The GVF measurement and flow regime study of gas-water flows by ERT sensor

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***Abstract*—Two typical 8-electrodes electrical resistance tomography (ERT) sensors installed on the venturi throat were used to measure gas-water two-phase flows both in horizontal and vertical pipeline with different gas volume fraction (GVF) and liquid flow rate. The range of GVF is from 8% to 95% and liquid flow rate is from 1m3/h to 6m3/h. By observing glass window and 3D ERT reconstruction image, the gas-water flow distributions can be visualized in real-time. A normalization process of reconstructed image is used to describe the relative conductivity. Meanwhile GVF is calculated according to Maxwell and Begovich models.**

Keywords—electrical resistance tomography, gas-liquid flow, GVF, flow regime

I. INTRODUCTION

Gas-liquid two-phase flows widely exist in petroleum, chemical engineering, metallurgy engineering and other industrial processes. On-line accurate measurement of gas-liquid two-phase flows is significantly valuable to improve production efficiency and security[1][2]. Compare with single phase flow, multiphase flows are more complex, unpredictable and hard to modeling. It is still a challenge problem to accurately measure multiphase flows considering the existence of relative movement and complex and variable flow regimes[3]. Electrical resistance tomography (ERT) has been a researcher hot spot in the field of industrial process parameter measurement [4][5]. ERT has the advantages of non-intrusive, easy, low cost, non-radioactive and quick response and has been proven to be a powerful tool to measure the distribution of the conductive flow, say gas-water flows [6]. In this work, an experimental facility with ERT sensors located on vertical and horizontal venturi throat are used to investigate the dynamic experiments of gas-water two-phase flow regimes. Gas volume fraction (GVF) in different flow conditions, say from 8.07% to 95.38% and water flow rate is from 1 to 6m3/h are estimated. 3-D images are reconstructed to reveal the flow regimes base ERT sensors measurements.

II. METHODOLOGY

A. Principle

A typical ERT system is composed of three main parts including ERT sensor, data acquisition system and the image reconstruction unit/computer [7]. ERT sensor is used to measure mutual impedance, which consists of a set of electrodes mounted around pipe wall. The role of data acquisition system is to provide excitation current for sensors and convert analog electrical signals with noises to reliable digital measurements for image reconstruction unit. Due to media conductivity is different, i.e. water has a higher conductivity than gas, the conductivity distribution will change with media distribution, then it will affect the electric field distribution in the domain of interest and result in the difference on the voltage measurements of ERT electrodes pairs. So by measuring potential difference between ERT electrodes pairs, the phase distribution can be obtained. The exciting mode used in ERT is two electrodes current exciting mode. Current is injected into a pair of adjacent electrodes and then the voltages are measured from other pairs of adjacent electrodes, a total of N*(N-3)/2 independent measurements can be made where N is the number of electrodes [8].

The problems of ERT can be divided into two categories: the forward problem and inverse problem [9]. In image reconstruction, to reduce system errors caused by the methods of FEM mesh generation, measurement circuit, experimental environment, etc, the voltage measurements should be normalized. In general, take the measurements when the pipe is full of water as the high calibration, so the normalization formula is given by:

$$V_n = (V_m - V_w) / V_w \quad (1)$$

where V_n is normalized voltage measurements, V_m is measured voltage data, V_w is the calibration data. The relationship between normalized voltage measurements and conductivity distribution [10]can be expressed as:

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$$V_n = -S_n \sigma_n \ (2)$$

where Sn is normalized sensitivity matrix and formulated as equation (3), σ_n is normalized conductivity distribution. The minus sign indicates conductivity and measurements have opposite change direction.

$$S_n^{i,j} = S^{i,j} / \sum_{k=1}^{M} S^{i,k} \ (3)$$

where S is sensitivity matrix , j is pixel number and M is total number of image pixels.

It is necessary to find the inverse of Sn to solve σ_n based on the known measurements Vn, but Sn is always irreversible, therefore direct solving method does not work. In Linear back projection (LBP) [11], transpose matrix S_n^T is used as an approximation of S_n^{-1}.

$$g = -S_n^T V_n \ (4)$$

where g is the gray level of reconstruction image and can reflect conductivity distribution in field. To make the gray value equal to relative conductivity, i.e. range is from 0 to 1, a normalization process for reconstruction image are made [12].

$$g' = g / (-S^T u) = (S_n^T V_n) / (S_n^T u) \ (5)$$

$$g'' = 1/(1+g') \ (6)$$

where u=[1 1 ... 1]T. If the error of each cell caused by image reconstruction algorithm is considered to be linear, the relationship between g'' and relative conductivity can be given by:

$$g'' = \sigma_m / \sigma_w \ (7)$$

For the gas-water flows, the conductivity of mixture is less than conductivity of water single flow, therefore the gray value of image should be between 0 and 1.

