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EXPERIMENTAL INVESTIGATIONS OF CAVITATING FLOWS IN A VENTURI TUBE

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Abstract

This article presents results of the experimental measurements of the cavitation phenomena in a Venturi tube with water as the working medium. Three variants of such tube were tested. Angles of converging and diverging sections are equal to 45° and 45°, 30° and 60°, 45° and 60°, respectively. In every case the throat diameter is equal to 3 mm and the throat length to 6 mm. The average flow velocity ranges from 0.1 to 0.5 m/s. During measurements, the average flow velocity, upstream and downstream pressure and water temperature were recorded. Additionally, by the use of a high-speed camera and a simple digital camera, information about the size and the shape of the bubble clouds for different flow conditions was collected. The aim of the article is data acquisition for the further numerical analyses. The experimental runs executed for this paper are to help provide more information about this type of flow, since numerical modeling of the cavitation phenomena in Venturi tubes is still very difficult and in many cases even quantitative agreement is impossible to obtain.

Introduction

Cavitation phenomena could be defined as the evaporation process of a liquid in areas where the local pressure drops below the saturation pressure. This pressure depends in turn on the temperature of the liquid. If the pressure increases (in space or in time), the vapour bubbles disappear. Cavitation is generally undesirable due to its negative consequences: erosion, noise, vibrations and energy losses (BAGIEŃSKI 1998).

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In real-life applications, cavitation occurs even if the local value of the pressure is higher than the saturation pressure. Such state is due to the fact that in real fluids small bubbles of the non-dissolved gases exist. The presence of such bubbles (called nuclei) is observed for each kind of liquid it may cause a change in the tensile stress of the liquid, in terms of decreasing it. (BAGIEŃSKI 1998). The tensile stress for „clear" water (for temperatures in the 5–15°C range) reaches values of approximately 27 MPa and depends on the temperature of liquid. The increase of temperature translates into a drop of the value of tensile stress. The tensile stress is reduced to zero at approximately 374°C (KNAPP et al. 1970). Change in tensile strength may also change other material properties, which depend upon it: density, viscosity, surface tension and air content (NOSKIEVIČ 1969).

However, it is possible for cavitation to still occur, even in the absence of nuclei. The theory of liquid disturbance describes the phenomenon of homogeneous nucleation. This theory relates to the possibility of creating bubbles with critical dimensions in water without any nuclei. Liquids, considered at the molecule level, are in the dynamic state, which means that these molecules are in continuous motion. Through the motion of the molecules, empty spaces may be formed between them. Under favourable conditions, i.e. increase of temperature or/and drop of pressure, these spaces could turn into bubbles with critical dimensions (APFEL 1972).

The discovery of a new physical phenomenon in 1894, responsible for destruction of a ship propeller (REYNOLDS 1894), opened a new period in the world of technical science. The scale of negative after-effects of the appearance of unexpected vapour bubbles in water persuaded scientists to familiarize with the unknown phenomenon. The observations conducted in natural environment could not help to find the answer to many questions. The only way to shed light on the enigmatic phenomenon was an experiment. Experimental studies of cavitating flows are carried out until 1935 (HUNSAKER 1935). The story of Venturis as the object of the interests of scientists started in 1952 (RANDALL 1952). Since 1962, the experimental investigations of the flow inside Venturis have taken into account also the influence of cavitation (NUMACHI et al. 1962, NUMACHI, KOBAYASCHI 1964). The complex character of the cavitation phenomenon resulted in experimental studies of cavitating flow inside Venturis to be continued to this day (ABDULAZIZ 2014, DECAIX, GONCALVES 2013).

