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Fusion Research of Electrical Tomography with Other Sensors for Two-phase Flow Measurement

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The two-phase flow widely exists in the nature and industrial processes. The measurement of two-phase flows, including gas/solids, gas/liquid and liquid/liquid flows, is still challenging. Fusions of electrical tomography with conventional sensors provide possibilities to improve two-phase flow accurate measurement. In this paper, fusions of (1) electrical resistance tomography (ERT) with electromagnetic (EM) flowmeter, (2) electrical capacitance tomography (ECT) with ERT and (3) ECT with electrostatic sensor are introduced. Some research results of fusion methods are presented and discussed. This paper can provide the theoretical support for the multi-sensor fusion for two-phase flow measurement.

Keywords: Two-phase flow measurement, electrical tomography, fusion, multi-sensor

1. INTRODUCTION

WITH THE DEVELOPMENT of science and technology, the research on flow characteristics and changing rules of two-phase flow and measurement of flow parameters is of great significance. In addition, as the requirements of measurement, energy efficiency and control in industrial processes increase, requirements of two-phase flow parameter measurement are more and more urgent.

At present, the technical lines of two-phase flow parameter measurement can be divided into three categories [1]-[5]: (1) the use of conventional single-phase flow measurement techniques and instrumentations to realize the two-phase flow measurement. (2) Soft measure technique (Soft sensor) is employed to study and solve the two-phase flow measurement. Soft measurement (Soft sensor) is the on-line process parameter estimation method for the two-phase flows measurement using the easily online acquired assistant process variables and off-line information analysis techniques. In soft measuring techniques, the fuzzy mathematics, state estimation, parameter identification, wavelet transform, artificial neural network, pattern recognition, and modern spectral estimation theories are commonly adopted. (3) The modern new techniques such as radiation, laser, optical fiber, nuclear magnetic resonance, ultrasonic, microwave, spectrum, new tracer, cross-correlation and the process tomography techniques are applied in the two-phase flow parameter measurement.

As we know, single-phase flow parameter measurement is relatively mature. For example, electromagnetic flowmeter, Coriolis mass flowmeter and Parshall flume can be used for accurate flow measurement of water [6] or conductive fluids. While two-phase flow measurement in general has been investigated for many years, accurate measurement of two-phase flows, including gas/solids, gas/liquid and liquid/liquid flows, is still challenging [2], [7], [8] because:

(1) Two-phase flows are very complex in the aspects of phase fraction distribution, flow regime, velocity and acceleration, flow disturbances, etc. Gas/liquid flows are heterogeneous. Therefore, local measurement is insufficient to reveal the distribution of the medium.

(2) All existing two-phase flowmeters are flow-regime dependent and suffer from severe non-linearity problems. Two-phase flows have different flow patterns, such as bubble flow, slug flow, turbulence flow and annular flow, etc. Therefore, the known regime is very important to the two-phase flow measurement.

(3) The velocity and acceleration of gas and liquid vary over a wide range. The difference in velocities between gas and liquid phases causes difficulties for data interpretation and errors in measurement. In addition, the weak leakage of pipeline can also lead to the velocity and acceleration of gas and liquid varying over a wide range [9], [10].

Up to now, there is no universal gas/liquid or gas/solids flowmeter because of the above difficulties. However, the development of data fusion techniques provides opportunities for dealing with the above problems.

Industrial process tomography has potential in measurement of two-phase flows [2], [11], [12], but it is difficult to obtain accurate measurement by tomography alone [11]. It is possible to obtain accurate measurement by fusion of industrial tomography with conventional sensors [11]. In this paper, fusions of (1) electrical resistance tomography (ERT) with electromagnetic (EM) flowmeter, (2) electrical capacitance tomography (ECT) with ERT and (3) ECT with electrostatic sensor are introduced. Some research results of fusion methods are presented and discussed. The paper can provide the theoretical support for the multi-sensor fusion for two-phase flow measurement.

2. FUSION OF ERT WITH ELECTROMAGNETIC (EM) FLOWMETER

ERT technology is a non-invasive measurement method [3], [4], [13]. Two-phase or multi-phase flows are its main measurement object. In this paper, gas/conductive liquid two-phase flow measurement is discussed. The physical basis of ERT technology is based on different substances with different conductivity, then the conductivity distribution of the substances inside the sensitive field can be judged and the distribution of substances in the field can be deduced [3], [14]. The schematic of ERT technology is shown in Fig.1.