B. Calculation of GVF

Theoretically, voltage measurement is inversely proportional to conductivity, therefore the mixture conductivity ratio of gas-water flows σ_m / σ_w can be calculated by V_n.

$$\sigma_{\mathrm{m}} / \sigma_w = 1/(V_n + 1) \ (8)$$

The relationship between conductivity and GVF varies from one flow regime to the next. In this paper, two models are used to calculate GVF. One is Maxwell model [13], which is the most common model:

$$GVF = 1 - \frac{3\sigma_m / \sigma_w}{\sigma_m / \sigma_w + 2} \ (9)$$

The other one is Begovich model [14], which applies to annular flow, and the formula is shown below:

$$GVF = 1 - \sigma_m / \sigma_w \ (10)$$

According to formula (8), (9) and (10), it is found that the actual conductivity of water is not necessary for calculating GVF, V_n, i.e. voltage measurements of the gas-water flows is used to calculate the GVF.

III. EXPERIMENTS

A series of dynamic experiments of gas-water two-phase flows in horizontal and vertical pipeline were run on a semi-industrial gas-oil-water multiphase facility in Graduate School at ShenZhen, Tsinghua University. Fig. 1 shows the scheme of the facility. Oil and water stored in the separator can be simply separated based on gravity principle. The pipelines shown in blue color represent the gas, oil and water each single phase. Oil and water phases are pumped from the separator and gas phase will be generated from gas compressor. Thus three-phase mixture will go pass through the horizontal and vertical 2, 3 or 4 inches test line (in gray color). The length of test line is design as 8 meters. Different sensor sections, e.g. ECT, ERT or ultrasound can be located on the test line. The maximum flow rate of oil, gas and water are 25 m3/h, 18 m3/h and 750 Nm3/h respectively. The maximum pressure the facility can hold is 1.2 Mpa.

In this paper, two 8-electrodes ERT sensors are located in venturi throat section where the inner diameter is 30 mm, one of which was installed on horizontal pipeline and the other one was installed on vertical pipeline. The length of ERT sensors are 60mm and the electrodes are 30mm. The 16-channel AC-based ERT data acquisition system is used to take measurements from two ERT sensors. The excitation frequency for ERT system is 20 kHz and the signal-to-noise ratio of the hardware system is ~62 dB. The data sampling frequency is about 120 frame/s.

In this work, both horizontal and vertical flow with different GVF and liquid phase flow rate were tested. The range of GVF is from 8.07% to 95.38% and liquid phase flow rate is from 1 to 6m3/h. The gas-water two-phase flows are generated under 0.6 Mpa pressure condition. The temperature of the flow is about 26 degree centigrade. Table 1 shows the summary of experimental conditions. In the course of the experiment, the data are collected after waiting about 15 minutes to stabilize flow rates and the sampling time is about 180 seconds.

TABLE I. SUMMARY OF EXPERIMENTAL CONDITIONS

Index	Liquid phase flow rate[m^3/h]	GVF[%]	P[kPa]	T[℃]
1	1	34.62/54.68/72.83/95.25	600	26
2	2	10.95/28.31/50/73.01/90.51/95.38	600	26
3	3	12.05/27.21/54.26/68.67/88.91/95.11	600	26
4	4	8.07/27.88/53.30/67.43/87.75	600	26
5	6	11.60/32.35/49.97/71.37/89.88	600	26

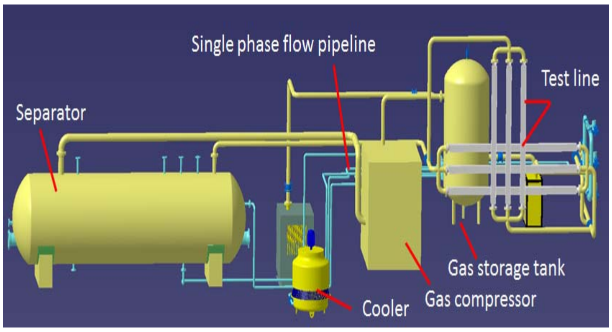


Fig. 1. Scheme of gas-oil-water flow facility.

