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Application of electrical resistance tomography system to monitor gas/liquid two-phase flow in a horizontal pipe

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Abstract

The Electrical Resistance Tomography (ERT) technique possesses great potential in monitoring widely exiting industrial two/multi-phase flow. For vertical pipe flow and inclined pipe flow, some application studies with exciting results have been reported, but there is rarely a paper regarding the application of ERT to horizontal gas/liquid pipe flow. This paper addresses this issue and proposes a smart method, Liquid Level Detection method, to conventional ERT system. The enhanced ERT system using the new method can monitor horizontal pipe flow effectively and its application is no longer restricted by the flow conditions. Some experimental results from monitoring an air/water slug pipe flow are presented.

Keywords: Electrical resistance tomography (ERT); Flow regimes identification

1. Introduction

Electrical Resistance Tomography (ERT) technique has greatly progressed since it was invented in the 1980s as a kind of Process Tomography (PT) technique. With a lot of advantages [2], such as visualization, high speed, low cost, no radiation hazard, and non-intrusive, etc, ERT is a promising technique to monitor widely existing industrial conductive two/multi-phase flows, not only providing conductivity images, but also being able to measure some flow parameters [9]. Some researchers have presented their attractive investigation results on this subject. For example, Loh et al. used ERT to monitor a non-conductive solid and conductive liquid two-phase flow in vertical and inclined pipes [7]; Cho et al. demonstrated that it was feasible to apply EIT (Electrical Impedance Tomography) to visualize the bubble distribution in a two-phase flow [8]; Tsoukalas et al. proposed a neurofuzzy methodology for flow identification based on signals obtained from an impedance void meter [4].

However, until today, there has rarely been a paper regarding the application of the ERT technique in monitoring gas/liquid two-phase flow in horizontal pipes. To understand why, flow regimes in horizontal pipes and vertical pipes are shown in Figs. 1 and 2 separately [1]. An intrinsic difference between the two groups of flows can be seen: the gas phase is always encircled by liquid phase so it does not touch the pipe wall in vertical flows, but in some horizontal flows, such as stratified flow, wave flow, slug flow and plug flow, under the gravity action the gas–liquid separation phenomenon exists and

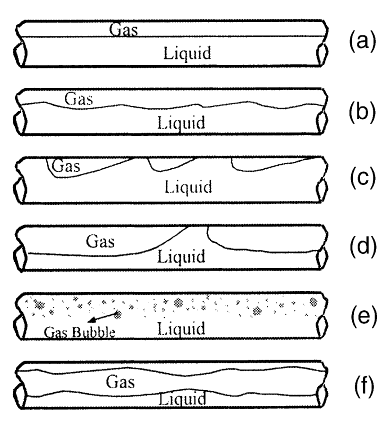

Fig. 1. Gas/liquid two-phase flow regimes in horizontal pipe. (a) Stratified flow (b) wave flow (c) slug flow (d) plug flow (e) bubbly flow (f) annular flow.

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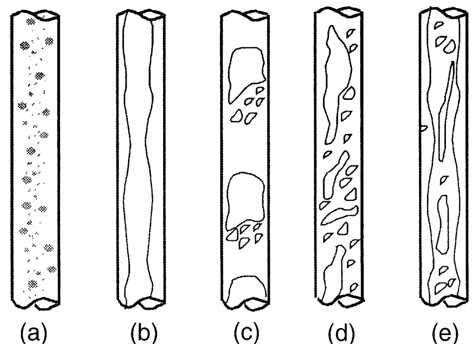

Fig. 2. Gas/liquid two-phase flow regimes in vertical pipe. (a) Bubbly flow; (b) annular flow; (c) slug flow; (d) chum flow; (e) annular wispy flow.

