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Application of the EIT Technique for DCHXs

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Abstract

This paper investigates the possibility of applying the EIT(Electrical Impedance Tomographic) technique as a means to reconstruct the image of dispersed phase droplets in a Direct Contact Heat Exchanger(DCHX). Two different cases of the DCHX are considered : 1) a case where the fluid(Dowtherm J) lighter than water is injected into the spray column through a perforated plate at the bottom of the column and 2) a case where heavier fluids(Phthalates) stream through the spray column from top to bottom. The paper also introduces theoretical backgrounds of the technique concerning the forward and inverse problems. A number examples are given for the static model in this regard where the assumed image is reconstructed using the technique. The results so obtained are examined by the experimental investigation which has been carried out using one or two stationery objects($>10^{12}\,\Omega$cm) immersed in a stagnant body of saline water($300\,\Omega$cm).

1. Introduction

1.1 Monitoring of the dispersed phase in two-phase flows

Understanding the physical phenomena involved in two-phase flows with concomitant phase changes due to heat transfer is very important in analyzing thermal energy systems. Many experimental systems such as LDV(Laser Dopler Velocimetry), PIV(Particle Image Velocimetry) and other optical probes are devised to monitor the bubble configuration and its motion in a fluid stream. Recently, EIT(Electric Impedance Tomography) technique, which was invented to obtain the tomographic image of human organ, is introduced to investigate the bubble dynamics. The major difficult y in EIT technique lies in image reconstruction problem. The Hessian matrix occurred in iterative image reconstruction problem based on Newton-Raphson method is usually ill-conditioned. Furthermore, the contrast which is the ratio of impedance of continuous phase(usually water) to that of dispersed phase(usually water or vapor) is very high in two-phase flows. To resolve these problems, some modifications to the existing schemes are introduced and tested in the present study. Sample reconstructed images are examined in this regard for the given artificial dispersed phase distributions.

1.2 Thermal hydraulics of DCHXs

Heat transfer can take place in a DCHX with negligible temperature differences since there exist no intermediate barriers between two streams of fluid. A small temperature difference is enough to trigger the heat flow between two immiscible fluids where one is dispersed in the other due to the effects of buoyancy and surface tension. The operational schemes involved are quite different from those of conventional heat exchangers.

The direct contact heat transfer between droplets of the dispersed phase and the continuous phase is complex, It depends not only on the thermal properties of each phase, but also on the dynamics of the drops themselves. Most experiments in spray columns carried out to date have utilized drops less than 7.5mm in diameter, more extensively drops between 1.0mm and 3.0mm have been utilized.

When the drops have low thermal conductivity, as is the case with hydrocarbons, it is likely that the governing resistance to heat transfer is internal to the drops. Jacobs and Golafshani[2] investigated a model using the assumption of no drop internal resistance to heat transfer and another where the heat transfer was governed by diffusion within the drop. The latter model showed the best agreement with the temperature profile data, expecially when it accounted for drop growth.

Stamps and et al.[3] developed a heat transfer model for a liquid-liquid spray column employing a one-dimensional dispersion model. Assuming the drop size and the wake volumes to be constant and the transverse temperature uniform, and also assuming known heat transfer coefficients between each of three parallel streams, i.e., the upward-flowing dispersed phase drops, the wakes attached to the drops, and downward-flowing continuous phase, they were able to choose wake volume to drop volume values and heat transfer coefficients to fit known experimental temperature profiles for a variety of spray column experiments.

In a liquid-liquid spray column, drops produced by a pressure distributor with identical multiple openings are never perfectly uniform. Individual drop diameters are varied by some mean, and the distribution may be narrow or broad. Harvath[4] reported that low nozzle velocities could result in a two-peak distribution, which persisted to be broad until a certain velocity was reached after which smaller uniform drops were produced. Steiner and Hartland[5] explained this by pointing out that low nozzle velocities result in single drop formation. At higher velocities, additional openings start to operate and some drops are formed by jetting break-up, which corresponds to the second peak in the distribution. Reaching a certain high nozzle velocity, all drops are produced by jetting break-up, and drops become uniform again.

