

## **DIGITAL PARTICLE IMAGE VELOCIMETRY (DPIV) CORRELATION ALGORITHM FOR ANALYSIS OF TWO-PHASE FLOW**

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### **Abstract**

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

Visualization of liquid flow in the shell – side enables analysis of flow parameters by the used image processing and analysis methods.

**Key words:** flow visualization, particle image velocimetry (PIV).

### **1 Digital Particle Image Velocimetry**

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],[3]. 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 domain or in the frequency domain. The digital spatial correlation function  $R_{II}$  required the evaluation of the following expression [2]:

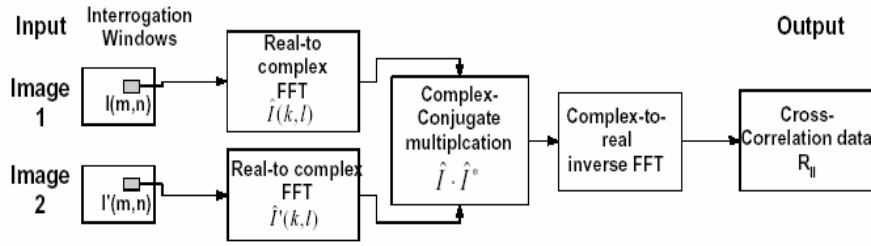
$$R_{II}(x_1, x_2) = \sum_{i=-K}^K \sum_{j=-L}^L I(i, j) I'(i + x_1, j + x_2) \quad (1)$$

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  $24 \times 24$  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]:

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

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 1. 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.1:** Cross correlation procedure.

The final algorithm filtered the vector fields. The vectors collect at a single spatial location were combined into a time record of velocity. Vectors that fell outside of 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]:

$$L_{ij} = \int_0^{\infty} f(r_j) dr_j \quad (3)$$

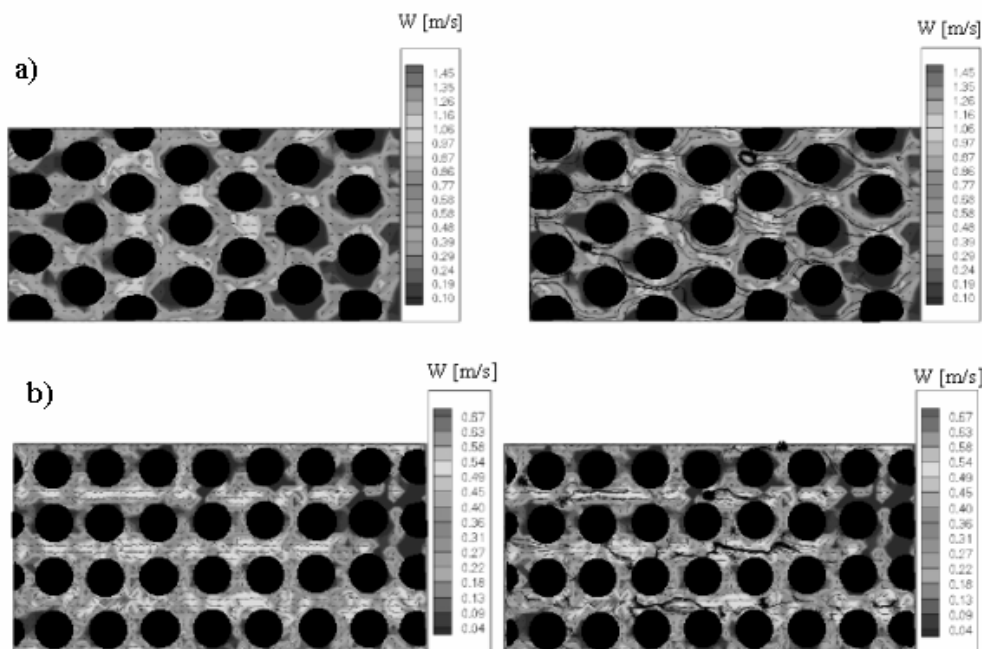
The spatial correlation function is defined as:

$$f(r_j) = \frac{u_i'(x+r_j)u_i'(x)}{u_i'(x)u_i'(x)} \quad (4)$$

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.

## 2 Velocity fields

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 frequency of 103 Hz by the use of digital high speed CCD camera. The bubbles of gas in shell-side are particle markers. The recording sequences of flow were conducted for two-phase gas-liquid flow across tube bundle, which were placed in triangular - staggered and square in-line arrangement for bubbles pattern. The velocities of phases were following for liquid  $V_L=(0,20 - 0,70)$  m/s and gas  $V_G=(0,50 - 7,0)$  m/s. The sequence of consecutive images was recorded during two-phase flow in shell-side, next were determined velocity fields of liquid using the correlation of images method (cross correlation DPIV ) (fig.2),[4].



**Fig.2:** Liquid velocity fields and particles motion in the shell-side (DPIV correlation algorithm), [4].

- 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 given interval of time, makes possible to receive the flow parameter, which characterizes velocity of liquid flow. Distributions of velocity fields in dependence of 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 number of particle markers is not large (fig.2). The graphs showing velocity fields are presented in “figure 2”, where area 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 having an influence on change of trajectory of particles motion (fig.2) as well as causing vortex generating behind tubes. Liquid flow around tubes is irregular for triangular – staggered arrangement also for this one there is a 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 Conclusions

The results of flow visualization and digital processing methods allowed to receive detailed conclusions to the point of the hydrodynamic 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 shell-side,
- The velocity of field stabilization is following between fifth and sixth row of tubes, but stabilization of velocity field is ensured much closer, with reference to an initial shell-side for in-line than staggered arrangements.
- On the basis on distribution of velocity fields have been ascertained that staggered arrangements, which are applied in heat exchanger, are more efficient with regards to the flux of heat transfer. The triangular arrangement in actual heat exchangers is equivalent to the staggered arrangement.

### Nomenclature

d – diameter	QL – square in-line
t- spacing	V <sub>L</sub> – apparent velocity of liquid
TS – triangular - staggered	V <sub>G</sub> – apparent velocity of gas

### 4 References

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