Prosimy cytować jako: Inż. Ap. Chem. 2013, 52, 5, 431-432

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Distribution of heat exchange coefficient and vertical two-phase cross-flow structures examination over tube bundles, using DPIV and electrochemical methods

Introduction

The classic shell and tube heat exchangers are commonly used flow-through apparatus for heat exchange. Two-phase mixture flow in the space between tube bundle exist in many shell and tube heat exchangers. It is characterized by a high fluctuations that result from the oscillatory nature of the two-phase flow and the complex geometrical shape of tube bundle, irregularity of flow around tubes and the occurrence of the flow heterogeneous areas. The effect of non-uniformity of two-phase flow becomes an important parameter describing the flow of a mixture of gas-liquid in the tube bundle, and its identification is important for the design and operation of heat exchangers. In the literature, a few experimental studies of cross flow over tube bundle with DPIV technique have been conducted [*Chen and Guo, 2000; Iwaki et al., 2004*] Also electrochemical technique was used for heat exchanger examination [*Wilk, 2009*] Therefore, it is important to continue study the flow in the space between tubes, especially in the first rows, in which occurs an evolution of the two-phase flow. Although there is no literature position describing combination of DPIV and electrochemical techniques.

More detailed knowledge of his character is helpful in the design of heat exchangers. Two measuring techniques were applied to gather information about heat exchange intensity on tube surface and velocity distribution outside those tubes. Electrochemical technique based on heat and mass transfer analogy was used to calculate heat exchange coefficient on tubes surface. Digital Particle Image Velocimetry (DPIV) technique was applied to create velocity fields around examined tubes.

Experimental Setup

Scheme of the measurement set-up is shown on Fig. 1. The study involved two sets of tube bundles – *1* made of plexiglass – staggered and in line with tubes diameter of 15 mm and pitch $t/d = 1.66$. At the bottom of the exchanger was placed mixing chamber – *2* of the two phases. Electrolyte from the tank – *3* was pumped with centrifugal pump with magnetic clutch – *4*.

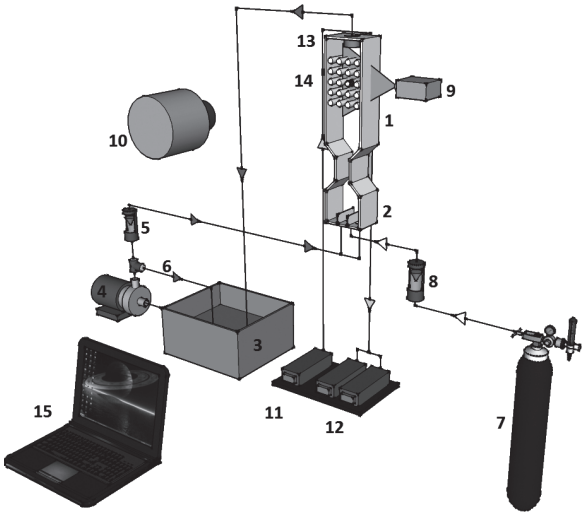

Fig. 1. Experimental setup

Electrolyte flow was measured with rotameter – *5*. In the absence of the pump speed control, adjustable liquid flow took place through the circulation valve (bypass) – *6*. Nitrogen from the tank – *7* was pumped through the rotameter – *8*. After the departure of the heat exchanger two phase mixture flow into the tank in which phase separation occurred.

Flow field was illuminated by a continuous green laser – *9* with power of 1 W, producing a light beam of wavelength $\lambda = 532$ nm. Illuminated flow field was recorded by CMOS camera – *10* at a resolution of 1024×1024 pixels. Flow images were recorded directly as a bitmap at a frequency of 462 Hz. To measure the current nickel electrode system was used. Electrodes immersed in an aqueous solution of potassium in the form of nickel anode grid were located at the outlet of the electrolyte from the heat exchanger. The applied electrical system – *11, 12* permit the delivery of a specific, stepwise increasing and stabilized voltage direct current flowing through the electrolyte solution between the cathode – *13* and the anode – *14* as well as saving measured voltage and current values – *15*.

