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Image Capturing of Dispersed Phases in DCHXs by Electric Tomography

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Abstract

This paper introduces the physical phenomena involved in Direct Contact Heat Exchangers (DCHXs) and also investigates the possibility of applying of EIT(Electrical Impedance Tomography) technique for capturing the images of dispersed phases as they stream through a stagnant body of water. A number of cases are studied where two dimensional cross-sectional static images are given for fictitious and actual masses present in a column of water(saline solution). 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 elucidation of complicated flow field where the dispersed phase fluid tends to change its shape and size constantly during its journey through the other phase(water). This paper presents a number of results with different types of dispersed phases that are immiscible with water. The EIT technique has been employed in this context to test its applicability in capturing the dynamic images of dispersed phases. It shows static images of dispersed phases where dynamic images could be obtained by simply extending the algorithms and strategies employed in the present analysis.

1. Introduction

1.1 Image reconstruction of dispersed phases in a DCHX

Two-phase flows occur in many thermal energy systems which generally involve dynamic heat transfer between different phases. A DCHX is one of such examples where small droplets are dispersed and stream through a continuous phase exchanging thermal energy with it. Many measurement systems, such as LDV(Laser Dopler Velocimetry), PIV(Particle Image Velocimetry) and other optical probes, are developed which enable monitoring of the dispersed phase in a flow field of any DCHXs. Recently, EIT (Electric Impedance Tomography) technique, which was originally invented to obtain the tomographic image of human organ, is introduced to investigate the dynamic motion of dispersed phases in multiphase flows. 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 cope with these predicaments in the solution procedure, some modifications to the well-known methods are proposed and tested in the present study. Reconstructed images of fictitious masses as well as real ones are examined to assess the validity of the present scheme in extending its scope to the dynamic realm of multiphase flows.

1.2 Operating Principle of Different Types of DCHXs

There exist great opportunities for development of DCHXs for the utilization of solar energy. A DCHX is based on the direct contact heat transfer concept where one fluid is brought in intimate contact with another at a different temperature. Highly efficient heat transfer can result. 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.

Direct contact heat transfer can take place between one stream of a solid and one stream of a solid, liquid or a gas, or between a liquid and a gas or another liquid. Most familiar applications of DCHXs are found in cooling towers(air and water), evaporative coolers(air and water), and open feed water exchangers (steam and water). The latter are found in most thermal power plants.

Direct contact processes are characterized by extremely efficient heat transfer with very small associated capital costs, both comparisons being relative to conventional(closed) heat exchangers. A great deal of work have been done to develop more efficient and more reliable DCHX for many years. Among them, the spray-column form has drawn more attention than others in solar applications because of its simple but highly efficient design. A diagram of this type of device is shown in Fig. 1. In this case, the lighter fluid is injected into the spray-column through a perforated plate at the bottom of the column.

The design also could be modified to disperse a heavier fluid from the top of the column.

It may be that a passive solar water heater might be developed using DCHX concepts. One possible configuration is shown in Fig. 2. Here it is assumed that a fluid that is less dense than water in both the liquid and vapor phases is used as the "heater fluid." This would be the case with simple hydrocarbon substances. A common refrigerant could also be used, and some of these fluids have a liquid phase that is more dense than water,