The main function of Venturis is a passive control of the mass flow rate. These devices are a common application in industry. The Venturis as an application can be found first in parts of hydraulic systems, where a constant mass flow rate is expected. Their big advantage is the assurance of an unchanging flow rate independent from the variable pressure in a chamber. Through these features, Venturis, as a precise tool, could be used as a flow meter (GHASEMMI, FASIH 2011). Their construction consists of three parts: a converging section (nozzle), throat, and a diverging section (diffuser). To the most essential features of Venturis, which have an influence on the mass flow rate and the flow character, belong the throat diameter, the throat length and the diffuser angle (ASHRAFIZADEH, GHASEMMI 2015). The broad applications of Venturi tubes support the simple form of the device. Additionally, their construction does not have any moving parts. Consequently, the production of Venturis does not require a lot of finance and these devices are characterized by high reliability. Therefore, use of these devices is on the one hand practical and on the other hand economical (GHASEMMI, FASIH 2011).

Venturi tubes, despite that they are a basic geometry, they are devices with varied shapes. In the classical form of Venturi tube presented in ISO 5167-1:2005, the angle of diverging section ranges from 7 to 15° and the angle of converging section is 21°. Scientists analysed also other shapes of Venturi tubes. NUMACHI et al. (1962) investigated in 1962 Herschel Venturi-tube. This tube is characterised by a sharper converging angle and is also the current research object. Brinkhorst et al. presented in 2015 the results of numerical simulations of cavitating flow in Herschel Venturi tube. They analyzed the influence of geometry parameters on the stability of the mass flow rate. Additionally, the authors made the same investigations for toroidal Venturi nozzle (ISO 9300:2005) which is distinguished by a radius in the converging section and a direct transition to the diverging section.An important type of a Venturi tube is an asymmetric Venturi (BARRE et al. 2009, RODIO, CONGEDO 2014, CHARIERRE et al. 2015). BARRE et al. (2009) presented double optical probe measurements and numerical studies based on the code Fine™/Turbo and a barotropic approach. Rodio and Congedo prepared a stochastic analysis of cavitating flow. CHARIERRE et al. studied an aperiodic cavitation pocket in an asymmetric Venturi using chosen homogeneous models.

The main aim of the investigations of the cavitation phenomenon is to build new simulation models for different kinds of Venturi tubes using the homogeneous approach.The motivation to begin such investigations relate to the cavitation phenomena in Venturi tubes was the fact that the current available and most popular cavitation models are still too poor for such flows. Results from numerical modeling are too different from observations even on the qualitative level. According to the literature, the prediction of the cavitation phenomenon in the Venturi tubes in one of the most difficult cases and further investigations in this field are needed (PALAU-SALVADOR et al. 2007). For this reason, the Venturi tubes are often the subject of research of cavitating flows (BAYLA et al. 2009, TAMHANKAR et al. 2014, BRINKHORST et al. 2015). Despite widespread interest of scientists in this field, having a large number of different shapes for Venturi tubes impedes finding the expected experimental results for the chosen shape. For the mentioned study, recording the best accuracy of the Venturi tubes performance in experimental measurements is necessary. For this purpose, a new test rig was designed and built, which is presented in this article.

The article has the following structure: the first part is devoted to acquaint the reader with the design assumption. Knowledge of the validation process of the numerical models enables the reader to understand the detailed construction of the test rig. The description of the test rig, which is the second part of the article, starts with the history of investigation of cavitating flows at the Faculty of Technical Sciences and presents a comparison between the old and the new version of the test rig. After the introduction, a diagram of the device and the detailed presentation of the most important components follows. The next step of the article is the overview of the technical data and the description of the typical measurement process. The third part of the article is presentation of the capabilities of the experimental investigation of cavitating flows using the new test rig. The article ends with conclusions on the results obtained.

