Nuclear Engineering and Design 278 (2014) 134–140

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Image reconstruction using voltage–current system in electrical impedance tomography

Bong Seok Kim[a], Anil Kumar Khambampati[b], Yeong Jun Jang[c], Kyung Youn Kim[d], Sin Kim[e,*]

[a] BK21+ Clean Energy Convergence and Integration Center for Human Resources Training and Education, Jeju National University, Jeju 690-756, Republic of Korea
[b] Institute for Nuclear Science and Technology, Jeju National University, Jeju 690-756, Republic of Korea
[c] Department of Nuclear and Energy Engineering, Jeju National University, Jeju 690-756, Republic of Korea
[d] Department of Electronic Engineering, Jeju National University, Jeju 690-756, Republic of Korea
[e] School of Energy Systems Engineering, Chung-Ang University, Seoul 156-756, Republic of Korea

HIGHLIGHTS

- Voltage applied and current measured (VC) system is proposed to image binary mixtures using EIT.
- Based on the complete electrode model, the forward problem of VC system is formulated with the conductance matrix.
- The accuracy of reconstructed images is improved using the proposed method.
- Data collection and image reconstruction procedure is relatively simple and easy compared to current applied and voltage measured (CV) system.

ARTICLE INFO

Article history:
Received 28 January 2014
Received in revised form 17 July 2014
Accepted 19 July 2014

ABSTRACT

Electrical impedance tomography (EIT) has been used as an alternative imaging modality to visualize binary mixture like two-phase flows because of its high temporal resolution for monitoring fast transient processes. In this paper, voltage applied and current measured (VC) system based on complete electrode model is applied to image binary mixtures. The forward problem is formulated with the conductance matrix and a non-iterative inverse method is used to estimate the conductivity distribution. The proposed method with VC system needs simpler hardware as compared to conventional current applied and voltage measured system. Both numerical simulations and phantom experiments have been carried out to evaluate the performance of the proposed method through quantitative parameters. Results show a promising performance of VC system as an imaging modality for binary mixtures.

1. Introduction

Binary mixtures like two-phase flows are common in many engineering applications and their monitoring is usually involved with the engineering system controls and safe operations. As one of tomographic noninvasive modalities, electrical impedance tomography (EIT) has been used to monitor two-phase flow processes (Jones et al., 1993; George et al., 2000). In EIT, the domain (e.g. flow field in a pipe) is excited electrically by the electrical currents injected through the electrodes placed discretely along the domain boundary (or pipe wall). The excited electric field in the domain is determined in accordance with the geometry, the boundary conditions, and the internal distribution of the electrical properties like conductivity. The distribution of the electrical property corresponds to the phase distribution. In this, the excited voltages on the electrodes can be measured and these data along with the injected currents are used to reconstruct the internal conductivity distribution or the phase distribution. If the voltages are applied to the electrodes, the electric currents are measured and used for the reconstruction.

The image reconstruction in EIT is composed of two problems: the forward and the inverse problems. The forward problem obtains the electrical field with the given geometry, the boundary conditions, and the assumed conductivity distribution, while in the inverse problem the conductivity distribution is estimated by minimizing the difference between the calculated and the measured electrical signals on the electrodes.

* Corresponding author. Tel.: +82 2 820 5073.
E-mail address: sinkim@cau.ac.kr (S. Kim).

http://dx.doi.org/10.1016/j.nucengdes.2014.07.023
0029-5493/

The EIT was initially developed as an alternative medical imaging modality to the conventional radiological or ultrasonic imaging methods (Webster, 1990). However, its advantages such as low cost and fast response are quite attractive for monitoring transient processes like two-phase flows.

This work is not the first application of EIT to the imaging of two-phase flows and there have been many attempts. In a review paper of Ceccio and George (1996), progresses in the electrical impedance techniques for multiphase flow measurements at that time were discussed. Beck and co-workers at the University of Manchester Institute of Science and Technology (UMIST) and Jones and co-workers at Rensselaer Polytechnic Institute (RPI) were noticed. While the UMIST group improved the backprojection algorithm (Plaskowski et al., 1995), the RPI group extended Yorkey's resistive network (Jones et al., 1993). Later, George et al. (2000) applied the EIT system developed at Sandia National Laboratories to monitor solid–liquid and gas–liquid flows by utilizing Newton's algorithm with finite element solutions. Also, their results were successfully compared to those from a gamma-densitometry tomography system. The image reconstruction algorithms have become more sophisticated along with the development of medical EIT. Using the fact that there are only two distinct conductivities in gas–liquid two-phase flows, interesting algorithms such as the mesh-grouping (Cho et al., 2001; Kim et al., 2014) and the boundary estimation (Han and Prosperetti, 1999; Khambampati et al., 2012) have been suggested. On the other hand, the application of EIT has been widened to various two-phase measurements. EIT was applied to detect the liquid level in horizontal flow (Ma et al., 2001), velocity measurements with a dual-plane EIT system (Wu et al., 2005), and characterization of fluid dynamics in particulate two-phase systems (Wang, 2005).

