

Solid-Liquid Two-Phase Flow Image Reconstruction Based on ERT Technique in Microchannel

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Abstract

Monitoring the flow behaviour on the micro-scale is very important in many industrial and biochemical process, the multiphase coexistence in microchannel provides many attractive characteristics compared to a single-phase flow. The precise flow rate control and well-defined channel geometries make it possible for us to make detailed investigation on multiphase flow phenomena on micro scale. This paper aims at the solid-liquid two phase flow visualization in the cross-sections of a novel microchannel based on the electrical resistance tomography (ERT) technique. Experimental results reveal that ERT image reconstruction technique base on Agilent data acquisition system can effectively detect the particle distribution in the microchannel.

Keywords: two-phase flow, microchannel, Agilent instrument, ERT

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1. Introduction

In the past decades, the new research area of multiphase flow on the micro-scale was rapidly developed due to the appearance of microtechnology [1,2] and availability of fabricating complicated sensing configuration on micro scales using Micro-Electro-Mechanical Systems (MEMS) technology. A number of investigations on microchannel have been partially discussed in some reviews according to modelling study [3], flow pattern analysis [4], flow engineering and applications: heat transfer [5], micro reactor [6] and DNA analysis [7]. However, the fluids of interest in such applications are rarely single-phase liquids, a clear understanding of the micro-scale effects on multiphase flow is still rudimentary, one of the reasons is surely a lack of experimental techniques which allow for sensing the material in very limited space. Many optical measuring methods such as micro particle image velocimetry (micro PIV) and micro laser induced fluorescence (micro-LIF) [8] have been used attempting to visualize the multiphase distribution in microchannel, but these methods can't overcome their inherent optical scattering problem which becomes even more severe within the limited dimension.

Process tomography, as a rapid developing visualizing technique, has been applied to multiphase flow measurement within conventional volume using technique such as Electrical Capacitance Tomography (ECT) [9] and Electrical Resistance Tomography (ERT) [10]. Since it has the advantages such as non-intrusiveness and excellent time resolution, it has great potential to be applied to the research of multiphase flow in microchannel in the future. Some attempts have been made in recent year to visualize the two-phase flow in microchannel using ECT technique[11], but the capacitance-sensing electrodes can't be made very small to give a sufficient capacitance change; resistance electrodes can be made very tiny and resistance information has been successfully retrieved [2], but the measurements between any electrode combinations were not fulfilled concurrently inside the microchannel, so the ERT technique has not been completely applied in the visualization of two phase flow.

In this paper, Agilent based Data acquisition unit was constructed for resistivity data retrieval from any needed electrode pairing combination within microchannel. The concentration of each phase can be computed based on the knowledge of the electrical conductivity of each phase, yielding the two-phase concentration tomogram.

2. ERT system for microchannel

The ERT working principle consists of injecting electrical current between a pair of electrodes and measuring the potential differences between the remaining electrode pairs. This procedure is repeated for all the other electrode pairs until a full rotation of the electrical field is completed to form a set of measurements. In our experiment, the ERT system is composed of a hardware part, which includes the sensor of electrodes array within microchannel, the data acquisition system based on Agilent measurement instrument, flow rate controlling pump and a computer with image reconstruction algorithm to reconstruct images.