Assumptions

There are three basic approaches to integrate numerical fluid analyses with experiments (SOBIESKI 2013). The first approach (Fig. 1*a*) supposes only one-way interaction of experimental data with numerical analyses (CFD – Computational Fluid Dynamic). However, during creation of the simulation model it may happen that the experimental data proves to be insufficient or its quality will be too low. There is no possibility to repeat the investigation, so the results of the numerical simulations could be incorrect. The second approach (Fig. 1*b*) submits a correction to the previous version. The experiment can be repeated, if it is necessary, which translates in an improvement of the compatibility of the results between the real case and the virtual model. The disadvantage of this approach are time and cost needed for the repetition of the experiment. Besides, in some cases the experiment cannot be performed again. The best way to integrate the experimental and numerical investigations is the application of the following methodology (Fig. 1*c*): first, the preliminary numerical model is created. Then the experiment is planned and performed taking into account the knowledge about requirements of the numerical model. Finally, the preliminary numerical model is corrected and calibrated. In the current investigation, this methodology is applied, therefore at the beginning of investigations, the preliminary numerical model was created.

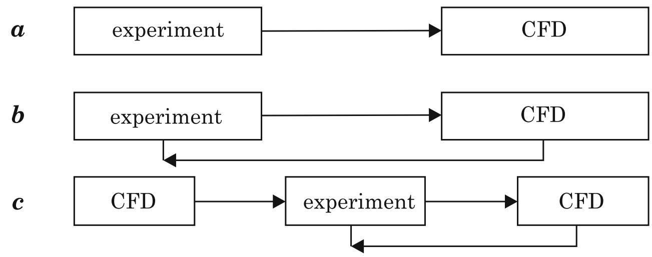

Fig. 1. Basic approaches to integrate numerical fluid analyses
Source: SOBIESKI (2013).

The data for numerical fluid simulations can be divided into three groups: geometry data, data defining the kind of fluid and information about the boundary conditions. The geometry data is necessary for mesh preparation. The rule for this case is as follows: the simpler geometry of the grid, the easier the meshing process will be and a shorter calculation time will be required. The data describing the physical medium includes information about the density and viscosity of the fluid. Since the analysed case concerns water, only its temperature has to be known. The temperature is an important parameter for cavitation phenomenon because it can change details the saturation pressure. For this reason, the experimental measurements should be performed with a constant temperature. There are three methods to establish the desired temperature. The first method assumes use of cold water and fast measurements. In the second approach the measurement may be performed after a time in which the system achieves the state of the thermodynamic equilibrium (the temperature will be constant). The third method assumes the automatic control of the temperature. This solution is the most convenient. The last set of information concerns boundary conditions. These terms should be understood as flow parameters. These parameters can be included in the simulation model in two ways. The first way assumes introducing information about the inlet velocity and outlet pressure. In the second method, information about the total inlet pressure and the dynamic inlet pressure should be used. In this case is important to enter the additional data about the reference values. The presented test rig meets the design assumptions.

Laboratory setup and methods

Test rig

The idea of experimental and numerical investigations of cavitation in hydraulic systems started at the Department of Mechanic and Basics of

Machine Construction at the Faculty of Technical Sciences of the University of Warmia and Mazury in Olsztyn between 2002 and 2004. The first test rig was created for the purpose of investigating cavitating flows. Using this test rig, photos were taken of the cavitation cloud behind the cavitation inducer and vibroacoustic analyses on the basis of the noise measurements in the flow were conducted (SOBIESKI 2004, 2005).

In 2010, this prototype was replaced with a new test rig (Fig. 2), which is directly intended for performing experiments of turbulent and cavitating flows, as well as many other flow phenomena. The device was made within the framework of the project TECH 2010. In comparison with the prototype, the new test rig was improved and has a few advantages. Some of these advantages are: having an inter alia with smaller dimensions, having the ability of motion using the wheels, automatic acquiring and saving of the signal from all sensors, direct displaying of the data, simple control of the flow velocity and the liquid temperature, as well as the independence from the connection to the water mains.