In Fig.1, it is assumed that conductivity of the conductive fluid inside the field is σ_1 and conductivity of the bubble is σ_2. After the excitation current is injected through the boundary electrodes-m and n, potential distribution that is related to conductivity distribution is generated in the field, and then the boundary voltage which is related to potential distribution in the field can be measured between the boundary electrodes-i and j.

Therefore, the steps that use ERT to obtain the distribution of substances inside the field are as follows [14]: (1) excitation current is applied to the excitation electrodes; (2) the voltages on the other electrodes（data acquisition）are measured; (3) the internal conductivity distribution of sensitive field using linear back projection (LBP) algorithm is calculated; and (4) the distribution of substances inside the field is obtained.

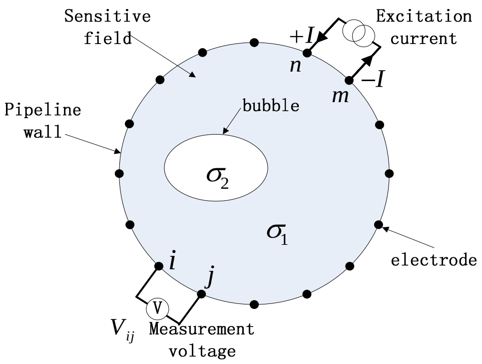

Fig.1. Schematic diagram of ERT sensor

At present, ERT technology with characteristics of visualization and non-invasive measurement has potential advantages in two-phase flow measurement. But there are shortcomings in the accurate measurement of dynamic parameters of fluid, such as average velocity measure, etc.

Electromagnetic (EM) flowmeter has many advantages in the measurement of single-phase conductive liquid flow. Especially in the average velocity measurement, the accurate measurement can be realized. The most basic principle of EM flowmeter is Faraday's law of electromagnetic induction [15]. Based on the above study, an attempt has been made to use ERT with EM flowmeter to realize the accurate measurement in gas/conductive liquid two-phase flow [11], [16].The whole measuring system is shown in Fig.2.

The advantages of EM flowmeter for conducting fluid are used to compensate for the shortcomings of ERT in the aspect of continuous phase measurement. Using the ERT system, the phase size, void fraction and flow regime parameters can be obtained. If the average velocity of the flow is known, then the parameters Q_c、Q_d、M and V can also be obtained.

In the EM flowmeter, cutting magnetic field lines are the liquid that has a certain electric conductivity and the length is the distance between electrodes, as shown in Fig.3.

In Fig.3, the EM flowmeter section is defined as Ω, the conductive fluid flows in a direction back to the reader, $\overline{\upsilon}$ is the average velocity; inner radius of the pipe cross-section is R, radius of the bubble is a, magnetic induction strength is B_0 (in this paper, the EM flowmeter that has a uniform magnetic field strength is discussed) pointing to the positive direction of X-axis, angular coordinates of the two electrodes-1 and 2 are φ_1 and φ_2, and the potential values are E_1 and E_2. Then the output of EM flowmeter can be calculated by the following formula [16],

$$
\begin{aligned}
&E = E_1 - E_2 \\
&E_1 = \frac{2B_0}{\pi R}\int_{\varphi_2}^{\varphi_1}\int_a^R W_y(\varphi)\upsilon(r)rdrd\theta \\
&E_2 = \frac{2B_0}{\pi R}\int_a^R \upsilon(r)rdr\int_{\varphi_2}^{\varphi_1} W_y(\varphi)d\theta
\end{aligned}
\tag{1}
$$

In equation (1), B_0 is constant of magnetic flux density, E_1 is potential of electrode 1, E_2 is potential of electrode 2, E is output voltage of EM, r is distance from any point to the center in a pipe cross-section, R is radius of pipe cross-section, $v(r)$ is the velocity distribution function of r, W is weight function, W_y is component of W in the y-axis, θ is angle between r and the positive x-axis, φ is angular coordinate, φ_1 is angle between electrode 1 and the positive x-axis, φ_2 is angle between electrode 2 and the positive x-axis, Ω is space domain of conductive liquid, a is radius of bubble in pipe cross-section of two-phase flow.