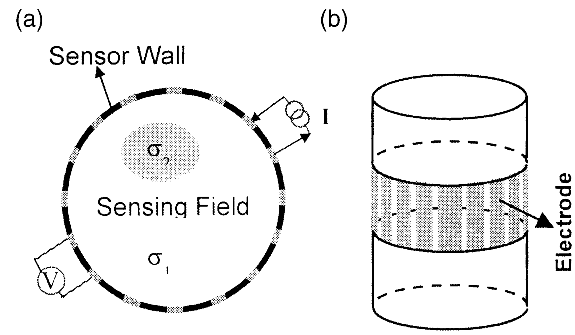

Fig. 3. Sensing array of TERT-1 system. (a) Cross-sectional image (b) 3D image. Electrode size: 5×12 mm^2; pipe inner diameter: 50.0 mm.

the gas phase may touch the pipe wall frequently. So in horizontal flows, some electrodes may lose their continuous electrical contact with the measured flow, which results in false voltage data and hence incorrect images.

Because stratified flow, wave flow, slug flow and plug flow are exist most widely in horizontal pipes, conventional ERT technique cannot be used to monitor horizontal pipe flow. To widen the ERT application range, this paper will concentrate on the interface characterization of horizontal pipe flow using an ERT system. The regularity of ERT voltage data collected under horizontal air/water flow condition has been determined. A smart method based on the regularity, called Liquid Level Detection method, can detect the water surface position effectively, which greatly enhances the ability of an ERT system in monitoring conductive horizontal two-phase pipe flow. Some experimental results and conclusions are given.

2. Measurement experiments

Experiments presented in this paper use an ERT system to monitor an air/water two-phase flow in horizontal pipe. The ERT system is developed by the process tomography group in Tianjin University, PR China, marked as TERT-1. Experiments were carried out on the flow loop set up in the Institute of Mechanics, Chinese Academy of Sciences.

2.1. TERT-1 ERT system [10]

Fig. 3 shows the sensing array of the TERT-1 system. Sixteen titanium electrodes are flush-mounted on the inner sensor wall with equal spaces, which are used to inject current into the sensing field and also to transfer the responded potentials. Obviously, at the relatively low working frequencies of ERT technique, almost no current can be injected from and no potential can be transferred from an electrode if it contacts the non-conductive phase.

Voltage data (208) (only 104 data are independent) for each frame of image are collected by the TERT-1 Data Acquisition System (DAS) working in an adjacent measurement protocol [2] with a data collection speed of 7.04 frames/s at frequency of 23.44 kHz.

Fig. 4 shows the block diagram of the TERT-1 system architecture. Because the ERT technique assumes an in-phase response, an in-phase demodulator is therefore used in the system. The phase shifts caused by the gas component are ignored in the measurements.

2.2. Air/water two-phase pipe flow loop [3]

Fig. 5 describes the simplified scheme of the flow loop used in this paper's experiments. By controlling the pressure and flow rates of injected air and water, many two-phase flow regimes, such as bubbly flow, stratified flow, plug flow, slug flow, and wavy flow, can be developed in this facility. The flow loop is made of transparent Plexiglas pipe, totalling 20 m long with an inner diameter of 50.0 mm. The flow condition in the pipe can be watched directly, so it was easy to check the correctness of a flow measurement result. The ERT sensor is installed far from the jet pump where a flow regime is steadily created.

2.3. Liquid level detection method

In horizontal stratified flow, wave flow, slug flow, or plug flow, a curved liquid surface may frequently exist (as shown in Fig. 6).

The electrodes above the water surface may lose their electrical contact with the sensing field, which causes a great phase-shift in response potentials on these electrodes. Because the DAS of the ERT system neglects the phase shifts among all measurements, voltage data on these electrodes cannot reflect the true conductivity distribution. Even some voltage data are zero. The ERT image reconstruction algorithms cannot treat zero data, so the ERT system cannot reconstruct flow images from these measurements.