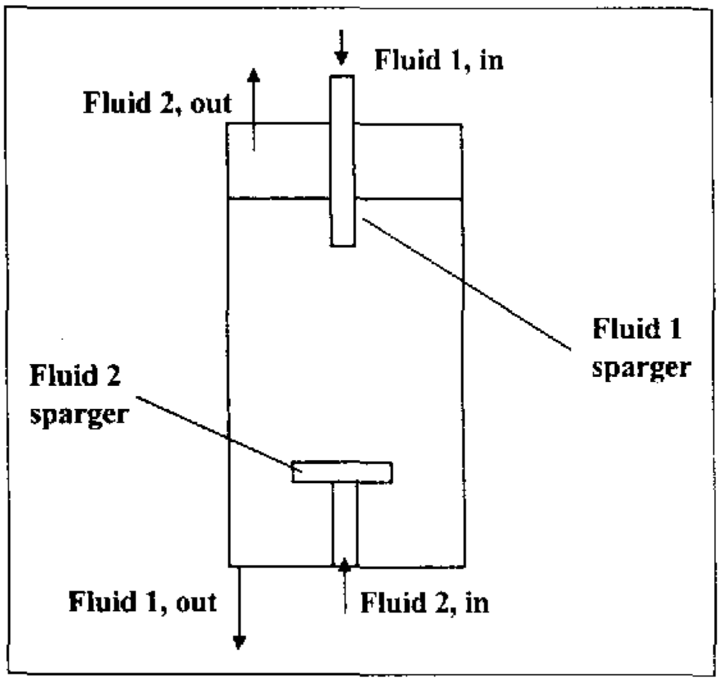


Fig. 1. Diagram of a simple spray column. In this case shown here, fluid 2 must be less dense than fluid 1.

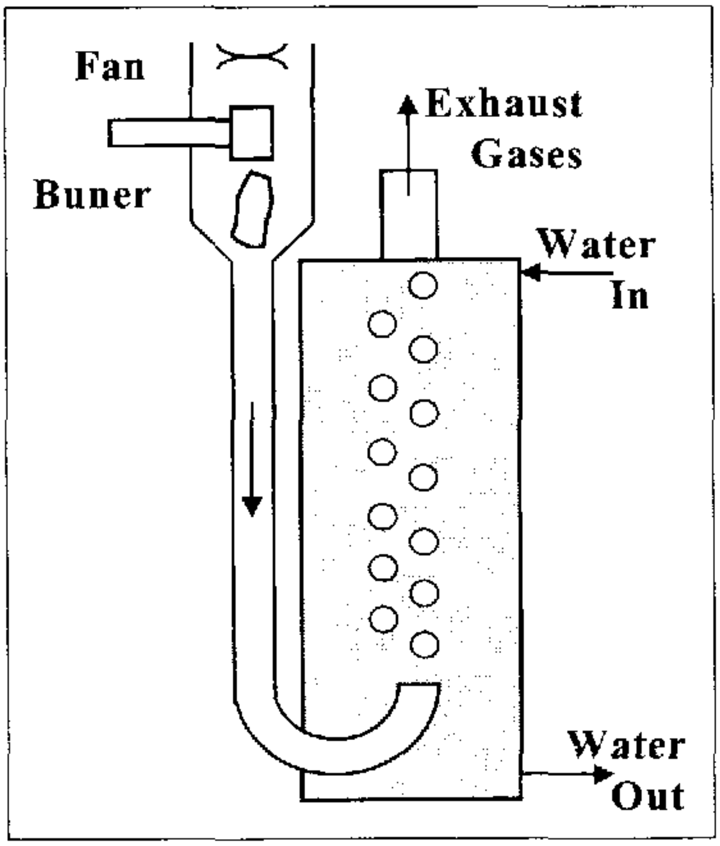


Fig. 3. A possible configuration of a direct-contact combustion water heater.

