PIV-system for flow measurements on the benchmark of promising fast neutron nuclear reactor

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Abstract. Carrying out spatio-temporal flow fields parameters is one of the most important and complicated problem within the modeling of heat and hydrophysical processes in operating regimes of the power plants (including nuclear (NPP)). Particle Image Velocimetry (PIV) method (based on the flow visualization, using laser illumination) fits best to satisfy the demands of such measurements. For the experiments on large-scale models of NPP, there is a number of problems in the application of this method, for example, large scales of the flows of the investigated model objects; a noticeable variability of the flow parameters processes with strong temperature fluctuations, leading to optical distortions; necessity of combining imaging and contact gauges probing etc. In this paper we describe PIV- system specifically designed for the study of heat and hydrophysical processes in large-scale model setup of promising fast neutron reactor. The system allows the PIV-measurements for the conditions of complicated configuration of the reactor model, reflections and distortions section of the laser sheet, blackout, in a closed volume. The illumination system using of two lasers and two video cameras with synchronization, allows to obtain an image of the flow in the whole volume of investigation. The use of filtering techniques and method of masks images enabled us to reduce the number of incorrect measurement of flow velocity vectors by an order. The method of conversion of image coordinates and velocity field in the reference model of the reactor using a virtual 3D simulation targets, without loss of accuracy in comparison with a method of using physical objects in filming area was released. The results of measurements of velocity fields in various modes, both stationary (operational), as well as in non-stationary (emergency). These results are compared with measurements of temperature distribution, which were carried out simultaneously. The obtained data set can be used for verifying CFD codes.

1 Introduction

In engineering practice, models of different scales and complexities are often used to research thermohydraulic processes in Nuclear Power Plants (NPP).

In this case, the research can be subdivided into three basic types:

(1) the simplest type is the simulation of individual, often small nodes, for example, of the flows in pipes and tees [1, 2];

(2) the simulation of thermohydraulics of individual elements of NPS, for example, the investigation of processes in the fuel-element assemblies [3-5];

(3) the most complicated type includes benchmarks - complex large-scale models of NPP [6-8].

The main objective of all investigations on the models is to try to simulate the actual situation as closely as possible, study it under controlled conditions and, if needed, verify the calculation procedures. Recently, Compute Fluid Dynamics methods have been used more often for the numerical simulation of thermohydraulic processes in NPP. The most complete and representative verification of the numerical simulation results can be performed using experimental data about velocity fields. The Particle Image Velocimetry (PIV) is the most modern method for their measurement. There are many variations of this method [9]; its essence lies in the visualization of flows by adding microparticles to them, illumination of required sections with a laser sheet, filming the visualized field of view with one or more digital cameras, and software processing to calculate velocity fields. During the laboratory experiments of the first and the second types, the standard serially produced measuring PIV systems are usually applied with minimal modifications [1-3]. However, in the experiments on large-scale benchmarks, a number of difficulties occur that are associated, for example, with a complex configuration and the large volumes of the investigated model objects, a wide range of changes in the parameters of thermohydraulic processes with strong temperature fluctuations, resulting in optical distortions, with the necessity of combining the visualization and contact measurements, etc.

There is no published data about investigations on the characteristics of using PIV methods on test benches that are comparable in their parameters with the model under consideration here. Therefore, the objective of this

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work is to fill this gap in using PIV methods. A special system and methods of measurements were developed.

2 General description of the reactor model

In order to confirm the effectiveness of the emergency heat-removing system of a proposed fast reactor, the TISEI test bench was developed and manufactured and an experimental study of heatexchange and hydrodynamic processes was performed at the OKBM Afrikantov. The test bench consists of a large-scale model of a reactor and the loop of emergency heat-removing system. The external outlines and elevations of the test-bench equipment and reactor are geometrically similar; the simulation scale was taken equal to 1 : 5. Water is used in the test bench as a coolant unlike in a regular plant, in which liquid sodium is used. The power of the core model in the rated operation mode does not exceed 350 kW. To use visualization-based methods, polyamide particles with a 1.03 g/cm3 density and 20 µm in diameter were added to the water.
The reactor model is a sector with an opening angle of 80 degrees; it includes all of the basic components of a proposed fast reactor (Fig. 1). The test bench was described in more detail in [8].