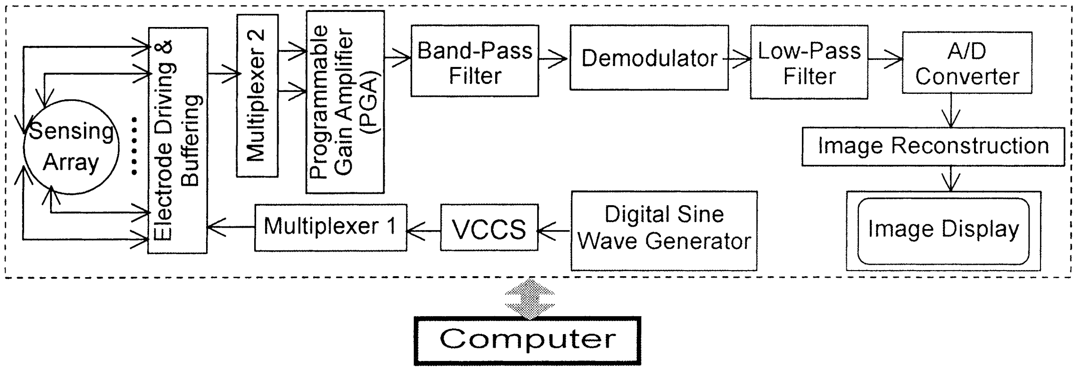

Fig. 4. Block diagram of TERT-1 system.

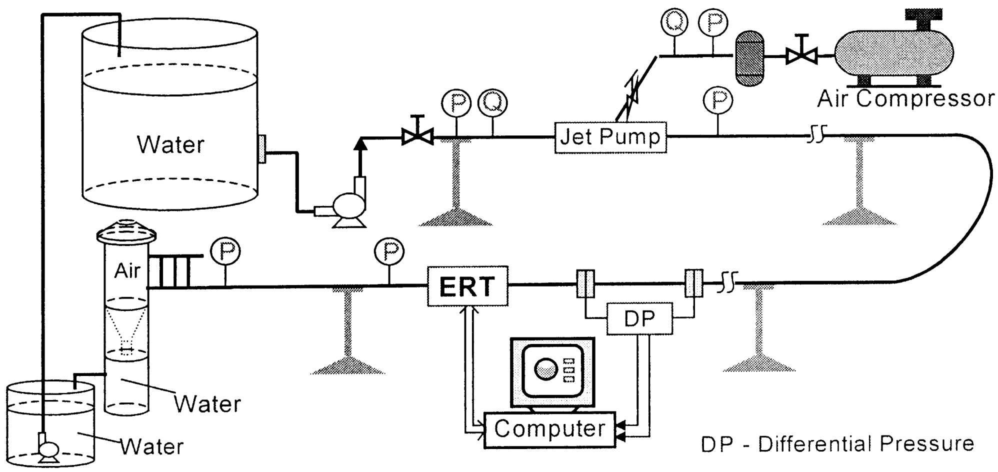

Fig. 5. Schematic of the air/water two-phase flow loop.

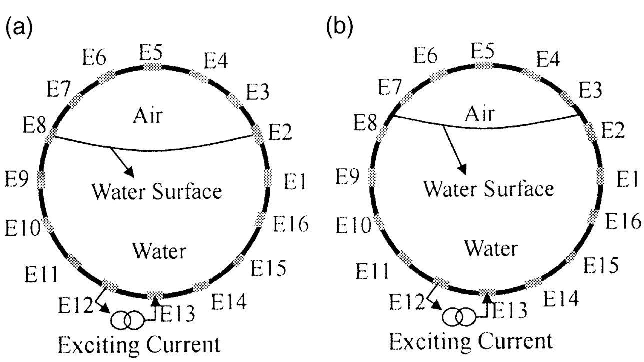

Fig. 6. Positions of air/water interface at cross section plane. (a) Touching electrodes, (b) touching pipe wall.

However, experiments showed that there is a common feature in the voltage data when some electrodes are above the water surface. Three sets of voltage data collected by TERT-1 system for full water flow and two air/water stratified flows are given in Table 1. Tap water was used in the experiments. An exciting current of 1.5 mA(P–P) was injected at electrodes E12 and E13 on the bottom of the pipe (see Fig. 6). The voltage data shown in the table were measured with a gain of 100.

