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Image Reconstruction of Dispersed Phases in DCHXs

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Abstract — This paper studies the possibility of applying the EIT (Electrical Impedance Tomography) technique for investigating the formation and movement of dispersed phase droplets as they stream through a Direct Contact Heat Exchanger (DCHX). In most direct contact liquid-liquid heat exchangers, oil or hydrocarbon with a density different (lighter or heavier) from water is normally used as dispersed working fluid. The main difficulty that arises with this arrangement lies in the extraction of performance parameters and visualization of dispersed phase fluids if required. In order to delve into these problems, this paper introduces a number of cases regarding the operation and principle of DCHXs and investigates the possibility of applying the EIT technique whose results are given for several examples.

1. Introduction

1-1. Measurement of the Dispersed Phase in Two-phase Flows

It is very important to understand two-phase flows governed by phase changes due to heat transfer in thermal energy system. 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 difficulty 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

The temperature driving force required for the conventional heat exchanger is greatly reduced in the direct contact heat exchanger system which operates with a negligibly small temperature driving force. In most direct contact liquid-liquid heat exchangers, oil or hydrocarbon with a density less than water is normally used as the dispersed working fluid. In this case, the lighter fluid is injected into the spray column through a perforated plate at the bottom of the column. The main difficulty that arises with this arrangement lies in the control of the interface at the top of the column. The interface must remain fixed as water is introduced into the column immediately below the interface. Another problem of this type is the rate of coalescence of the droplets, which influences the location of the interface at the top of the column. The rate of coalescence can be catalyzed by introduction of a honeycomb structure at the desired interface location. The main requirement is that the material is preferentially wet by the dispersed phase, Ward *et al.* [2].

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 7.5 mm in diameter, more extensively drops between 1.0 mm and 3.0 mm 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 [3] 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.* [4] 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.

Moresco and Marschall [5] showed that the measured overall area heat transfer coefficients were much lower than those predicted by correlations of external heat transfer coefficients for oil dispersed in water systems. It could thus be concluded that the heat transfer resistance lay mainly inside the drops.

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 [6] 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 [7] 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.

Ward and *et al.* [2] tested the direct contact liquid-liquid heat exchangers in the systems which was associated with solar heated and cooled building to establish the technical feasibility and economic practicality. In this experiment, Diethyl Phthalate and Dimethyl Phthalate, Butyl Benzyl Phthalate as dispersed phase liquids were proved·to be promising working fluids in the future for their utilization in the direct contact heat transfer.

2. Image Reconstruction Schemes

There are two different types of schemes that could be used for the image reconstruction in EIT. Of these, 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 so-called "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(ρ) and $v=[v_1, v_2, v_3 \cdots, v_M]^T$ 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 :

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

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

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

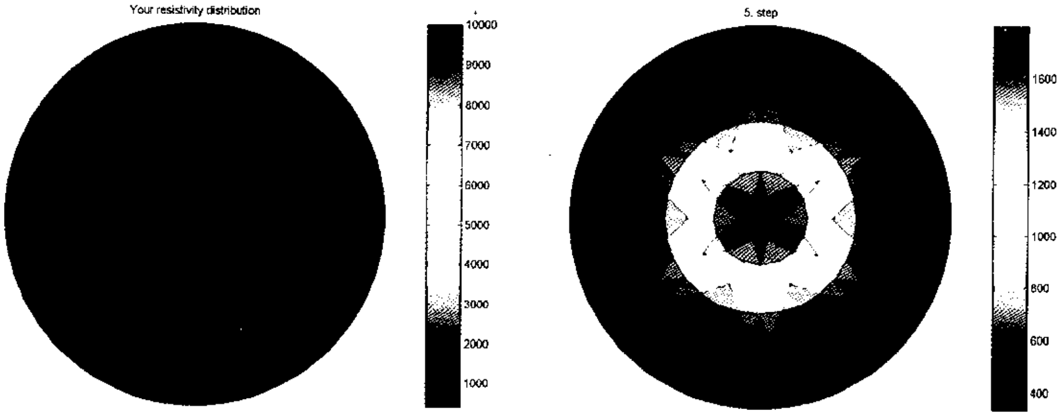
Here, the Hessian matrix H and the Jacobian matrix J are defined as given in the following :

