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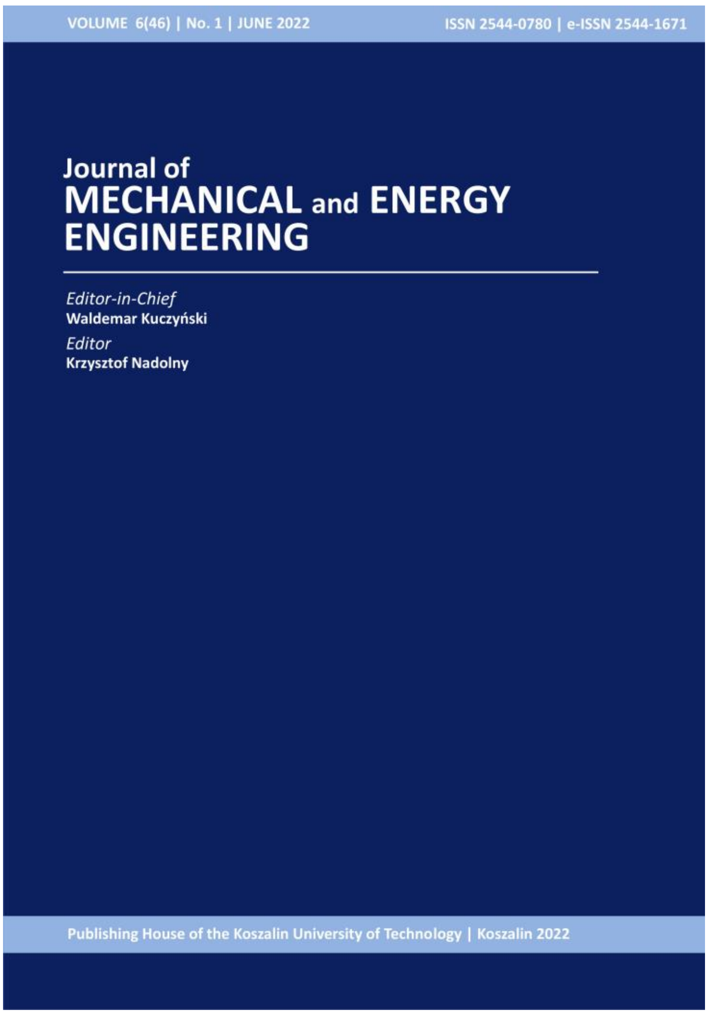

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THE USE OF PIV METHODS IN THE STUDY OF TWO-PHASE FLOWS IN SMALL DIAMETER CHANNELS

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Abstract: The PIV (Particle Image Velocimetry) method is one of the optical, non-invasive measurement methods for measuring fluid velocity and it can be used in the study of two-phase gas-liquid flows to determine velocity fields. The velocity distribution of the liquid and gas phases influences the formation of two-phase flow structures and, consequently, the mechanisms of energy and moment exchange in the two-phase flow. The article concerns the application of the PIV method in the assessment of hydrodynamic phenomena occurring during two-phase flow realized in pipe minichannels with internal diameters d > 2 mm. Fluorescent marker particles with a density close to that of water were used in the research. The preliminary tests were carried out on the adiabatic water-air mixture. The research aimed to check the applicability of PIV methods also in non-adiabatic flows. As a result of preliminary studies, the velocity maps of the liquid phase, histograms and velocity profiles in the vertical section of the minichannel tested were obtained.

