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Experimental circuit for the generation of cavitation in oil flow

Jana Jablonská [1], *Milada Kozubková* [1] *and Patrik Marcalík* [1,*]

[1] VŠB-Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Hydromechanics and Hydraulic Equipment, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic

Abstract. The paper deals with the flow of oil through an experimental hydraulic circuit with a convergent divergent nozzle with a circular cross-section. Under different physical conditions, i.e. changes in pressure, flow and temperature, the formation and development of cavitation is monitored. As it is a highly dynamic flow in a transparent nozzle, cavitation is monitored using a high-speed camera and the frequency of formation and dissolution of the cavitation bubble and the movement of the cavitation cloud is then determined. The authors deal with the issue of the amount of dissolved or undissolved air in the hydraulic oil. Both variants of air influence the formation, development and size of the cavitation area. This cavitation is in this case called air cavitation. In technical practice, the issue of air cavitation is relevant, especially in the pump suction, where vacuum, leaks and hence air intake may occur.

1 Introduction

Cavitation is a problematic and usually undesirable phenomenon in the technical practice of hydraulics and the transport of liquids. In hydraulic circuits it can cause material wear, degradation of working fluid and degradation of hydraulic components. Cavitation is a phenomenon in which gas filled cavities are formed and destroyed in the liquid. If these cavities implode near the walls (material), the surface may be damaged, this is what is called cavitation damage. If we compare cavitation in two typical fluids used in hydraulics, i.e. in water and oil, it can be said that cavitation in water is more often described in literature [1, 3, 7, 8], and both steam and air cavitation can be achieved. The slow growth of the cavitation bubble caused by air diffusion is called air (gaseous) cavitation. Sudden immediate enlargement of the cavitation bubble, predominantly filled with a steam of the flowing liquid, we call the vapor cavitation.

The steam cavitation phenomenon occurs when the pressure in the liquid is reduced to the saturated vapor pressure of the selected liquid.

The liquid begins to evaporate and the cavitation bubbles are formed, filled with steam evaporating from the liquid. These bubbles are further carried by flowing liquid into the area of higher pressure, where the vapor condensates and the cavitation cavities are formed. The cavity is filled with the surrounding liquid, which penetrates into them at high speed, which creates a large shock that negatively affects the material and also the liquid. Cavitation Bubbles filling a part of the liquid stream form the so-called cavitation area. When the pressure drops on the level of saturated vapor pressure, it is the so-called initial cavitation, where less pressure pulsation of the flow medium is manifested in the unstable cavitation zone. Further reduction of the inlet pressure leads to the enlargement and stabilization of the cavitation area. The cavitation area is described primarily by shape as a capsule (where a certain space is filled with cavitation bubbles).

The reason for the emergence of the volatile pocket cavitation area can be the separation of the current from the wrapped surface. The cause of the formation is the whirling of the liquid between the main current and the wrapped surface, where the instability of this area is expressed as Strouhal's number

$$Sr = \frac{L \cdot f}{v} \tag{1}$$

Where L is the characteristic dimension of the area, f is the frequency of the loosed vortex, v is the velocity of the flow. [1, 2, 3]

The saturated vapor pressure p_w is dependent on the temperature of the flowing medium, for example for water temperature of 20 °C the saturated vapor pressure is 2367.8 Pa, where for oil of the same temperature saturated pressure is 1 Pa [4]. The dependence of water temperature (under operating conditions) to cavitation does not affect the development of cavitation very much, since the dependence of density and viscosity on the temperature is not so significant.

The simplest form of the cavity is a gas bubble filled with dissolved air. These bubbles form the germs of cavitation, they arise sooner than steam bubbles and suppress steam cavitation. [7] The chapter "Properties of mineral oil" is in more detail devoted to air.

