Flow Measurement and Instrumentation 62 (2018) 37–43

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Image reconstruction method along electrical field centre lines using a modified mixed normalization model for electrical capacitance tomography

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ARTICLE INFO

Keywords:
Two-phase flow
Electrical capacitance tomography
Image reconstruction
Mixed normalization model
Electrical field centre line

ABSTRACT

During the process of image reconstruction for electrical capacitance tomography (ECT), normalization of measured capacitance values is carried out with the low and high permittvity. The parallel normalization model (PM) and series normalization model (SM) are most commonly used. In recent years, using different combination methods such as electrical field centre line (EFCL) for PM and SM, several mixed normalization models (MM) obtained better description of the permittivity distribution of the two-phase media in pipe. In this paper, a new method of determining the weight factors of the PM and SM sensitivity matrix to form the MM sensitivity matrix is proposed. This weight factors are determined according to the minimum distance between the element and EFCL. Simulation and experimental test were carried out and the results show that both the accuracy and the shape fidelity can be improved obviously.

1. Introduction

Two-phase flow exists widely in industrial processes such as petroleum refining, chemical engineering and electricity generation. Electrical capacitance tomography (ECT) is one kind of process tomography (PT) technique that was developed during the late 1980s, which can provide visualization measurement results of two-phase flow in real time through the cross-sectional reconstructed images of the permittivity distribution in pipe [1,2]. Using the accurately reconstructed images, other parameter such as void fraction of two-phase flow can be calculated [3–6]. Unfortunately, ECT image reconstruction is a typical ill-posed problem and its solution is unstable [7]. As a result, the accuracy of image reconstruction algorithms will limit the application of ECT in industrial field. A variety of algorithms have been studied to improve the visualization quality [8–15]. Image algorithms of ECT can be divided into non-iterative and iterative algorithms. For any kind of image reconstruction algorithms, sensitivity matrix and capacitance measurement normalization model are necessary.

As can be seen in [16], capacitance measurement normalization model is the description of two-phase media distribution. The parallel normalization model (PM) is the firstly and commonly used model [17]. Yang and Byars presented the series normalization model (SM) and obtained the better reconstructed images [18]. Dong and Guo used the combined parallel and series normalization, in which the optimal weight factor was obtained by minimizing the error between the measured capacitance and the capacitance estimated from the image using Tikhonov regularization algorithm [16]. For all the above algorithms, the sensitivity matrix calculated with the parallel normalization model is still used.

In 2001, Loser et al. considered the influence of permittivity distribution on the electrical field lines in the imaging area and calculated the new sensitivity matrix [19]. Followed that, Kim et al. presented the sensitivity matrix generated using mixed normalization model (MM) based on the electrical field centre line (EFCL) in 2007 [20]. Zhang and Wang presented a new combined normalization model (CM) to calculate the new sensitivity matrix, and the optimal weight factor for the mixed capacitance normalization measurements was determined using the Landweber iterative algorithm with optimal step length in 2009 [21]. Following the work of [21], a new method to obtain the sensitivity matrix based on the minimum distance between the element and EFCL is presented. Simulation and experiments were carried out and the results showed that the quality of reconstruction images can be improved obviously compared with PM, SM and CM.

2. Theory of capacitance normalization model for ECT

2.1. Parallel and series normalization models for ECT

The 12-electrode ECT sensor can be seen in Fig. 1(a). The electrode pair $i-j$ is treated as an ideal parallel-plate capacitance sensor. ε_h and ε_l

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https://doi.org/10.1016/j.flowmeasinst.2018.05.011
Received 18 December 2017; Received in revised form 11 May 2018; Accepted 14 May 2018

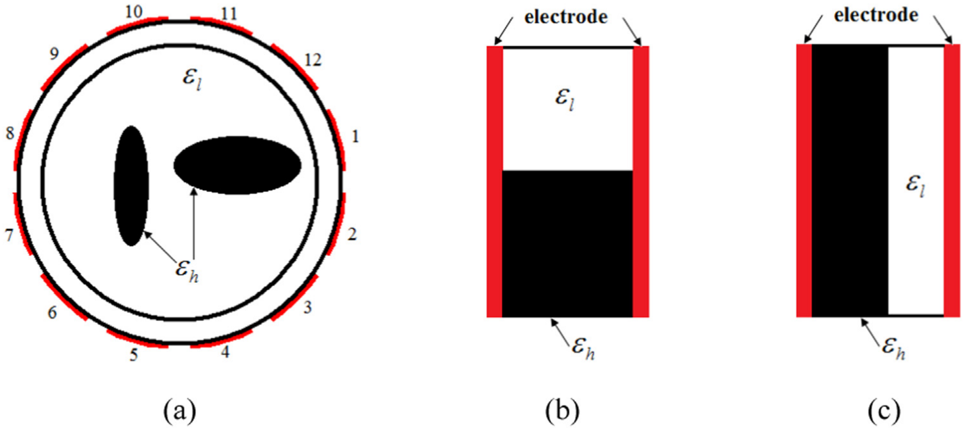

Fig. 1. Sensor and capacitance model: (*a*) 12-electrode ECT sensor, (*b*) parallel capacitance model and (*c*) series capacitance model.

is the high and low permittivity of two-phase media, respectively. Fig. 1(b) and (c) show the parallel capacitance model and series capacitance model of parallel-plate capacitor, in which the proportion of media with high permittivity are $z_1(0 \le z_1 \le 1)$ and $z_2(0 \le z_2 \le 1)$, respectively. The capacitance values are C_l and C_h when the permittivity of media between two electrodes is ε_l and ε_h, respectively.