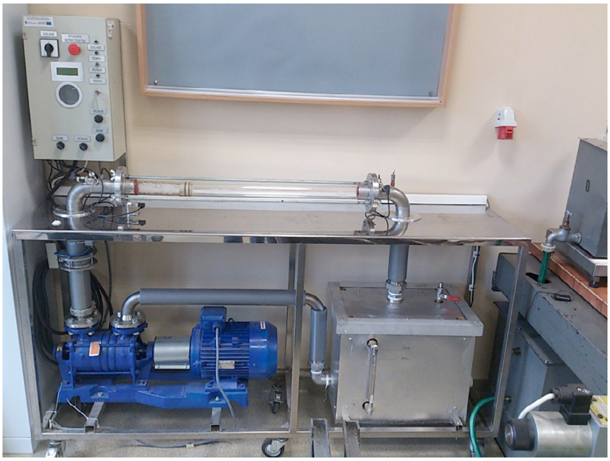

Fig. 2. The test rig from 2010

The scheme of the test rig is presented in the Figure 3. The whole device weighs approximately 115 kg. Its weight with water increases to approximately 195 kg. The test rig is 190 cm in height, 50 cm in width and 180 cm in length. The independence from the connection to the water mains is ensured by the hydraulic system with closed water circulation. The used self-priming pump up to 10 bar is suitable for liquids with the temperature not exceeding 110^{o}C, density not exceeding 1300 kg/m^3 and viscosity not exceeding 150 mm^2/s. The maximum permissible size of impurities in form of indelible solid particles is

0.5 mm. The pump can obtain a maximum efficiency at level of 7 m^3/h, which translates into a linear velocity of water in the cavitation chamber of 1 m/s. A motor having a power of 5.5 kW is used as a drive to the self-priming pump.

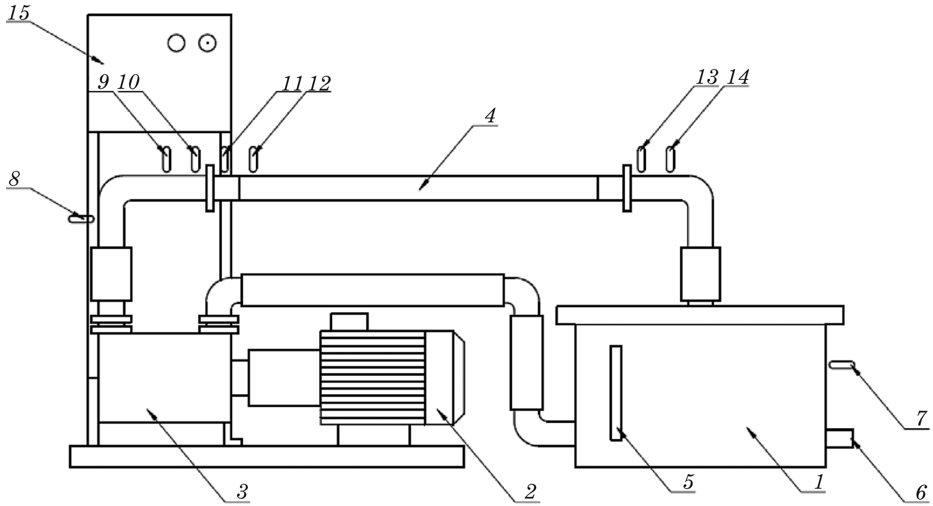

Fig. 3. The diagram of the test rig from 2010: *1* – water tank, *2* – motor, *3* – water pump, *4* – cavitation chamber, *5* – water indicator, *6* – heater, *7* – water level sensor, *8* – velocity inlet sensor, *9* – pressure inlet sensor, *10* – temperature inlet sensor, *11* – proximity sensor of the chamber, *12* – additional proximity sensor, *13* – pressure outlet sensor, *14* – temperature outlet sensor, *15* – control panel

The test rig is equipped with seven sensors that can work with temperature below 100°C and humidity below 50%. The measurements can be started, when the external temperature is between 0 and 40°C. The sensor of water level in the water tank is located in the right wall. The sensor is placed about 26 cm above the tank bottom, which corresponds to 46 l of liquid. It is the minimum safe level at which the water pump can be started. The direct control of filling level is enabled through the water indicator. The last sensors, placed below the tabletop, give information about the linear fluid velocity. To reduce the fluctuations of the signal, a filter with time constant of nine seconds was applied. Consequently, the data in display are delayed with regard to the correct flow.