Keywords: two-phase flow, minichannels, flow structures, PIV

1. INTRODUCTION

The PIV method is used to measure velocity fields by analyzing the movement of inert marker particles introduced into the system. To visualize the movement of marker particles, laser light is most often used, illuminating the selected flow plane. A video camera is responsible for registering the change in the position over time of marker particles [1]. The system for applying the PIV method during the two-phase flow consists of a test object in which a fluid flow takes place, containing appropriately selected marker molecules (in terms of density, size, and an ability to reflect laser light or generate light by fluorescence). Most often, it is recommended that the markers are selected so that their density is close to the density of the tested factor and that they do not generate physical or chemical changes in their environment. The markers should be distributed evenly throughout the volume, which is particularly important for markers with diameters below a few micrometres as they tend to form conglomerates. The maximum diameter of the tracer particles decreases with the increasing fluid velocity. The amount, size and concentration of tracer molecules should be controlled and determined individually for each measurement system. Most often, markers are made of such materials as polystyrene, aluminium, magnesium or, in the case of refrigerants, glass [2–5]. The measurement data is in the form of a plurality of images recorded with a known frequency representing the change in the position of the marker particles. Based on these images, using statistical methods, it is possible to determine the speed of movement of the marker particles and ultimately the speed of the medium in which the particles move. Using multiple-image recording methods, which is the dominant direction of the PIV method application, the mean shift of marker particles is determined using the CCF (Cross-Correlation Function) method [6–10].

The knowledge of the speed distribution of individual phases allows for the identification and description of the interphase interface disturbance process, which influences the formation of the individual structures of the two-phase flow. In the case of non-adiabatic flows (boiling or condensation), the type of the flow structure formed affects the heat transfer process and flow resistance. The increase in the thickness of the condensate layer acts as an increase in the thickness of the insulation, i.e. it inhibits heat transfer, but it also reduces the flow resistance. The assessment of these phenomena is therefore crucial both at the stage of the design and operation works.

2. TWO-PHASE FLOW STRUCTURES

In the process of the two-phase flow in a channel, the influence of external forces and their components on the flow varies depending on the configuration of the channel axis in space. One of these forces is gravity, which influences the formation of the flow structures. When the diameter of the channel decreases, the influence of gravity on the flow decreases and the influence of surface tension on the forming flow structures is enhanced. During the two-phase flow in conventional channels (diameter above 3 mm) with a horizontal axis, there are such flow structures as dispersion, which includes mist and bubble flow (with very small gas bubbles), annular, stratified structures, which include the wave substructure, and stratified structures, which include slug, plug and bubble substructures (with a much larger bubble diameter than in the case of the dispersive structure). From the physical point of view, the individual flow structures are characterized by different parameters [11,12]. Fig. 1 shows a schematic diagram of the basic two-phase flow structures in a horizontal channel. The mist structure (M) is characterized by the fact that gas flows through the entire cross-section of the channel with small liquid droplets "suspended" in it.

The annular structure (A), on the other hand, consists of a gas phase flowing at a high speed in the channel core and a liquid film formed on the inner surface of the channel. The stratified structure (SS) consists of a liquid flowing in the lower part of the channel and a gas phase in the upper part. On the other hand, the wave structure (W) is formed when disturbances in the form of waves appear on the phase interface in a stratified structure. This is due to an increase in gas phase velocity. The plug structure (P) consists of the formation of gas bubbles in the flow, which can reach a size comparable to the diameter of the channel and move mainly in the upper part of the cross-section. The slug structure (S), on the other hand, arises with increasing flow rates as shear stresses increase the waveband, forming gas bubbles along the flow direction in the channel. In this way, a certain amount of the liquid with small bubbles and large bubbles occupying a major part of the cross-section of the channel alternately flows in the channel. The last type of the flow is the bubble structure (B), it is a structure in which regular-shaped gas bubbles flow in the liquid.

At high flow rates, there is a large speed difference between the liquid and gas phases. This is due to the significant difference in the density of the liquid and gas phases. At low values of the channel filling degree, the inertia forces separate the liquid phase from the gas phase, which results in the formation of a thin liquid layer on the channel walls. This creates an annular structure. The high velocity of the gas phase in the channel core causes disturbances at the interface, which causes the gas to entrain liquid particles [13,14].

