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MEASUREMENT OF LOCAL PARAMETERS OF A LIQUID FLOW USING ELECTRICAL IMPEDANCE SENSORS

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The paper considers a method for measuring liquid flow parameters based on simultaneous recordkeeping of the spatial distribution of characteristics of complex conductivity and dielectric permittivity of a liquid. Measurements can be carried out simultaneously in a great number of measuring nodes. The sensor is assembled on a grid basis and consists of two groups of wire electrodes, spaced apart along two parallel planes; the projection of the intersection locations of the electrodes forms measurement nodes. The method offers a good space and time localization. The measurement rate can work up to tens of thous ands of readings at all measurement nodes per second. This fact makes it possible to investigate non-steady processes of heat and mass transfer. The investigators tested the method by measuring the evolution of a liquid droplet in some amount of another liquid.

Keywords: hydrodynamics, mass transfer, diffusion, conductivity sensor, dielectric permittivity, electrical conductivity, electrochemistry

Introduction

Despite all the advantages of noncontact methods for investigation of transfer processes of, such as flow visualization, Doppler laser anemometer, Particle Image Velocimetry (PIV) method [1], their application is not always possible or it is difficult. In such cases, contact methods for study of transfer processes are used. Among a wide variety of contact methods the ones based on measurements of electrical properties of the medium can be distinguished. In this case, the processes of heat or mass transfer are associated with changes in the electrical properties of the medium. The changes in the electrical properties can be natural (multiphase flows) or model ones (using electrically contrasting markers in single phase flows). The investigation of such changes in electrical properties makes it possible to restore characteristics of heat and mass exchange processes. One of these methods is a field recording of the electrical properties of the medium through conductivity probes combined on the grid basis. This type of a sensor was developed and tested in [2-4], in particular, in order to record parameters of a fluid bubble flow. In this case, the electrically contrasting marker is a gas phase.

To study the mixing of liquids it is necessary to improve the design of the sensor and measurement system, first of all in terms of a significant increase in sensitivity to determine a persistent signal at the lowest possible conductivity of the liquid. For this purpose, the authors developed a grid electrical impedance sensor. The sensor consisted of two groups of wire electrodes spaced apart and arranged against each other. The first group of electrodes actuated electric signals (reference generators), while the second group received them. The spatial intersection of the two electrode groups formed a measuring area consisting of a set of nodes. Each of the nodes was formed by a pair of generator-receiver electrodes. Parameters were measured in the gap between the two electrodes, one of which was used as a voltage supply, and the second one was used as a current receiver. On the basis of the measured current, the investigators determined an effective electrical impedance of the medium in the space between the electrodes. The electrical specifications of a node were measured by connecting of the corresponding actuating electrode to the voltage supply and recording of the passing current at the receiving electrode. Inactive actuating electrodes were connected to a zero potential. By supplying in series the potentials to all actuating electrodes with the current measurement at the receiving electrodes, the experimenters registered a three dimensional cross-section of electrical parameters of the media in which a grid probe was placed. The dilution development of the electrically contrasting marker defined the local parameters of thermal-hydraulic processes in the liquid flow.

The scope of the sensor apply is not limited by single-phase media. It can be used for the investigation of mass transfer processes in rheological complicated and multiphase media, for determining the gas content in two-phase flows of liquid-gas. The method has already been used by the authors for the investigation of heat exchange when a liquid flows in a channel with columns [5]. In this paper there is an example of application of the method to measure non-steady process of diffusion of a liquid droplet falling into an unlimited amount of liquid.

1. Features of measurement of non-steady processes in a liquid

In the investigation of the processes of heat and mass transfer in a single-phase flow any suitable for its properties (density, viscosity) liquid can be used as a marker. Its electrical properties should be different from those of the main flow. Differences can be in their electrical conductivity or specific dielectric permittivity.