For the parallel model shown in Fig. 1(*b*), the measured capacitance C_m can be expressed as:

$$C_m = (1 - z_1)C_l + z_1 C_h \tag{1}$$

So we can obtain z_1 as follows:

$$z_1 = \frac{C_m - C_l}{C_h - C_l} \tag{2}$$

As to the series model shown in Fig. 1(*c*), the measured capacitance C_m can be expressed as:

$$\frac{1}{C_m} = (1 - z_2)\frac{1}{C_l} + z_2\frac{1}{C_h} \tag{3}$$

And hence z_2 can be expressed as follows:

$$z_2 = \left(\frac{1}{C_m} - \frac{1}{C_l}\right) / \left(\frac{1}{C_h} - \frac{1}{C_l}\right) \tag{4}$$

It can be seen from Eqs. (2) and (4) that the proportion of high permittivity media z_1 and z_2 can be calculated using parallel and series capacitance normalization models according to the distribution.

For ECT system, when the parallel normalization model (PM) or series normalization model (SM) are used for all the electrode pairs, the PM and SM for ECT system can be expressed as the following Eqs. (5) and (6) [21].

$$\boldsymbol{\lambda}^{\mathrm{P}} = \frac{\mathbf{C}^m - \mathbf{C}^l}{\mathbf{C}^h - \mathbf{C}^l} \tag{5}$$

$$\boldsymbol{\lambda}^{\mathrm{S}} = \frac{1/\mathbf{C}^m - 1/\mathbf{C}^l}{1/\mathbf{C}^h - 1/\mathbf{C}^l} \tag{6}$$

where $\boldsymbol{\lambda}^{\mathrm{P}}$ and $\boldsymbol{\lambda}^{\mathrm{S}}$ are the normalized capacitance vectors based on PM and SM respectively. $\mathbf{C}^m$ is the measured capacitance vector, while $\mathbf{C}^h$ and $\mathbf{C}^l$ are the capacitance vectors when the pipe is full of high and low permittivity material, respectively.

The corresponding sensitivity matrix of PM and SM can be obtained according to Eqs. (7) and (8) [21].

$$\mathbf{S}^{\mathrm{P}}_{i,j}(k) = \frac{\mu(k)\cdot\boldsymbol{\lambda}^{\mathrm{P}}_{i,j}(k)}{\varepsilon_h - \varepsilon_l} \tag{7}$$

$$\mathbf{S}^{\mathrm{S}}_{i,j}(k) = \frac{\mu(k)\cdot\boldsymbol{\lambda}^{\mathrm{S}}_{i,j}(k)}{\varepsilon_h - \varepsilon_l} \tag{8}$$

where $\mathbf{S}^{\mathrm{P}}_{i,j}(k)$ and $\mathbf{S}^{\mathrm{S}}_{i,j}(k)$ are the sensitivities of the kth element when the capacitance of the electrode pair $i-j$ is measured and is normalized based on PM and SM, respectively. $\mu(k)$ is the correction factor with regard to the area of the kth in-pipe element.

PM and SM are commonly used for ECT image reconstruction to simplify the calculation. However, it can be seen from Fig. 2 that the two-phase flow regimes are very complicated and the process of the transformation from one kind of flow regime to another one is speedy. Furthermore, for the flow regimes shown in Fig. 2, neither PM nor SM can be used for any electrode pair $i-j$ to accurately calculate the proportion of high permittivity media because the media distribution between different electrode pair $i-j$ cannot be simply described as parallel or series model.

Additionally, for the existence of 'soft-field' effect, the relation between capacitance and media distribution is nonlinear, which can be illustrated by Figs. 3 and 4 in detail.

There is one object close to electrode 7 in Fig. 3(*a*) and another object close to electrode 1 in Fig. 3(*b*). When these two objects exist simultaneously in pipe, we can obtain Fig. 3(*c*). When electrode 1 is excited, the corresponding 11 capacitance values between electrode 1 and the remaining electrodes 2–12 ($\mathbf{C}_{1-2}$, $\mathbf{C}_{1-3}$, $\cdots$, $\mathbf{C}_{1-12}$) for the three flow regimes in Fig. 3 were calculated, which were shown in Fig. 4.

For the reason of the nonlinear relation between measured capacitance values and the permittivity distribution and the 'soft-field' characteristic. It can be seen from Fig. 4 that all the 11 capacitance values of flow regime in Fig. 3(*c*) are not equal to the sum of the capacitance values of Fig. 3(*a*) and (*b*), which means the PM is not accurate. Meanwhile, it can be inferred that the use of SM will also be inaccurate. In order to describe the media distribution more accurately, the new

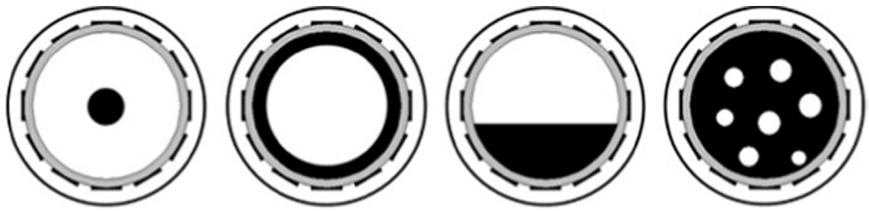

Fig. 2. Four typical flow regimes.