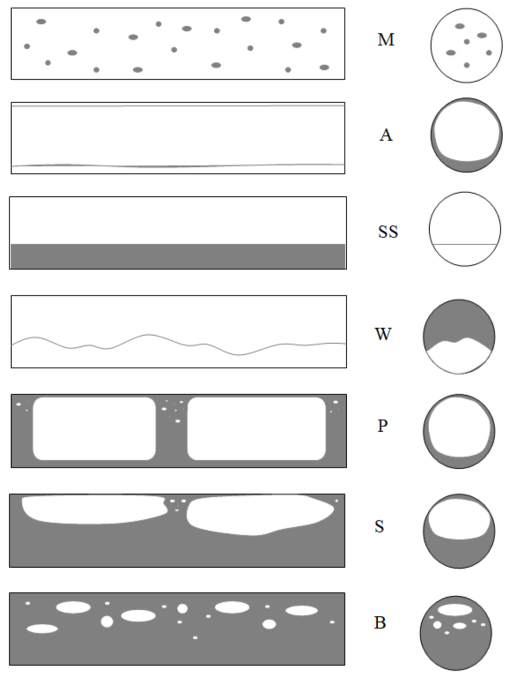

Fig. 1. Schematic diagram of adiabatic flow structures in a conventional horizontal channel: M – mist flow, A - annular flow, SS – stratified flow, W – wave flow, S – slug, P – plug, B – bubble flow [2]

3. TEST STAND

The tests were carried out during a two-phase, adiabatic flow of water-air type in three glass mini-pipe channels with a hydraulic diameter of d = 2; 1 and 0.7 mm. A marker in the form of fluorescent polymer particles coated with rhodamine B with a density close to the water was used for the tests. Fig. 2 shows a block diagram of the measuring station, which included: Dantec Dynamics FlowSense EO 4M CCD camera recording flow phenomena, Dantec Dynamics DualPower TR pulsed laser, the mini-channel tested (Fig. 3), the data acquisition system with a Berkeley Nucleonics Corp Model pulse generator 575-8 and auxiliary devices in the form of gas and liquid flow meters, a degassing chamber and a chamber for mixing the tracer particles with the liquid tested, as well as a pump forcing the liquid flow and a compressor responsible for generating the airflow.

The flow rates of both fluids were regulated by valves and by-passes. Both the PIV system control and image processing and the actual PIV analysis were performed using Dantec Dynamics DynamicStudio 7.1 software. As a result of the research, instantaneous and averaged flow velocity fields in the cross-section of the mini-channel were obtained, which were the basis for further analysis.

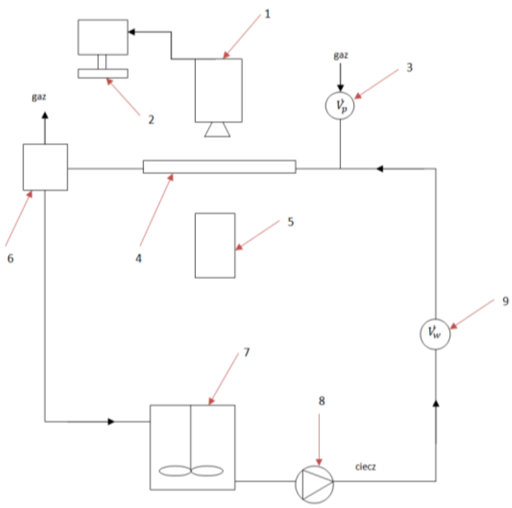

Fig. 2. Block diagram of the measuring station: 1 – camera, 2 – data acquisition system, 3 – gas flow meter, 4 – measuring section, 5 – laser, 6 – degassing chamber, 7 – mixing chamber, 8 – pump, 9 – liquid flow meter

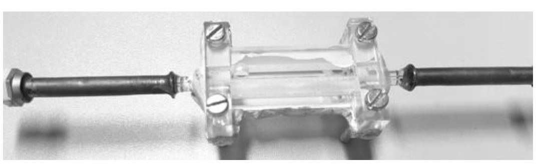

Fig. 3. View of the measuring section used in the research

4. RESULTS OF OWN RESEARCH CARRIED OUT WITH THE PIV METHOD

One of the issues that can be analyzed using the PIV method is an assessment of flow fluctuations during the operation of the mini-channel. The example presented below focuses on an analysis of the dynamics of slug flow. The slug structure can occur in a very wide range of flow parameters, which entails considerable differences in flow hydrodynamics, despite the constant functioning of the flow within one two-phase structure. The different characteristics of the slug flow may be manifested in the morphology of the interface, the distribution of the liquid and gas phases concentration, the dominance of heterogeneous or homogeneous nature, and even local changes in the phase flow direction. Fig. 4 shows the results of PIV measurements for the slug flow in the minichannel tested.

