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Application of the digital image correlation algorithms for evaluation of two-phase flow in the heat exchanger

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Abstract

The aim of this research work is application of digital image analysis for working out the method, which will allow to evaluate irregularity rate of two-phase flow across various geometry of tube bundle in aspect of the shell – and – tube heat exchanger optimization. Visualization of liquid flow in the shell – side enables analysis of flow parameters by the used image processing and analysis methods.

Images of two-phase flow were obtained with the use of digital high speed CCD camera, then were analysed, to obtain information about hydrodynamics of flow with respect to tube bundle arrangement. Optical techniques of measurement, based on correlation algorithms, allow accurate determination of stabilization of velocity fields for the whole field of flow in shell-side, based on the area size criterion of “still zones” behind rows of tubes. The aim of work was also estimation of the influence of geometrical parameters (tube arrangements, the tube spacings, number of rows) on the homogeneity of two-phase flow in the heat exchangers along with complex analysis of flow area, especially the “still zones”.

1. Introduction

In different types of chemical apparatus two-phase gas-liquid flows occur very often. The two-phase flow takes place along and across tubes bundle in the heat exchangers. Application of the flow visualization and digital image analysis method allow to determine local and overall flow parameters, and investigation of hydrodynamics of liquid flow inside the tube bundle, based on techniques of digital image processing. The classical shell – and – tube heat exchangers are commonly applied for heat transfer in flow apparatus. In order to increase liquid flow velocity inside the shell – side, the flow is intensified by the use of sectional cross baffles, and minimizing superficies of heat exchangers. Two-phase mixture flow is characterized by significant fluctuations. Fluctuations are

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a result of complicated geometry and oscillatory nature of two-phase flow in the shell-side.

One-phase flow across tubes bundle is well-known and exists in a lot of experimental and theoretical methods concerning pressure drop, void fraction, and velocity flow analysis. In case of two-phase flow, it is characterized by quite a lot of irregularities of velocity and pressure fields with respect to the shell-side geometry and nature of two-phase flow. Difficulties in conducting the research of two-phase flow in shell-side result from these causes. In such a way, there is still a lack of two-phase flow recognition methods in other fields, such as: stabilization of velocity and pressure fields as well as influence of shell-side geometry on distribution of the velocity fields, the shape and size of flow area during two-phase flow in the shell-side.

In the case of two-phase flow, effects between the phase boundaries appear simultaneously. Dynamics of gas-liquid system is significantly larger than in the case of other systems. Mutual effects of gas-liquid system take turns at time and location, causing a change of two-phase profile and finally decide about distribution of velocity, pressure, and temperature fields.

Two-phase flow in the shell-side is determined by shell-side geometry simultaneously. The shell-side defines the flow area of two-phase mixture, where velocity of flow is maximum in small passages of shell-side. The areas behind the tubes surface exhibit few fluctuations and became named “still zones” (figs.1 and 2). The velocity of flow and the gas void fraction in the still zones are considerably smaller than in passages of the shell-side. The shell-side decides about local disturbances of velocity fields, trajectories of gas flow, large area of all groups of gas particles concentration. The velocity of flow stabilization for all of shell-side areas might be estimated on the basis of the coefficient of heat transfer criterion values or surface of still zones behind the rows of tubes. The last criterion was used in the current research work. Besides, an evaluation of velocity flow stabilization by counting of still zones surface behind the rows of tubes might be realized by visual estimation of velocity stabilization field, an irregularity of distribution of these fields, whirling measurement shell-side by using the stream lines with reference to the obtained results of numerical simulations of two-phase flow in the shell-side of heat exchanger.

Development of digital techniques made possible gathering of large records of data. Digital devices and techniques have created new measurement possibilities.

The optical techniques, as well as the digital image analysis might be used for operation, estimation and optimization of the apparatus and two-phase flow setups.

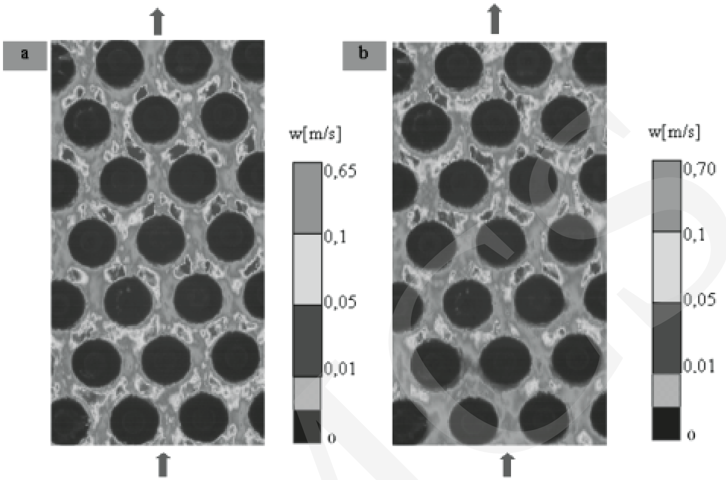


Fig. 1. Still zones visualization behind the row of tubes for triangular - staggered arrangement d20t30TS, V_L = 0.64 m/s and V_G = 2.78 m/s, b) V_L = 0.88 m/s and V_G = 2.78 m/s