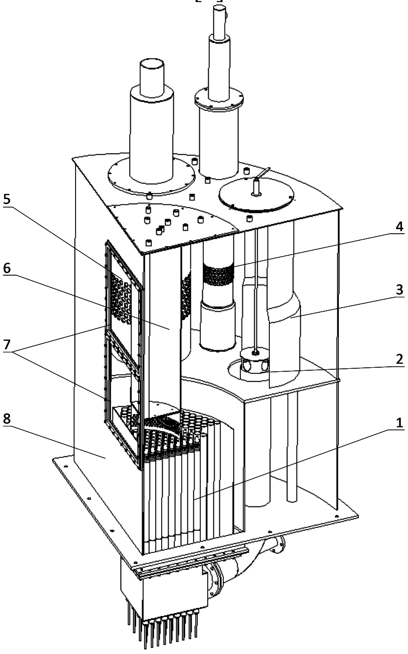


Fig.1. The model of a proposed fast reactor: (1) core with heating elements; (2) valve with manual drive; (3) the displacer of the main circulation pump of the primary coolant circuit (a part of the displacer is shown only); (4) independent heat exchanger of the emergency heat removingsystem; (5) intermediate heat exchanger; (6) the displacer of the central column; (7) transparent windows; and (8).

3 Scheme and hardware of the PIV-system

The internal chamber of the model of the reactor tank sector has a very complex configuration. In addition, thermal probes are installed inside it (these are not shown at Fig. 1), which consist of vertical rods with a diameter of ~7 mm on which the temperature gauges are fastened. The problem was posed to obtain the velocity fields in a maximally large volume area inside the tank, simultaneously using both the top and the bottom windows for measurements. The measurements should be carried out in the sections on the independent and intermediate heat exchangers. The arrangement of laser illumination and filming of the required sections in the presence of numerous shading and reflecting elements is a complicated problem. Taking the features of the construction of the reactor model into account, the configuration of the illumination and video filming was chosen simultaneous using two compact continuous diode-pumped lasers and two cameras (see Fig. 2). The general arrangement of applying the PIV method is similar to that described in [10].

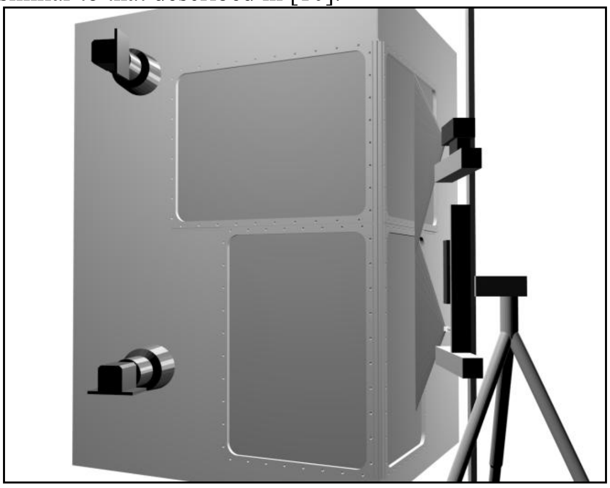


Fig. 2. The scheme of camcorders and lasers disposition (isometric projection).

Solid-state diode-pumped CW lasers in the visible range of the LCS-DTL-413 type were used. The emission wavelength was 527 nm (green light) and the laser power was 1.5 W. Two highly sensitive CygnetRaptor camcorders were used for video filming (the rated resolution was 2048×1088 pixels at a frame rate of 50 frames/s). Both lasers and optical elements were installed on a single tripod (Fig. 2), which greatly facilitated the displacement of the system elements for the replacement of the illumination section.
The required sections of view on the independent and intermediate heat exchangers were chosen taking in to account the structural features of the test bench and thermal probes used regularly to measure the temperature distribution. Fig. 3 illustrates the top view to the cross-section.

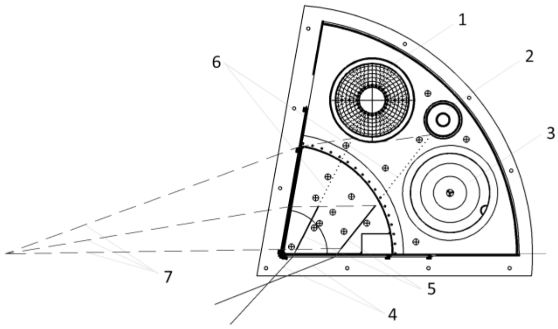


Fig.3. The outline of the sections and filming region inside the test bench (the top view of the test bench): (1) intermediate heatexchanger; (2) independent heat exchanger; (3) the displacer of the main circulation pump of the primary coolant circuit; (4) sections of laser planes before the inlet to the reactor-tank model; (5) filming regions that are under the central rotary column on the images; (6) the remaining part of the image over the entire height; and (7) the contours of boundaries of the optical image. The circles that are crossed out denote the positions of the thermal probes.

