Electrical Capacitance Tomography Measurement of Flow Patterns and Film Thickness in a Thermosyphon

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An experimental study was performed to evaluate the suitability of using an electrical capacitance tomography (ECT) system to visualize the flow patterns, and to measure the film thickness of the annular flow in a two-phase closed thermosyphon (TPCT). The performance of the ECT system was examined over a range of flow conditions. The experimental data were compared with the visual observations and existing correlations. Results indicated that the ECT system, with the linear back projection (LBP) algorithm, could be used to give an on-line qualitative image of the flow patterns. The Landweber iteration algorithm with optimal step length was implemented off-line to reconstruct high-resolution images. Then, the images were analyzed to obtain the film thickness of the annular flow. The experimental data compared well with the Nusselt's equation in low vapor velocity range, but showed an increasing deficiency with the increase of vapor velocity.

Keywords: thermosyphon, electrical capacitance tomography, film thickness, flow pattern.

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Introduction

A two-phase closed thermosyphon (TPCT) is basically a gravity assisted wickless heat pipe. The schematic of the working principle of the TPCT is shown in Fig.1. It is a closed container filled with a small amount of working fluid. The vapor travels upwards to the condenser section where it is converted into liquid, then flows downwards on the wall as a thin film by gravity.

The condensation heat transfer inside a TPCT has been investigated in a large number of experiments and analytical studies\cite{1,2}, with the consistent conclusion that the condensation process inside a TPCT is much more complex than the Nusselt's condensation. Various flow patterns, such as rivulet flow, annular flow and pulsating flow, may occur in different working conditions\cite{3}. On-line visualization of these flow patterns is of particular interest to the research work of TPCTs. The annular flow is the dominant flow pattern in the steady working state of a TPCT. The film thickness of the annular flow is an important parameter which determines the thermal performance of a TPCT. Little work has been published concerning the measurement of the thin film thickness inside a tube. The traditional approach is the electrical conductance technique, which requires a wire probe stretched across the tube's cross-section. This may cause inconvenience in installation and disturb the film. Therefore, experimental measurement of the film thickness has been considerably limited. As a result, many analytical models have been developed in the absence of reliable data on the true flow conditions.

Fig.1 Schematic diagram of a TPCT
Electrical capacitance tomography (ECT) is a non-intrusive and on-line technique which has been ideally suited to visualizing two component flows of different electrical permittivities. In this paper, the use of ECT is examined for visualizing the flow patterns, and facilitated to measure the film thickness of the annular flow in a TPCT.

**ECT System**

An ECT system generally consists of a capacitance sensor, sensing electronics for data acquisition, and a computer system for image reconstruction, interpretation and display, see Fig.2. The sensor has a number of electrodes wrapped around the area to be imaged. The capacitances for all the independent combinations of electrode pairs are measured. These values are then used to reconstruct, via reconstruction algorithms, an image of the permittivity distribution and hence the material distribution within the test section. The image can then be analyzed for the specific requirements of the application.

Existing ECT systems could use various algorithms to calculate permittivity distribution by solving the inverse problem. The choice of the algorithm is highly application dependent and thus there is no general-purpose algorithm.

In ECT, the relationship between the capacitance and the material distribution is non-linear. This is the main difficulty in image reconstruction for ECT. In practice, this non-linear problem is simplified to a linear approximation in the form:

\[ C = SG \]  

where, \( C \in R^m \) is the capacitance vector, \( S \in R^{m \times n} \) is a coefficient matrix, \( G \in R^n \) is the image vector or the material distribution in the sensing area, \( m \) is the number of the independent capacitances, e.g. \( m = 12 \times 11 / 2 = 66 \) for a 12-electrode system, \( n \) is the number of pixels in the imaging region.

In Equation (1), the matrix \( S \) reflects the changes of \( C \) corresponding to a change in \( G \). Therefore, it is called sensitivity map. The goal of ECT is to produce the image vector based on the measured capacitances. This process is called image reconstruction.

\[ G = S^{-1}C \]  

In reality, however, the number of elements in an image vector is much larger than that in a capacitance vector, i.e. \( n >> m \). \( S^{-1} \) does not exist. As a result, image reconstruction for ECT is not straightforward and other methods for solution must be used.

The first attempt to reconstruct images for ECT was made using linear back projection \[4\]. If \( S \) is considered to be a linear map from the image vector space to the capacitance vector space, \( S^T \) can be considered as a related map from the capacitance vector space to the image vector space, giving an approximate solution.

\[ G = S^T C \]  

In this paper, the ECT system used the linear back projection (LBP) algorithm to visualize the flow patterns in a TPCT.

The LBP algorithm is an appropriate technique which is particularly suitable for on-line use because of its computational simplicity and high speed (100 images can be captured per second). However, due to the non-linear relationship between the permittivity distribution and the capacitances, it is difficult to find an accurate solution using the LBP algorithm. To improve the image quality, the inverse problem has to be solved iteratively.

The Landweber iteration is a comparatively slow but effective algorithm, which is the most widely used iterative method for ECT \[5\], and in most cases produces the best images.

\[ G(0) = S^T C \]