An aqueous NaCl salt solution can be used as a marker. In a wide temperature range, the kinematic viscosity of salt water is slightly dependent on its salinity [7]. When changing the salt concentration from 0.01 to 10 grams per litre, the solution viscosity changes by less than 2% (at a constant temperature of the solution in the range between 10 and 70°C). At a salt concentration of 10 g/l, the salt water density changes by 1%. These conditions make for the investigation of mass transfer processes in water plants.

To investigate mass transfer in single-phase flows using a matrix sensor, an electronic signal processing system with high dynamic range is required. In a single-phase liquid flow, electrical conductivity is a measured parameter of medium. It depends on the salinity and temperature of the liquid and can vary over a wide range. The specific conductivity of the aqueous salt solution at a concentration of 1 g/l is 2000 μS/cm at a temperature of 25°C. The conductivity of technical distilled water is 10 μS/cm. The specific conductivity of the solution is dependent to the order of (1+0,025(T-25°C) and it grows by 2% per 1 degree [8]. Taking into account the temperature dependence (the flow temperature of 25°C to 45°C), the dynamic range of conductivity is 50 dB for the tracer with the salinity of 1 g/l. To record a nodal impedance with the resolution not less than 1% (throughout the conductivity range), the analog-to-digital system of signal recording should be of at least 40 dB reduced resolution. The measuring system with a dynamic range of 90 dB makes it possible to record a node impedance with 1% relative resolution of the measured value. Such a resolution is available throughout the specific conductivity range (from 10 to 3000 μS/cm), and it is enough for experimental research under laboratory conditions.

To reduce the effect of stimulated electrolysis at the electrodes of the grid probe, the constant signal level of actuation electrodes should not exceed the value of the electrochemical potential of the electrolyte decomposition. For NaCl solution under standard conditions this requirement limits the electrode voltage to the value of 2.19 V. [8]

A detailed investigation of electrical impedance parameters of the grid sensor was carried out at a special laboratory test bench, consisting of a cylindrical vessel of 100 mm in diameter and 200 mm in height. To study static characteristics of the matrix probe, the vessel was filled with aqueous NaCl salt solution in different concentrations. The chord electrodes of the sensor formed 36 measuring nodes (6 to 6 frame at a pitch of 10 mm). The diameter of the sensor electrodes was 0.4 mm, the measuring gap between the planes was 3 mm. The salinity of the aqueous solution was varied in the range between 8 and 800 mg/l that corresponded to a change in the electrical conductivity from 10 to 1700 μS/cm (at a temperature 25°C, Na [mg/l] ~ 0,7*G[μS/cm]). The temperature of the working liquid and the tracer was 23°C. The recording of the matrix sensor readings was carried out at the rate of 25 frames/sec. After recording, all measurement results were translated into the nodal values of the effective salinity. The authors used a piecewise-linear interpolation based on calibration data obtained for the water with a salinity of 10, 22, 35, 60, 110 and 210 mg/l (at the temperature of 23°C). After the initial processing, all the obtained salinity values were scaled and reduced to a range between 0 and 1. A value of zero corresponded to the salinity equal to the salinity of the working liquid (16 mg/l), and the value of one corresponded to the initial salinity of the tracer, equal to 200 mg/l. The use of the developed recording system and analog signals processing with a wide dynamic range on the basis of [6] made it possible to obtain the time resolution of at least 25 readings per second. That fact enabled the experimenters to investigate the non-steady process of dilution of the tracer body while it moved relative to the sensor plane.

2. The example of local parameters measurements

The demonstration of method possibilities for its use in a non-steady process can be clearly presented on the basis of the experiment on the diffusion of a liquid droplet falling into some amount of a liquid. For this purpose, an experimental plant was assembled. It consisted of a cylinder vessel of 70 mm in diameter and 200 mm in height containing a liquid. Inside the vessel, at a height of 100 mm from its bottom, a grid sensor was mounted. Its 36 nodes were formed by two planes. In each plane there were 6 wire electrodes. The grid pitch was 10 mm, the measuring gap between the wire electrodes at the nodes of their virtual intersection was 2 mm, and the diameter of the wire electrodes was 0.25 mm. Over the vessel, at a height of 50 mm, there was a nozzle for supplying a tracer in the form of a liquid droplet. The schematic view of the plant is shown in Figure 1. As a working liquid, distilled water (salinity of 16 mg/l) was used. It filled the vessel to a level of +50 mm above the sensor plane. As a tracer the experimenters used an aqueous solution of sodium chloride (NaCl), at a concentration of 200 mg/l.

