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ANALYTICAL ANALYSIS OF CAVITATING FLOW IN VENTURI TUBE ON THE BASIS OF EXPERIMENTAL DATA

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Abstract

The content of this article is a direct continuation of the prior experimental works on the topic of cloud cavitation in Venturis. The results of the experimental tests were used to create a set of characteristics for three types of Venturis. The article has two aims: 1) verification of the similarity between the characteristics obtained and reported in the literature, 2) verification of the range of the obtained characteristics with respect to parallel diagrams. Both aims were achieved, which confirms that the quality of the prior results of the experimental measurements is at least sufficient to realize the main objective of the whole project: creation of numerical models of cavitating flow in Venturis. The literature overview showed that the issue has been not solved until today, even at the qualitative level. This reason was the motivation for the undertaken research, including contents of the article.

Introduction

The Venturis (Fig. 1) are devices, which have the main role of the control of mass flow rate. Their advantage is a simple rule describing the control mechanism. The mass flow rate is proportional to the throat area. Throat area is the middle part of the cavitating Venturi, between converging and diverging section. Cavitating Venturis are useful especially in devices that require a very small liquid flow rate with constant delivery. Examples of such necessities are:

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flow ratio about few grams per second, have e.g. lab scale monopropellants or hybrid rocket motors. To provide such small flow rate, it is necessary to use Venturis with small throat diameters. The small size of the throat may result in problems with viscous phenomena and varying downstream pressure in the performance of the Venturis (GHASEMMI, FASIH 2011, ASHRAFIZADEH, GHASEMMI 2015). The Venturis are not a common topic in the research world. There is a small amount of work, which consider this issue, so the request for such study is huge.

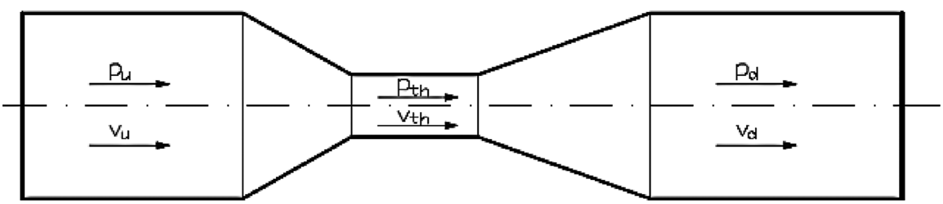

Fig. 1. Schematic of a Venturi: p_u – upstream pressure [Pa], v_u – upstream velocity [m/s], p_{th} – pressure in the throat [Pa], v_{th} – velocity in the throat [m/s], p_d – downstream pressure [Pa] and v_d – downstream velocity [m/s]

The history of the experimental investigations of cavitating Venturis dates back to the 1960s. In this time, RANDALL (1952) presented his pioneering works concerning construction and principles of operation of cavitating Venturis in rocket applications. After a long pause, scientists came back to the topic in 1990s. UNGAR et al. (1994) investigated Venturis under low inlet sub-cooling. Based on their research, it is known that in these devices during work at unchoked mode a decrease of downstream pressure can lead to overflow. Ungar in cooperation with MAL (1994) presented work which aimed to investigate the influence of alternative geometries of Venturis on the overflow conditions. LIOU et al. (1998) continued research on the topic of the small cavitating Venturis under low inlet sub-cooling. Simultaneously began the first numerical simulations of the flow in Venturis. NAVICKAS and CHEN (1993), among others, are pioneers of computer calculation in this field. They concentrated their research on the flow characteristic. The results of their numerical calculations were an irrefutable proof of the usefulness of this method to obtain significant parameters of the Venturis. XU et al. (2002) continued numerical investigation of cavitating Venturis using a homogeneous flow model. The scientists validated the results of simulations e.g. mass flow rate and oscillation frequency with the data obtained in experiments. HARADA et al. (2006) presented results of experimental investigations of the flow in a Venturi channel using the PIV method. GHASEMMI and FASIH (2011) examined small sized cavitating Venturis in three ways: under different upstream and constant downstream conditions, under constant upstream and different downstream conditions Venturi and under variable downstream conditions. The newest works consider the accuracy of the numerical simulations of small-sized cavitating Venturis (ASHRAFIZADEH, GHASEMMI 2015) or insert image analysis to show vapour formation during the cavitating process (ABDULAZIZ 2014). Abdulaziz proposed a new model to predict vapour void fraction and validated it using the results of the image analysis.

