in the vertical pipe will also be lower than those at the position of plane 1, as listed in Table 1.

Figure 5 shows the plot of the calculated mean concentration at the different plane positions against the axial position with slug regime. To obtain preferable results, the mean concentration at each plane is calculated by using the average value of three sets of data, and each set of data consists of 350 images. The fluctuation of mean value among the three sets of data is around 5%. As mentioned above, the void fraction near the left pipe well (electrode 5) is higher than those near the right as a result of the position of air injector.

Table 1. Mean concentration of different planes under the same superficial velocities.

Superficial water velocity	Superficial gas Velocity	Plane 1	Plane 2	Plane 3	Plane 4	Flow pattern in vertical pipe
0.785 m/s	0.008~0.024 m/s	0.51%	0.13%	0.24%	0.28%	Bubble
0.785 m/s	0.051~0.076 m/s	1.63%	0.32%	0.56%	0.70%	Bubbly
0.008 m/s	0.170~0.254 m/s	10.9%	6.99%	8.39%	7.98%	Slug

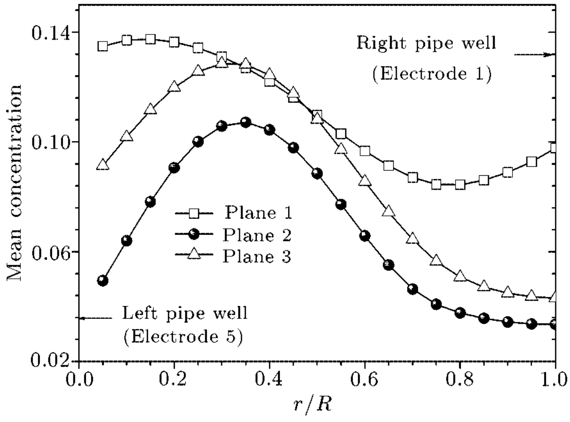

Fig. 5. Dependence of the mean in-situ concentration on the axial position within slug regime under superficial gas velocity 0.170–0.254 m/s and superficial water velocity 0.008 m/s.

In summary, to understand the performance of a two-phase jet pump which influences on the flow pattern, we have experimentally investigated the in-situ phase fraction and flow patterns in a jet pump on a vertical pipe using the ERT technique. A series of experiments are carried out, and an ITS 2000 ERT system is used to monitor the gas–liquid flows in jet pump and vertical pipes at different superficial velocities. The results suggest the flow patterns recognition using ERT system can not only be applied for most two-phase flow regimes, but also for the visualization of the complex system. Furthermore, the visualizations of a rapid mixing process in the throat of a jet pump obtained in the present work provide a reliable basis for theoretical study and optimal design of jet pumps.

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References

[1] Folsom H G 1948 *Chem. Eng. Progress* **44** 765
[2] Takashima Y 1952 *J Sci. Res. Inst.* **46** 230
[3] Jiao B 1985 *Behavior of Hydraulic Jet Pumps When Handing A Gas–Liquid Mixture* (University of Tulsa, OK)
[4] He P J et al 2004 *Adv. in Water Sci.* **15** 296
[5] Xu J Y Wu Y X and Li D H 2005 *J. of Exp. in Fluid Mech.* **19** 49
[6] Wang M et al 2001 *Proceedings of the 2nd World Congress on Industrial Process Tomography* (Hannover Germany ISBN0853162247) p726
[7] Wu Y et al 2005 *Can. J. of Chem. Eng.* **83** 37
[8] Cao L F et al. 2005 *Chin. Phys. Lett.* **22** 865
[9] Ding D H et al 2004 *Chin. Phys. Lett.* **21** 1067
[10] Zhai F X et al 2005 *Chin. Phys. Lett.* **22** 2843
[11] Tang Y Z et al 2004 *Chin. Phys. Lett.* **21** 1064
[12] Maxwell J C 1881 *A Treatise on Electricity and Magnetism* (Oxford: Clarendon Press)
[13] George D L et al 2000 *Int. J. of Multiphase Flow* **26** 549
[14] Wang M Mann R Dickin F J 1999 *Chem. Eng. Comm.* **175** 49