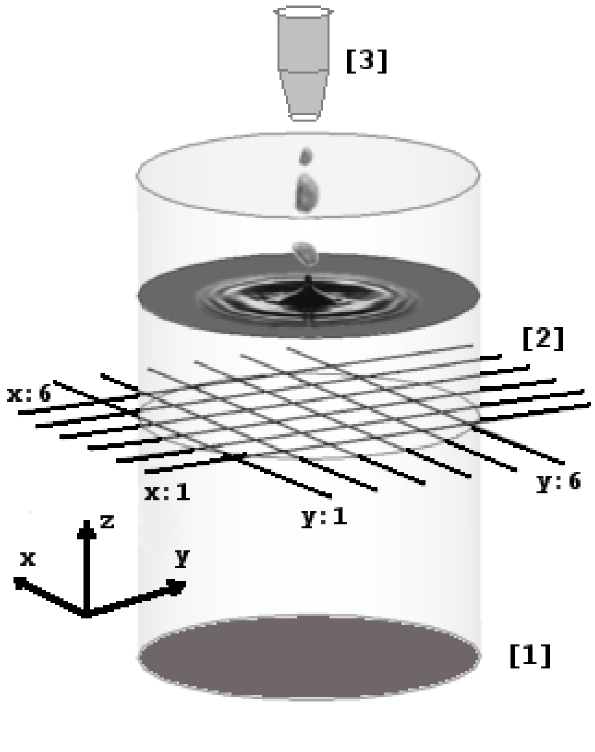


Fig.1. The schematic view of the experimental plant:
[1] – a cylindrical vessel with water, [2] – a grid sensor, [3] – a nozzle for generating a liquid droplet

The tracer in the amount of 2 ml, was fed through a nozzle at a rate of 2 ml/sec. While being supplied, the tracer formed a dropping streamlet of 3-5 droplets. The temperature of the working liquid and the tracer was 23°C. The recording of the grid sensor readings was made at a rate of 25 frames/sec. The readings of the grid sensor showed a local conductivity in the node area. Conductivity fields were scaled into fields of NaCl concentration according to the method described in [7]. The scaling coefficient for each node was determined by the calibration on the basis of laboratory conductivity meter MAPK 603/1. After calculating the concentration, all readings were reduced to dimensionless form by normalizing to the salinity of the initial tracer 200 mg/l.

On the basis of the measurements a three-dimensional space-time sectional view with two space and a time axes was developed. The space axes were formed by electrode guides of the grid sensors. The time axis was associated with the moments of recording of the grid sensor readings. The intersection point of the electrodes x:1 and y:1 was selected as zero point on the coordinate axes X and Y (Figure 1). The moment of the registration of the first data frame was taken as a zero point on the time axis.

Figure 2 shows a sampled run of measurements, which shows a two-dimensional distribution of the normalized salinity in the XY plane at different moments of time. This series of four frames shows a change in salinity in the droplet passing area through the grid sensor with respect to time. The local salinity of each node is normalized; the tracer salinity is 200 mg/l. The one value corresponds to 100% concentration of the original tracer. It is possible to determine the size of the main body of the droplet and observe the process of diffusion of the droplet in the liquid judging by the intensity of the changes in its salinity.

