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Voidage measurement based on genetic algorithm and electrical capacitance tomography*

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Abstract: A new voidage measurement method based on electrical capacitance tomography (ECT) technique, Genetic Algorithm (GA) and Partial Least Square (PLS) method was proposed. The voidage measurement model, linear capacitance combination, was developed to measure on-line voidage. GA and PLS method were used to determine the coefficients of the voidage measurement model. GA was used to explore the optimal capacitance combination which gave significant contribution to the voidage measurement. PLS method was applied to determine the weight coefficient of the contribution of each capacitance to the voidage measurement. Flow pattern identification result was introduced to improve the voidage measurement accuracy. Experimental results showed that the proposed voidage measurement method is effective and that the measurement accuracy is satisfactory.

Key words: Voidage, Two-phase flow, Genetic Algorithm (GA), Electrical capacitance tomography (ECT)
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INTRODUCTION

Two-phase flow exists widely in chemical, petroleum and metallurgical industries. The voidage is one of the most important parameters of two-phase flow because the measurement of the voidage is important for safety, environmental protection, energy conservation and quality assurance in industry (Hewitt, 1978; Lin, 1992). Although many voidage measurement methods have been proposed, it is still difficult to measure the voidage due to the complexity of the characteristics of two-phase flow (Li, 1991). It is necessary to explore a new voidage measurement method.

The conventional 2-electrode capacitance measurement method has the advantages of simplicity and speed. Unfortunately, this method is flow pattern dependent. The change of the flow pattern may cause great voidage measurement error.

Electrical capacitance tomography (ECT) is an attractive and promising technique to measure the voidage and has been studied in recent years (Li and Huang, 2000; Huang *et al*., 2003). In conventional voidage measurement methods based on ECT, the voidage value is estimated by the cross-sectional reconstructed images of the voidage distribution of two-phase flow. A high quality image is necessary for determining the precise voidage. Reconstructing a high quality image needs a complex and time-consuming image reconstruction algorithm, but this method cannot meet the real-time requirement of the measurement.

The voidage measurement method proposed in this paper considers the influence of the flow pattern on the voidage measurement and does not use the time-consuming image reconstruction algorithm. Based on the flow pattern identification result, a corresponding voidage measurement model, the linear combination of the capacitance values obtained

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from 12-electrode ECT sensor, was adopted to estimate the on-line voidage. The process of the flow pattern identification is implemented by the flow pattern identification unit. The voidage measurement model related to the flow pattern identification result is pre-developed by Genetic Algorithm (GA) and Partial Least Square (PLS) method. At first, GA is used to explore the optimal capacitance combination to which each capacitance gives a significant contribution to the voidage measurement. Then, PLS method is further applied to determine the contribution of each capacitance to the voidage measurement, the weight coefficient. In the practical voidage measurement process, the relevant voidage measurement model is selected to estimate the voidage according to the real-time flow pattern identification result. Thus, the influence of the flow pattern on the voidage measurement can be minimized. Meanwhile, the voidage is estimated directly using the capacitance values instead of the reconstructed image, which improves the real-time performance of the voidage measurement.

ECT MEASUREMENT SYSTEM

Fig.1 shows the schematic of the voidage measurement system, the main components of which are a 12-electrode capacitance sensor, a data acquisition unit and a computer. The functions of the sensor include measuring capacitance between all possible combination pairs of the electrodes and converting the measured capacitance values into voltage signals. The data acquisition unit performs data collection, channel control, digitalization and data communication with the computer. The data are transferred to the computer through the data acquisition unit. Based on these data, the voidage of gas-oil two-phase flow is estimated.

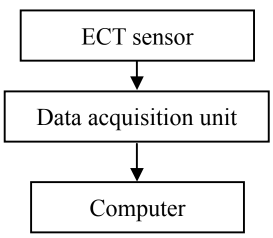

Fig.1 Voidage measurement system

VOIDAGE MEASUREMENT MODEL

The 12-electrode ECT system can provide 66 independent measurement capacitances that provide information on the cross-sectional voidage distribution. It has been shown that the voidage can be calculated by using the cross-sectional image obtained using 66 capacitance measurements. Hence, it is possible to calculate the voidage using the 66 independent capacitance measurements in another simple way. In this work, it is proposed to measure the voidage using the voidage measurement model which is the linear combination of the capacitance measurements. The voidage measurement model is developed in two steps. The first step is to select the capacitance measurements necessary for the voidage measurement. The second step is to determine the contribution of the necessary capacitance measurements.

Sixty-six independent capacitance measurements give different contributions to the voidage measurement. Some of them are significant to the voidage measurement, while others are not significant. Exploring the significant and not significant capacitance measurements is a combinatorial optimization problem. GA is considered to be a good algorithm to solve the combinatorial optimization problem (Xuan and Cheng, 2004; Leite and Topping, 1998; Han *et al*., 2002). So, in this work, GA is selected to determine the optimal capacitance combination.