The most interesting part of the test rig, i.e. the cavitation chamber, is placed above the tabletop. The plexiglas pipe has the internal diameter of 50 mm. The distance between both flanges is 1,000 mm. The cavitation chamber is only one of the variants of the system, which can be investigated using the presented test rig. The elbows of the inlet and outlet pipes are equipped with sensor sets, which include temperature and pressure sensors. The precision of each temperature sensor is 0.5°C. The pressure measuring range is between 0 and 10 bars. Additionally, on the right side of the left flange of the cavitation chamber, is placed a proximity sensor which has the aim to counteract switching on the hydraulic system in case there is a lack of the cavitation chamber.

The operating panel ensures the control of measurements. It has three flip switches to turn on power, motor and heater. Determination of temperature and percentage use of the motor is made by two independent potentiometers. The values of the given and the current temperature of water in the elbows of the inlet and outlet pipe and the percentage use of the motor are displayed on the LCD monitor. To other information, which can be found on the LCD monitor, belong the water pressure in the elbows of the inlet and outlet pipe and the linear velocity of the flow.

Venturis

In the analysed case, the cavitation inducers are three Venturi tubes (Fig. 4), which have their dimensions presented in the Figure 4. The angles of converging section were selected for the first Venturi as 45° (Fig. 4*a*), for the second 60° (Fig. 4*b*) and for the third 30° (Fig. 4*c*). The angles of diverging sections were selected as 45°, 30° and 60°, respectively. The throat has diameter of 3 mm and 6 mm length. The outside diameter of the Venturi tube is 50 mm. The Venturi is placed within 300 mm of the left edge of the cavitation chamber.

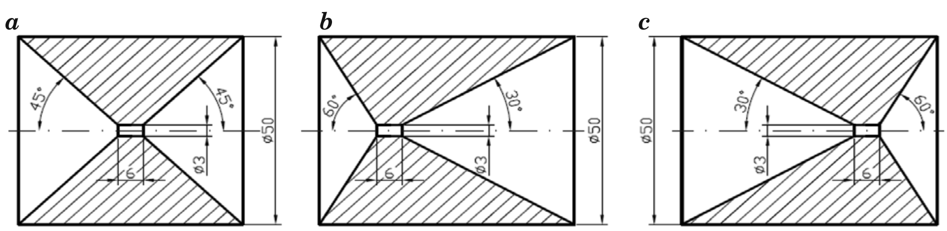

Fig. 4. Dimensions of the Venturi tube

Experimental method

To investigate the behaviour of the flow in the Venturi channel and the cavitation chamber an experiment has been conducted. In the experiment, the velocity flow and the temperatures and pressure at the inlet and outlet of the cavitation chamber have been measured. During the test, the value of the downstream pressure was constant; the value of the upstream pressure was variable. The data obtained in the experiment is presented in form of tables. The shapes of the cavitation cloud have been registered using a high-speed camera (Olympus i-SPEED TR, 1000 frames per second) and a simple digital camera (Nicon Coolpix P610).

Results and discussion

The first and main aim of experimental measurements is obtaining data for numerical analyses. The division of the essential information was presented in the first section of the article. The second part of the data, which concerns the physical medium, was reduced to the reference temperature. During tests of the laboratory device, the temperature was between 19 and 40°C.

Table 1

Results of experimental measurements for the first Venturi (Fig. 4*a*)

No.	u	T_1	T_2	p_u	p_q	$p_u – p_q$
	m/s	°C	°C	Pa	Pa	Pa
1	0.1	20.2	19.8	481,325	4.99	481,320
2	0.2	20.5	20.1	677,325	19.96	677,305
3	0.3	20.9	20.8	776,325	44.91	776,280
4	0.4	21.1	21.2	846,325	79.84	846,245
5	0.5	21.4	21.7	964,325	124.75	964,200

Table 2

Results of experimental measurements for the second Venturi (Fig. 4*b*)