In the present study of experimental investigations, Diethyl Phthalate, Dimethyl Phthalate, and Dowtherm J are examined for their fluid dynamic characteristics and the applicability of EIT technique for the image reconstruction as these fluids are dispersed creating small droplets within DCHXs.

2. Theoretical Developments of Image Reconstruction using EIT

There are two approaches that could be hired for the image reconstruction using EIT. One is called the "Forward Problem" which determines the boundary voltage values from the given internal resistivity(impedance) distribution and injected currents. The other is the "Inverse Problem" whose ultimate goal is to resolve the unknown internal resistivity distribution on the basis of injected currents and boundary voltage measurements. A forward problem satisfies the following Laplace equation to obtain the boundary voltage values from the known resistivity distribution:

$$\nabla \cdot (1/\rho \nabla u) = 0 \tag{1}$$

Here u and ρ stands for voltage and impedance, respectively. To resolve this equation, diverse numerical methods could be applied unless one violates the given physical model or the boundary conditions. The Finite Element Method(FEM), Finite Difference Method(FDM) and Boundary Element Method(BEM) are some of the applicable methods. There are many numerical techniques to deal with inverse problems. In the present investigation, the well-known Newton-Raphson method is used as it deems most efficient and simple to handle the given the problem.

The Newton-Raphson method here finds a new set of internal resistivities which minimizes the aggregate sum of the square of the difference between the measured and calculated values of the boundary voltage using FEM based on the assumed resistivity distribution:

$$\Phi(\rho) = \frac{1}{2}[f(\rho) - v]^T[f(\rho) - v] \tag{2}$$

where $f(\rho)$ and $v=[v_1, v_2, v_3 \cdot\cdot\cdot, v_M]^T$ respectively symbolizes the calculated and measured values of boundary voltage. Therefore, the crux of the said problem becomes the resolution of the resistivity distribution(ρ) subjected to the following condition:

$$\Phi'(\rho) = [f'(\rho)]^T[f(\rho) - v] = 0 \tag{3}$$

However, since the equation (2) is nonlinear, it requires the iterative linearization as given below:

$$\Phi'(\rho^{k+1}) \approx \Phi'(\rho^{k}) + \Phi''(\rho^{k})(\rho^{k+1} - \rho^{k}) = 0 \qquad (4)$$

Arranging the expression in an appropriate manner, it results in the following:

$$\Delta\rho^{k} = \rho^{k+1} - \rho^{k} = -H^{-1}\{J^{T}[f(\rho^{k}) - v]\} \qquad (5)$$

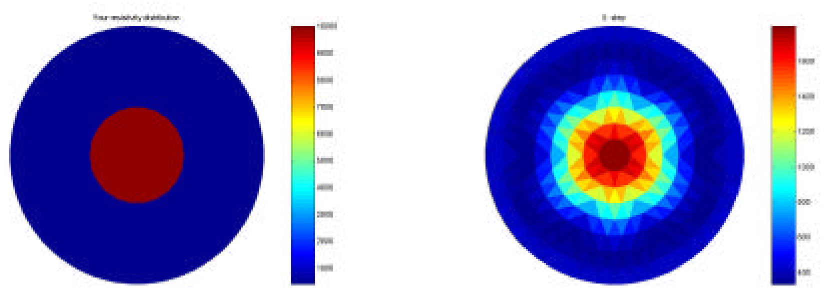
Here, the Hessian matrix H and the Jacobian matrix J are defined as given in the following:

$$H = J^{T}J \quad \text{and} \quad J = \frac{\partial f_i}{\partial \rho_j} \qquad (6)$$

whereas f_i is the ith boundary voltage and ρ_i is the resistivity of the jth element.