The simplest hydraulic device for examining the hydrodynamic conditions and the influence of the liquid temperature at the beginning of the cavitation phenomenon is convergent divergent nozzle with a circular cross-section (onward referred to as CD nozzle). The advantage of the CD nozzle is simple, you can

* Corresponding author: patrik.marcalik@vsb.cz

approximately determine the pressure by use of the Bernoulli equation and estimate the formation of cavitation. One of the typical parameters by which cavitation is determined is the cavitation number

$$\sigma = \frac{2(p_{in} - p_w)}{\varrho \cdot v_{max}^2} \qquad (2)$$

where p_{in} is the absolute pressure at the inlet of the CD nozzle, p_w is the saturated vapor pressure of the liquid at a given temperature, ρ is the density of the liquid at a given temperature, v_{max} is the speed at the narrowest point of the CD nozzle. The critical cavitation number indicates when cavitation in the given physical conditions (density, temperature, media type) starts to occur in the specified geometry. [1, 2]

2 Properties of mineral oil

In hydraulic oils, air exists in two forms, either as air undissolved in a mixture with oil or as dissolved air in oil. If the liquid (oil) is not saturated with air, then the air dissolves by the diffusion theory. [5, 8] The undissolved air in the oil is found in the form of bubbles, adversely affecting its compressibility and therefore the rigidity of the system. Dissolved air represents the molecules of air that are in the oil and its quantity is governed by Henry's law. The release of air from the oil causes a so-called gas cavitation

$$V_D = V \cdot k \cdot \frac{p_{out}}{p_{in}} \qquad (3)$$

Where V_D is the volumetric amount of air in the oil in the dissolved state, V the volume of the oil, p_{out} is the atmospheric final pressure, p_{in} is the initial atmospheric pressure, k is the absorption coefficient (k = 0.093 to 0.11) [5, 8].

Henry's dependence can be neglected for temperatures ranging from 20 to 80 °C. The amount of air in the oil is approximately 11 % of the oils volume, where the value proportionally increases with the pressure. If, due to the change in pressure and temperature, the equilibrium level is disturbed, at which the oil is saturated with air, the release of the air molecules followed by the formation of bubbles which subsequently increases the amount of undissolved air in the oil and creates a mixture of oil with air, or, conversely, more air in the oil is dissolved. The release of air from the oil takes place much faster than its dissolution, and depends on three main parameters: [5]

1. oil viscosity,
2. the size of the surface area between oil and air,
3. movement state (calm, laminar or turbulent flow).

Literature [6], fig. 1 describes the relationship between the pressure, temperature and amount of dissolved air in the oil, where at 20 °C and atmospheric pressure 10 % of the air is present in the oil. At the same pressure at 80 000 Pa, there is approximately 8% of the dissolved air. Table 1 of the same literature shows the limit values of the volume fraction of air for standard new oils. In the described hydraulic system, the used hydraulic oil is RENOLIN VG 46, whose limit value of dissolved air in the oil is 10%.

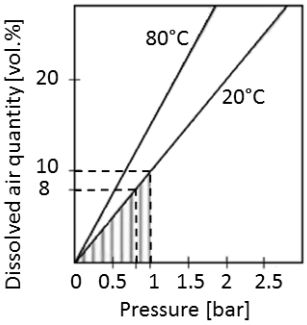


Fig. 1. Dissolved air in oil in volume percentage depending on pressure and temperature. [6]

Table 1. Limit values of air volume fraction for typical standard fresh oil [6]

ISO VG/Type	32	46	68	100
Turbine Oil DIN 51515 ISO 8068	5	5	6	-
Hydraulic Fluid HLP/HM DIN 51524/2 ISO 11158	5	10	13	21st

The literature [1] states that the maximum air solubility in oil is 9.3 % - 11.3 %. The time at which half of the air is released or dissolved is referred to as the half-life of t_p and for the air release in oil is t_p = (3.6 to 7.6) s and for dissolution t_p = (6.1 to 10.2) s [1]. The literature [5] states that 25 % to 30 % of the air is dissolved in oil immediately, i.e. over a period of up to 1 s, which is explained by the immediate saturation of the thin layer of oil in contact with air.