No.	u	T_1	T_2	p_u	p_q	$p_u – p_q$
	m/s	°C	°C	Pa	Pa	Pa
1	0.1	31.1	32.1	657,325	4.99	657,320
2	0.2	32.6	32.9	757,325	19.96	757,305
3	0.3	35.6	36.1	1,022,325	44.91	1,022,280

Table 3

Results of experimental measurements for the third Venturi (Fig. 4*c*)

No.	u	T_1	T_2	p_u	p_q	$p_u – p_q$
	m/s	°C	°C	Pa	Pa	Pa
1	0.1	24.1	24.2	534,325	4.99	534,320
2	0.2	24.7	24.8	719,325	19.96	719,305
3	0.3	28	28	811,325	44.91	811,280
4	0.4	29.7	29.4	980,325	79.84	980,245
5	0.5	35.8	35.6	1,099,325	124.75	1,152,200

The last part of data includes boundary conditions, in other words, flow parameters. In case of cavitation simulation both ways of defining of flow parameters, velocity inlet – pressure outlet and pressure inlet – pressure outlet, are possible. All desired information are either displayed on the LCD monitor (average fluid velocity – u, inlet total pressure – p_u and outlet total pressure – p_d) or calculated based on this information (dynamic pressure – p_q, difference between the inlet total pressure and the inlet dynamic pressure $p_u - p_q$). In the tables 1–3 data from the experimental measurements is presented. Pressure in the outlet of cavitation chamber (p_d) has a constant value of 101.325 Pa.

From the data presented in the Tables 1–3 it is evident that the maximum average velocity at the inlet of the cavitation chamber is 0.5 m/s. In the case of the second type of Venturi, the maximum average value of the velocity achieves only 0.3 m/s. The temperature of the medium starts from 19°C and finishes before reaching 40°C. The total pressure at the inlet of cavitation chamber varies from about 4 bar (for the average velocity at the inlet equal to 0.1 m/s) to 10 bar (for 0.5 m/s). The differences between upstream total pressure and upstream average velocity for the analysed variants of Venturis are notable. For the upstream average velocity equal to 0.1 m/s the value of the upstream total pressure starts from 3.8 bar for the first type of Venturi, for the third type achieves value 4.33 bar and for the second 5.56 bar. The differences are visible in the whole of the experimental measurements. For the upstream average velocity of 0.3 m/s, the value of the upstream total pressure starts from 6.75 bar for the first type of Venturi, for the third type achieves value 7.1 bar and for the second 9.21 bar. Additionally, the maximum upstream average velocity for the second type of Venturi is only 0.3 m/s, which is a direct indicator that changes in the angles of Venturi influences the upstream velocity and upstream pressure. ASHRAFIZADEH and GHASEMMI (2015) indicate that changing of the diverging section angle does not affect the values of upstream pressure and velocity. However, the changes of the converging section angle are not without impact on these values.

The second aim of experimental measurements is obtaining data that is useful by post-processing. The test rig has not any instrumentation that would allow collecting data for validation process. The simplest and the most common method is evaluation of the intensity and size of the cavitation cloud based on photos. Photos can be made using a high-speed camera (Fig. 5–7) or even a simple camera (Fig. 8). Photos can be compared with distribution of vapour volume fraction in the chamber from numerical simulations. In the Figures 5*a*–5*e* are presented cavitation clouds for the first type of Venturi for five upstream velocities: 0.1, 0.2, 0.3, 0.4 and 0.5 m/s. For the velocity equal to 0.1 m/s, the cavitation cloud is only faintly visible. Increasing velocity leads