The positions of the cameras was chosen based on the necessity to maximize the dimensions of the field of vision. The bottom camcorder was placed at the level of the bottom of the central column and the top camcorder was placed in the middle of the height of the top window of the model of reactor. To reduce the distortion level to the same scale and dimension of the filming area, the camcorders were installed at the maximum possible distance from the reactor sector.

For filming through the bottom window, the camcorder was installed in the usual orientation, since the area was horizontally stretched to provide the ability to capture the area under the central column; for filming through the top window, the cameras was turned by 90 degrees to maximize the vertical dimension. Fig. 3 presents the general arrangement of the cameras and lasers from different angles. The plane of filming the sections on the independent and intermediate heat exchangers was located at an angle to the optical axis of 51 and 62 degrees, respectively. Therefore, in order to obtain a focused image in the entire area, special lenses of the tilt-shift type were applied with the ability for mechanical rotation and displacement of the lens axis relative to the plane of the receiver of the CCD camera.

Visual fields of the bottom and top cameras partly overlap. This is done for the further linking of the measured velocity fields. It was revealed during the preliminary experiments that using a frame rate below the maximum value of 50 frames/s leads to the impossibility of correct calculation of particle displacements as they are moving away from the laser sheet. The cause is both the high value of the velocity component that is normal to the laser sheet and thermal distortion, which can lead to a local displacement of the laser plane. Therefore, the maximum rate was chosen with the conservation of the base resolution for all modes.

4 Image preprocessing and determination of the velocity fields

To calculate the velocity fields from the obtained digital images, the standard for PIV-method digital image processing was used [9]. The images were partitioned with a rectangular grid into fragments (interrogation windows) with a size of 64×64 pixels. For the functions of the intensity distribution, the cross-correlation function (CCF) was then computed on the images of two interrogation windows with the same location on a pair of consecutive frames. The location of its maximum corresponded to the average value of the displacement in the region of this fragment between frames.

By dividing the displacement value the time interval between the frames, one can define the velocity. The field velocity in the investigated flow is characterized by strong heterogeneity (for example, see Section 5). The subpixel adjustment of the location of the CCF maximum at three points that are the closest to the peak was used by means of a 2D Gaussian function (for more detail, see [9]).

To reduce the influence of the features of the background image on the results of the CCF computation, the background was subtracted. A dynamic procedure of subtraction of the background was used. The background image for each frame was calculated on the basis of several neighboring frames: the so-called sliding window method was applied. The window dimension equals 11 frames: the initial frame, 5 previous frames and 5 subsequent frames were used for calculation. The minimum value of the intensity at this point for the entire set of 11 frames in the window is chosen for the intensity level corresponding to the background image. In this way, all bright objects that are displaced during the calculation period are removed from the image: if the particle image is lacking even in one of the frames on this pixel (in the case of the movement of particles), the pixel will take the value of the background image.

Then, when calculating the CCF in each experiment (record), at first, the uniform rectangular grid with a pitch of 32 pixels is formed (50% overlap for the comparison window with a dimension of 64×64 pixels).

However, there are fields in the images in which the images of particles were overlapped by construction elements, including the thermal probes (the image configuration is complicated). Therefore, it is not necessary to carry out calculations at the grid nodes that fall within these fields, as erroneous displacement (velocity) values are derived in any case. To avoid unnecessary calculations at the grid formation, a masking method was developed. The mask is a file obtained from the initial image by binarization: the null values correspond to the masked regions, which must be excluded from the calculations (particles are not visible in these regions); the nonzero values correspond to the regions in which particles are visible and in which their displacement can be calculated. Fig. 4 shows example of such mask.

Before the generation of a grid of interrogation windows for calculating the CCF, a rectangle that includes all of the unmasked points was found in the image for each mask. Hereafter, the interrogation windows to calculate the CCF were chosen only within this rectangle. In this case, the CCF was derived only for interrogation windows that consist of at least half of the unmasked points. To calculate the velocity field, the maximum possible number of frames was used. Successive frames were chosen for comparison and each frame was compared with the following frame. Thus, for a subrecord consisting of 50 frames (1 second of record), 49 velocity fields were computed and such calculations were carried out for all subrecords in the record.