IV. RESULTS AND DISCUSSIONS

A. Image reconstruction of flow regimes

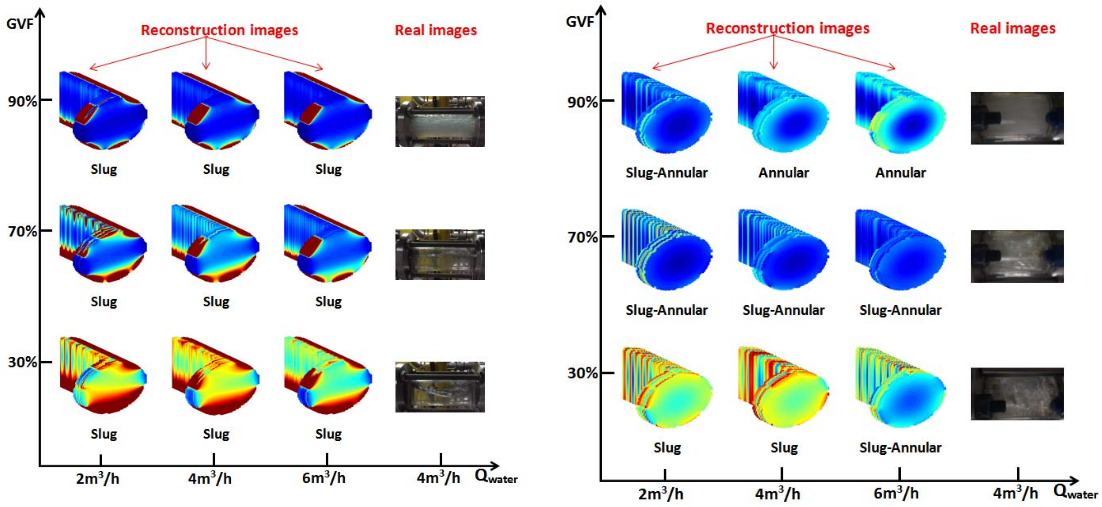
3D images are reconstructed to reveal the flow regimes of gas-water two-phase flows in both horizontal and vertical pipeline. Fig. 2 shows partial results for horizontal flow and vertical flow, including the images of Qwater= 2, 4 and 6 m3/h and GVF =30%, 70% and 90%. The 3D images consist of 3000 frames instantaneous 2D images and the imaging algorithm is shown as equation (4), (5) and (6). The real images of flow in pipeline when Qwater= 4 m3/h and GVF = 30%, 70% and 90% are also provided. For the horizontal flow, the real images when the pipe is almost full of water are specifically chosen to illustrate that horizontal flow is slug flow but not simple stratified flow, which can be easy to seen from the reconstruction images. For vertical flow, the selection criteria is that the flow regime presented in image should most like annular flow.

As shown in Fig. 2, gas-water flow in horizontal pipeline present slug under all test conditions as summarized in Table 1, and due to the effect of gravity, there was always a water layer in the bottom of pipe. If the water flow rate is constant and GVF increases, i.e. gas flow rate increases, it is observed that the height of interface between water and oil and the gray value in the top of cross-section decreases. In other word, the liquid holdup reduces and void fraction increases. Besides, as gas flow rate increases, more and more water disperses in gas, flow regime has the trend from slug flow to mist flow. For the case that GVF remains the same and water flow rate increase, i.e. water flow rate and gas flow rate rise proportionately, the flow pattern is still slug flow but the frequency of liquid slug increases.

For vertical pipeline, the flow regime is between slug and annular flow. Gas-water flows show slug when the GVF and water flow rate are small, which can be seen from the images. The blue represents full gas and it appeared from time to time in the slug flow images. With the increase of GVF and water flow rate, a gas core appeared in the middle of the pipe and the liquid slug frequency increased. It has the trend from slug flow to annular flow. It is also found that the images are more symmetrical than horizontal pipeline.

B. Calculation of GVF

The 20 independent measurements can be categorized into three groups, i.e. adjacent-pair, 1-electrode apart and and 2-electrode apart measurements. Fig. 3 shows the relationship between average normalized voltage measurements of different groups and reference GVF for both horizontal and vertical flows. When GVF is small, the normalized voltage measurements is close to zero and it will increase with GVF. For ERT on horizontal pipeline, the measurements grow non-linearly as the GVF increases, which conforms with the Maxwell model. But for ERT on vertical pipeline, the measurements present linear growth when GVF is greater than 50%. This illustrates that Maxwell model does not apply to annular flow. It is found that voltage measurements in the group with the same GVF are different, especially if GVF is greater than 50%. This is because although the GVF is the same, the flow rate of water and gas are various, and the superficial velocity of flow is also diverse, so the flow regimes present differently, which can be seen from reconstructed images shown in Fig. 2 . Among all measurements, the measurement of adjacent electrodes in horizontal pipe is least affected by the flow velocity. Comparing with horizontal scatter plots, the vertical scatter plots of adjacent electrodes, 1-electrode apart and 2-electrode apart measurements are similar, particularly, they are nearly identical. This indicates that the flow regime of vertical flow is more symmetrical.