The work presented in this article is a continuation of the prior works, especially the experimental measurements presented in the work of (NIEDZWIEDZKA, SOBIESKI 2016). Results of experimental measurements of three types of Venturis with different angles of converging and diverging section and constant throat diameter are presented. The results of experimental measurements are subjected to further analysis and as a result characteristics of Venturis performance are developed. The main aim of the investigations was to analyse the degree of compliance of the obtained characteristics with the characteristics reported in the literature (ABDULAZIZ 2014, ASHRAFIZADEH, GHASEMMI 2015, GHASEMMI, FASIH 2011). The additional aim was estimating the range in which it is possible to make characteristics of Venturis performance using the test rig.

It should be added, that the investigations are not only an interpretation of the obtained experimental data, but firstly a material for numerical simulations which will be the topic of the future works. Development of numerical models of flows with cavitation is the main aim of the authors' research project.

Theoretical background

The construction of a Venturi tube assumes a division into three parts: converging section, throat and diverging section. According to the continuity equation (Eq. 2) and Bernoulli's equation (Eq. 3), the change of the cross section area of a fluid flux (here described by the diameters) is closely connected to the changes in pressure at the inlet and outlet of the Venturi (GHASEMMI, FASIH 2011). The relationship between the values of these pressures, e.g. pressure ratio (see eq. (10)), is decided about the character of mass flow rate (see eq. 1). If the pressure ratio is smaller than 0.8, the mass flow rate is constant and also independent from the downstream pressure. Additionally, at these conditions cavitation appears. This operation mode can be determined as „choked". When the pressure ratio exceeds 0.8, cavitation does not occur, in the Venturi the phenomenon of overflow can be observed and the mass flow rate decreases. It means, the actual mass flow rate is smaller than expected constant value. The relationship between the actual and expected mass flow rate is called mass flow ratio. This mode of operation is determined as „unchoked" or „all-liquid" mode. The relationship between mass flow ratio and pressure ratio (measurements under different downstream pressure conditions) is shown in Figure 2. The general principle, which describes the conditions necessary for the occurrence of cavitation phenomenon, refers to the relationship between the actual and the saturation pressure of the analysed fluid. According to this principle, the transition from liquid to vapour phase in the throat comes when the static pressure drops below the saturated liquid pressure. The reduction of the static pressure in the throat is a consequence of the acceleration process in the converging section (ASHRAFIZADEH, GHASEMMI 2015).

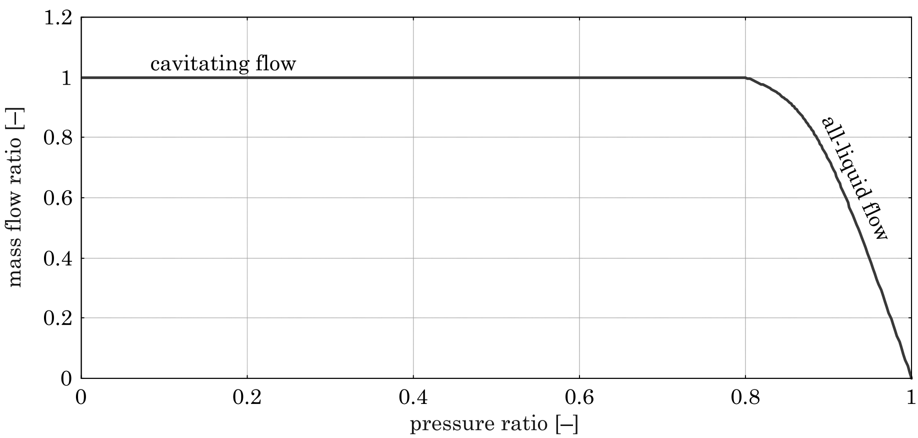

Fig. 2. Characterization curve of cavitating Venturi

Mass flow rate through a Venturi

The mass flow rate through a Venturi is given as

$$\dot{m} = A_{th}\rho_l v_{th} \tag{1}$$

where:
$\dot{m}$ – mass flow rate [kg/s],
A_{th} – cross section area of the throat [m^2],
ρ_l – liquid density [kg/m^3],
v_{th} – fluid velocity in the throat [m/s], is accounted for basis of two equations.