For the experiment hydraulic oil marked RENOLIN VG 46 was used with its dependence of density and kinematic viscosity at temperature.

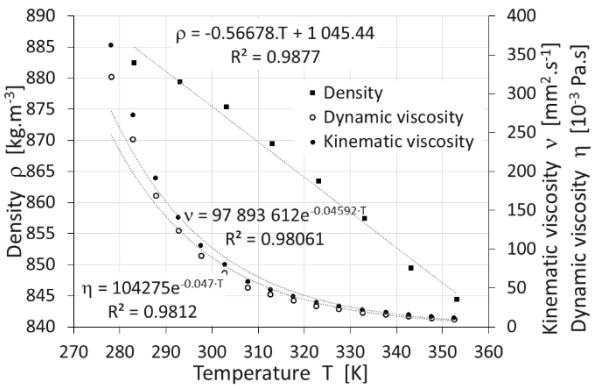


Fig. 2. Physical Properties OF VG46 oil depending on temperature.

3 Methods of diagnosis of cavitation

More often, high-speed cameras are used to identify and measure cavitation. This is a device with a high frame rate, so it is mainly used for short time in terms of storing large data. Using this method, a transparent equipment and suitable illumination should be used. For subsequent analysis, we get a digital record from which you can identify many other data such as bubble size, speed of growth and extinction of bubbles, speed of movement of bubbles and the like.

The cavitation status can also be assessed by means of a laser, using either the Tyndale phenomenon, where the dispersion of the light on the cavitation bubbles is examined in a homogeneous environment of the liquid, or by the method of dispersion of the light on the emerging and disappearing cavitation bubbles. [3]

Cavitation can also be specified using vibroacoustic diagnostics or by examining worn parts. The use of vibroacoustic diagnostics can be a problem in technical practice, as it is necessary to isolate the system from surrounding sources of noise and vibrations, but in laboratory conditions this method is usable. [9]

4 Measuring circuit

From tank 1 the liquid is pumped through the regulation hydrogenerator with tilting plate 3. Heater 2 represents the heating element inside the tank, through which the oil is heated to the given temperature. The circuit is protected against overload by a safety valve 4. The flowmeter 6 is located between the ball valves 5, on which the temperature and flow rate values are obtained. Then the vertical CD nozzle 9 is placed. Before and after CD nozzle pressure sensors 7 are placed, P_1 before the nozzle and P_2 behind the nozzle. From the nozzle the liquid flows through the waste filter 10 to the next tank. From there, it is pumped back into tank 1 by means of a hydrogenerator 11 and this causes the liquid to be mixed.

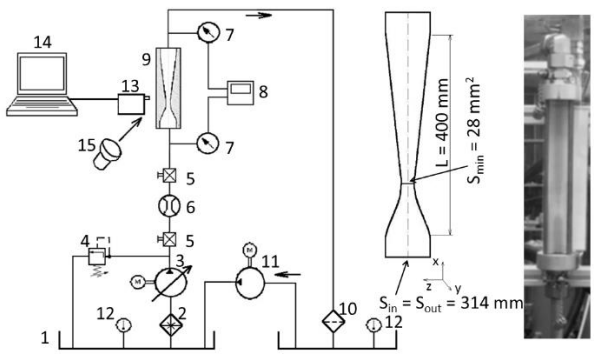


Fig. 3. Measuring circuit diagram – 1 tank, 2 heater, 3 hydro-generator, 4 safety valve, 5 ball valve, 6 flow meter, 7 pressure sensors, 8 evaluation and recording equipment, 9 convergent divergent nozzle, 10 waste filter, 11 hydrogenator, 12 thermometer, 13 high-speed camera, 14 PC – computer, 15 light.