(a) horizontal pipe (b) vertical pipe

Fig. 2. 3D ERT image reconstruction of gas-water two-phase flows, red represents full water, blue represents full gas.

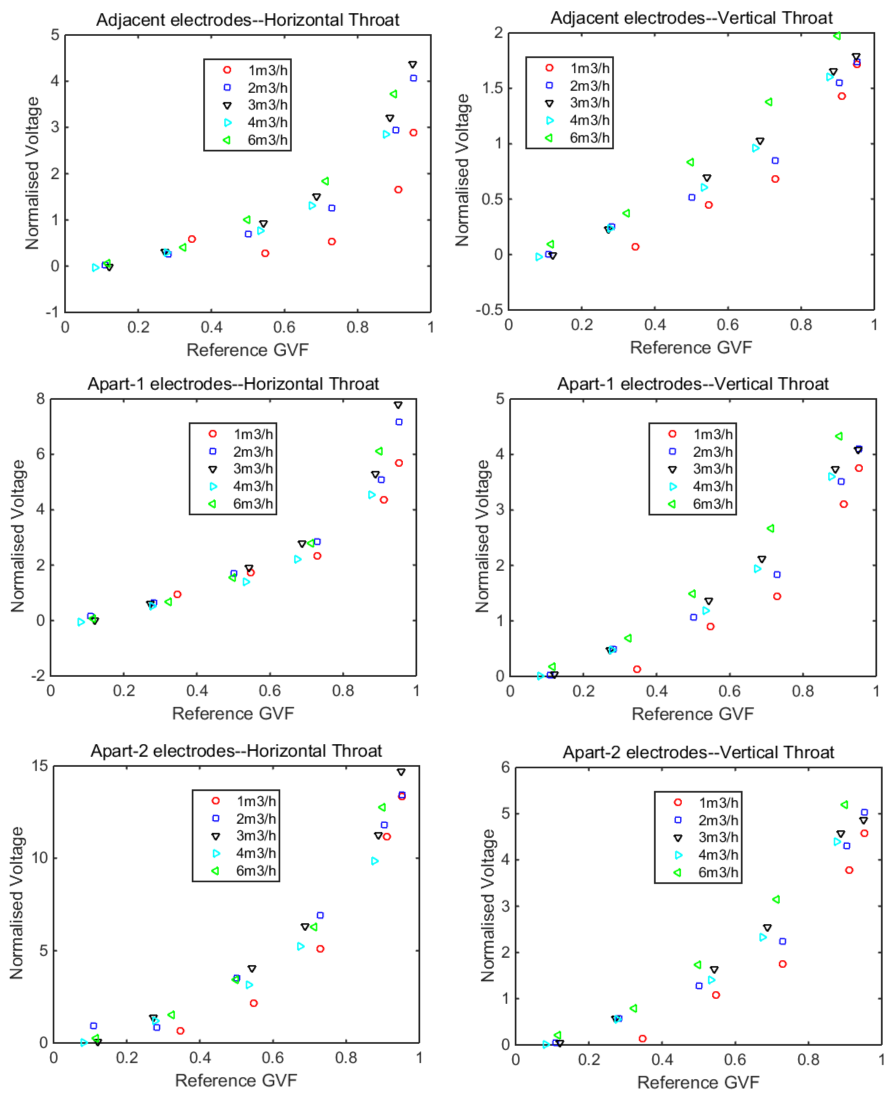
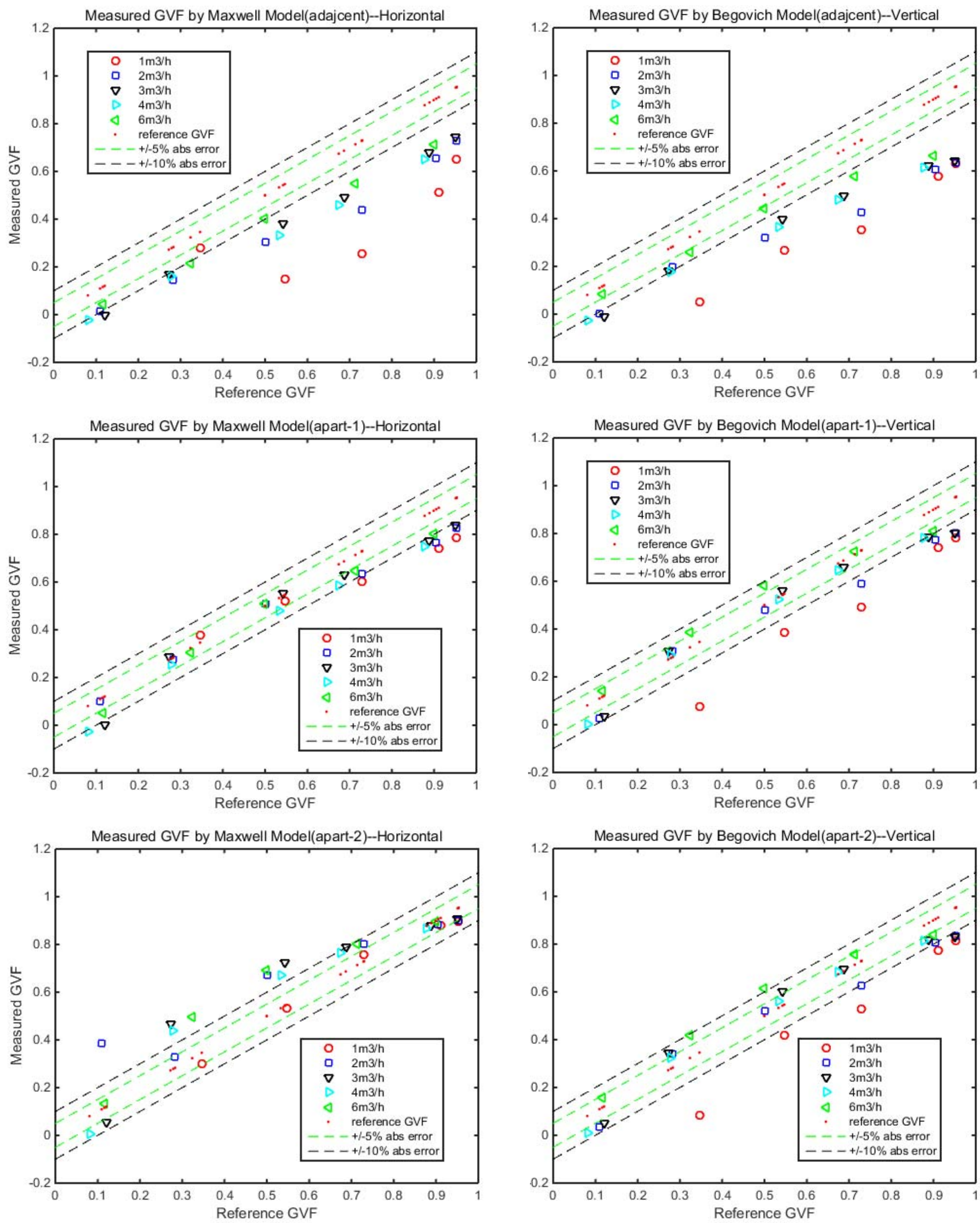