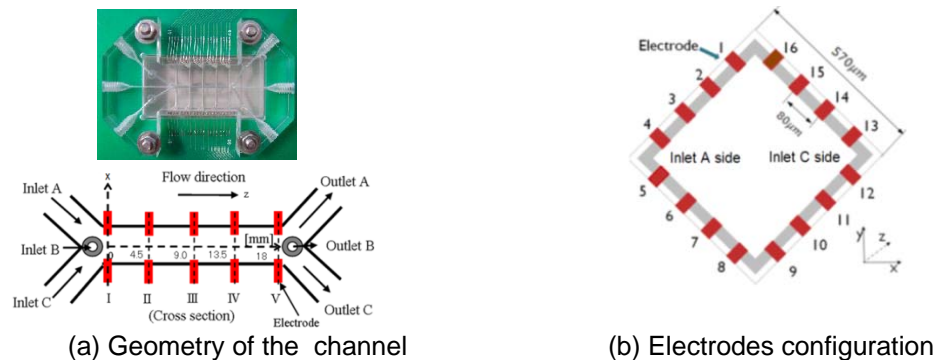


Figure 1. The configuration of the microchannel

2.1. Microchannel geometry

The microchannel [Covalent Materials Corporation, Japan] used in this research has rectangular configuration as showed in Figure 1. On the quartz-glass-made framework ($570\mu\text{m}$ width), there are totally five measuring cross-sections, neighboring cross-sections are separated from each other by 4.5mm . In each cross-section, 16 resistance electrodes are embedded, which are separated from each other by $80\mu\text{m}$. The inlets configuration used for microfluids injection is Y configuration as showed in Fig.1 (b). Fluids with different physical property can be injected into it and mixed together to form a two-phase flow.

2.2. Data acquisition system

The data acquisition unit's function is to transmit the data sampled from micro resistance electrodes into the computer rapidly and accurately. Conventional ERT system P2000 ERT (Tomography Company) lack the ability to overcome the interference of contact resistance in the microchannel application due to its poor maximum exciting current frequency of only 153.6Hz . In our system high-tech Agilent measuring instruments was employed as data acquisition unit, the Agilent 34980A was used for channel switching and the Agilent E4980 impedance measurement meter for real time resistance measurement. 34932A, as a plug-in switching module of Agilent 34980A platform, was used for the control of electrode pairing operation as showed in Fig.3. Every row and column can be intersected to create the cross point. It has excellent scan velocity up to 100 ch/sec and at the sampling frequency of 1MHz the crosstalk can be deduced to -55dB . These excellent electrical features make Agilent family very suitable for measurement on the resistance distribution in the microchannel.

2.3. Flow rate controlling pump and computer for data analysis

IC3100 micro pumps (KD Scientific, USA) were used to synchronize the syringe injection process and control the flow rate of microfluids in the corresponding inlets, the flow rate can be accurately selected in a wide range from 0.01 ml/h to 2.0 ml/h . The state of the Agilent instruments were controlled and supervised by a 2.5GHz personal computer through GPIB interface for real time data processing.

3. Image reconstruction for ERT in microchannel

The goal of image reconstruction in ERT is to compute a tomogram representing the electrical resistivity distribution of materials flowing within some column from voltages measured at the periphery of the sensor in response to the injected electrical current.

To reconstruct the two phase flow image for ERT in microchannel, forward problem and inverse problem have to be solved. Knowing the resistivity distribution r and given current injection, the problem of finding the electrical potential V inside or on the boundary of channel between electrode pairs is called the forward problem, which can be denoted:

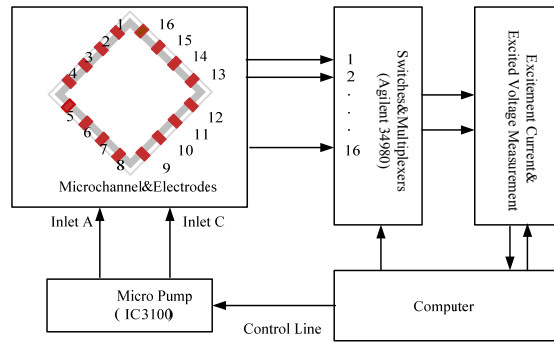


Figure 2. Data acquisition system and electrodes pairing configuration

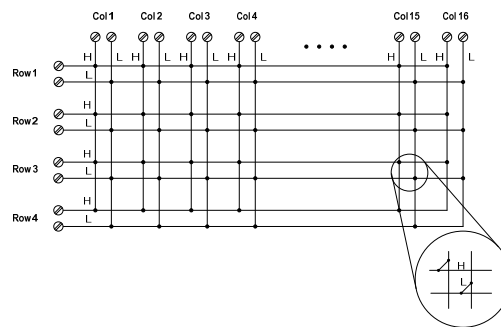


Figure 3. Simplified Schematic of 34932A switch module

$$V = F(r) \tag{1}$$

Where F is defined as the forward operator connecting resistivity distribution and electrical potential.

The change in voltage differences $V + \Delta V$ in response to a perturbation of resistivity distribution $r + \Delta r$ can be expressed by the Taylor expansion:

$$\Delta V = \frac{\partial F}{\partial r} (\Delta r) + O((\Delta r)^2) \tag{2}$$

Neglecting the higher order terms, Eq.(2) can be simplified to be the linear form:

$$\Delta V = S \Delta r \tag{3}$$

Using finite element methods (FEM), Δr can be subdivided into n discrete values. Every discrete value corresponds to one pixel of the image reconstructed. Suppose that there

are m voltages, then $S = \partial F(r) / \partial r$ is an $m \times n$ matrix. S is called Jacobian matrix or sensitivity matrix, which is computed based on multiple solutions of the *FEM* forward operator.