Table 1
Measurements by TERT-1 system (unit: V)

No.	Electrode pairs	Full water flow	Fig. 6(a)	Fig. 6(b)
0	E14–E15	6.38	6.94	6.65
1	E15–E16	3.99	3.84	3.90
2	E16–E1	1.86	1.58	1.71
3	E1–E2	1.05	0.85	0.92
4	E2–E3	0.68	7.90	3.92
5	E3–E4	0.48	7.60	8.15
6	E4–E5	0.46	2.37	7.21
7	E5–E6	0.45	0.24	1.35
8	E6–E7	0.53	0.00	0.00
9	E7–E8	0.70	0.00	0.00
10	E8–E9	1.12	0.49	0.77
11	E9–E10	2.36	1.98	2.19
12	E10–E11	7.06	6.73	6.90

It should be noticed that in columns 3 and 4 of Table 1, measurements on electrode pair E2–E3 are significantly larger than that on electrode pair E1–E2 but the voltage data measured on electrode pair E2–E3 in column 4 are not as large as that in column 3. Another important feature is that the measurements on electrode pairs of E6–E7 and E7–E8 in columns 3 and 4 are zero.

When the water surface is in another position, the collected data are similar to that presented in Table 1, i.e. the voltage data is large when the measured electrode pair is switched from under the water surface to above the water surface and zero when the measured electrode pair is switched from above the water surface to under the water surface.

Based on this reproducibility, a Liquid Level Detection method has been put forward by the authors. The flow chart of the method is shown in Fig. 7.
The Liquid Level Detection method identifies whether a water surface exists in the sensing plane and finds out its position, from only 13 measurements collected in one excitation. For a 16-electrode ERT system, a total of 14 water surface positions including full pipe states, as listed in Fig. 8 can be recognized by this method.

The Liquid Level Detection method working schemes, as shown in Fig. 9, have been proposed for the ERT system used in different flow conditions. If the flow regime is steady, the ERT system will use the Fig. 9(a) scheme, which works in Liquid Level Detection mode when the flow is stratified, wave, slug or plug flow, and works in conventional ERT mode when the flow is bubble flow or annular flow. If the flow regime is unsteady, the ERT system will adopt the combined working scheme of Fig. 9(b). The system will initially identify whether there is a water surface in the sensing plane (whether there is zero measurement data) in each

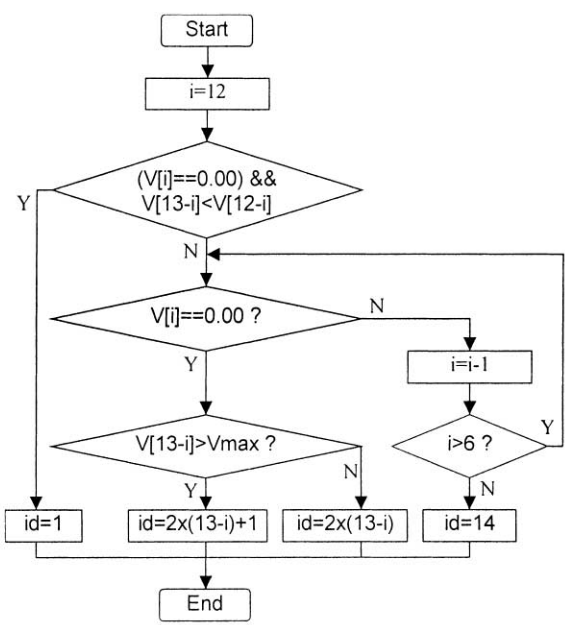

Fig. 7. Flow chart of the Liquid Level Detection Method. Here, $V[i]$ is the ith measurement of the total 13 measurements: V_{max} is the maximum value of the 13 measurements collected under full liquid flow condition; and id is the reference number of the liquid level position as shown in Fig. 8. *id*=14 indicates that there is no liquid surface in the sensing plane. The electrode number of the ERT system is 16.

measurement cycle. It will use the Liquid Level Detection method to give a flow image if there is a water surface, and will use conventional ERT technique to reconstruct flow image if there is no water surface in the sensing plane.