The first is the continuity equation

$$\dot{V} = A_u v_u = A_{th} v_{th} \tag{2}$$

where:
$\dot{V}$ – volume flow rate [m^3/s],
A_u – cross section area of the inlet pipe [m^2],
A_{th} – cross section area of the throat [m^2].

The second equation is the Bernoulli's equation (ABDULAZIZ 2014)

$$\frac{v_u^2}{2g} + \frac{p_u}{\rho_l g} + h = \frac{v_{th}^2}{2g} + \frac{p_{th}}{\rho_l g} + h \tag{3}$$

where:
g – acceleration [m^2/s],
h – elevation of the point above a reference plane [m].

Both equations (2 and 3) are valid for steady and incompressible flows. This assumption is also applied in the current description.

The development of the mass model for cavitating flow should be preceded by appropriate and necessary assumptions. According to the first assumptions, the flow in the converging part is isentropic. The second assumption concerns the density of the fluid, which should be constant and equal to the liquid density at the analysed operating temperature (ABDULAZIZ 2014).

The Bernoulli's equation (Eq. 3) will be used to obtain the dependence on the velocity in the throat. The formula for the upstream velocity will be added to this equation

$$v_u = \frac{A_{th}}{A_u} v_{th} \tag{4}$$

It is derived from the continuity equation (Eq. 2). The third term of the Bernoulli's equation (Eq. 3), the elevation of the point above a reference plane, can be omitted here, because in the experiment all parts of the Venturi are in the same height. Accordingly, accelerations in the both sides of the equation reduce. By substituting Eq. 4 in Eq. 3 the following formula is achieved:

$$\frac{\left(\frac{A_{th}\, v_{th}}{A_u}\right)^2}{2} + \frac{p_u}{\rho_l} = \frac{v_{th}^2}{2} + \frac{p_{th}}{\rho_l} \tag{5}$$

Then, moving all the terms containing v_{th} to the left side and the remaining terms to the right side

$$v_{th}^2 - \left(\frac{A_{th}\ v_{th}}{A_u}\right)^2 = \frac{2(p_u - p_{th})}{\rho_l}. \tag{6}$$

The final form of the dependence on the velocity in the throat has the form:

$$v_{th} = \sqrt{\frac{1}{\left(1 - \frac{A_{th}^2}{A_u^2}\right)} \cdot \frac{2(p_u - p_{th})}{\rho_l}} \tag{7}$$

By substituting v_{th} from Eq. 7 in Eq. 1, the final form of the mass flow rate formula for the Venturi is achieved:

$$\dot{m} = A_{th}\rho_l v_{th} = \frac{\pi d_{th}^2}{4}\sqrt{\frac{1}{\left(1 - \frac{A_{th}^2}{A_u^2}\right)} \cdot 2\rho_l\ (p_u - p_{th})} \tag{8}$$

The presented mass flow rate in the throat (Eq. 8) is only theoretical and should be used for the unchoked mode. To account for the actual value of the mass flow rate

$$\dot{m}_\alpha = C_d\ \frac{\pi d_{th}^2}{4}\sqrt{\frac{1}{\left(1 - \frac{A_{th}^2}{A_u^2}\right)} \cdot 2\rho_l\ (p_u - p_{th})} \tag{9}$$

the discharge coefficient C_d should be considered. For Venturis with a converging angle, at a setting higher than 10° the discharge coefficient takes value 0.99 (READER-HARRIS et al. 2001).

Pressure ratio, cavitation number and Reynolds number

Occurrence of cavitation phenomenon is closely connected to many values, which describe the character of the flow. To these values belong e.g. cavitation number, Reynolds number and Weber number. Two of them are considered in the paper, namely cavitation number and Reynolds number. Additionally, pressure ratio is analysed.