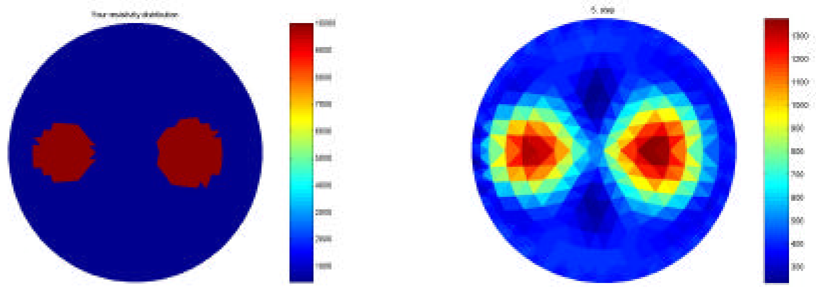
3. Preliminary Results of the Image Reconstruction

Before embarking on the real task with actual experimental data, preliminary tests are made using the aforementioned algorithm and solution procedure. Boundary voltages are resolved on the basis of the predefined resistivity distribution before they are used in place of the measured ones as required by the inverse problem. In doing so, the essential characteristics of the proposed algorithm are revealed without undue difficulties. Of course, all the information with regard to the internal electrical impedance is completely delivered by the image construction. Figs. 1 and 2 show the results of somewhat simple cases when there are only one or two masses of the dispersed phase present in an DCHX. In both examples, it is well demonstrated that 5 iterations are enough to locate and disclose the physical makeup of dispersed phases. Further iteration did little to improve the resolution of image reconstruction.



(a) (b)

Fig. 1. Single mass of dispersed phase : (a) assumed image and (b) reconstructed image.



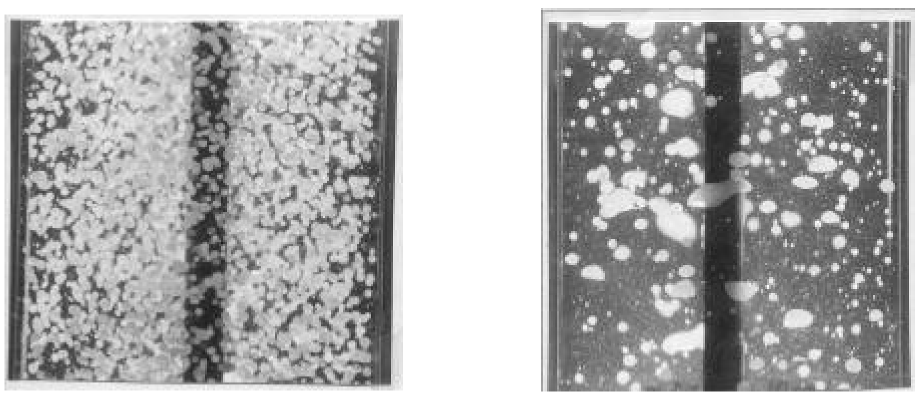
(a) (b)

Fig. 2 Two masses of dispersed phase : (a) assumed image and (b) reconstructed image.

4. Experimental Observation of the Dispersed Phases in DCHXs

4.1 Dispersed Phase Droplet Size Distributions

The mechanism of the drop formation for the dispersed working fluid determines the drop size which is closely connected with the thermal performance of the direct contact heat exchanger. According to previous findings, the drop sizes most effective to maximize heat transfer rates are in the range of 1mm to 2mm in diameter. Fig. 3 shows the formation of small droplets as well as rather large chunks of the dispersed phase liquid that are present in DCHXs.



(a) (b)

Fig. 3 Presence of dispersed phase in a DCHX: (a) uniform size masses(droplets), (b) small and large masses are mingled

These are the cases which could be observed in the operation of DCHXs where dispersed phases are heavier than the continuous phase and streams downward. The case of Phthalates consists one of such examples as shown in this figure. The Phathalate masses(droplets) are moving downward as they sink in a column of water.