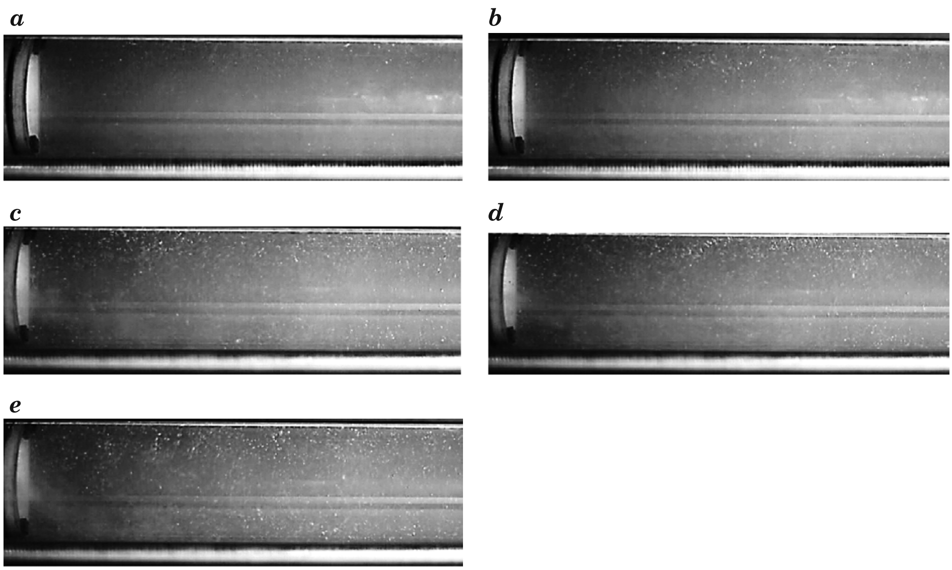

Fig. 5. Cavitation cloud at different velocities for the first type of Venturi: *a* – 0.1 m/s, *b* – 0.2 m/s, *c* – 0.3 m/s, *d* – 0.4 m/s, *e* – 0.5 m/s

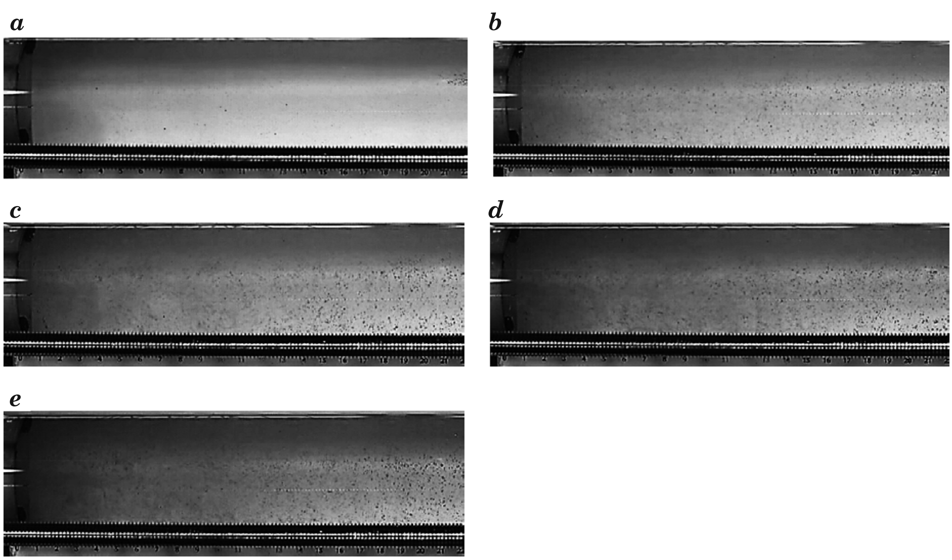

Fig. 6. Cavitation cloud at different velocities for the third type of Venturi: *a* – 0.1 m/s, *b* – 0.2 m/s, *c* – 0.3 m/s, *d* – 0.4 m/s, *e* – 0.5 m/s