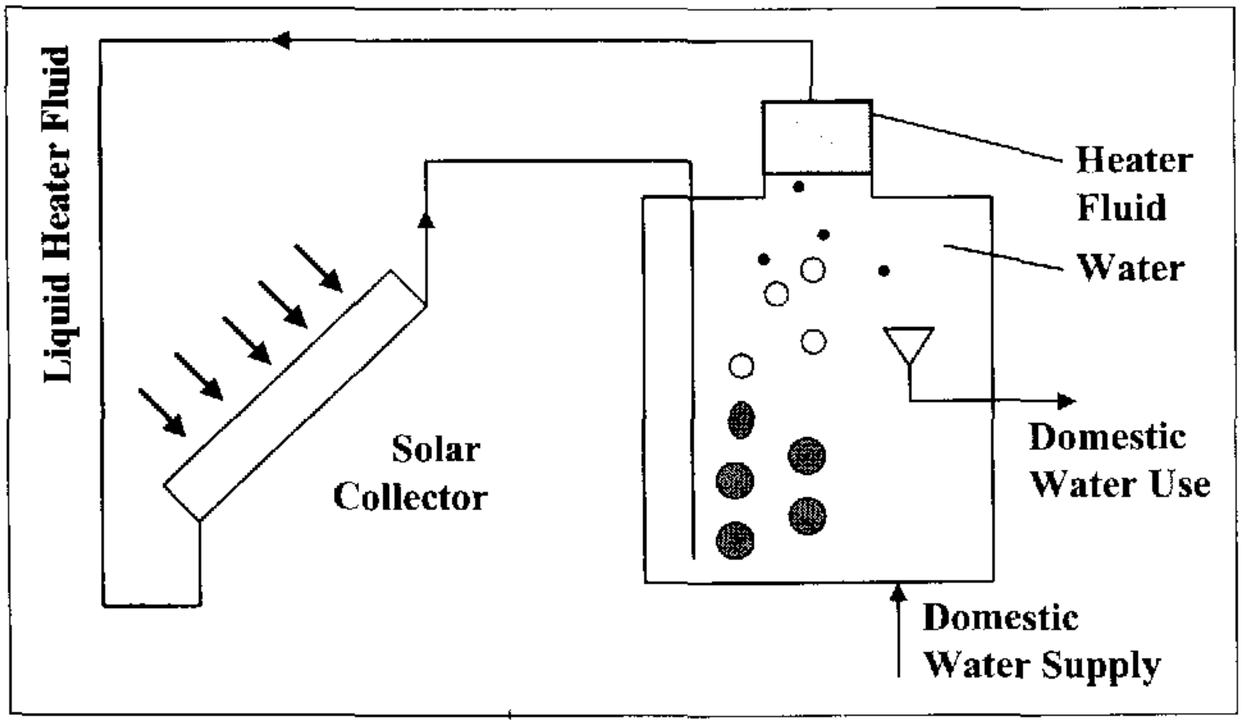


Fig. 2. Schematic of a possible direct contact device that operates as a key element in collector-storage passive system.

requiring a slightly different layout of the storage. The desirable aspects of the type of device shown may include: better heat transfer rates than conventional batch-type water heaters and the possibility of almost as good freeze protection as freeze-protected, active water heaters.

Another possible application, explored to a limited extent in Great Britain, is that of DCHX combustion water heater. Whenever gases are used to heat a liquid, direct contact processes can offer considerable cost benefits. this is because the heat transfer from a gas is generally quite poor compared to liquid or change-of-phase heat transfer. One possible configuration is shown in Fig. 3.

2. Methodology of the Image Reconstruction

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:

$$\nabla \cdot (1/\rho \nabla u) = 0 \qquad (1)$$

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:

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

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:

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

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:

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

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

$$\mathrm{H} = \mathrm{J}^{T}\mathrm{J} \quad \text{and} \quad \mathrm{J} = \frac{\partial \mathrm{f}_{i}}{\partial \rho_{j}} \tag{6}$$