When examining small diameter channels using optical methods, difficulties often arise in imaging the entire section, within which a given flow structure is identified. The solution in such situations is a partial analysis of individual areas of the structure. A similar methodology was used in the research, the results of which are presented in Fig. 4. For a PIV analysis, the optimal area for imaging was selected which, however, resulted in its linear dimension being significantly smaller than the length of the projective structure observed.

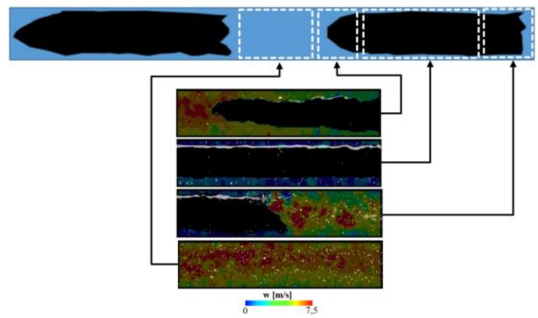

Fig. 4. An exemplary PIV analysis of the slug flow in a mini-channel with a diameter of $d = 2$ mm

Thus, four characteristic areas of the cork were analyzed: the frontal part, the middle part, the end part and the liquid-occupied space separating successive slug structures. The basic tool for assessing the flow fluctuation in the slug regime was the instantaneous velocity field of the liquid phase. The gas-phase (air) without tracers is not included in the calculation. However, single identification of marker particles (or fine liquid drops) in the plug area is possible, therefore they should be treated as measurement errors and eliminated with the use of median filtration for example.

When observing the front of a long projective structure, formed in the flow conditions tested, it can be concluded that a region of increased flow velocity is created directly in front of it. This area largely determines the speed of the cork face. A local decrease in the density of the medium flowing in this area, e.g. caused by the presence of a large number of fine gas-phase bubbles, may contribute to an increase in the speed of the slug front. Analogous observations can be made in the end region of the stopper, which borders - depending on the nature of the flow - with the liquid phase or a mixture of the liquid phase and fine gas bubbles. A characteristic element of the central area of the slug, which can be of a considerable length and have the morphological features of the annular flow, is the change in the disturbances of the interfacial surface in the form of waves formed on the surface of the liquid film, on the inner wall of the minichannel. Due to its location, the area between successive traffic jams serves as a buffer. The one- or two-phase nature of this area also affects the speed of the movement of slug structures.

The evaluation performed of velocity fields may be enriched with an analysis of velocity histograms showing the percentages of areas with a given flow velocity of the medium. Fig. 5 shows the instantaneous velocity histograms determined for the components of a long projective structure analogous to those shown in Fig. 4.

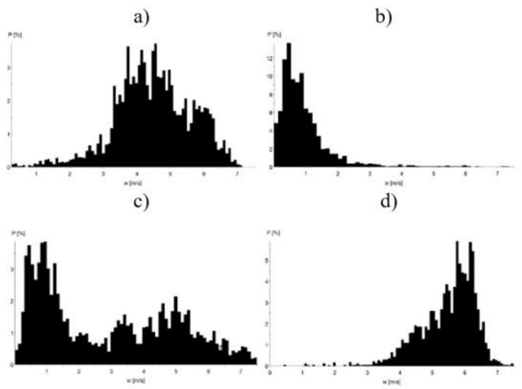

Fig. 5. Velocity histograms for individual parts of the slug structure: a) frontal, b) middle, c) end, d) separating area

By maintaining comparable volumetric fractions of the phases in the velocity field area analyzed and comparing the boundary parts of the slug structure (frontal part - final part), it is possible to determine the equilibrium state responsible for the uniformity of structure fluctuations over time. This balance can be reflected by a criterion number describing the similarity of the velocity histograms determined for both parts of the slug structure. Generally, it can be stated that the greater the similarity of the histograms is, the greater the pulse stability of the slug flow is. The predominance of the frontal or terminal portion of the slug structure in the percentage distribution of the histogram indicates an evolution of the structure and, for example, its expansion as a result of a faster movement of the slug face relative to its end portion.

Based on the instantaneous measurements, it is also possible to determine the averaged values of the parameters analyzed and their derivatives (e.g. vorticity, swirl strength, shear velocity). Fig. 6 and 7 show the averaged velocity field and the velocity profile inside the mini-channel tested for the slug structure analyzed.