In Liquid Level Detection mode, only ($N-3$, N denotes the electrode number) voltage data has to be collected, so the system's working process can be speeded up to N times the conventional ERT technique which collects $N(N-3)$ voltage data for reconstructing one frame of image.

In Fig. 9(b) working scheme, the DAS collects ($N-3$) voltage data if there is a water surface in the sensing plane and collect $N(N-3)$ voltage data if there is no water surface in the sensing plane. The maximum data collection number is $N(N-3)$ for one frame of image, which is no more than conventional ERT technique. The system working speed will be at least the same as that in conventional ERT mode.

3. Experiment results and discussion

Experiments using the TERT-1 system to detect the water surface in static stratified pipe flow validated the accuracy and the effectiveness of the Liquid Level Detection method. This section will present some results from a dynamic experiment. The authors applied the Liquid Level Detection method to monitor a slug flow in laboratory flow loop.

The electrode array is installed at the cross-section plane A–A′ in Fig. 9(a). The TERT-1 system can provide successive flow images at plane A–A′. Because the flow regime is steadily created in the measurement pipe, the flow images along the pipeline can be constructed using historical cross-sectional images at plane A–A′ and the time taken to acquire one sectional image and the mean water velocity at each image.

In this experiment, according to the design principle of the jet pump (its location refers to Fig. 5), the superficial velocity of water in the flow loop is constant, and it was calculated to be 0.84 m/s from the water flow rate measured in the experiment. The transition velocity of water is equal to its superficial velocity divided by the water held up at the sensing plane. The time taken to acquire one frame data is 8.2 ms. The side-view images of a 2 m length flow from the sensing plane A–A′ to the plane B–B′ at different times were captured and shown in Fig. 10(b–g). The plane A–A′ is at the right hand of each image. The side-view images match very well to real flow conditions from direct observation. A slug photograph taken under the same flow condition is shown in Fig. 11 for reference.

The side-view flow image makes the flow regime identification more straightforward. Some important parameters, such as slug length, and void fraction etc,

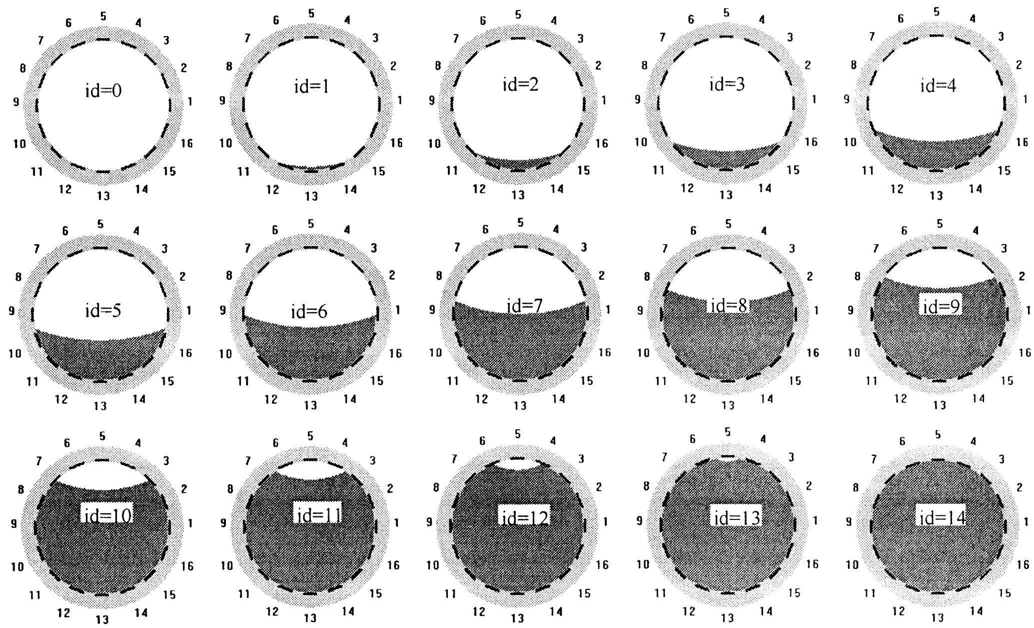

Fig. 8. Water surface positions assumed.