Fig. 3. The relationship between normalized voltage measurements and reference GVF: (left) horizontal and (right) vertical



As indicated by image reconstruction, the horizontal flow is slug flow and vertical flow is between slug flow and annular flow, thus different models are used to calculate GVF, i.e. Maxwell model is used in horizontal flow and Begovich model is used in vertical flow. The results are shown in Fig 4. For horizontal flow, the measurements of 1-electrodes apart are recommended to calculate GVF and the absolute error is less than 15%. For vertical flow, the results of 1-electrode and 2-electrode apart measurements are similar and the absolute error are less than 15% except the result of water flow rate equal 1m3/h. The vertical results are abnormal when GVF=30% and Qwater=1m3/h. This could be because that over lower flow velocity and liquid slug frequency result in that the data were collected when the pipe was full of water. As shown in the Fig. 4, when the GVF is greater than 90%, the calculated GVF is lower than reference GVF, probably because relative slip-movement between water and gas surfaces occurs growing influence of different velocity between water and gas.

V. CONCLUSION

This paper investigated the flow regime and GVF calculation of gas-water two phase flows both in horizontal and vertical pipeline with different GVF and liquid flow rate. In horizontal pipeline, gas-water flows present slug flow regime and the liquid slug frequency changes with the flow rates of gas and water. In vertical pipeline, with the increases of the gas-water flow rate, the flow regime of gas-water flow varies from slug flow to annular flow. Maxwell and Begovich models are used to calculate GVF of horizontal and vertical flow respectively. The measurements of 1-electrode apart are strongly advised where the absolute error is less than 15%. When GVF is high, the influence of relative movement between gas and water should be considered. Future work will focus on improvement of model to calculate both GVF and the flow rate.

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