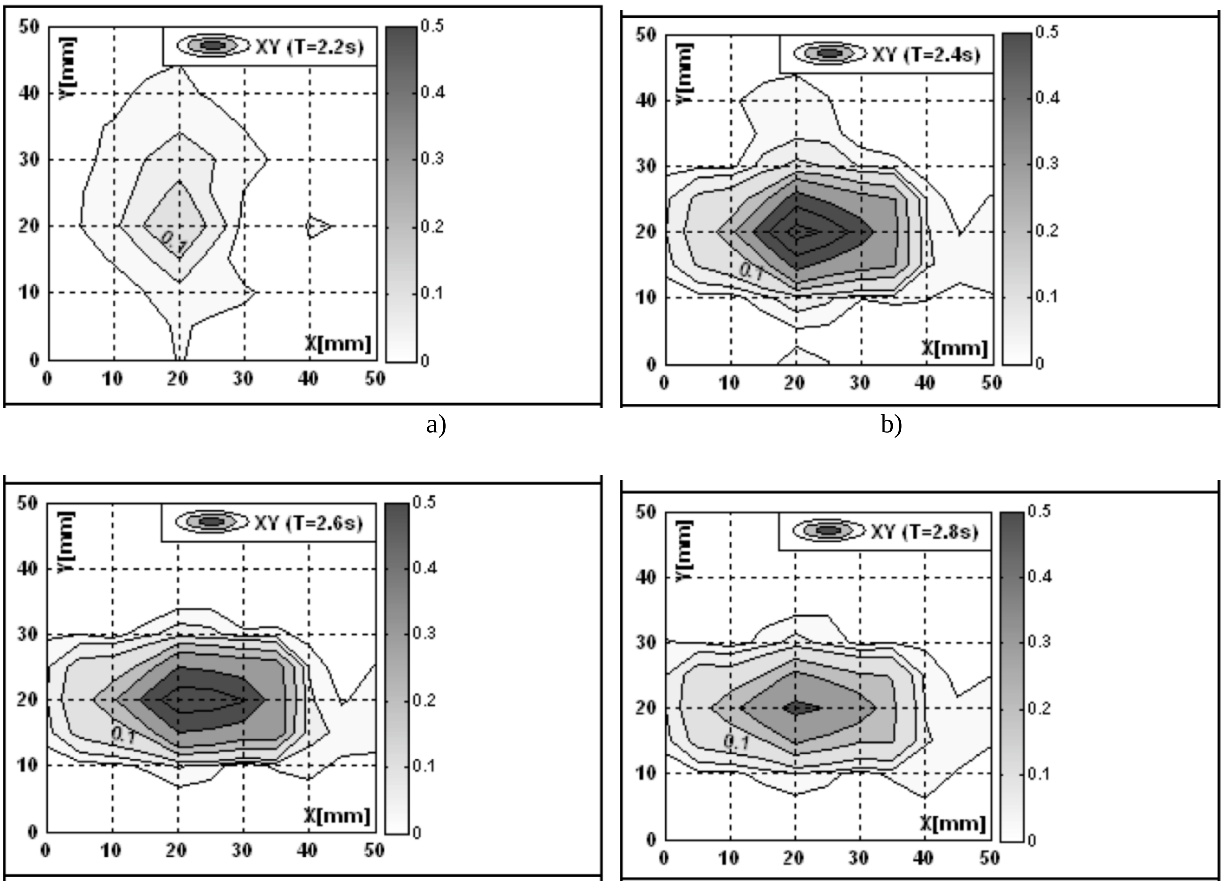
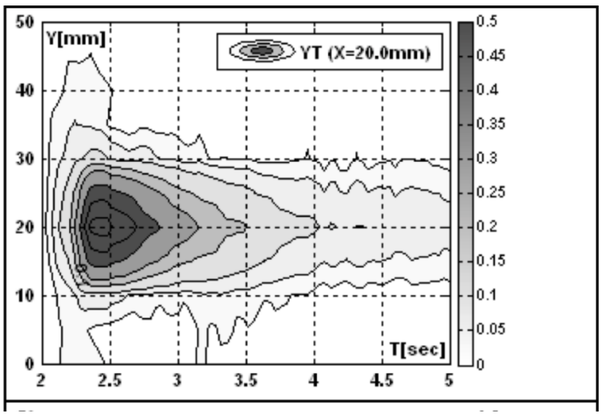