The measured element is the circular convergent divergent nozzle, a well-known shape with an inlet diameter of Ø 20 mm and diameter of the narrowest section of Ø 6 mm. The distance between the pressure sensors is 400 mm, see fig. 3. The relative pressure sensors of type PR15 with a range (-1 to 6) bar and ± 0.5% accuracy are used. For temperature measurement, the sensor Pt 100 is used with a range (-50 to 200) °C and the accuracy of ± 1 %, which is mounted on the flowmeter. Flow rate is measured by flowmeter GFM-70 with range (0.7 to 70) $dm^3 \cdot min^{-1}$ and accuracy ± 0.5 % [6, 8]. The high-speed Mini UX50 camera was used for visualization, with 8000 fps sampling frequency and 1280 x 296 resolution, aperture 1/10000 s. [7].

5 Evaluation of measurements

A series of measurements were made at the temperature change (T1 - T5) and the change of flow. Temperature T1 = 300 K corresponds to the oil temperature at the first series of measurements when the oil was not heated and the temperature T5 = 325 K corresponds to the last series of measurements that took place after the last oil heating. The oil was gradually heated with step of 5 K. Further heating was not possible due to the risk of oil degradation.

The measured flow rate values are from $1.7 \cdot 10^{-4}$ m^3/s to $5.9 \cdot 10^{-4}$ m^3/s. Fig. 4 presents dependence of pressure drop on volumetric flow for CD nozzle and effect of oil temperature. It is evident that pressure gradient increases with increasing flow. However, with increasing temperature, the pressure loss decreases, which is due to the change in the physical properties of the oil (see Fig. 2), when viscosity decreases with increasing temperature.

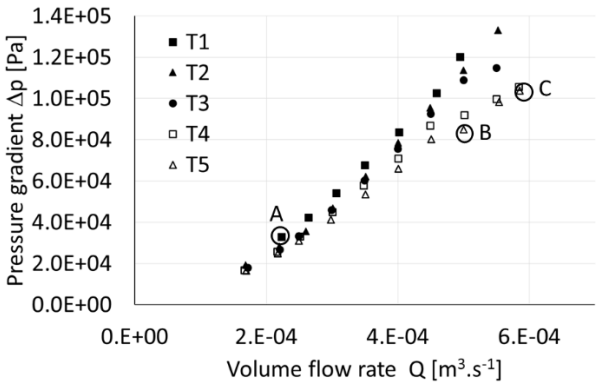


Fig. 4. Dependence of pressure gradient vs. volume flow rate.

In fig. 4, 5 and 6 the points are shown – measurements that will then be evaluated using a high-speed camera. Point A represents the flow without cavitation, point B of the initial cavitation and point C of the fully developed cavitation.

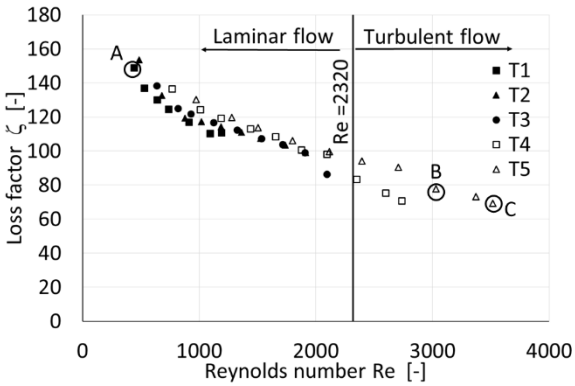


Fig. 5. Dependency of loss factor vs. Reynold number in narrowest section of veneer.

The Reynolds number *Re* is a function of the velocity *v* and the strongly kinematic viscosity *ν*, which depends on the temperature *T*.

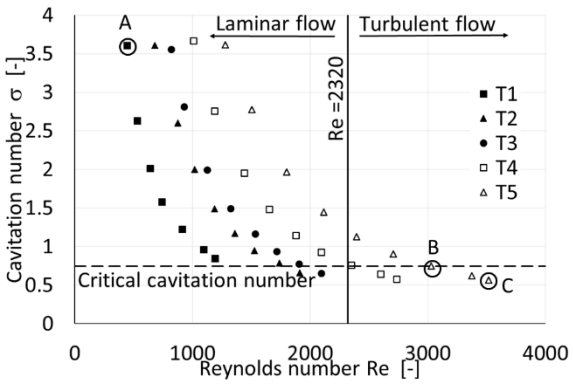


Fig. 6. Dependence of cavitation number on Reynolds number in the narrowest section of CD nozzle for different temperatures.