Pressure ratio

$$p_r = \frac{p_d}{p_u} \tag{10}$$

is a relationship between the downstream and upstream pressure, respectively p_d and p_u. This relationship is an important indicator for Venturis. The critical pressure ratio p_{rc} gives the information about the value which, if exceeded, leads to loss of the cavitating character. The literature gives that this value should be about 0.8 (ABDULAZIZ 2014). Cavitation number is:

$$\sigma = \frac{p_d - p_{\text{sat}}}{\frac{1}{2}\rho_l v_{th}^2} \tag{11}$$

where:
σ – cavitation number [–],
p_{sat} – saturation pressure [Pa],
is a dimensionless quantity, which is an useful instrument to the analysis of the occurrence and development conditions of cavitation phenomenon. Its formula (Eq. 11) is close to the Euler number, which is used for determination of the similarity of dynamic flows (BAGIEŃSKI 1998). For Venturis, cavitation number expresses the relationship between the difference of a downstream pressure from a saturation pressure at the corresponding temperature and the kinetic energy per volume. The expression for kinetic energy per volume consists of the dependence between liquid density ρ_l and velocity of the fluid in the throat v_{th}. Cavitation inception is possible when the cavitation number is equal to 1. Decreasing of the value is connected with the intensification of the phenomenon (ABDULAZIZ 2014, BAGIEŃSKI 1998).

In case of Venturis, cavitation number and pressure ratio take similar values. This can be explained through a mathematical analysis (ABDULAZIZ 2014). The starting point of this analysis is Eq. 11. After modification through simultaneously applying multiplication and division by upstream pressure, the following formula is obtained:

$$\sigma = \frac{p_u}{\frac{1}{2}\rho_l v_{th}^2}\left(\frac{p_d}{p_u} - \frac{p_{\text{sat}}}{p_u}\right) \tag{12}$$

Because of the very small value of the relationship of saturation pressure p_{sat} to upstream pressure p_u, it can be omitted. The modified form of the equation of the cavitation number (Eq. 12) is as follow:

$$\sigma = \frac{p_u}{\frac{1}{2}\,\rho_l v_{th}^2}\left(\frac{p_d}{p_u}\right) = \frac{p_d}{\frac{1}{2}\,\rho_l v_{th}^2} \tag{13}$$

After comparison of the equation (1) and (9) following expression is obtained

$$\rho_l A_{th} v_{th} = \rho_l \frac{\pi d_{th}^2}{4} v_{th} = C_d \frac{\pi d_{th}^2}{4} \sqrt{\frac{1}{\left(1 - \frac{A_{th}^2}{A_u^2}\right)} \cdot 2\rho_l \,(p_u - p_{th})} \tag{14}$$

The formula, after dividing by the throat area A_{th} and multiplying by liquid density ρ_l, velocity in the throat v_{th} and discharge coefficient C_d, translates into:

$$\rho_l^2 v_{th}^2 = C_d^2 \frac{1}{\left(1 - \frac{A_{th}^2}{A_u^2}\right)} 2\rho_l(p_u - p_{th}) \tag{15}$$

Through dividing both sides by 2 and liquid density ρ_l, the expression takes the following form:

$$\frac{1}{2}\,\rho_l v_{th}^2 = C_d^2 \frac{1}{\left(1 - \frac{A_{th}^2}{A_u^2}\right)} (p_u - p_{th}) \tag{16}$$

After substituting of Eq. 16 into Eq. 13 the cavitation number is expressed as follow:

$$\sigma = \frac{\left(1 - \frac{A_{th}^2}{A_u^2}\right) p_d}{C_d^2(p_u - p_{th})} \tag{17}$$

Due to the low value of the throat pressure p_{th} with respect to the upstream pressure p_u and the low value of the rest of part of Eq. 16, the cavitation number can be approximated to the form

$$\sigma \cong \frac{p_d}{p_u} \tag{18}$$

Reynolds number

$$\mathrm{Re} = \frac{v_u l}{\nu} \tag{19}$$

This represents a relationship between upstream velocity v_u, characteristic linear dimension l and kinematic viscosity ν. Reynolds number is a criterion for estimating the stability of fluid motion. Based on Reynolds number, the character of the flow, laminar or turbulent, can be specified.