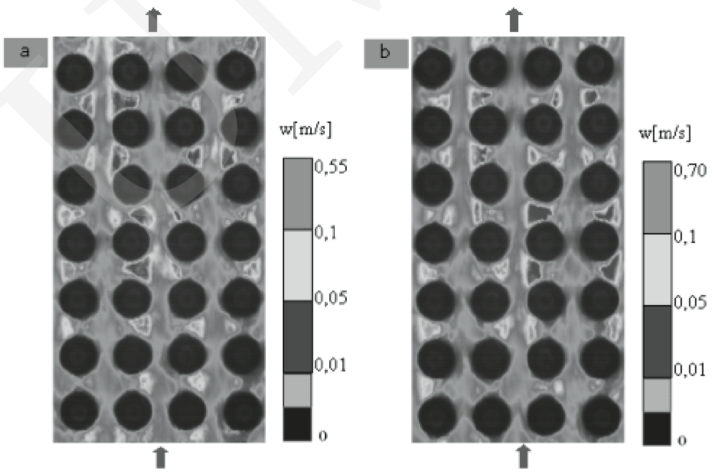


Fig. 2. Still zones visualization behind the row of tubes for the square in-line arrangement d20t30QL, a) V_L = 0.32 m/s and V_G = 1.85 m/s, b) V_L = 0.55 m/s and V_G = 1.85 m/s

2. DPIV correlation algorithm and the orthogonal dynamic programming algorithm for optical flow

Digital image anemometry with the use of particle tracers (Digital Particle Image Velocimetry) is a technique, which allows determination of velocity vectors of liquid flows by means of the image correlation method. Application of particle markers makes observations of flow and behaviour of layers of liquids possible [1].

Quantitative measurements of the flow and turbulence characteristics are obtained using DPIV. This is a non-intrusive optical technique that measures fluid velocity by tracking the displacement of tracer particles that have been added to the fluid. The particle locations are determined by capturing scattered light from the individual particles with a digital camera. The particle displacement in a small region of the image is calculated by comparing consecutive images. The velocity in the small region is then calculated by dividing the displacement distance by the known time delay between the images. The DPIV images were sub-divided into interrogation windows.

The calculation of the correlation function to determine the displacement vector for each window can be performed either in the spatial or frequency domain. The digital spatial correlation function R_{II} required the evaluation of the following expression [2]:

$$R_{II}\left(x_1,x_2\right)=\sum_{i=-K}^{K}\sum_{j=-L}^{L} I\left(i,j\right)I'\left(i+x_1,j+x_2\right), \tag{1}$$

where $I(i,j)$ represents the intensity value for the (i,j) pixel. This function statistically measures the degree of correlation between two samples $I(i,j)$ and $I'(i,j)$ for a given shift (x_1,x_2). The shift position where the pixel values align with each other gives the highest cross-correlation value, and represents the average displacement of the particles in a given interrogation window. The major drawback of this method is that it is highly computationally intensive since the number of computations necessary is proportional to the interrogation window size. Alternatively, the algorithm used to evaluate the particle displacements for this experiment was based on the frequency-domain correlation method. The images were divided into 24×24 pixel sub-windows with 50% overlap. The correlation plane was created by transforming the intensity function from the spatial to the frequency domain using the discrete Fourier transform [2]:

$$\hat{I}\left(k,l\right)=\frac{1}{N^2}\sum_{m=0}^{N-1}\sum_{n=0}^{N-1} I\left(r,s\right)\exp\left[-i2\Pi\left(mr/N+ns/N\right)\right], \tag{2}$$

where $\hat{I}(k,l)$ is the Fourier transform of the intensity function and N is the number of pixels in each interrogation window. The cross-correlation was then obtained by using the Fast Fourier Transform (FFT) algorithm which is computationally efficient since it utilizes the symmetry property between the even and odd coefficients of the Discrete Fourier Transform. The FFT algorithm followed the steps shown in Figure 3. The FFT cross-correlation method resulted in a single peak on the correlation plane that represented the average displacement of the particles in the window during the time delay between the illumination pulses. The position of the correlation peak was then estimated to sub-pixel accuracy by using a Gaussian fit function [2]. The displacement vector was defined by the location of the peak with respect to the center of the window.