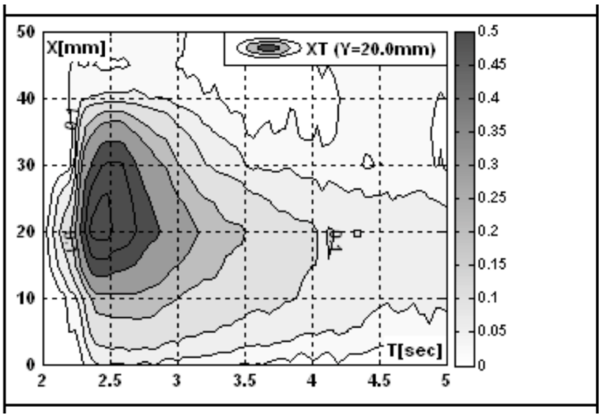
Fig.2. A typical frame series of the sensor readings. The tone scale on the right shows the normalized salinity level; salinity level distance: a) 0.02; b) 0.05; c) 0.1; d) 0.9

The droplet shape is seen more detailed in Figure 3. Two space-time sectional views are shown here. The first one shows a section in YT plane for the value of X equal to 20 mm. The second sectional view is in XT plane for the value of Y equal to 20 mm.

The scale ratio of the time axis to the coordinate axes is equal to 1:20, as if the investigated medium uniformly moved at a rate of 20 mm/sec. The resolution along the time axis T is equal to 25 readings per second. This fact makes it possible to study in detail the process of tracer body dilution as it moves relative to the sensor plane. In YT sectional view a symmetry plane for the value of Y equal to 20 mm may be emphasized. One can clearly see the front surface of the droplet preserving the impact structure, caused by the fall of the tracer droplets into the working liquid. In XT sectional view at Y equal to 20 mm there is an apparent asymmetry of the tracer body, which has a distinct shape of a large drop.



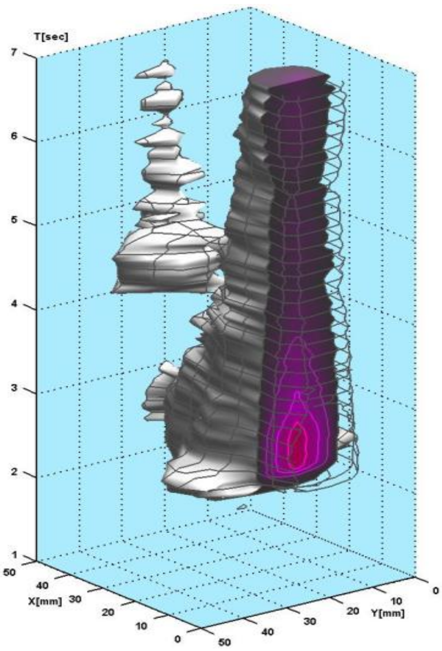
a)

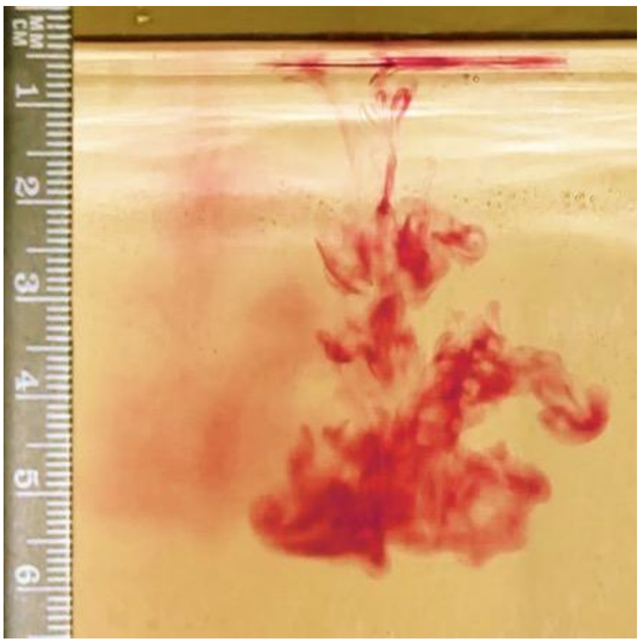


b)

Fig.3. Section views along the planes: a –YT; b – XT.