$$H=J^TJ \text{ and } J=\frac{\partial f_i}{\partial \rho_j} \tag{6}$$

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

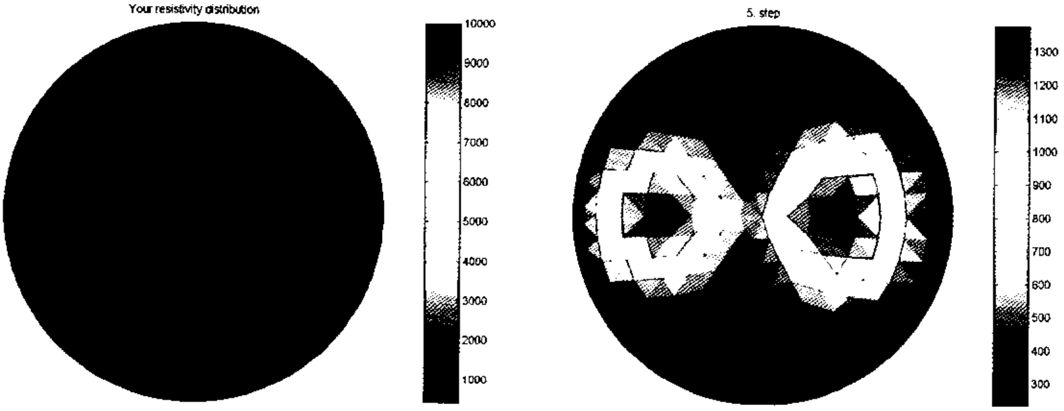
3. Image Reconstruction of Assumed Targets

To establish the reliability of the present method in



(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.

image reconstruction of dispersed phases in a DCHX, a number of tests are made using assumed images in a stagnant continuum. The aforementioned algorithm and the solution procedure are employed step by step in this regard. On the basis of the predefined resistivity distribution, boundary voltages are firstly obtained before they are used in place of the measured ones as required by the inverse problem. This clearly demonstrates the solution procedure involved in the proposed algorithm. All data that carry information regarding the internal electrical impedance are fully used in the image construction. Figures 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.

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 2 mm in diameter. Figure 3 shows the formation of small droplets as well as rather large chunks of the dispersed phase liquid that are present in DCHXs.

These are the cases which could be observed in the operation of DCHXs where dispersed phases are

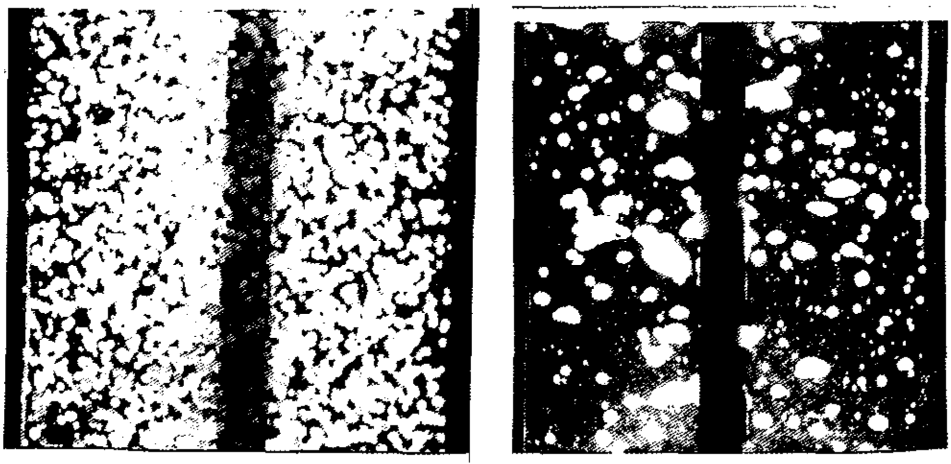

(a) (b)

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

Table 1. Physical properties of phathalate (Dimethyl)

Molecular formula	Specific gravity	Viscosity, poise	Specific heat, J/g°C	Thermal conductivity, W/cm°C	Freezing point, °C	Boiling point, °C
$C_8H_6O_4$	1.052	0.024	1.57	1.29×10^{-3}	−40.5	297.7

Table 2. Physical properties of dowtherm J.