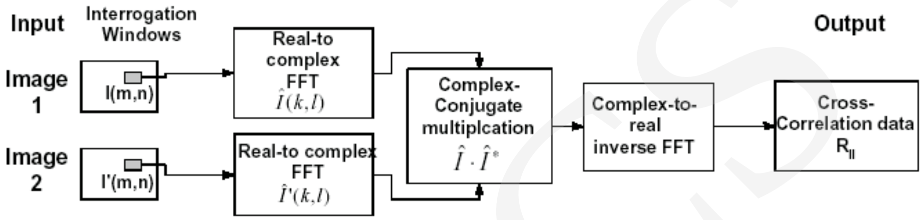


Fig. 3. Cross correlation procedure

The final algorithm filtered the vector fields. The vectors collected at a single spatial location were combined into a time record of velocity. Vectors that fell outside the predetermined maximum and minimum values were removed from the data set. A recursive filter was used to remove any vectors that lay beyond three standard deviations from the local time-average value. The time-average and standard deviation values were updated and the filter was repeated until zero vectors were removed in the final pass.

The integral length scale of the flow was calculated by measuring the area under the spatial correlation function [2]:

$$L_{ij} = \int_0^\infty f\left(r_j\right) dr_j \ . \tag{3}$$

The spatial correlation function is defined as:

$$f\left(r_j\right) = \frac{u_i^{'}\left(x + r_j\right) u_i^{'}\left(x\right)}{u_i^{'}\left(x\right) u_i^{'}\left(x\right)}, \tag{4}$$

where x is an arbitrary location, $u_i^{'}$ indicates the fluctuation of the i velocity component, and r_j is the distance in the j direction between the velocity measurements.

The Orthogonal Dynamic Programming (ODP) algorithm for optical flow detection from a pair of images was introduced by Quenot [3]. It has been extended to be able to operate on longer sequences of images and to search for subpixel displacements. The ODP based DPIV is referred to as ODP-PIV. Using the ODP-PIV a dense velocity vector field for every pixel of the image is obtained. The accuracy is better than 0.2 pixel/frame for four – image sequences [3].

Visualization of liquid flow in the shell-side enables analysis of flow parameters by the used image processing and analysis methods. Images were recorded with the frequency of 103Hz by the use of digital high speed CCD camera. The bubbles of gas in the shell-side are particle markers. The recording sequences of flow were conducted for two-phase gas-liquid flow across the tube bundle, which were placed in triangular – staggered and square in-line arrangement for bubbles pattern. The velocities of phases were following for liquid $V_L = (0.20\text{-}0.70)$ m/s and gas $V_G = (0.50\text{-}7.0)$ m/s. The sequence of consecutive images was recorded during two-phase flow in the shell-side, next there were determined velocity fields of liquid using the correlation of images method (cross correlation DPIV) (fig.4) and velocity vectors (ODP-PIV).

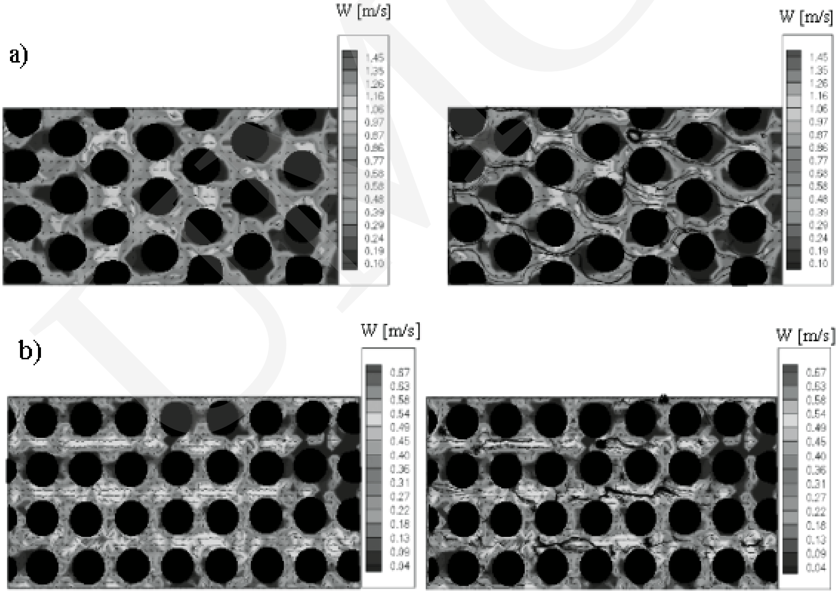
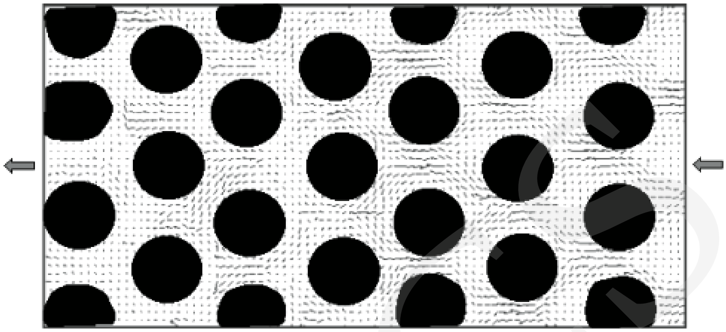