Finding the resistivity distribution r based on the measured voltages V is called the inverse problem of ERT. Based on the previous notation, the inverse problem is to find the inverse of the forward operator:

$$r = F^{-1}(V) \quad (4)$$

In its normalized linear form, the ERT inverse problem computes the inverse of the Jacobian matrix:

$$\Delta r = S^{-1} \Delta V \quad (5)$$

In general, the pixels of image are much more than the voltages measured, that means unknown resistivity values are more than known voltage measurements. So direct analytical solution for Eq. (4) or (5) does not exist. The ERT inverse problem is ill-posed. Only approximations of F^{-1} or S^{-1} can be found by numerical techniques. Approximations of S^{-1} are commonly derived using a least-squares method by computing a resistivity distribution, which minimizes the difference between the measured voltages and the simulated voltages:

$$\|\Delta V - S\Delta\tilde{r}\|_2^2 = \min \quad (6)$$

Both direct and iterative algorithms can be formulated using different approximations of S^{-1} , such like linear back-projection (LBP), Landweber method, Newton-Raphson method (NRM), and Tikhonov regularization method. In our experiment, we use the widely-used Tikhonov regularization method as the tool for image reconstruction.

The basic idea of Tikhonov regularization method is to add a bound term, which can change the ill-posed least-squares equation into a well-posed equation. Solve the minimum of this equation:

$$\min(\|\Delta V - S\Delta\tilde{r}\|_2^2 + \alpha\|\Delta\tilde{r}\|_2^2) \quad (7)$$

It is tantamount to solve the equation:

$$(S^T S + \alpha I)\Delta\tilde{r} = S^T \Delta V \quad (8)$$

The solution of Eq.(8) is unique if α is positive, and:

$$\Delta\tilde{r} = (S^T S + \alpha I)^{-1} S^T \Delta V = \hat{S}^{-1} \Delta V \quad (9)$$

where $\hat{S}^{-1} = (S^T S + \alpha I)^{-1} S^T$ is the Tikhonov regularization generalized inverse matrix of S , and α is the regularization parameter. So an iterative Tikhonov regularization method is defined in the following form:

$$\left. \begin{aligned} \Delta\tilde{r}_0 &= 0 \\ \Delta\tilde{r}_k &= \Delta\tilde{r}_{k-1} + (S^T S + \alpha I)^{-1} S^T (\Delta V - S\Delta\tilde{r}_{k-1}) \end{aligned} \right\} \quad (10)$$

When $k=1$, Eq. (10) is the normative Tikhonov regularization method. The preset stopping parameter of this iterative method is:

$$\beta = \frac{\|\Delta\tilde{r}_k - \Delta\tilde{r}_{k-1}\|}{\|\Delta\tilde{r}_{k-1}\|} \quad (11)$$

When β is less than a certain value, the iteration stops.

4. Test results

Some experiments were conducted to prove that ERT can be successfully applied to the measurement of two-phase flows in microchannel.

4.1. Experimental procedures

Two kinds of microfluids were used in this experiment. One of them is polymer microsphere suspension (Microgenics USA) with mean particle diameter of $2.0 \mu m$. The original particle density of the suspension is $1.0 g/cm^3$ and the microsphere has nonconductive property. The other is $0.9 g/cm^3 NaCl$ solution which is used for reference measurement and as the liquid flow in the liquid-solid two-phase flow. In our experiment, $0.9 g/cm^3 NaCl$ solution and polymer microsphere suspension were injected respectively into inlet A and inlet C simultaneously under the same volume rate of $0.01 ml/s$. In this case, two-phase microflow was formed in the microchannel and independent measurements were done on every cross-section.