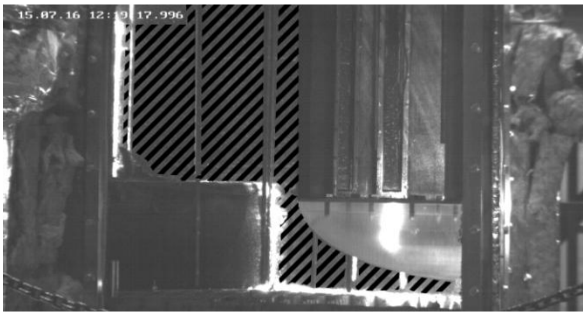


Fig. 4. Example of mask for the images obtained from the bottom camcorder. The shading denotes the fields that are not covered with a mask, i.e., suitable for calculating the displacements of particles.

As a result of the above-described processing procedure, the velocity fields were obtained for each image (except the last one in the subrecord). However, despite the struggle with static noise by subtracting thebackground and using precise masks, correct measurements of the particle displacements were not performed for each interrogation window. The final stage of filtration of the velocity values was performed via their difference from the time-average subrecord value. However, for dynamic modes, such filtering is inadmissible because the true velocity value at the points may change considerably. Therefore, the technique of two-pass median filtering based on the subrecords was developed. Processing was performed for each subrecord for each value of displacement.

The value of the median average was determined at the first pass. All of the values of the displacement whose difference from the average value exceeds the chosen threshold value of five pixels per frame were then rejected in the subrecord. The second stage is similar to the first one, but the average value was calculated from already filtered values and was closer to the true velocity value. The filtering interval at the second pass was chosen to be narrower at two pixels per frame.

After all of the processing stages, the instant velocity fields (in pixels per second) were derived, which were used for comparing the neighboring frames. These contained many missing values (due to errors); thus, the fields derived by averaging over time intervals of the subrecord were used as the main working fields. It should be noted that due to the sequential recording with two cameras, the velocity fields obtained in this way were shifted in relation to each other by a time of 1 second.

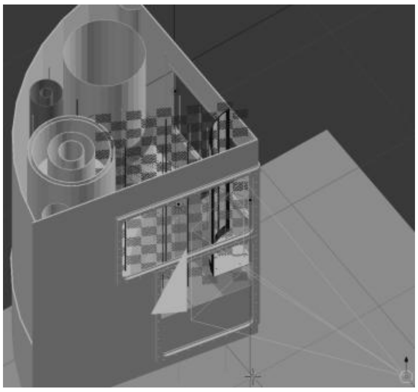
5 Rescaling between image and laboratory system

The real dimensions and coordinates of the obtained images in the reference system locked to the laser cross-section are unknown in the reference of reactor model. In addition, it should be noted that during processing by PIV methods, all calculations are performed in the coordinates of the image and dimensions are expressed in pixels. Therefore, the flow displacements (velocities) obtained as the result of the processing are expressed in pixels (pixels per frame).

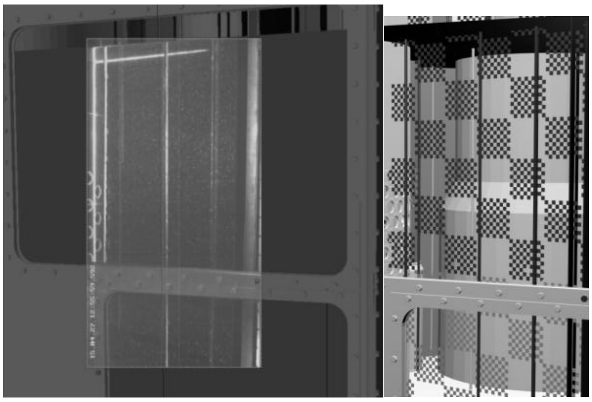
To recalculate the coordinates of the velocity - field grid nodes (the coordinates of the centers of interrogation windows) and velocities themselves into the coordinate system of the model, one or two (in the case of anisotropy of the camera sensor) scale factors are typically used. However, the features of the filming configuration (at an angle to plane, see Fig. 3) do not make it possible to introduce such a factor, as the scales of different parts of the image are very different. For correct recalculation, the transformation of the coordinates from the coordinate system of the image into the coordinate system of the laser cross-section is required; it is necessary to calculate a special projection matrix.