GA is developed based on the principle of the survival of the fittest. A better and better approximate solution is obtained by generation from an original population. From one generation to another, a new potential solution is improved using crossover and mutation operations on the individuals. The individuals are selected from the last generation according to the fitness of each individual. The genetic process will produce individuals with better performance than the previous ones, and thus the individual in the terminal generation can be considered as the approximate optimal solution.

The fitness function is considered to be as follows

$$f_i = \mathrm{e}^{-(\alpha-\tilde{\alpha}_i)^2} \Big/ \sum_{i=1}^{M} \mathrm{e}^{-(\alpha-\tilde{\alpha}_i)^2} \qquad (1)$$

where M is the size of the population and is set at 300,

α is the actual voidage, and $\tilde{\alpha}_i$ is the estimated voidage of the ith individual of the population.

The flowchart of Genetic Algorithm is shown in Fig.2.

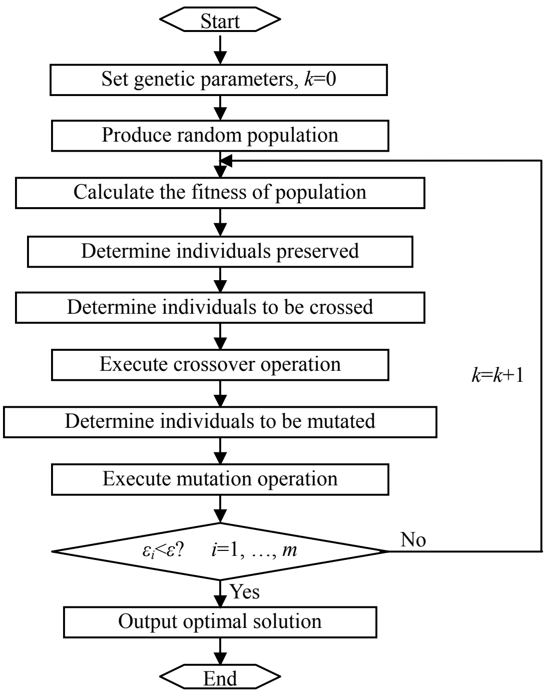

Fig.2 Flowchart **of Genetic Algorithm**

However, the optimal capacitance combination only gives the significant capacitance used in the voidage measurement, and the weight coefficient of each capacitance in the linear combination of the significant capacitance to the voidage measurement is 1. But in fact, for a specific flow state, the contribution of each significant capacitance to the voidage measurement is different. That is, the weight coefficients in the linear combination are fractions. A more important capacitance corresponds to a larger weight coefficient. Hence, the weight coefficients corresponding to the significant capacitances must be determined to improve the accuracy of the voidage measurement. PLS method is reported to be a good regression method that can eliminate the collinearity of the variables and preserve the variance of the variable matrix. The orthogonal components obtained from the variables include enough relativity among the variables, so, these orthogonal components can be used to develop the final model (Phillippe *et al*., 2005; Helland, 2001). In this work, PLS method is introduced to obtain the weight coefficient.

Finally, we obtain the voidage measurement model

$$\alpha=wc \tag{2}$$

where c is the normalized capacitance vector obtained from ECT sensor, w is the weight coefficient. Fig.3 shows the method by which the voidage measurement model is developed. At first, GA is applied to obtain the optimal capacitance combination corresponding to the voidage. Then, PLS method is further introduced to determine the weight coefficient in Eq.(2). At last, the final voidage measurement model, the linear combination of the capacitances, is developed.

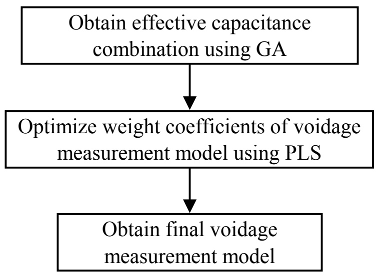

Fig.3 Development process of voidage measurement model

FLOW PATTERN IDENTIFICATION

Flow pattern indicates the flow states of two-phase flow in pipes. The typical flow patterns in horizontal pipes are shown in Fig.4a. These flow patterns include bubble flow, slug flow, stratified flow, annular flow, and so on. At the moment of the two-phase flow going through the cross section of the horizontal pipe, only three flow patterns (shown in Fig.4b) are recorded. That means only three flow patterns should be identified in our measurement system. Furthermore, according to the flow pattern identification result, a related voidage measurement model is selected to measure the voidage.