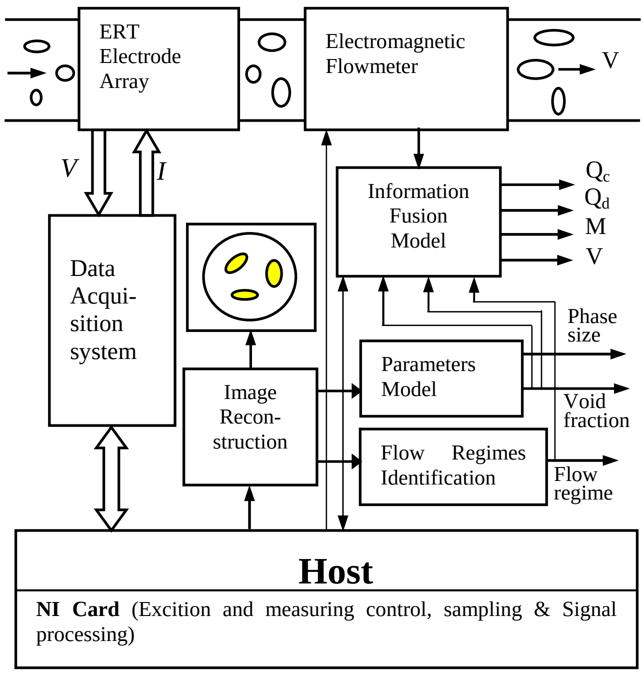

Fig.2. The diagram of the whole measuring system

From equation (1), the integration of weight function due to air core is as follows:

$$\int_{\varphi_2}^{\varphi_1} W_y(\varphi)d\theta = (\varphi_1 - \varphi_2)(\sin\varphi_1 - \sin\varphi_2) \qquad (2)$$

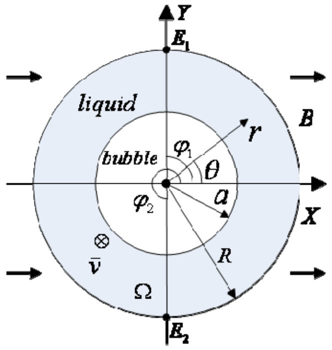

Fig.3. The electrodes section diagram of EM flow-meter

From equation (2), assumed that the two measuring electrodes are located in Y-axis, then $\varphi_1 = \frac{\pi}{2}, \varphi_2 = -\frac{\pi}{2}$, and then

$$\int_{\varphi_2}^{\varphi_1} W_y(\varphi)d\theta = 2\pi \qquad (3)$$

For axisymmetric flow,

$$\int_a^R \upsilon(r)rdr = \frac{\bar{\upsilon}(R^2 - a^2)}{2} \qquad (4)$$

In this case, the output of EM flowmeter is

$$E_1 - E_2 = 2B_0\bar{\upsilon}\frac{R^2 - a^2}{R} \qquad (5)$$

The $\bar{\upsilon}$ is average velocity of liquid and a can be obtained by ERT. The fusion of ERT with EM flowmeter not only expands application range of EM flowmeter into the two-phase flow fields, and deepens the theory of EM flowmeter measurements, but also implements multi-parameter accurate measurement of two-phase flow.

3. FUSION OF ECT WITH ERT

ECT is a kind of PT technology that has been growing the fastest in recent years. It is particularly suitable for the petroleum, chemical and other departments to monitor and control the production processes. ECT system mainly consists of three parts: (1) capacitance sensor; (2) electronic circuit; (3) image reconstruction and display [7], [17].

Generally, ERT measures conductive substances and ECT measures non-conductive substances. If the conductivity of the measured flow changes in a wide range, it needs to combine ERT with ECT [13]. ERT and ECT both provide a new visual measuring method for multi-phase flow parameter measurement. The fusion of ERT with ECT can constitute a multi-sensor system and provide more information for the accurate measurement of multi-phase flows [18]. For gas/oil/water three-phase flow, the measuring system is shown in Fig.4. [4], [18].

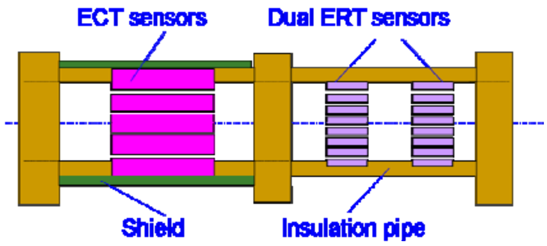

Fig.4. Fusion sensor of ECT sensors with dual ERT sensors

Because permittivity of gas is 1, permittivity of oil is about 2 and the permittivity of water is 80, the image of interface distribution of water and mixture of oil and gas can be reconstructed by measured data that was obtained by capacitance sensor array, as shown in Fig.5(a). The image of interface distribution of gas and mixture of oil and water can be reconstructed by ERT, as shown in Fig.5(b).