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

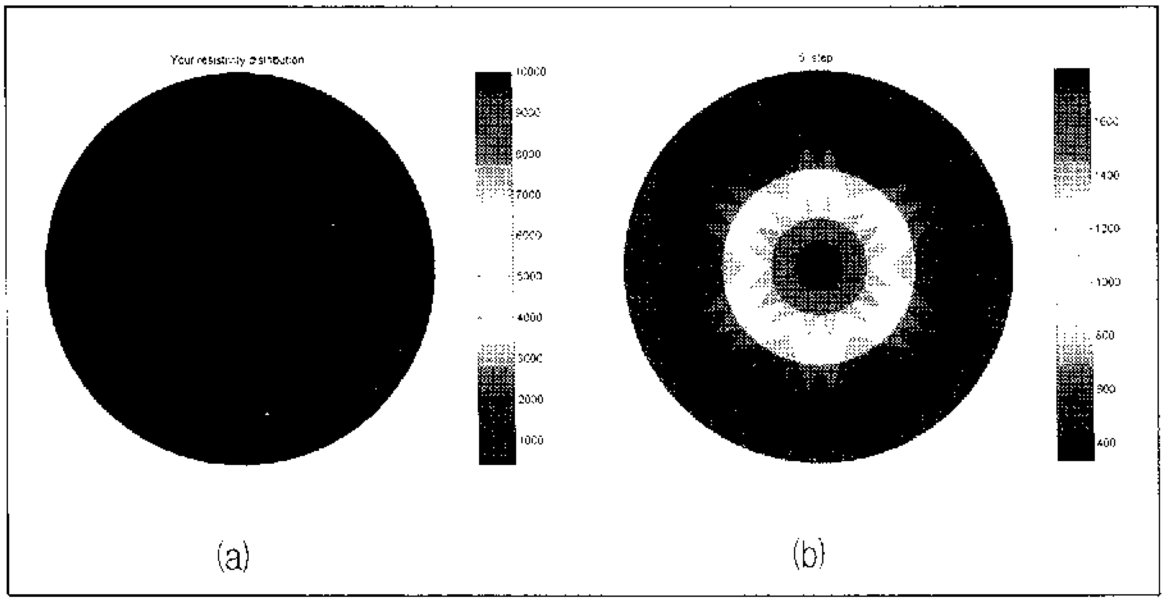
3. Preliminary Results of the Image Reconstruction

Before embark 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. 4 and 5 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 Results

4.1 Dispersed Phase Droplet Size Distributions

The mechanism of the drop formation for the dispersed working fluid determines the



(a) (b)

Fig. 4. Single mass of dispersed phase : (a) assumed image and (b) reconstructed image.

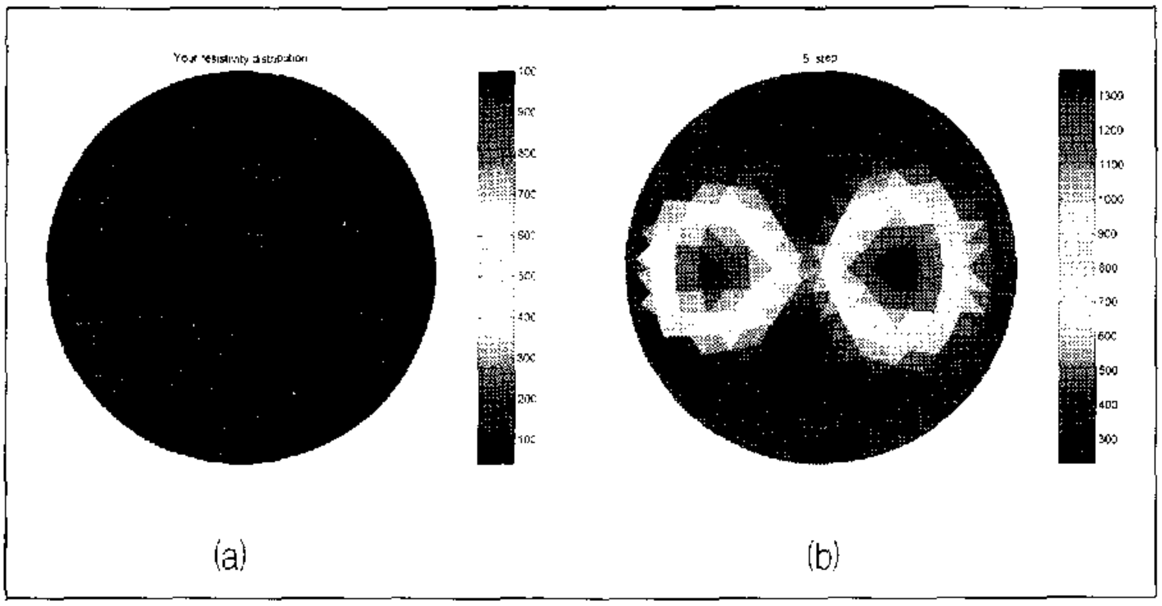


Fig. 5.
Two masses of dispersed phase : (a) assumed image and (b) reconstructed image.