As mentioned above, the EIT instruments may be classified into current–voltage (CV) (or current mode) and voltage–current (VC) (or voltage mode) systems. In the former, currents are injected through the electrodes and voltages are measured, in the latter, voltages are applied and currents are measured.

In the beginning of EIT development, VC system was developed by Henderson and Webster (1978). They designed an impedance camera to test the feasibility of impedance imaging of the thorax. Their system may be the first for electrical impedance imaging. In their system, constant voltage signal was applied and the resulting current was measured. Based on these data, an isoadmittance contour map was generated. The resolution of the image was relatively low due to the assumption that currents flowed in straight lines through the body.

However, despite requiring more complex hardware, CV system would produce better results than VC system due to unknown contact impedance (Nowicki, 1990). Moreover, VC system tends to increase the sensitivity to electrode placement and its size errors (Isaacson, 1986; Saulnier, 2005). Because of these reasons, CV system has become more common in conventional EIT. Barber et al. (1983) developed a 16-channel EIT system with current source. Resistivity images were reconstructed by employing backprojection method. Since then lots of EIT systems based on current excitation patterns have been developed and the images of the resistivity/conductivity distributions have been reconstructed based on applied currents and measured voltages so far.

Even though VC system is more vulnerable to the errors in electrode positioning and contact impedance than CV system, VC system has been used for breast cancer detection and diagnosis by a few research groups, for example Dartmouth group (Hartov et al., 2000; Kerner et al., 2002), TransScan group (Assenheimer et al., 2001; Scholz, 2002), KyungHee group (Oh et al., 2007; Seo et al., 2004) and RPI group (Liu et al., 2005; Kim et al., 2007).

It can be inferred from previous works, image reconstruction using VC system has been achieved with better accuracy although there are some issues to be handled such as electrode placement and contact impedance. In medical applications, the accurate placement of electrodes on human body may not be easy. Also, the accurate estimation of the contact impedance between the skin and the electrodes may be difficult and the contact impedance on each electrode will strongly depend on each contact condition. However, in the application of EIT to the imaging of two-phase flows through a fixed pipeline, the electrode placement can be accurately controlled. The contact impedance between the flow and the electrodes may be considered as a constant and can be easily estimated. Hence, major issues raised for VC system against CV system are resolved when EIT is applied to image two-phase flows through a fixed pipe.

Moreover, even with a single source, VC system can excite multiple electrodes at the same time while CV system can excite only two electrodes. It may be expected that when more electrodes are excited more information on the interior can be delivered. The excitation and data acquisition methods will be described in Section 2. Considering, CV system requires multiple current sources to excite multiple electrodes, it can be said that the hardware setup of VC system is simpler.

In this paper, a VC system is developed for binary mixture imaging. Based on the complete electrode model, the forward problem of VC system is formulated with the conductance matrix. Moreover, a new single source excitation in EIT is used and the resulting data are measured sequentially from all other electrodes, excluding excitation electrodes. In the inverse problem, the Jacobian matrix is computed as the derivative of the currents with respect to the conductivity and one-step Gauss–Newton (GN) method as an inverse solver is employed to reconstruct the internal conductivity distribution. Both numerical simulations and phantom experiments have been performed using single and multiple anomalies and the proposed VC system is compared against the conventional CV system.

2. EIT mathematical model and data acquisition

2.1. Current–voltage system

Typically in EIT, CV system is considered, which means that currents are applied and voltages are measured. The physical relationship between the conductivity distribution inside the domain and the boundary voltages is governed by a partial differential equation derived from Maxwell equations. When current I_l is injected through the electrode e_l on the surface $\partial\Omega$ and the conductivity distribution σ is known, the electric potential u in the domain Ω can be solved from the governing equation with the boundary conditions for the complete electrode model (Somersalo et al., 1992)

$$\nabla \cdot \sigma \nabla u = 0 \quad \text{in} \quad \Omega \tag{1}$$

$$u + z_l \sigma \frac{\partial u}{\partial \nu} = U_l \quad \text{on} \quad e_l, \quad l = 1, 2, \ldots, L \tag{2}$$

$$\int_{e_l} \sigma \frac{\partial u}{\partial \nu} ds = I_l \quad \text{on} \quad e_l, \quad l = 1, 2, \ldots, L \tag{3}$$

$$\sigma \frac{\partial u}{\partial \nu} = 0 \quad \text{on} \quad \partial\Omega \backslash \bigcup_{l=1}^{L} e_l \tag{4}$$

where z_l is the effective contact impedance between the electrode and the medium, U_l is the measured voltage on the electrode e_l, ν is the outward unit normal and L is the number of electrodes. In