By data fusion, the interface image of gas, oil, and water can be obtained, as shown in Fig.6.

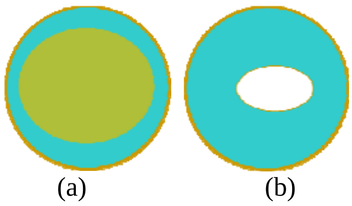

Fig.5. The image of ECT and ERT

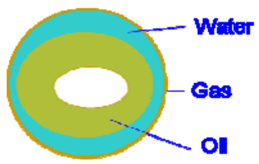

Fig.6. Gas/oil/water image

For multi-sensor measuring system, the core issue is how to process measuring data by the particular fusion algorithm. The following diagram shows us the data fusion process.

In Fig.7, ERT pixel grey calculation formula is:

$$\begin{bmatrix} g_{RT}[1] \\ g_{RT}[2] \\ \vdots \\ g_{RT}[i] \\ \vdots \\ g_{RT}[N] \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \cdots S_{1j} \cdots S_{1N} \\ S_{21} & S_{22} & S_{23} \cdots S_{2j} \cdots S_{2N} \\ \vdots & \vdots & \vdots \cdots \vdots \cdots \vdots \\ S_{i1} & S_{i2} & S_{i3} \cdots S_{ij} \cdots S_{iN} \\ \vdots & \vdots & \vdots \cdots \vdots \cdots \vdots \\ S_{M1} & S_{M2} & S_{M3} \cdots S_{Mj} \cdots S_{MN} \end{bmatrix}_{M\times N} \times \begin{bmatrix} V_1^L \\ V_2^L \\ \vdots \\ V_i^L \\ \vdots \\ V_N^L \end{bmatrix}_{N\times 1} \qquad (6)$$

In equation (6), $$V_i^L = \ln\left(\frac{V_i^{'}}{V_i}\right) \tag{7}$$

i =1, 2, …, 120.

Where $g_{RT}[i]$ represents the grey value of the *i*-the pixel unit in ERT, S_{ij} represents the sensitivity coefficient of *i*-th line and *j*-th column element of $M\times N$ sensitivity coefficient matrix composed by M meshes and N independent measurement number, $V_1^L, V_2^L, \cdots, and\ V_N^L$ are logarithm normalization values of N independent boundary voltage measurements, V_i is the *i*-th boundary voltage measurement value in the state of reference conductivity distribution, $V_i^{'}$ is the *i*-th boundary voltage measurement value in the state of changed conductivity distribution.

ECT pixel grey calculation formula is:

$$g_{CT}[k] = \frac{\sum_{v=u+1}^{Z}\sum_{u=1}^{Z-1}\lambda_{uv}S_{uv}(k)}{\sum_{v=u+1}^{Z}\sum_{u=1}^{Z-1}S_{uv}(k)} \tag{8}$$

Generally, Z can be 4, 8 or 12.

$g_{CT}[k]$ is the grey value of the *k*-th pixel unit in ECT, $S_{uv}(k)$ is the sensitive field function of *k*-th pixel to the pair of *u* and *v* plates, $\lambda_{u,v}$ is the normalized value of capacitance between *u* and *v* plates.

To the process of pixel-pixel grey data fusion, arithmetic is shown as follows,

$$g_{RCT}[i] = \begin{cases} gl[15] & if \quad g_{RT}[i] = 15 \\ gl[7] & if \quad g_{CT}[i] = 0 \\ else \quad gl[0] & \end{cases} \tag{9}$$

gl is grey level between 0 and 15.
0 (black) represents water;
15 (white) represents gas;
7 (balanced color) represents oil.

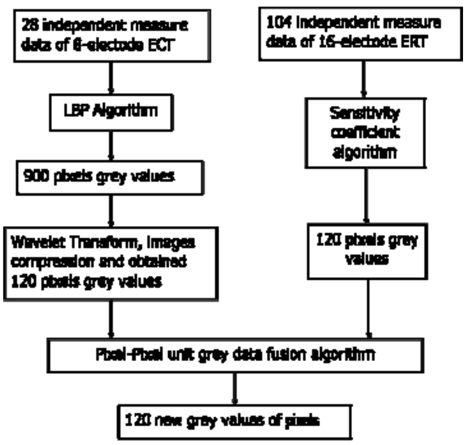

Fig.7. The diagram of data fusion process

Because ERT and ECT have a characteristic called soft field, nonlinear must be considered. The conditions are not the same for different flows and it should be considered whether it is suitable for industrial on-line measurements.