Table 1. Physical properties of Phathalate(Dimethyl)

Molecular Formula	Specific Density	Viscosity, Poise	Specific Heat, J/g℃	Thermal Conductivity, W/cm℃	Freezing Point, ℃	Boiling Point, ℃
$C_8H_6O_4$	1.052	0.024	1.57	1.29×10^{-3}	-40.5	297.7

Table 2. Physical properties of Dowtherm J

Molecular Formula	Specific Density	Viscosity, Poise	Specific Heat, J/g℃	Thermal Conductivity, W/cm℃	Heat Capacity, J/cm^3℃	Freezing Point, ℃	Boiling Point, ℃
alkylated aromatic	0.8067	0.0036	2.07	1.26×10^{-3}	1.67	-73.3	181.1

Fig. 4 shows small droplets formed on the surface of a distribution plate before they are separated and find their way in the upper direction. The droplets are those of Dowtherm J which is slightly lighter than water.

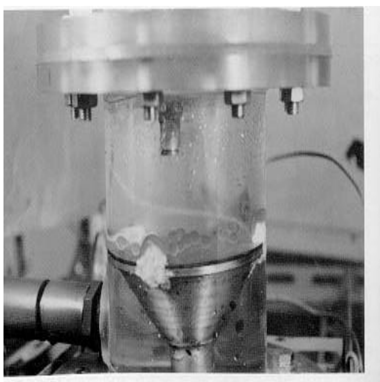


Fig. 4 Droplets of Dowtherm J formed on the surface of a distribution plate

When there is a great difference in its conductivity(or resistivity) between the dispersed and the continuous phase, the EIT technique is quite efficient in finding the location and geometric shape of the dispersed phase. This case has been studied for the cases when one or two cylindrical objects of nearly the same impedance as Dowtherm J are placed in a column of saline solution(0.15%) whose electric resistivity is 330Ωcm. For Dowtherm J, the electrical resistivity is measured to be over $10^{12}\Omega$cm, which is practically infinite when compared to the saline solution. The actual measurements are made by embedding 32 stainless steel electrodes around the cylindrical vessel which holds the saline solution. Currents are injected through these electrodes and the resulting voltages are measured to electrically analyze the domain of interest. A schematic diagram of the experimental setup is given in Fig. 5. Fig. 6 and 7 are the results of the aforementioned cases where actual and reconstructed images of the immersed object(s) are given for different locations. The size of the object is also examined as it deems to influence the clarity of the reconstructed image. It is quite obvious that the present technique is fairly accurate in locating the tarketed mass(object), even though more work is needed to obtain clear images. The clarity of the reconstructed image appears to be dependent on the size of the tarketed mass as well as the removal of noises in measured data. Subsequent research is currently underway to improve the technology in this regard.