Fig. 4. Liquid velocity fields and particles motion in the shell-side (DPIV correlation algorithm),
a) Triangular – staggered arrangement d20t30TS for $V_L = 0.47$ m/s and $V_G = 0.57$ m/s,
b) Square in-line arrangement d20t30QL for $V_L = 0.42$ m/s and $V_G = 0.69$ m/s

Dislocation of markers floating through liquid, in a given interval of time, makes the possible to obtain the flow parameter, which characterizes velocity of liquid flow. Distributions of velocity fields in depending on geometry of tubes arrangement, staggered either in-line, has decided about values of heat transfer coefficient. Trajectories of particle markers motion were designed for the flow pattern estimation. Changes of flow direction were evaluated using motion of trajectories analysis, an area, where flow has stopped as well as still zones, where a number of particle markers is not large (fig.4).

a)



b)

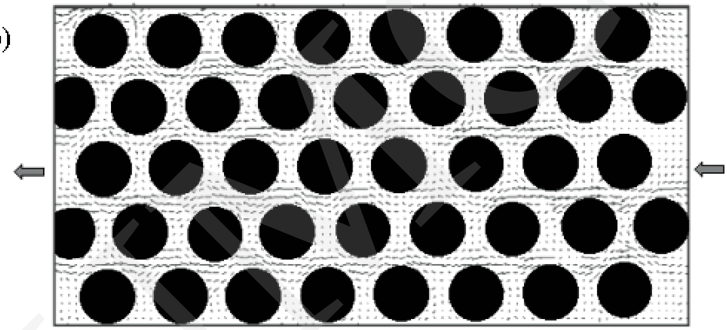


Fig. 5. Velocity vectors (ODP – PIV algorithm), a) Triangular – staggered arrangement d20t30TS for V_L = 0.69 m/s and V_G = 0.69 m/s, b) Triangular in-line arrangement d20t30QL for V_L = 0.67 m/s and V_G = 0.67 m/s

The graphs showing velocity fields are presented in "figure 4", where areas of local disturbances of velocity were located, caused by geometry of selected arrangement. The pattern of tubes arrangement has caused thus local turbulences.

The consecutives of tubes row have influence on change of trajectory of particles motion (fig.4) as well as cause vortex generating behind tubes.

Liquid flow around tubes is irregular for triangular – staggered arrangement also for this one there is larger flow dynamics, where flux of liquid strikes in every row of tubes. It caused that coefficient of heat transfer value for that arrangement is larger than other geometrical arrangements, but pressure loss is larger.

3. An irregularity of liquid flow in the shell-side

Areas of still zones occur directly behind tubes in the shell-side [2]. In these areas, for small velocity of gas, flow dynamics does not change, but along with rising velocity of flow vortices begin to form.

In the case of liquid flow in the shell-side of heat exchanger, flow has been characterized to occur in two areas [4]:

– area of vortex behind tubes,
– area of large gas flow velocity between passages in the shell-side.

The velocity of flow stabilization, based on quantity of still zones criterion allows to define the area in the shell-side, where flow velocity stabilization appears and the heat transfer coefficient. The comparisons of flow stabilization can be made with respect to the quantity of still zones in the calculated area for each row of tubes as well as on the base of velocity field stabilization (fig.5, fig.6).