An adjacent current injection and measurement pattern was used. The frequency of the injected excitement current was set $50 kHz$ at an amplitude of $10 mA$. Electric current was first injected into electrode pair of 1 and 2. The voltages between the other adjacent electrodes were measured. The excitement current was injected into the next adjacent electrodes successively and voltages between the other adjacent electrodes which are not the current injected electrodes were measured. The same measurement strategy was circulated until electric current was injected into every electrode. In order to reduce the influence of contact resistance, voltages on the current injected electrodes were not measured. Since there are 16 electrodes in each cross-section, and every time of current injecting 13 data of voltage can be obtained. So $16 \times (16-3) = 208$ data of voltage can be measured on every cross-section. The COMSOL Multiphysics 3.5 software was used to determine the boundary voltages that are generated around the sensor when the excitation current signal is applied. Figure 4 gives representative results for the 16-electrode in microchannel, a single particle with $5 \mu m$ diameter located near the top right of the diagram, suggesting that the invading solid phase can result in the change of equipotentials distribution.

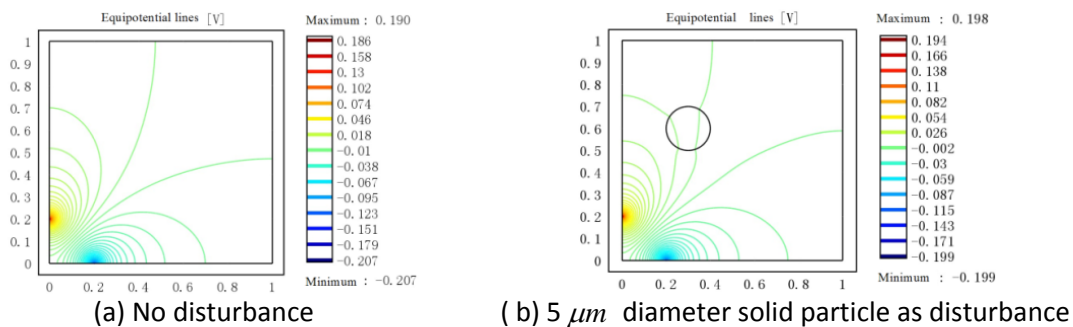


Figure 4. Predicted equipotentials in the cross-section from finite element modeling

4.2. Experimental results

Figure 5 shows the voltages measured in the experiment, figure (a), (b) and (c) are the corresponding voltages measured on cross-section I, III and V as examples, all of them have obvious change with the controlled two phase flow inside the microchannel with the highest voltage level about $3.5 mV$. It proves that the contact resistance can be effectively suppressed and the measured boundary voltages are very sensitive to the changes of resistivity distribution in the microchannel under the experimental condition.