In the flow pattern identification unit, two flow pattern identification methods can do the flow pattern identification. One flow pattern identification method shown in Fig.5a combines the image reconstructed by Linear Back Projection (LBP) algorithm and the fuzzy

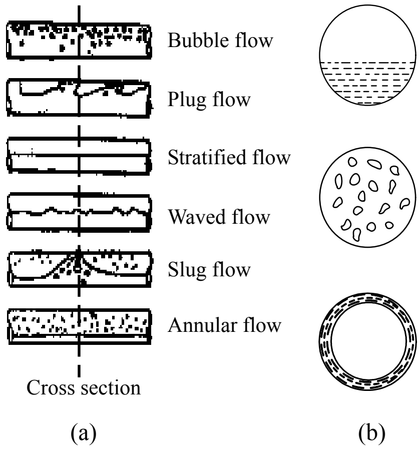

Fig.4 Flow patterns in horizontal pipes. (a) Flow patterns along the flow direction; (b) Flow patterns on cross section

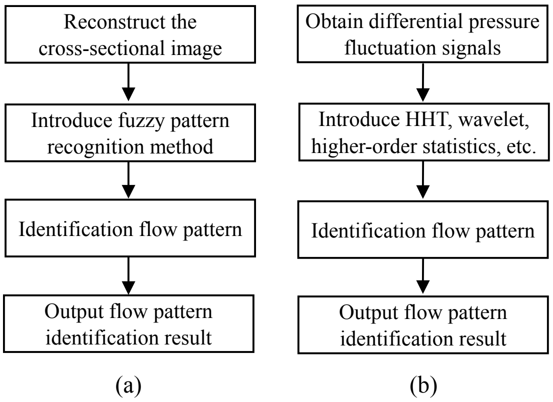

Fig.5 Flow pattern identification unit. (a) The method based on the reconstructed image; (b) The method based on the differential pressure signals

pattern recognition method (Shao *et al*., 2003). One other shown in Fig.5b combines the differential pressure fluctuation signals and Hilbert-Huang Transform (HHT), wavelets analysis, higher-order statistics (Ji *et al*., 2001; Ding *et al*., 2004a; 2004b), etc.

The previous research result from our research group showed that the flow pattern identification method based on the cross-sectional reconstructed image gives almost the same accuracy with the method based on the differential pressure fluctuation signals. So, we can select the method based on the reconstructed image or alternatively select the method based on the differential pressure fluctuation signals to do the flow pattern identification.

PRACTICAL VOIDAGE MEASUREMENT PROCESS

The practical voidage measurement process is shown in Fig.6. In the first step, 66 independent capacitance measurements from the ECT sensor are acquired. In the second step, the flow pattern identification approach is implemented and the flow pattern identification result is obtained. In the third step, according to the flow pattern identification result, the relevant suitable voidage measurement model corresponding to the identified flow pattern is selected to calculate the voidage value. In the last step, the on-line voidage value is outputted.

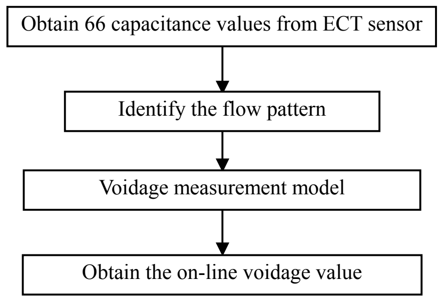

Fig.6 Practical voidage measurement process

EXPERIMENTAL RESULTS

Because there was no effective method to calibrate the dynamic voidage, static experiments were considered to test the proposed voidage measurement method. The inner diameter of the experiment pipeline was 50 mm. Perspex pipes with the different diameters and oil were selected as the experimental materials. The proposed voidage measurement method was tested using static physical models (three flow patterns shown in Fig.4) simulating the typical distribution patterns of two-component flow.

Experimental results are shown in Fig.7. Because the flow pattern had been identified before the voidage was calculated, the influence of the flow pattern on the result of the voidage measurement is not significant. Moreover, the maximum error of the voidage measurement was less than 5% and the total voidage measurement time was less than 0.1 s. The experimental results showed that the accuracy and real-time performance of the proposed voidage measurement method are satisfactory.

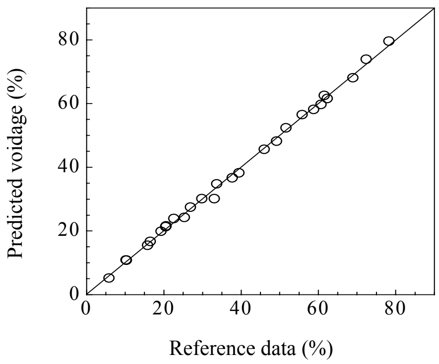

Fig.7 Experimental results

CONCLUSION

A voidage measurement method based on ECT technique, GA, and PLS method was proposed. Experimental results showed that the proposed method is effective and can reduce the influence of the flow pattern on the voidage measurement. The maximum error of the voidage measurement is less than 5%, and the total voidage measurement time is less than 0.1 s. The accuracy and real-time performance of the proposed voidage measurement method were satisfactory.

Compared with the voidage measurement method based on ECT technique, the proposed method avoids using the complicated and time-consuming image reconstruction algorithm, and ensures the accuracy of the voidage measurement. Compared with the conventional 2-electrode voidage measurement method, the flow introduction of pattern identification introduced in the proposed method overcomes the influence of the flow pattern on the voidage measurement.

This paper also provides an example of the application of GA to process parameter measurement.

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