4. Fusion of ECT with Electrostatic Sensor

For gas/solids flow measurement, a new practical method is proposed, that is the fusion of ECT with electrostatic sensors. This method can realize the accurate measurement of gas/solids two-phase flow. ECT is used to measure concentration and electrostatic sensors are used to measure charge of flowing solids. By cross-correlation calculation, the superficial velocity of solids can be obtained. The designed measuring system is shown in Fig.8.

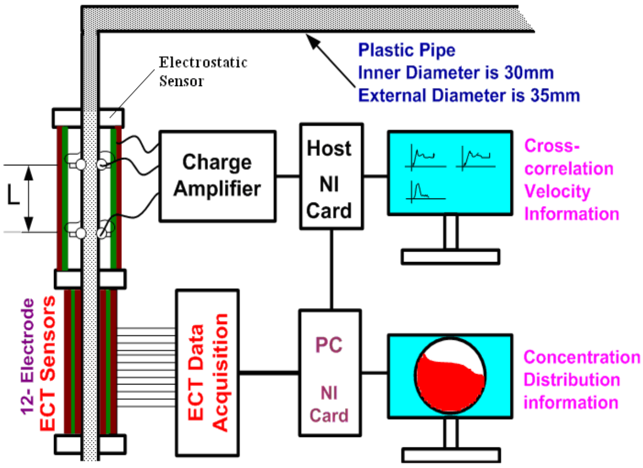

Fig.8. The fusion system of ECT with Electrostatic sensors

For the fusion of ECT sensors with electrostatic sensors, the detailed diagram of ECT and electrostatic sensors for gas/solids flow measurement is shown in Fig.9.

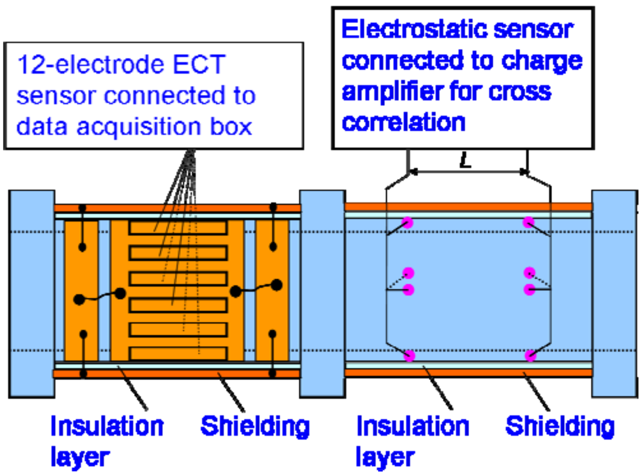

Fig.9. The diagram of ECT and electrostatic sensors

For the electrostatic sensor, four electrodes are installed in perpendicular and connected together, then connected to the charge amplifier. The section of electrostatic sensor is shown in Fig.10.

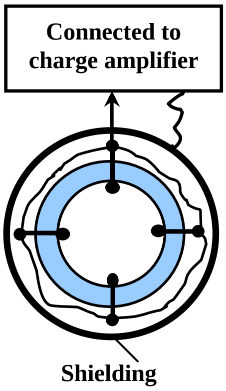

Fig.10. The section diagram of electrostatic sensor

If the induced electrostatic signal on the electrodes is very weak, the signal picked up by the electrostatic sensor must be amplified by the circuit, as shown in Fig.11. In the circuit, the electrode is connected to the invert terminal of amplifier. C_f and R_f are feedback elements. C_f is an integration capacitor. High performance of the capacitor is demanded.

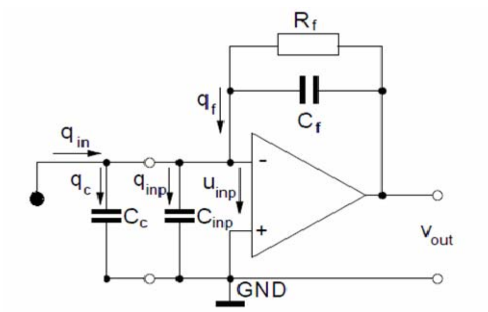

Fig.11. The diagram of charge amplifier

In Fig.11, the output signal of the amplifier can be described by the following formula:

$$V_{out} = -\frac{q_{in}}{C_f} \tag{10}$$

From the above equation, it can be seen that the output signal voltage is proportional to the size of input charge signal and is inversely proportional to the integral feedback capacitance value.