Molecular formula	Specific gravity	Viscosity, poise	Specific heat, J/g°C	Thermal conductivity, W/cm°C	Heat capacity, J/cm3°C	Freezing point, °C	Boiling point, °C
alkylated aromatic	0.8067	0.0036	2.07	1.26×10^{-3}	1.67	−73.3	181.1

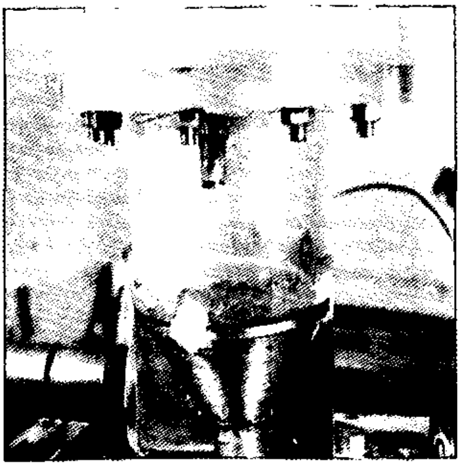


Fig. 4. Droplets of dowtherm J formed on the surface of a distribution plate.

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.

Figure 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. 5. Presence of three phases in a DCHX.

Figure 5 features a very special case when there are two dispersed phases present in a single continuous phase. This is made by injecting LNG bubbles through a nozzle located at the bottom of a cylindrical column of water. The water is stagnant and as the LNG bubbles arise within the column they are mingled with ice pieces formed and separated from the frigid nozzle surface. Also there is a possibility of creating ice pieces or slurries by arising dispersed phases if they are formed by liquids of high heat capacity. It deems that the proposed EIT technique could play a vital role in detecting such phenomena without invoking truly complex methods or measuring techniques. The following example demonstrates such a case where the dispersed phase is identified without undue difficulties.

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 case when one cylindrical object of nearly the same impedance as Dowtherm J is placed in a column of saline solution (0.15%) whose electric resistivity is 330 Ωcm. For Dowtherm J, the electrical resistivity is measured to be over 10^{12} Ωcm, 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

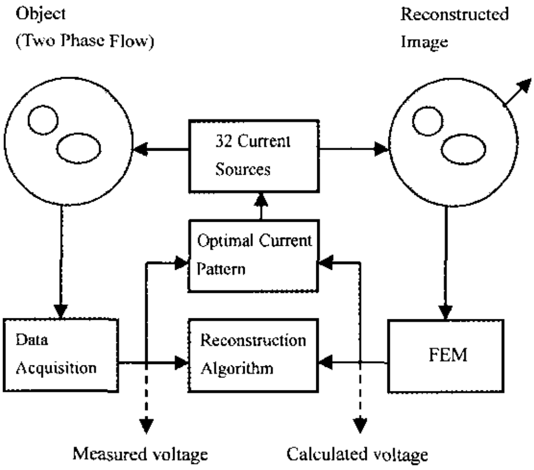


Fig. 6. Schematic diagram of the experimental apparatus.

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. 6. Figure 7 is the result of the aforementioned case where actual and reconstructed images of the immersed object