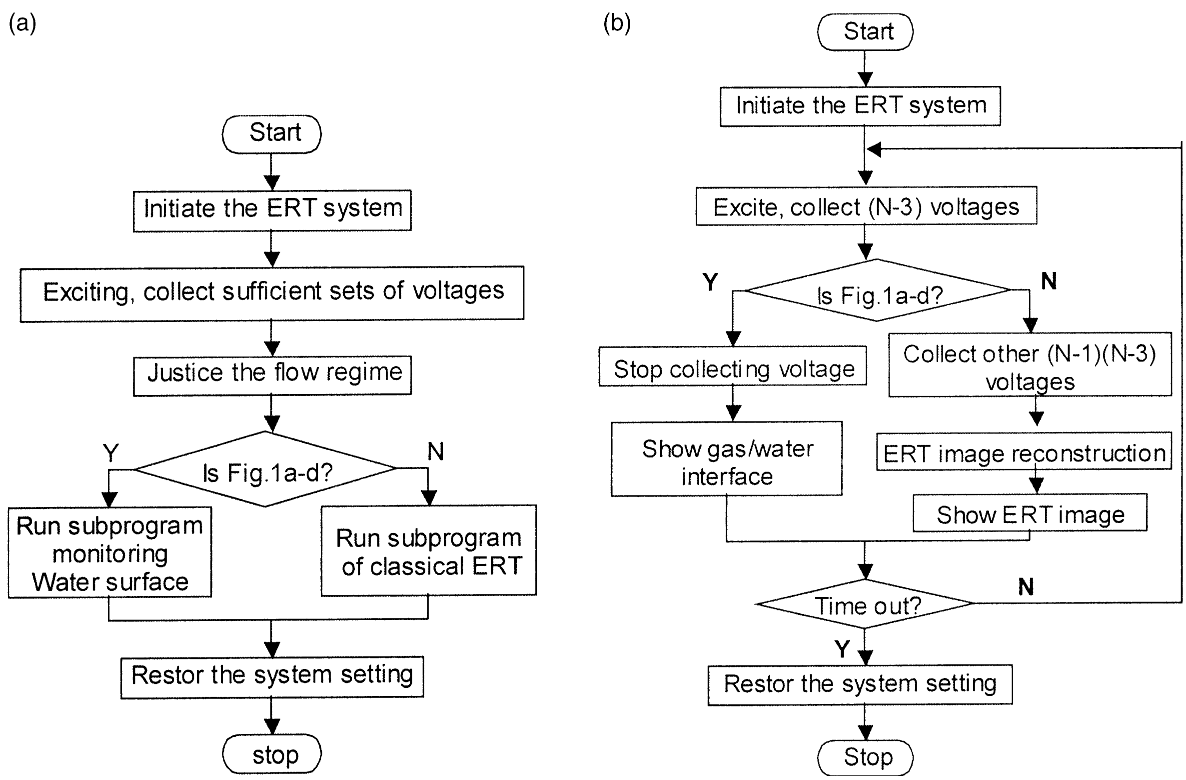

Fig. 9. Two working schemes of the enhanced ERT system used to monitor horizontal air/water pipe flow. (a) Flow regime is steady, (b) flow regime is unsteady.

can be estimated from cross-sectional images (as shown in Fig. 8) and side-view images as well. These parameters are important to process measurement and process control. In practical flow, the water velocity is unknown and should be measured by some kind of proper method.