Experimental setup and methods

The diagram of the test rig is presented in the Figure 3. The test rig is constructed from acid-proof profiles and pipes with diameters of 60 mm and 50 mm. The main parts of the test rig belong to water tank, motor, and water pump as well as cavitation chamber. The water tank has the capacity of 70 l. The used pump self-priming up to 10 bars is suitable for liquids with the temperature not exceeding 110°C, density not exceeding 1,300 kg/m^3 and viscosity not exceeding 150 mm^2/s. A motor having a power of 5.5 kW is used as a drive to the self-priming pump. The test rig is equipped with seven sensors that can work with temperature below 100°C and humidity below 50%. The

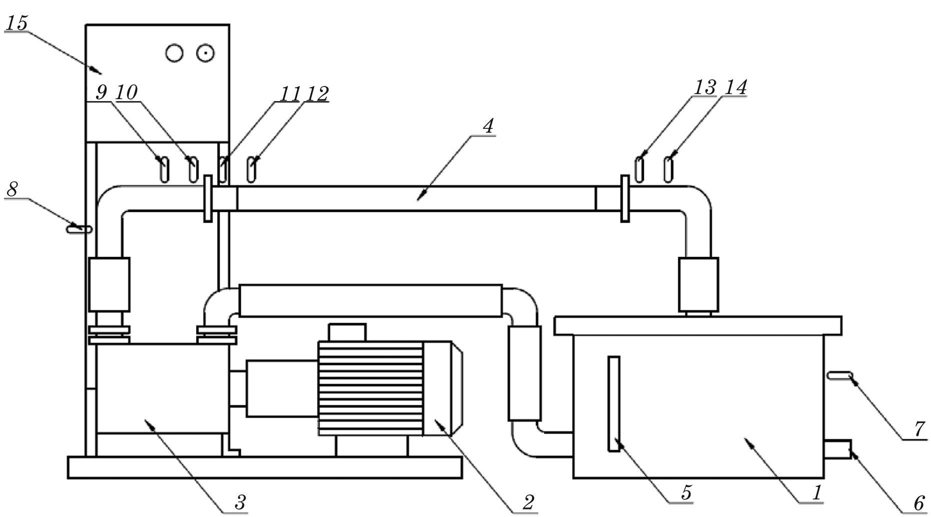

Fig. 3. The diagram of the test rig: *1* – water tank, *2* – motor, *3* – water pump, *4* – cavitation chamber, *5* – water indicator, *6* – heater, *7* – sensor of water level, *8* – velocity inlet sensor, *9* – pressure inlet sensor, *10* – temperature inlet sensor, *11* – proximity sensor of the chamber, *12* – additional proximity sensor, *13* – pressure outlet sensor, *14* – temperature outlet sensor, *15* – control panel
Source: NIEDŹWIEDZKA, SOBIESKI (2016).

seven sensors are: a water level sensor, a sensor for determining of flow velocity at the inlet, sensors of temperature and pressure at the inlet and outlet of the cavitation chamber, a proximity sensor which aims to counteract the switching of the hydraulic system in case of lack of the cavitation chamber and an additional proximity sensor. The other details of the test rig are in the work (NIEDŹWIEDZKA, SOBIESKI 2016).

Three types of Venturis, with throat diameter of 3 mm and angles of converging and diverging sections for the first type ($v1$) 45° and 45° (Fig. 4*a*), for the second type ($v2$) 60° and 30° (Fig. 4*b*) and for the third type ($v3$) and 30° and 60° (Fig. 4*c*), were designed and built. The throat length is 6 mm and the outside diameter of the Venturi is 50 mm.

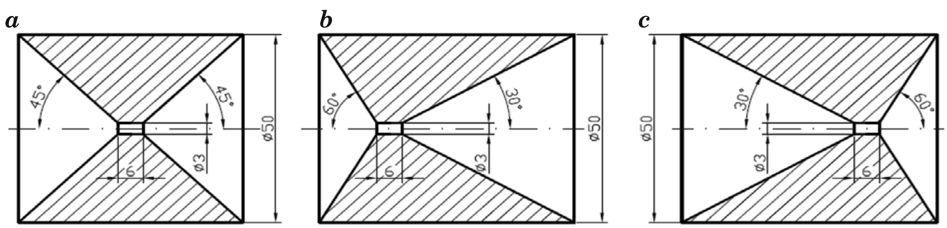

Fig. 4. Dimensions of the Venturi tubes
Source: NIEDŹWIEDZKA, SOBIESKI (2016).