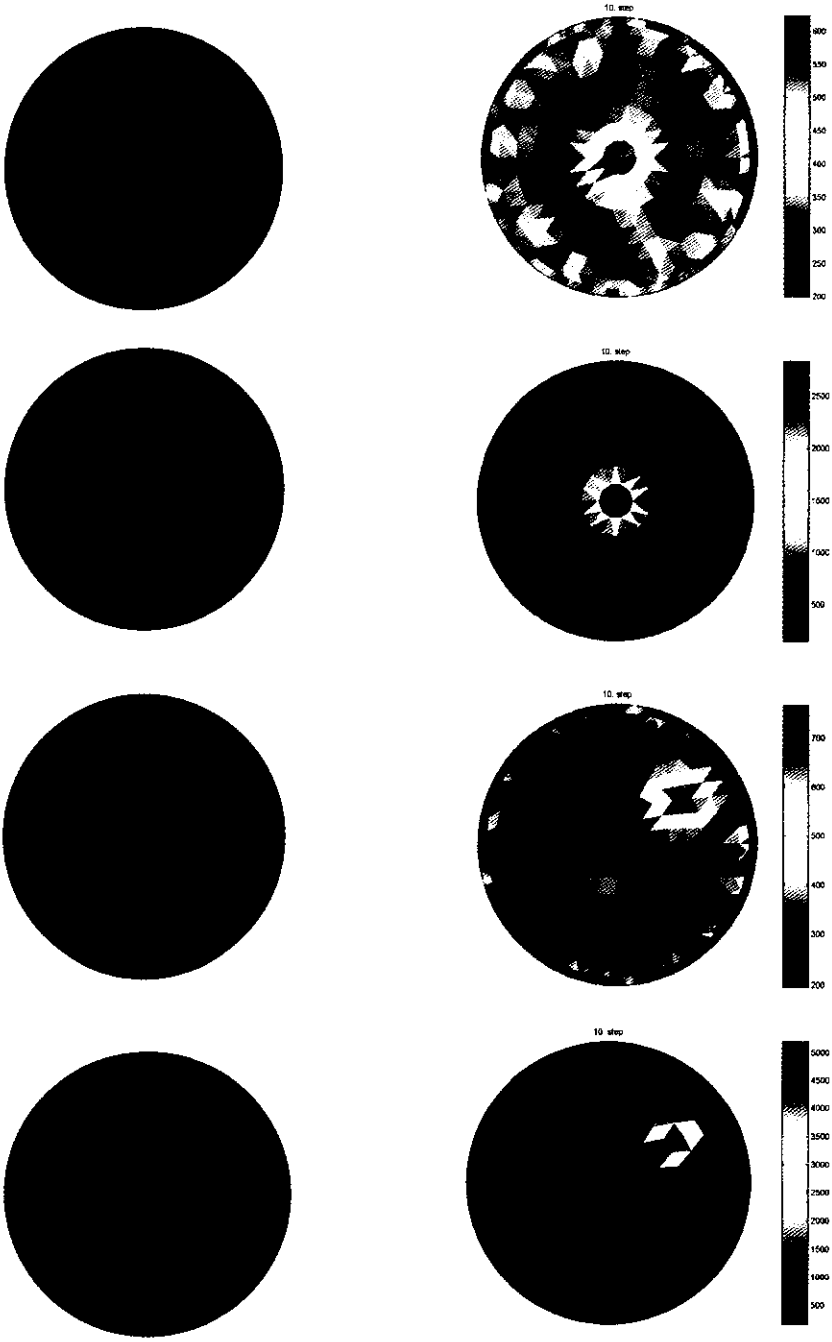


Fig. 7. Reconstructed results for a cylindrical object, which has nearly the same electric resistivity ($>10^{12}\ \Omega$cm) as Dowtherm J, immersed in a saline solution (300 Ωcm) : (a) actual image (b) reconstructed image.

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.

4-2. Holdup of the Dispersed Phase

Holdup is defined as the fraction of the effective volume of the heat exchanger occupied by the dispersed phase. Holdup is considered to be dependent on flowrates, liquid system properties, operating temperatures, and drop sizes. Holdup is an important parameter which determines relative velocity and evaluates total contact surface area between continuous phase and dispersed phase droplets (masses).

When small droplets are uniformly distributed in a DCHX, the method of Bruggeman [8] or its equivalent could be introduced to determine the holdup which is a very important variable greatly affecting the heat transfer characteristics of a DCHX. In such cases, it is not necessary to invoke the present method. Statistical approaches are more appropriate and accurate to investigate the performance of a DCHX.

5. Conclusions

The presence of dispersed phases in DCHXs has been studied in view of their detection using the EIT technique. Different cases of DCHXs using two immiscible liquids are considered as these cases offer good examples of applying the technique without undue difficulties. Also considered are the case of three phase problem which needs further investigation to resolve the complicated physical phenomena involved with the operation of such DCHXs. Although what's been done and accomplished here barely establishes the basics of applying the EIT technique to the complicated world of DCHXs, it has shown what could be done or should be done in order to harness the technology most effectively in the areas of direct contact heat and mass transfer.

Acknowledgements

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