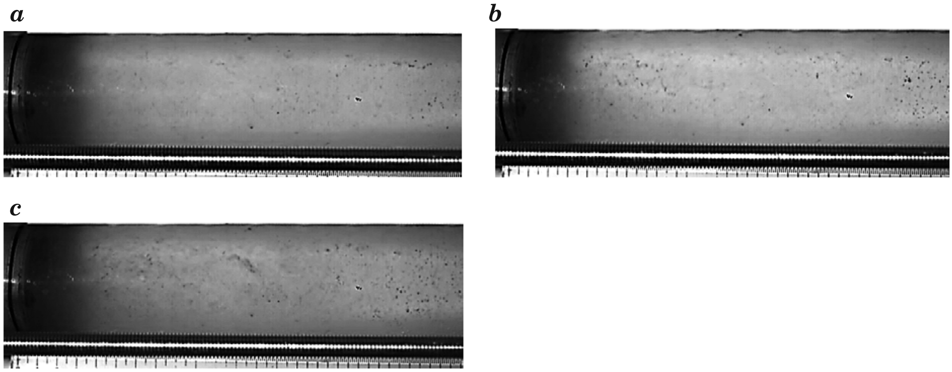

Fig. 7. Cavitation cloud at different velocities for the second type of Venturi: *a* – 0.1 m/s, *b* – 0.2 m/s, *c* – 0.3 m/s

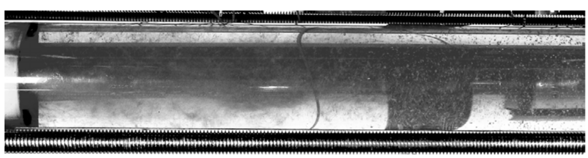

Fig. 8. Photo of cavitation cloud made using a simple camera

to clearer contours between the vapour bubbles and water. Starting from the 0.3 m/s velocity, it is visible that the stream of vapour bubbles after leaving of the diverging section heads for the downstream part of the cavitation chamber and then bounces upstream, forming a hook shape. Between the cavitation clouds for the first and the third type of Venturi (Fig. 6*a*–6*e*) there are many similarities. Among these a blurred shape of the cavitation cloud for the low upstream velocity (Fig. 6*a*) and the increasing of its intensity for higher velocities (Fig. 6*b*–6*e*). The difference between the analysed cavitation clouds is their shape. For the third type of Venturi, the cavitation cloud has no hook form anymore, but a slightly wavy line. The shape for a second type of Venturi is different from the above described (Fig. 7*a*–7*c*). A hook form or a slightly wavy line is no more visible. The cavitation cloud spreads to the whole volume of the cavitation chamber for each of the analysed upstream velocities. Increasing of the upstream velocity leads to increasing of the intensity of the cavitation cloud and its length.

Conclusions

Based on the experimental measurements the following concluding remarks can be made:

– Using the test rig, in objects like a Venturi tube, cavitating flow can be observed.

– The control range of the test rig is sufficient to obtain an intensive and broad cavitating cloud.

– Using the measuring system of the test rig, essential data about pressure and velocity at the inlet and outlet of the cavitation chamber and the water temperature can be obtained.

– Based on the experimental data and the dimensions of the cavitation chamber numerical models for the considered flow cases can be prepared. It means that the main aim of the experimental measurements is achieved.

– Use of the high-speed camera gives a qualitative observation of the intensity and extent of the cavitation cloud. The gathered results should be sufficient material to make comparisons between the experiment and numerical simulations. More over, as shown in the literature study, the most important in the case of Venturis is quality of the experimental and numerical data.

– Using a simple camera did not give enough good results in terms of quality. This method, which is simpler and more accessible, is only of auxiliary importance.

– The type of Venturi and flow parameters has influence on the intensity and extent of the cavitation cloud. In the considered investigation range three forms of cavitation cloud were observed: a hook form, a slightly wavy line and dispersed.

– Reconstruction of the right flow structure in numerical models will be probably the most difficult stage of the numerical simulations.

– A better quality of the experimental data can be achieved using Particle Image Velocimetry (PIV), but currently we do not have access to such measurement systems. To resolve this problem we will try to use an alternative method, which was developed in cooperation with the Department of Electrical and Power Engineering, Electronics and Automation, and will be presented in a future publication.

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