In the experiment the mass flow rate was examined only under different upstream pressure conditions. Using the data obtained in the experiment it is possible to determine mass flow rate, pressure ratio, cavitation number and Reynolds number. Based on this data adequate diagrams can be created, describing relationships between the values.

Results and discussion

In this section performance of the cavitating Venturi has been studied based on the experimental data from the work (NIEDŹWIEDZKA, SOBIESKI 2016). The most attention in discussion is devoted to the mass flow rate, which is the most crucial value for Venturis. The relationships between the mass flow rate and the following values: pressure ratio, cavitation number, Reynolds number and upstream pressure are analysed. Data, which is obligatory for the diagrams, is collected in Tables 1–3.

According to the information from the theoretical background, the low values of the pressure ratio for all Venturi types indicate that the flow is cavitating. The maximum value of pressure ratio for the first type of Venturi is

Table 1

Data for calculating of the diagrams for the first type of Venturi

p_u [Pa]	t_u [°C]	v_{th} [m/s]	p_{th} [Pa]	p_r [–]	σ [–]	Re [–]	m_{th} [kg/s]
481,325	20.2	30.95	2,366	0.211	0.207	5,000	0.217
677,325	20.5	36.74	2,410	0.150	0.147	10,000	0.257
776,325	20.9	39.34	2,470	0.131	0.128	15,000	0.275
846,325	21.1	41.08	2,500	0.120	0.117	20,000	0.287
964,325	21.4	43.86	2,547	0.105	0.103	25,000	0.307

Table 2

Data for calculating of the diagrams for the second type of Venturi

p_u [Pa]	t_u [°C]	v_{th} [m/s]	p_{th} [Pa]	p_r [–]	σ [–]	Re [–]	m_{th} [kg/s]
657,325	31.1	36.13	4,515	0.154	0.148	5,000	0.253
757,325	32.6	38.79	4,915	0.134	0.128	10,000	0.271
1,022,325	35.6	45.09	5,808	0.099	0.094	15,000	0.315

Table 3

Data for calculating of the diagrams for the third type of Venturi

p_u [Pa]	t_u [°C]	v_{th} [m/s]	p_{th} [Pa]	p_r [–]	σ [–]	Re [–]	m_{th} [kg/s]
534,325	24.1	32.60	3000	0.190	0.185	5,000	0.228
719,325	24.7	37.85	3109	0.141	0.137	10,000	0.265
811,325	28	40.19	3778	0.125	0.121	15,000	0.281
980,325	29.7	44.19	4168	0.103	0.100	20,000	0.309
1,099,325	35.8	46.76	5872	0.092	0.087	25,000	0.327

0.211 and the minimum 0.105 (Tab. 1). For the remaining Venturis, the pressure ratio ranges from 0.154 to 0.094 for the second and from 0.190 to 0.092 for the third Venturi type (Tab. 2, 3). The cavitation number takes the similar values in case of all Venturis. It is a proof that these two values can be used interchangeably. This observation is supported by Figure 5, where the relationship between cavitation number and pressure ratio is presented.

The mass flow rate achieves the average value 0.27 kg/s for the first type of Venturi and 0.28 kg/s for the second and third type of Venturi. Applying Venturi as a flow meter supposes that the mass flow rate at invariable upstream pressure and variable downstream pressure conditions is constant for the pressure ratio in the range from 0 to 0.8. Due to the construction of the test rig, it is impossible to make such characteristic for the chosen Venturis.

However, the relationship between the upstream pressure and the mass flow rate can be presented (Fig. 6). These characteristics have a curve form for each of the analysed Venturis. A similar diagram showing a relationship between these variables for other Venturis was presented in work of other scientists (GHASEMMI, FASIH 2011). It confirms that the results of the experimental tests in terms of quality are correct.

Figures 7 and 8 show the relationship between the mass flow rate and the cavitation number and pressure ratio. Their characteristics are summarised by curves with similar shapes. It is a visualization of the possibility of the interchangeable application of pressure ratio and cavitation number. The presented characteristics show that the value of the mass flow rate drops with the increase of the pressure ratio or cavitation number.