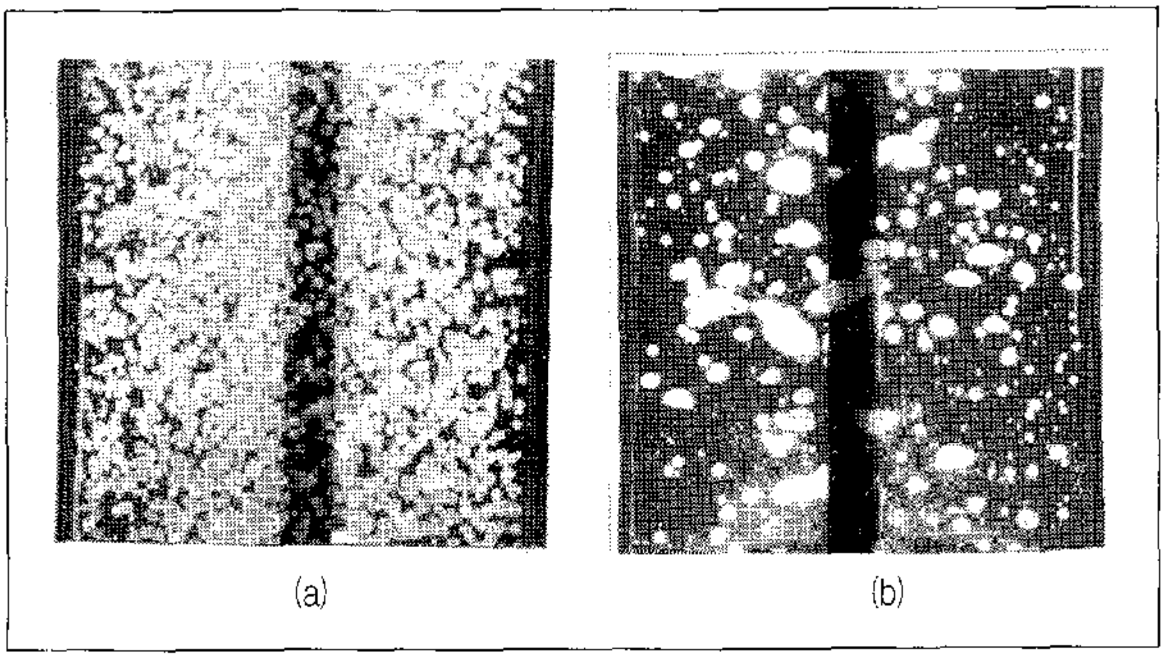


Fig. 6.
Presence of dispersed phase in a DCHX: (a) uniform size masses(droplets), (b) small and large masses are mingled

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. 6 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 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.

Fig. 7 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.

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

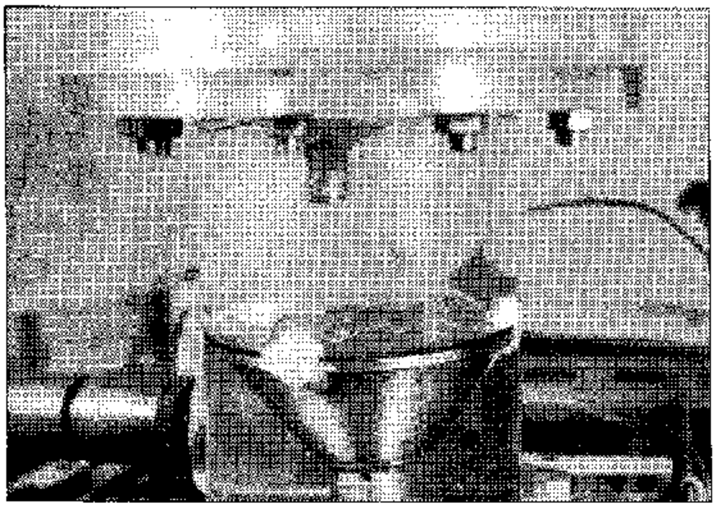


Fig. 7. Droplets of Dowtherm J formed on the surface of a distribution plate

Fig. 8. Presence of three phases in a DCHX

Fig. 8 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.