In fact, additionally, the electrostatic induction signal needs to be amplified by AC preamplifier, and the output signal of preamplifier also needs to be further processed using the circuits including full-wave rectifier, low-pass filter, programmable amplifier and DC isolating, etc. The whole principle diagram of circuits is shown in Fig.12.

From Fig.12, it can be seen that the programmable amplifier (PGA) is adopted so as to realize the different magnitude signal amplifications under the condition of different pipe size, different size and material of solid particles, and different flow rates of solids. The final output signal voltage can be effectively controlled in the range of 1 to 5 volts by using the PGA.

Two kinds of PGA can be used and their amplification factors are 1, 10, 100, 1000 and 1, 2, 4, 8, respectively. PGA magnification selection is controlled by data acquisition and processing software. In practice, “0” and “1” electrical levels of two control pins of PGA are set by software, thus they can realize PGA magnification selection. If the control pins of PGA are set as “00, 01, 10, 11”, then the PGA magnification is correspondingly set as “1, 10, 100, 1000” or “1, 2, 4, 8”. PGA settings must be evaluated first, and then adjusted according to the actual requirements.

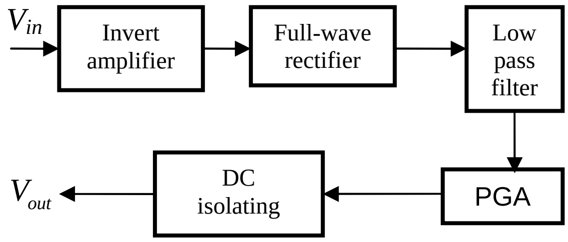

Fig.12. The diagram of further signal processing

The processed signal of electrostatic sensor is collected by data acquisition card. In order to obtain the solid velocity, the collected signals of two channels need to be processed by discrete correlation operation, as shown in Fig. 13.

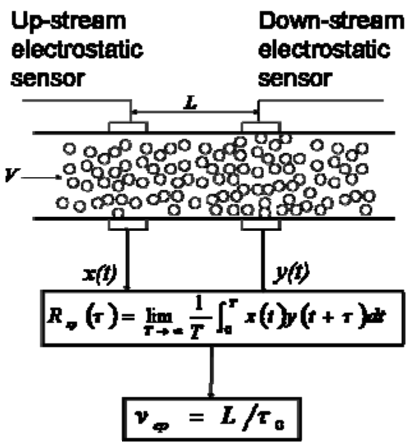

Fig.13. The diagram of correlation operation

The numerical calculation formula for cross-correlation is as follows,

$$\begin{aligned} &\hat{R}_k(j\Delta) = \frac{1}{N}\sum_{i=1}^{N} x_k(i\Delta) y_k(i\Delta + j\Delta) \\ &j = 0, 1, 2 \cdots m,\ m < N \\ &k = 0, 1, 2 \cdots N - m \end{aligned} \tag{11}$$

At last, the time that the largest peak of the diagram of $\hat{R}_k - t$ corresponds to is delay time τ_0, and then the average velocity can be obtained. Many experiments have been conducted and the results are good. It is feasible to use this method to realize the accurate measurement of gas/solids flow.

5. Conclusions

A theoretical basis for electrical tomography and fusion with other sensors for multiphase flow measurement is provided. The following conclusions can be obtained.

(1) It is possible to measure gas/conductive liquid flows by fusion of ERT with EM flowmeter; (2) It is possible to measure oil/gas/water flows by fusion of ERT with ECT; (3) Dense gas/solids flows can be measured by ECT; (4) Superficial velocity of solids can be measured by electrostatic sensors cross-correlation; (5) It is possible to measure gas/solids flows by fusion of ECT with electrostatic sensors; (6) Fusion of multi-sensors provides possibility of multi-phase flow measurement; (7) In the three operating modes, all the pipe materials of fusion sensors are insulating such as plastic, nylon, Teflon, etc. Pipeline material such as steel, plastic, etc. has almost no effect on the several measurement operating modes.

Future work includes: (1) Calibration and correction needed to derive true velocity from superficial velocity; (2) Design parameters need to be optimized: sampling rate, L, length of window; (3) Measurement of concentration of dilute flow is challenging for ECT.

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