The next relationship between the mass flow rate and Reynolds number in the pipe is shown in Figure 9. The Reynolds numbers tested for the analysed

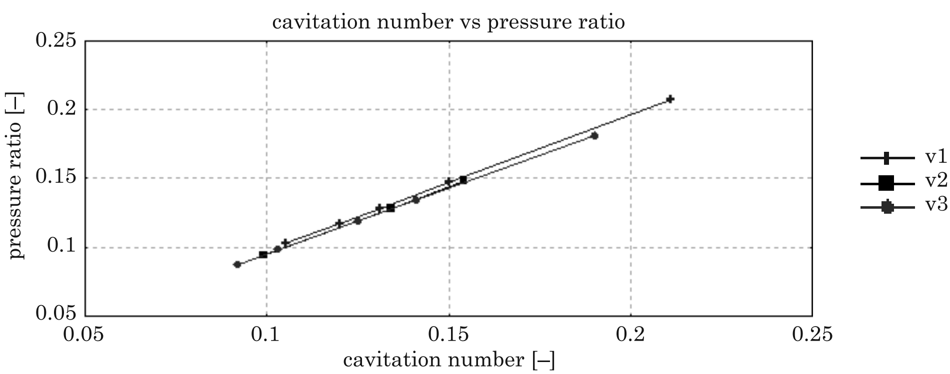

Fig. 5. Cavitation number versus Venturi pressure ratio

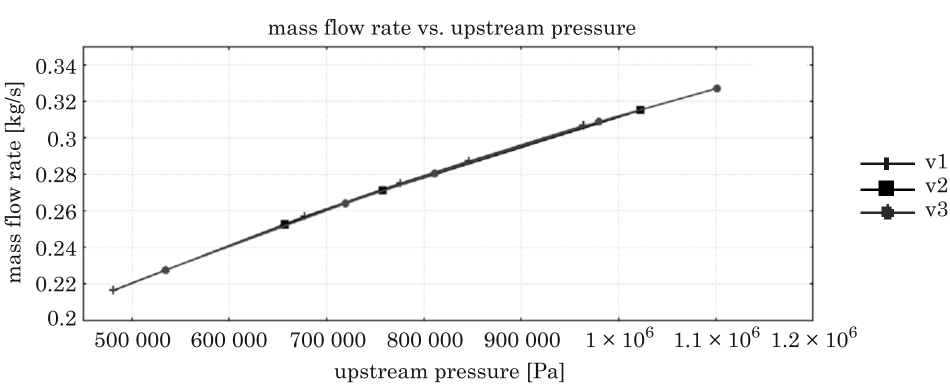

Fig. 6. Mass flow rate versus upstream pressure

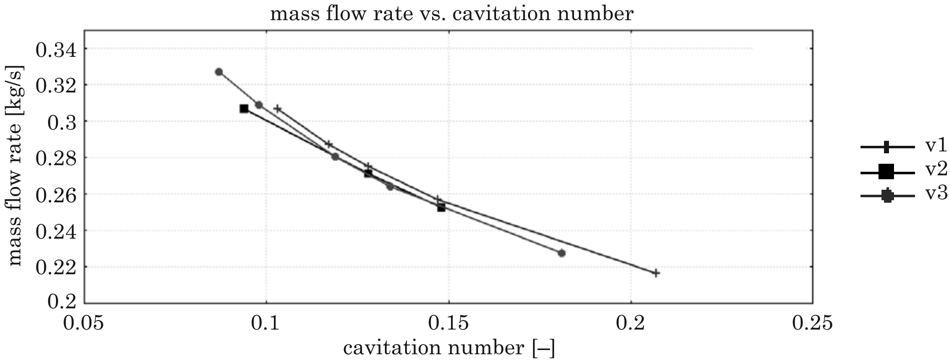

Fig. 7. Mass flow rate versus cavitation number

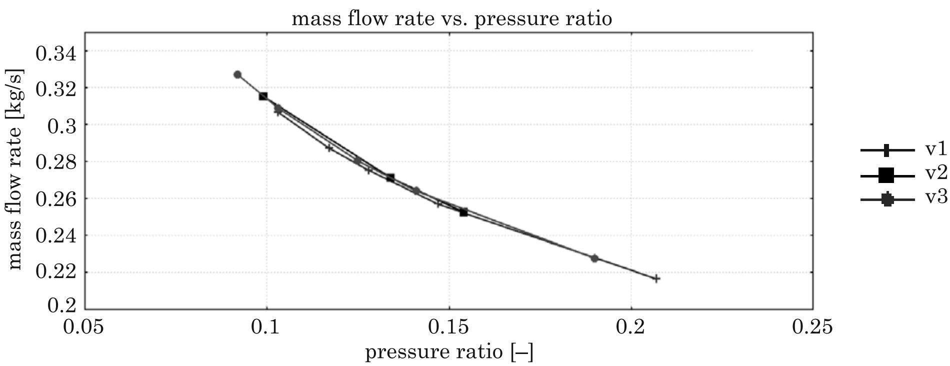

Fig. 8. Mass flow rate versus pressure ratio

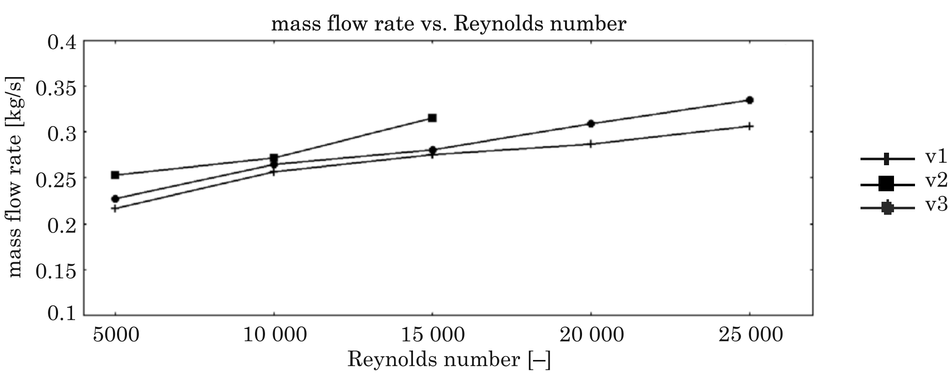

Fig. 9. Mass flow rate versus Reynolds number

flow are in the range from 5,000 to 25,000. The lowest value is higher than the critical Reynolds number for pipes. It shows that the flow in the whole of the experimental measurements has a turbulent character. This information is important in the context of the next step of investigations, i.e. the numerical modelling. The issue of which turbulence models should be used is open.

Conclusions

The article presents results of the examination of the effects of changes in angles of converging and diverging sections of small-sized Venturis on their operating characteristics. Three chosen Venturis have throat diameters of 3 mm and angles of converging and diverging section 45° and 45°, 60° and 30°, 30° and 60°. The Venturis have been examined under different upstream and constant downstream conditions. The following concluding remarks can be made:

– The construction of the test rig in the present configuration prevents carrying out measurements with variable downstream conditions. Because of this restriction, it is not possible anymore to make the most important characterization curve of cavitating Venturi, which describes the usefulness of the device as a flow meter. The critical pressure ratio for the analysed Venturis could not be specified.

– The Venturi in the analysed system works only in „choked" mode. The pressure ratio is in the range from 0.092 to 0.211. It means that the flow inside the Venturi has a cavitating character, what was confirmed during the experiments.

– Cavitation number and pressure ratio can be used for small sized cavitating Venturis interchangeably.

– The simultaneous changes in angles of converging and diverging sections have significant effect on starting point of upstream pressure and Reynolds number of the working Venturi. The decrease of the angle of converging sections results in the drop of the maximum Reynolds number. The shape of the analysed characteristics is similar for all Venturis.

– Characteristics of the upstream pressure and the mass flow rate have a curve form for each of the analysed Venturis. A similar diagram showing a relationship between these variables for other Venturis was presented in work of other scientists (GHASEMMI, FASIH 2011). It confirms that the results of the experimental tests in terms of quality are correct.

– The aims of the future works are simulations of cavitating flow in Venturis. The presented characteristics confirm rightness of the choice of the cavitation inductors.

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