4.2 Image reconstruction of dispersed phases using EIT technique

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 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. 9. Fig. 10 is the result of the aforementioned case where actual and reconstructed images of the immersed object 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 targeted 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 targeted mass as well as the removal of noises in measured data. Subsequent research is currently underway to improve the technology in this regard.

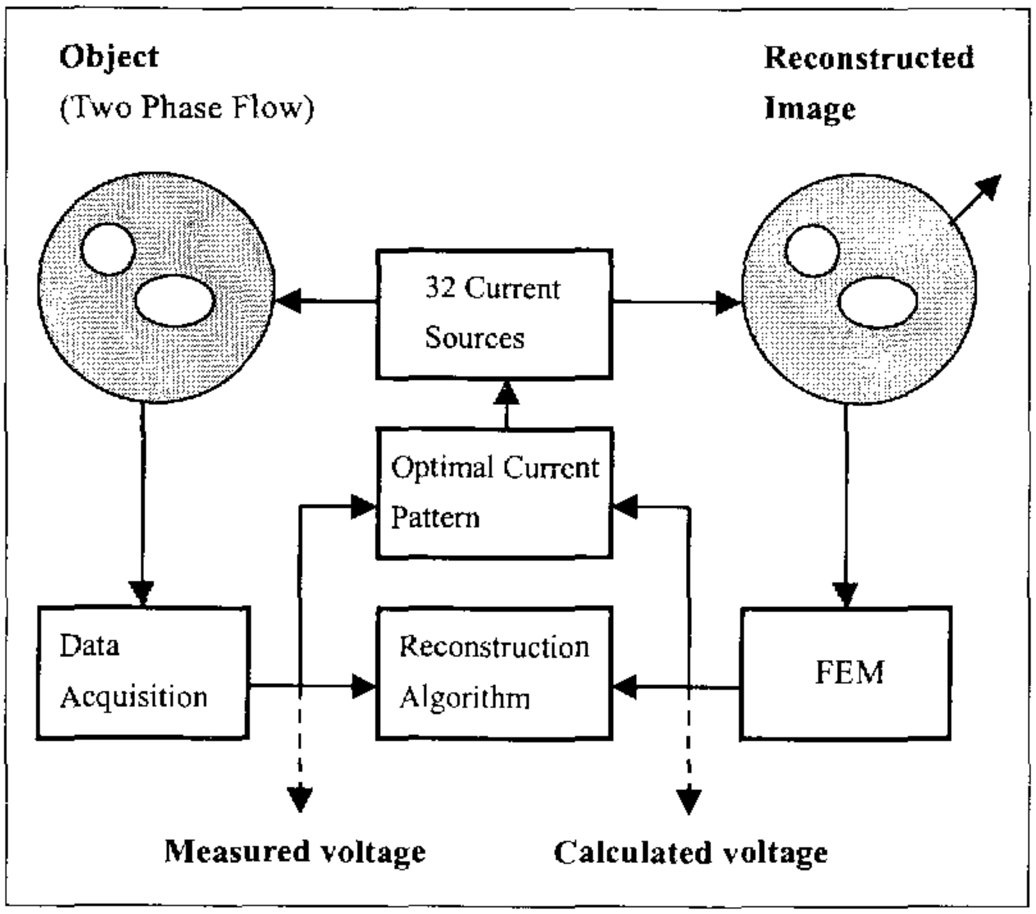


Fig. 9.
Schematic diagram of the experimental apparatus

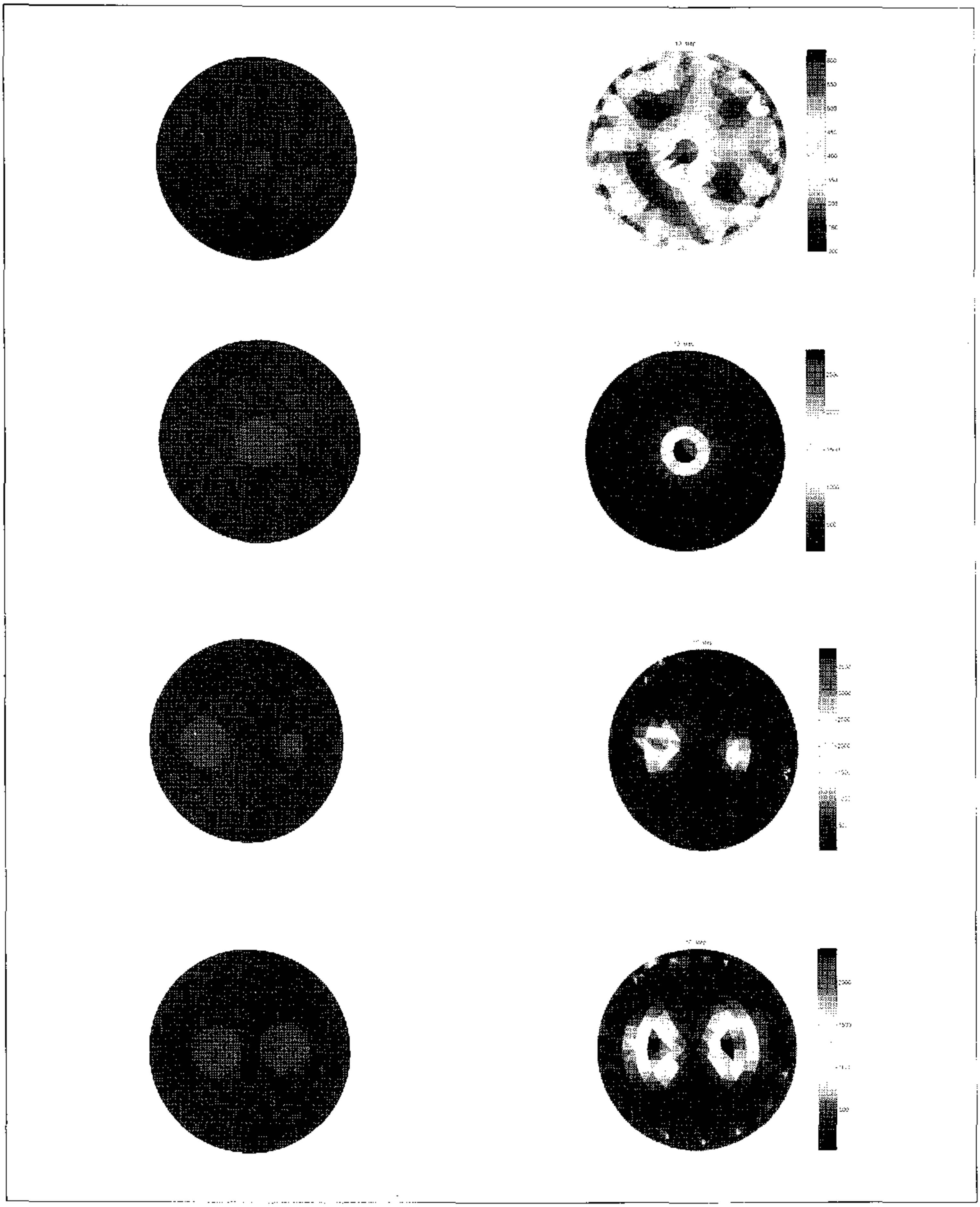


Fig. 10. Reconstructed results for a cylindrical object, which has nearly the same electric resistivity($>10^{12}$ Ωcm) as Dowtherm J, immersed in a saline solution(300Ωcm) :
(a) actual image (b) reconstructed image

5. Conclusions

A study has been carried out to examine the formation and movement of dispersed phases in DCHXs. Different types of DCHXs are introduced and their operating principles are reviewed in view of fluid mechanical characteristics of dispersed phases. Different cases of DCHXs using two immiscible liquids are considered as these cases offer good examples of applying the EIT 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 the results introduced here barely establish the basics of applying the EIT technique for the image extraction and reconstruction of dispersed phases in a DCHX, they demonstrate quite clearly the possibility of using the EIT technique to this end for better understanding of dispersed phases with their physical involvements in a DCHX.

Acknowledgements

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