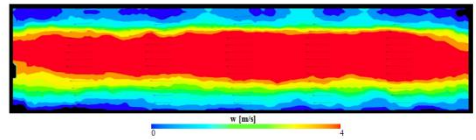

Fig. 6. Average velocity field for slug structure

Optical methods recording large series of images make it possible to average the results obtained. The importance of the possibility of making an evaluation of processes based on averaged parameters results from the frequent use of such parameters in process calculations, e.g. heat transfer, mass transfer, flow resistance, strength parameters, physical changes or chemical reactions. The possibility of a non-invasive, experimental verification of averaged parameters is therefore an important advantage of the PIV method.

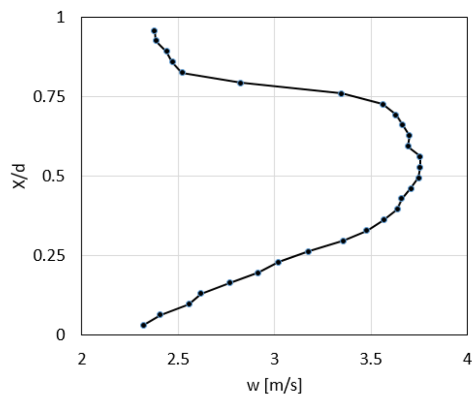

Fig. 7. Average velocity profile for slug flow

5. CONCLUSIONS

Based on the conducted preliminary research, the following conclusions can be drawn.

1. PIV methods can be successfully applied to the analysis of two-phase adiabatic and non-adiabatic flow, including the condensation process. Remember to select the appropriate markers that will not react with the refrigerant and will have the right size and density.
2. PIV methods can be used to measure the velocity of both phases, as well as to determine the frequency of plugs, slug and gas bubbles formation in a two-phase flow.
3. The difference in velocity between the gas and liquid phases influences the shape of the interface and its deformation, and thus the formation of flow structures.
4. In non-adiabatic flow, the influence of the flow structure on the heat transfer process is important. Deposits of the liquid on the surface channel, as well as the increase in its velocity, inhibit the heat transfer process, due to the thermal resistance of the liquid, which acts as insulation on the surface of the channel in the two-phase flow process.

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Nomenclature

Symbols

d – diameter, m
$\dot{V}$ – volumetric flow rate, m^3/s
w – velocity, m/s
P – percentage velocity, %
X – transverse dimension of the mini-channel, mm

Subscripts

g – gas
l – liquid

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Biographical notes

Małgorzata Sikora received her M.Sc. degree in Environmental Engineering (specialization: heating and air conditioning) and PhD (with honours) in Machinery Construction and Operation from Koszalin University of Technology, in 2008 and 2011 respectively. In 2021 she obtained the title of habilitated doctor at the Cracow University of Technology in the discipline of Environmental Engineering, Mining and Power Engineering. Since 2011 she has been an assistant in the Department of Heating and Refrigeration Engineering at the Koszalin University of Technology. Currently, she works as an assistant professor in the Department of Power Engineering. Her scientific interests concern a heat and flow phenomenon during refrigerants condensation, refrigeration and heat pumps. She has participated in few national research projects, 1 international education project (Tempus Energy). She has presented the results of her work at numerous international and national conferences, she has published 20 articles in journals from the Web of Science list and about 50 papers printed in national and international conferences materials. She is also co-author of 2 monographs published in English, author of 1 monography published in Polish and 1 didactic textbook.

Grzegorz Ligus Ph.D. (Eng.), graduated from the Faculty of Mechanical Engineering of Opole University of Technology (2004) He obtained his doctoral degree at Opole University of Technology (2008), his doctoral thesis concerning the field of machine construction and operation. Until 2010 he was working as the Head of the Environmental Engineering Department in the Institute of Ceramics and Building Materials in Opole. Currently he works as Assistant Professor in the Department of Process and Environmental Engineering of the Faculty of Mechanical Engineering at the Opole University of Technology. Scientific interests: aero- and hydrodynamics in single- and multiphase systems, experimental fluid mechanics (especially PIV method).