Electrodes are shown on Fig. 2. The cathode was used as a nickel-plated brass plaque on the circumference of the tube, anode was a nickel net with area significantly higher than cathode.

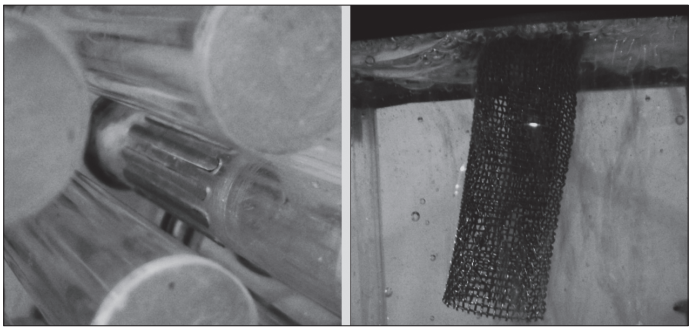

Fig. 2. Nickel electrodes

System uses two analog modules. The task of the first of them was applying to the system current with established and growing voltage, the other module were responsible for reading the current values of each of the plaques from the perimeter of the tube. In order to properly control all the software modules was written using the *LabVIEW* programming environment. This enabled the determination of values such as minimum and maximum voltage, and its increment. All data were archived immediately after the measurement as a text file. Control and archiving was conducted using a measuring station.

Measurements

The measurements were performed for three different flow rates of gas and liquid, the liquid phase was set respectively 2,22, 2,78 and $3{,}33 \cdot 10^{-4}$ m^3/s, gas on 2,78, 8,33 and $11{,}67 \cdot 10^{-6}$ m^3/s. Measurement series were performed for the staggered and in-line setup. Images were recorded with macro lens to obtain the velocity field around the electrode placed instead one of the tubes in fourth row. Current values from this electrode wad used for electrochemical calculations.

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Electrochemical calculation methodology

Electrochemical measurements are based on measuring the intensity of the electrical voltage and current changes during the controlled diffusion of ions at the electrode. Current is caused to the flow of solution of an equimolar mixture of $K_3FE(CN)_6$ and $K_4Fe(CN)_6$, in the presence of sodium hydroxide as base electrolyte over the electrodes. Scheme of the oxidation-reduction process at the electrodes is showed on Fig. 3.

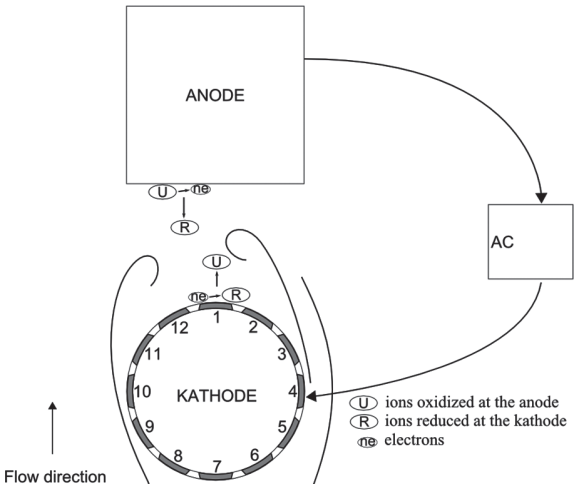

Fig. 3. Scheme of the oxidation-reduction process at the electrodes

After connecting the constant, stabilized voltage, between the electrodes an electrical circuit is formed. Initially, current increases with increasing voltage until the incident at which the diffusion-controlled electron transfer occurs on the surface of the electrodes under constant current value.