In the shell-side along with the increasing number of rows the still zone areas, located behind the area of tubes decrease. A number of still zones in the initials of tubes row, decreases for staggered arrangements and reaches the fifth tube in the row. In the still zones, liquid flow has significantly smaller intensity than in the flow zones. A quantity of still zones affects unfavourably the heat transfer coefficient [5]. The heat transfer coefficient is considerably larger during turbulent flow, increasing with the increase of velocity. However, velocity in still zones is significantly smaller than in the case of passages in the shell-side, where the maximum of flow velocity occurs [6]. In the still zones gas bubbles accumulate, blocking and then starting oscillations which are maintained. Based on zone areas influence on heat transfer coefficient, it was assumed that heat transfer at the beginning of tubes row is significantly smaller because the number of still zones is considerably larger.

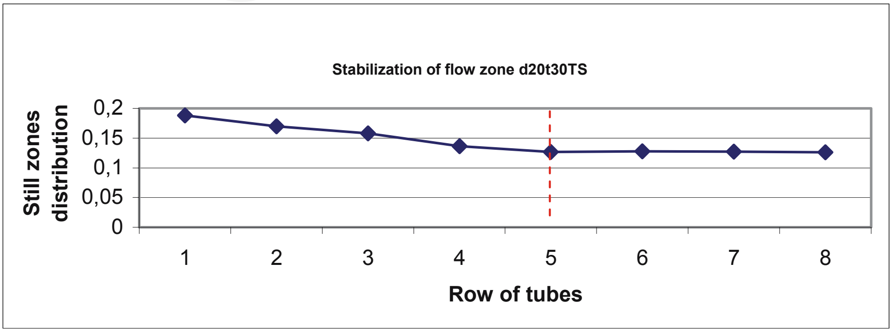


Fig. 5. Distribution of still zones area in the shell-side for traingular staggered arrangement $V_L = 0.57$ m/s and $V_G = 0.69$ m/s

The number of still zones decreases on the fifth row of tubes, thus the coefficient of heat transfer and the area of still zones increase. The heat transfer coefficient stabilizes in the sequence of tubes row.

Stabilization of still zone areas is between the fifth and the sixth rows of tubes in the case of in-line arrangements. Similarly, fields of velocity stabilize between the fifth and the sixth rows of tubes (fig.6).

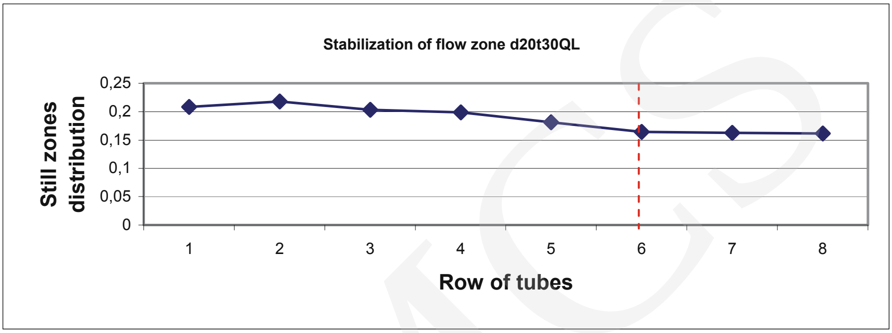


Fig. 6. Distribution of still zones area in the shell-side for square in-line arrangement $V_L = 0.42$ m/s, $V_G = 0.69$ m/s

Stabilization of velocity field and an area of still zones is closer at the beginning of the shell-side, in the case of smaller spacing across tubes contrary to larger spacing across tubes. However, still zone areas increase for larger spacing in the longitudinal direction, which decreases the mixture flow, because the effect of interaction between the geometry and the tube increases in the tubes bundle. A number of still zones is larger for in-line than staggered arrangements in the case of the same flux of phases. It causes larger flow fluctuations, irregularities, generating vortex structures for liquid flow across staggered arrangements rather than in-line arrangements. It follows that heat transfer is larger for staggered arrangements.

3. Conclusions

The results of flow visualization and digital processing methods allowed to obtain detailed conclusions about the hydrodynamics of two-phase flow in an area of shell-side, which are following:

- optical techniques of measurement, based on correlation algorithms, allow accurate determination of stabilization of velocity fields for the whole field of flow in the shell-side,
- the number of still zones is considerably larger for in-line arrangements than staggered arrangements for the same spacing. That contributes to increase of heat transfer flux, because in the still zones there are significantly smaller turbulent flows. An increase of two-phase mixture velocity is caused by decreasing area of still zones.

– the velocity of field stabilization is found between the fifth and sixth rows of tubes, but stabilization of velocity field is ensured much closer, with reference to an initial shell-side for in-line than staggered arrangements.
– as follows from the distribution of velocity fileds staggered arrangements, applied in the heat exchanger, are more efficient with regard to the flux of heat transfer. The triangular arrangement in the actual heat exchangers is equivalent to the staggered arrangement.

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