In XYT space, the reconstructed three-dimensional surface of the tracer body is seen. It is built at the salinity level of 0.025, Figure 4.





a) b)

Fig.4. A three-dimensional isosurface of the drop-tracer body at the salinity level of 0.025 in XYT space:
a) – a visual tracer image; b) – drops in the liquid

In addition, a cutout in YT plane at X=10 mm is shown. In this cutout the nucleus structure of the tracer body is clearly seen. Besides the main body of the tracer, the figure shows a separate drop inclusion, traces of which can be observed for three seconds.

For qualitative testing of the accuracy of NaCl concentration recovery when the drop was moving, the method for optical visualization was used. When visualizing, $KMnO_4$ solution was used. The result of visualization is shown in Figure 4b. As Figure 4 shows, there is a satisfactory adequacy between recovered pattern of the drop motion based on the measurement results using the grid sensor, and its visual recording.

Conclusion

As a result of the study, the investigators made next step forward in the development of matrix diagnostics method based on recordkeeping of the space distribution of complex conductivity and dielectric permittivity of a liquid. They developed a laboratory prototype of a grid sensor which made it possible to carry out the recording in the range of electrical conductivity of a liquid between 10 μS and 4000 μS at a conductivity resolution of 1 μS. Test experiments confirmed the operation capacity of the sensor when measuring hydrodynamic characteristics of nonsteady liquid flows.

The method for investigation of heat and mass transfer processes using an electric impedance grid sensor offers good space and time localization. The measurement rate can be of thousands of frames per second making it possible to investigate nonsteady processes of heat and mass transfer at high rates of flows under study. The measurement node density is determined by reasonable perturbations that can be made in the test media. The diameter of the conductor wires of the grid sensor as the main parameter of the perturbation of a liquid flow is determined by the rate and structure of the flow under investigation.

REFERENCES

1 Tropea, Cameron; Yarin, Alexander L.; Foss, John F. *Handbook of Experimental Fluid Mechanics*. Springer, 2007, 1557 p.

2 Prasser H. M, Bottger A., Zschau J. New Electrode-Mesh Tomograph for Gas-Liquid Flows. *Flow Measurements and Instruments*, 1998, No.9, pp.111-119.

3 Descamps M.N. et al. Three-phase concentration measurement in a vertical pipe a comparison between wire mesh sensor and optical fibre probe. *Proceeding of the 6th International Conference on Multiphase Flow*, Leipzig, Germany, 2007, pp. 1205-1221.

4 Prasser H.-M. Novel experimental measuring techniques required to provide data for CFD validation. *Nuclear Engineering and Design*. H.-M. Prasser, 2008, No. 238, pp. 744 -770.

5 Lisenkov E.A., Lobachyov S.M., Bezrukov Yu.A., Seleznev A.V., Pribaturin N.A., Glavny V.G., Volkov S.E. Investigation of coolant mixing in VVER-1000 reactor fuel assembly. Heavy Engineering, 2012, No. 9, pp. 5-13.

6 Glavny V.G., Bakakin G.V., Meledin V.G., Rakhmanov V.V., Sadbakov O.Yu. A module of signal pre-processing for thermophysical experiments. Instruments and Experimental Techniques, 2007, No. 2, pp. 166-167.

7 Kwak H., Zhang G., Chen S. The effects of salt type and salinity on formation water viscosity and NMR response. *Proceeding of the International Symposium of the Society of Core Analyst*. Toronto, Canada, 2005, pp. 1-13.

8 Miomandre F., Sadki S., Audebert P., Meallet-Renault R. *Electrochemistry.* Technosphere, 2008, 360 p.

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