The simplest solution for determining the projection matrix is the arrangement of real physical marks with known dimensions and coordinates in the reference system of the benchmark in the field of the laser cross-section inside the tank of the benchmark, obtaining the images of such targets, and calculating the coordinate-transformation matrix. In this case, the marks should be used in the working configuration, i.e., they should be located in test bench filled with water (for the proper accounting of refraction) and in the laser plane, since the particles in this plane during the filming are illuminated with the laser and recorded with the camera.

However, installing the real calibrating elements into the model was a necessary procedure. In this case, when changing the laser sheet positions, new holes for new calibration would be required. Therefore, the method of virtual 3D-simulation of marks and their images was developed. The Blender free-access software environment was used (Fig. 5a), which makes it possible to synthesize images derived from virtual camcorders taking a great number of factors into account, including the light refraction. The position of the camcorders in 3D models was chosen close to the measured one. A system of automatic tuning of camcorders based on the attainment of the coincidence of artificial and real images of the motionless elements of the model (Fig. 5b) was developed as well. To determine how the image coordinates are transformed into real coordinates, calibration grids placed on the 3D model in the field in which the laser plane was placed during experiments (Fig. 5a, 5c) were used.



(a)



(b) (c)

Fig. 5. a) The 3D model with the grid inserted into the region of the laser sheet used for calculations in Blender software; (b)combination of the image derived in the experiment with the top camcorder with the calculated image; (c) an example of rendering the image derived from the top camcorder; the grid is located on the site of the laser plane directed to the intermediate heat exchanger.

The difference of the results of this transformation from the transformations based on the physical marks amounted to 0.2% on average, thus showing the high accuracy of the proposed method. Fig. 6 shows examples of the obtained velocity fields in the coordinates of the reactor benchmark in the laser sheet sections in the intermediate and independent heat exchangers in one of the modes.

6 Conclusion

A system for performing measurements by the PIV method, which is designed to study the thermohydraulic processes in a large-scale model of a proposed fast reactor was developed. The system makes it possible to measure reflections and distortions of the laser sheet section as well as shadowing at the maximum (among such measurements that are known to the authors) spatial scales for a complicated reactor model configuration, as well as in a closed volume.

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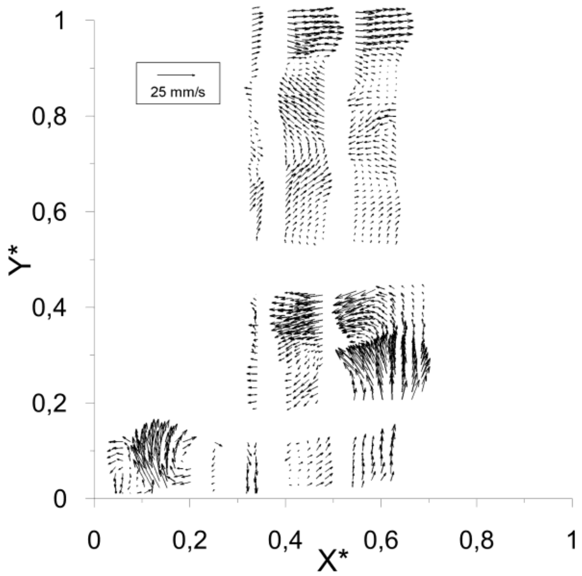
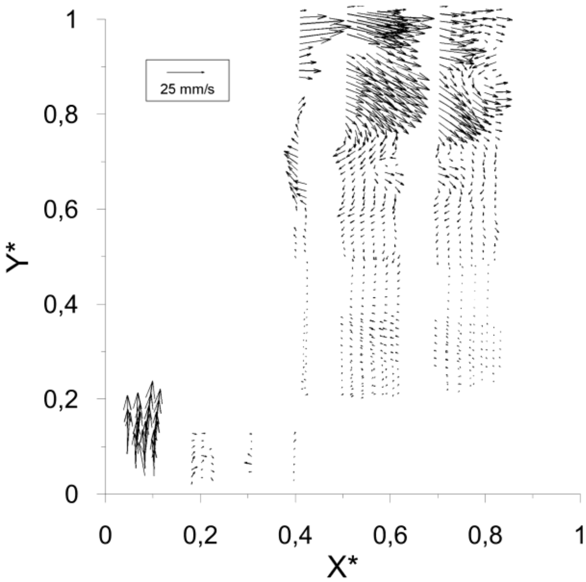


(a)



(b)

Fig. 6. Examples of the velocity fields for one of the modes that were derived by averaging over a subrecord for the sections on independent (a) and intermediate (b) heat exchangers. The coordinates are dimensionless: X* = X [mm]/1200, Y* = Y[mm]/1200.

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