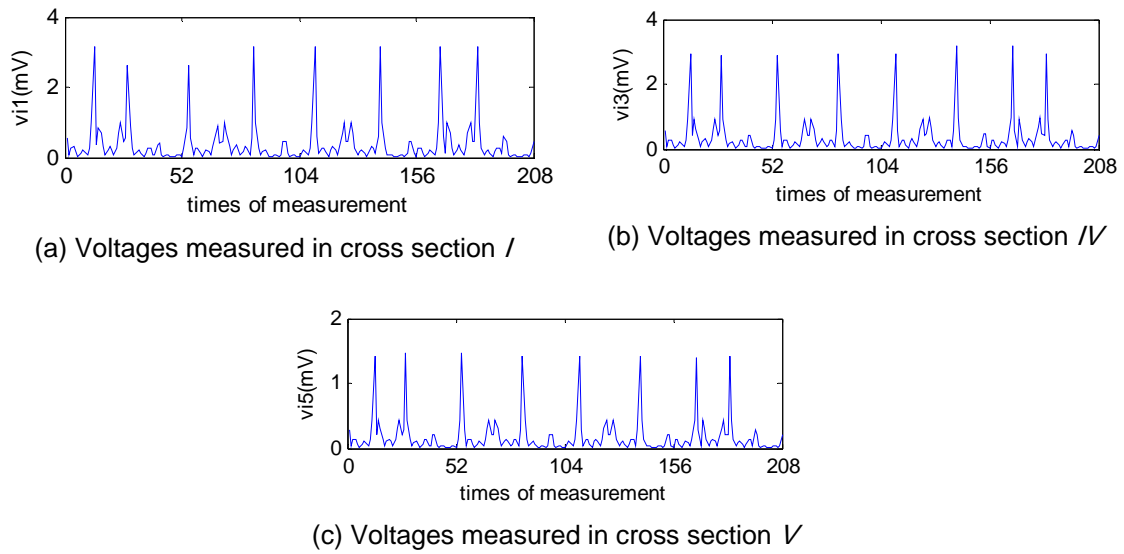


Figure 5. Voltages measured in some sample cross sections

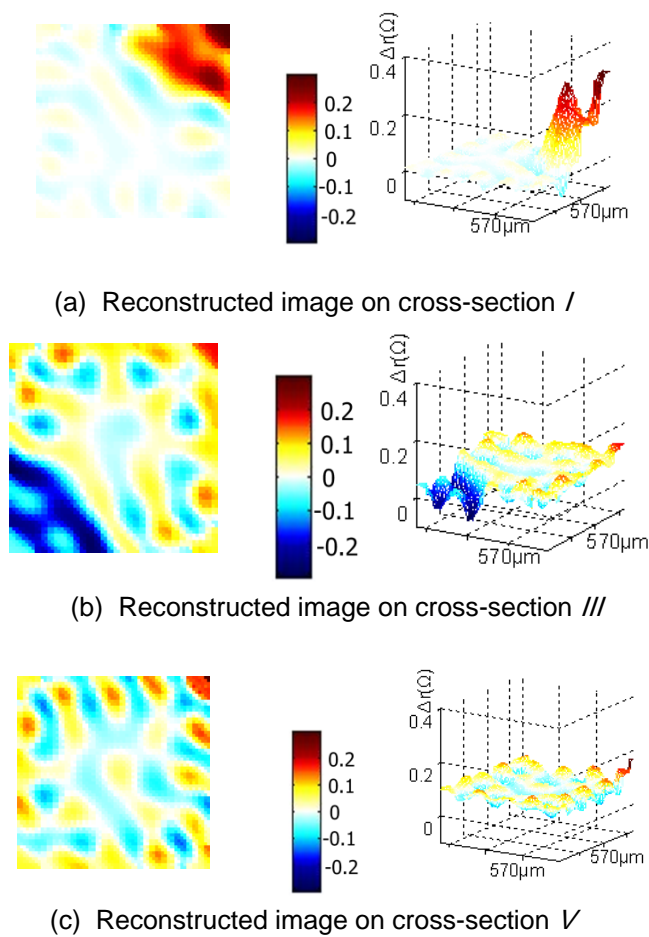


Figure 6. 2-D and 3-D Resistivity distribution on some sample cross-sections

4.3 Image reconstruction

The changes of the resistivity distribution (Δr) in every cross-section were reconstructed based on the measured boundary voltages using the iterated Tikhonov regularization algorithm mentioned above. Choose $\alpha = 0.01$, and stopping parameter β not greater than 0.001 to facilitate the convergence of non-linear inverse problem. In this case the 2-D and 3-D reconstructed images of the Δr in some cross-sections were shown in Figure 6 as examples.

Figure 6 reveals the changes of resistivity distribution in all of the five cross-sections in the microchannel. We can see that along the flow direction from cross section I to cross-section V, Polymer microsphere suspension and NaCl solution resolve into each other gradually except in cross-section I, NaCl solution just meet each other. The test result also reveals that under certain flow rate, polymer micro particles have already dispersed evenly near cross-section V.

The reconstructed images of Δr on every cross-section show that the polymer micro particles seem to have the tendency to disperse evenly within the liquid medium. This phenomenon agrees with the theory which claims that when two different phases are injected as adjacent streams into one channel, one phase will often encapsulates the other phase. Although the test results is not very satisfactory, it agree basically with the real experiment condition which suggests that the Agilent based measuring system can really work.

5. Conclusion

We use syringe injection method to generate a stable liquid-solid two-phase flow in a novel experimental microchannel for image reconstruction of the two-phase flow on the micro-scale. The voltage change on the micro sensor can be effectively obtained and flow phenomena of the microfluids can be detected using the High Tech Agilent measurement strategy together with certain image reconstruction algorithm. The image of solid-liquid two phase flow was successfully reconstructed using Agilent data acquisition system, the presence of the nonconductive microsphere in the microfluids can alter the resistivity distribution inside the microchannel.

Since all of the experimental results are based on non-conductive microsphere with same particle size and same flow rate, more detailed research should be done using particles of different physical property under other different test condition, meanwhile, the real time 3-dimension dynamic image reconstruction can not be realized up to now due to the hardware setup restriction.

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