The shape of the water surface in the above discussion is simply assumed to be a concave line and allocated at some assigned positions (centre points of electrodes and centre points of intervals between electrodes, as shown in Fig. 7) in the sensing plane. Although this may cause parameter estimation error to some degree, for some

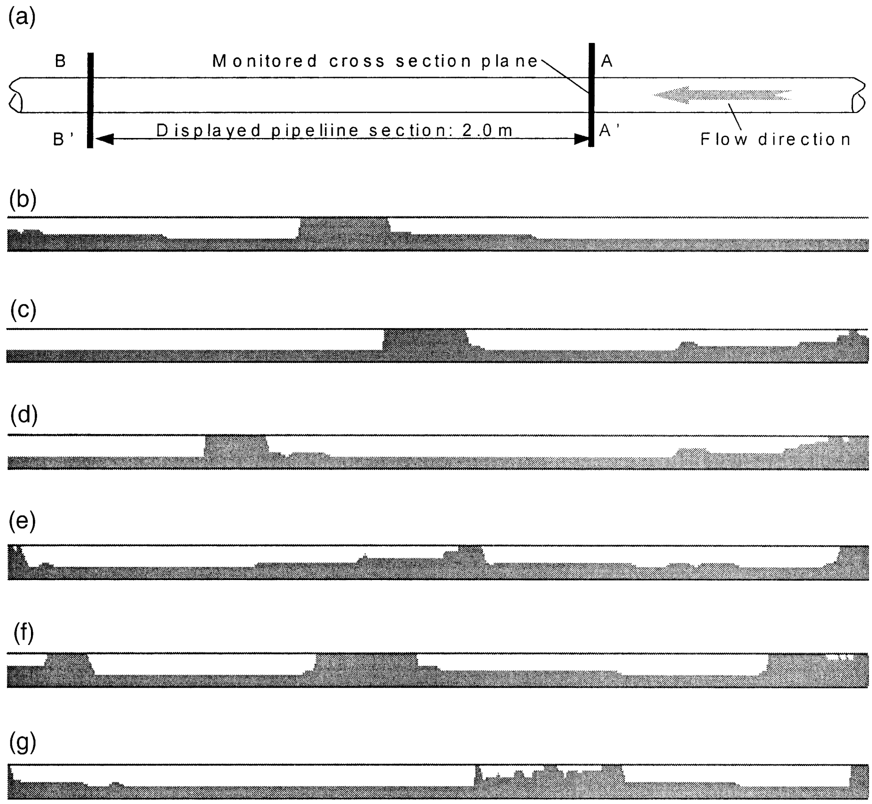

Fig. 10. Side-view images of a slug flow constructed using Liquid Level Detection method. (a) Illustration of displaying the side-view flow images, (b) side-view image at t=1.517 s (c) side-view image at t=3.854 s (d) side-view image at t=11.48 s (e) side-view image at t=25.4 s (f) side-view image at t=29.93 s (g) side-view image at t=38.13 s.

Fig. 11. A photograph of the slug flow.

application purposes, e.g. the identification of flow regimes, the exact position and shape of the liquid surface does not need to be known, or the estimation error is acceptable. In these cases, the ERT system with Liquid Level Detection method can be an effective monitoring means.

4. Conclusions

The Liquid Level Detection method proposed in this paper makes the ERT system able to monitor horizontal air/water pipe flows. Its imaging rate is much faster than the conventional ERT technique.

The precision of monitoring the water surface position is dependent on the electrode number in the ERT sensing array. The greater the number of electrodes, the better the precision. For the TERT-1 system with 16 electrodes, its electrode width and inner sensor diameter are 5 and 50.0 mm respectively, so the maximum monitoring error of the water surface position is less than 2.38 mm in the vertical direction.

When the ERT system works in Liquid Level Detection mode, there is plenty of information contained in the voltage data collected on the electrodes under the water surface that may be useful to improve the precision of water surface shape and position. Some mechanical models have already been proposed to predict the interface shape [5,6].

Other non-conductive gas and conductive liquid two-phase flows have similar electrical properties to air/water flow. So the Liquid Level Detection method can also be used to monitor other conductive gas/liquid pipe flows.

Combining the conventional ERT technique and the Liquid Level Detection method greatly enhances the ERT system to monitor horizontal conductive gas/liquid pipe flow.

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