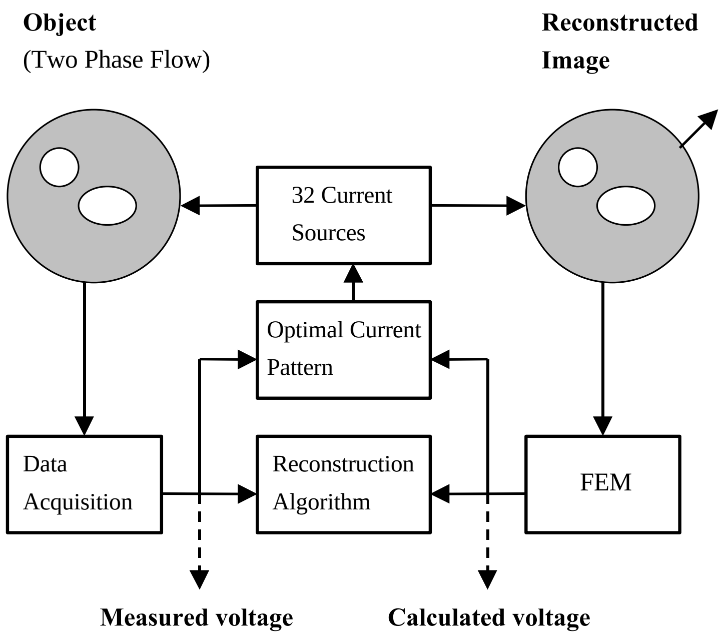


Fig. 5 Schematic diagram of the experimental apparatus

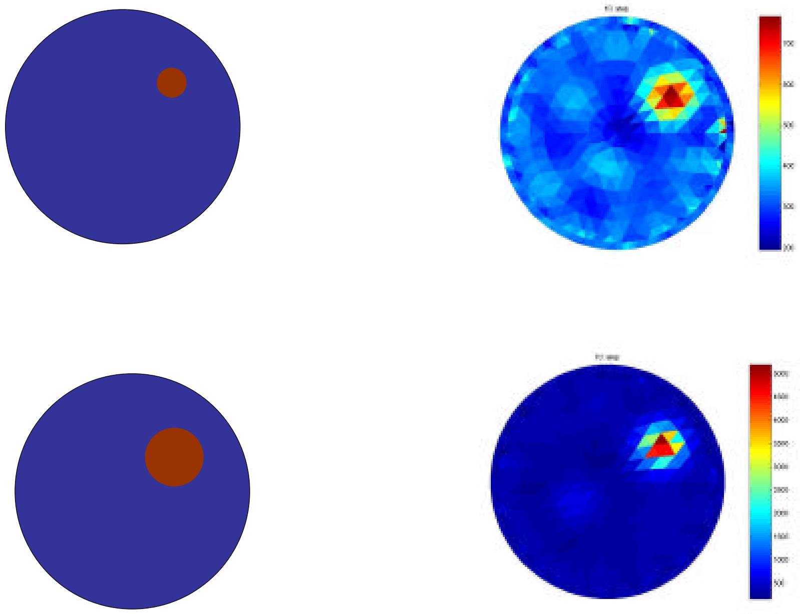


Fig. 6 Reconstructed results for a cylindrical object, which has nearly the same electric resistivity($>10^{12}\,\Omega$cm) as Dowtherm J, immersed in a saline solution(300Ωcm) : (a) actual image (b) reconstructed image

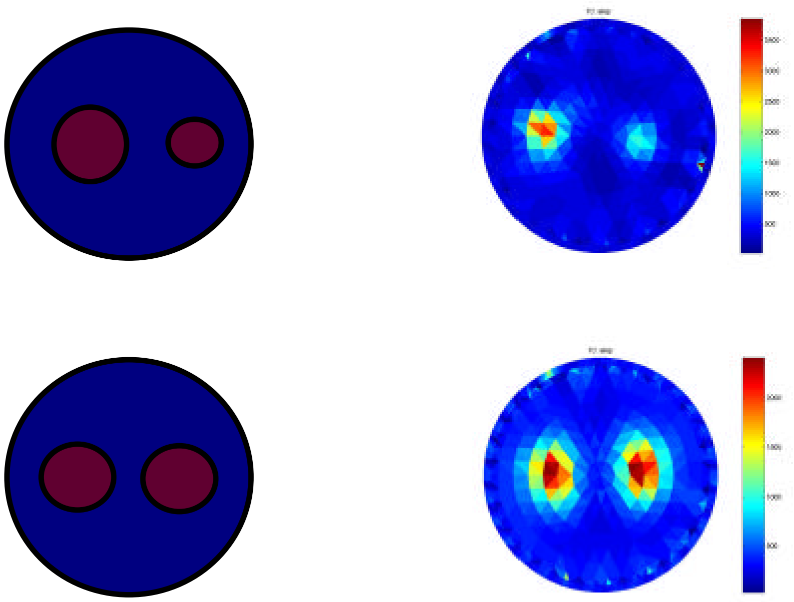


Fig. 7 Reconstructed results for two cylindrical objects, which has nearly the same electric resistivity($>10^{12}\,\Omega$cm) as Dowtherm J, immersed in a saline solution(300Ωcm) : (a) actual image (b) reconstructed image

5. Conclusions

The operation and characteristics of DCHXs are considered with the application of the EIT technique for the detection and image reconstuction of dispersed phases. Two different approaches are reviewed as theoretical investigations into the technique. Experimental results are also given which merely repeat the facts disclosed when delving into the problem theoretically with assumed images of applying EIT. The static model developed in the present analysis deems very useful in developing dynamic models which is yet to be tested.

Acknowledgements

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