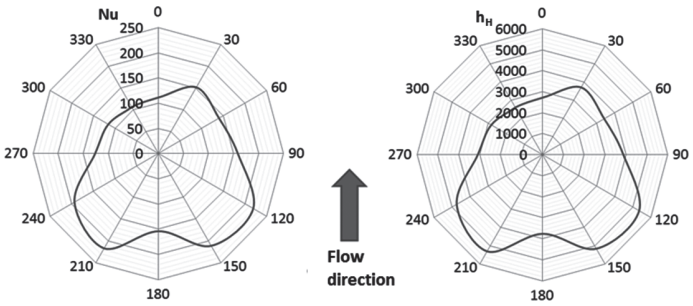

Fig. 4. Exemplary electrochemical calculations results

This value I_p is called the intensity of current plateau, the plateau current value is used to calculate the mass transfer coefficient which can be used in heat transfer calculation according to *Chilton and Colburn* [*1934*] heat and mass transfer analogy. Results were described with charts which examples are shown on Fig. 4.

DPIV measurements methodology

Fluid velocity field around the test tubes were calculated using DPIV. It is a method involving the recordings of the tracers introduced into liquid phase. Comparison of two successive images and determine their correlation coefficient allows the creation of instantaneous velocity vector fields. Images as bitmap images obtained directly from the recording were analysed using software dedicated for DPIV analysis. As a results, flow fields were created wich examples are showed on Fig. 5. Both results obtained with electrochemical and DPIV method were compared together in order to get an overview of velocity distribution around the tube and its influence to heat transfer intensity on its surface. Fig. 6 shows example comparison.

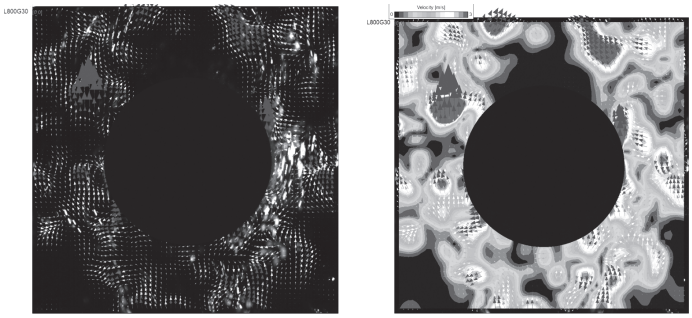

Fig. 5. Exemplary PIV measurements results

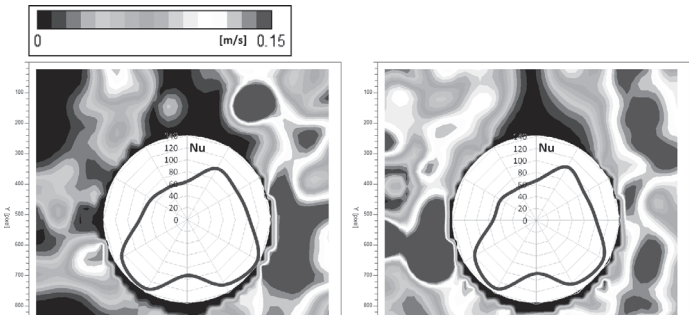

Fig. 6. Exemplary results of both used methods DPIV and electrochemical

Results and conclusions

In order to investigate structures over tube bundle and heat exchange intensity on tubes surface, detailed velocity data of liquid and gaseous phase was obtained using DPIV along with heat and mass transfer data using electrochemical method. Experiments for staggered and in-line tubes arrangement were conducted for different gas and liquid volumetric flow rates. The main results may be summarized as follows:

Staggered arrangement was characterized by greater uniformity of heat transfer coefficient. Also for this arrangement, minimum values of heat transfer coefficient on the frontal area of the tubes were smaller compared to in-line tube bundles. Average heat transfer coefficient was 6% lower for in-line bundle arrangement in comparison with to staggered tubes arrangement.

The flow of bubbles has a significant impact on the flow velocity of the liquid phase. Significant decrease of stagnation areas behind tubes was observed with increase of gas phase volume flow for both tubes alignment. Smaller stagnation areas for in-line tubes arrangement were observed in comparison with staggered tubes.

Creating, merging and disappearance of vortices was observed as well as the motion of the mixture in all directions, stagnation of the flow velocity or changes in local streams at the invariant phases brought into the test loop. Stagnation zones change their area and position during the measurements at fixed values of streams of the phases.

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This research was supported by Polish Ministry of Science and Higher Education research grant 4790/B/T02/2010/3.