From fig. 5 it is evident that with the increasing Reynolds number and therefore with increasing flow rate the loss coefficient decreases. However, the flow coefficient will rise. In a turbulent area, the reverse of the trend is not significant, as we still deal with a low-Reynolds numbers, i.e. the transition area between laminar and turbulent flow. The transverse line here shows the critical value of Reynolds number 2320.

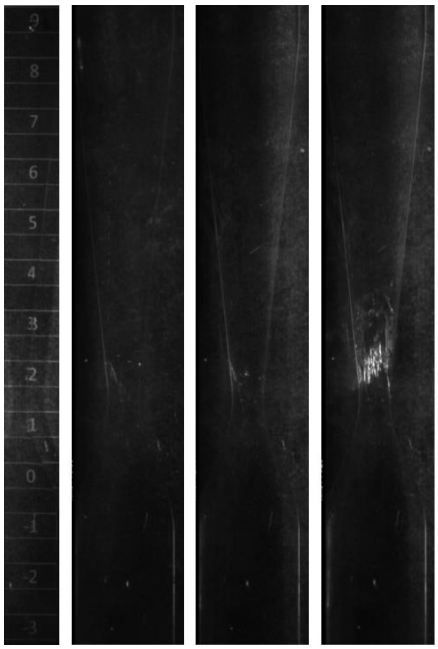
The value of Reynolds number at the inlet to the nozzle is between 133 and 1055, so it is a laminar flow. From fig. 6 it is evident that with the growing Reynolds number at the narrowest point of the nozzle the cavitation number decreases, and thus the conditions for the formation of cavitation are better. The first cavitation occurred during the second series of measurements (T2 see fig. 6), when the cavitation number was 0.658. Another measurement found that the critical value of the cavitation number, when the cavitation phenomenon occurred in the nozzle, was 0.747 (line, see fig. 6). Cavitation occurred at any other measurement when the cavitation number lower than 0.747 was reached.

Table 2. Evaluation of measurement T – temperature, Q – volumetric flow, p_1 - relative pressure at the entrance to the CD nozzle, p_2 - relative pressure on the output from CD nozzle and errors of measurement, σ – cavitation number.

Variant	A	B	C
	Without cavitation	Initial cavitation	Developed cavitation
T [K]	300	325	325
Errors T [K]	± 1.7	± 1.9	± 1.9
Q [$m^3 \cdot s^{-1}$]	$2.64 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$5.86 \cdot 10^{-4}$
Errors Q [$m^3 \cdot s^{-1}$]	$\pm 7.62 \cdot 10^{-7}$	$\pm 1.44 \cdot 10^{-6}$	$\pm 1.69 \cdot 10^{-6}$
p_1 [Pa]	41900	84700	106900
Errors p_1 [Pa]	± 121	± 245	± 309
p_2 [Pa]	-2700	-300	3120
Errors p_2 [Pa]	± 8	± 0,9	± 9
σ	2.632	0.747	0.563
Errors σ	± 0,013	± 0,004	± 0,003

In Table 2, the measurement error of individual quantities is determined from the sensor error and assuming a uniform distribution of the error.

From fig. 7 A It is evident that there is no cavitation. Fig. 7 B presents the first cavitation bubbles, it is the initial cavitation phase when, according to table 2, the cavitation number is critical. In fig. 7 C is evident the fully developed cavitation phenomenon, the cavitation number has a value of 0.563.



A B C

Fig. 7. High-speed Camera images for each cavitation variant A, B, C.

The development of the bubble at the initial cavitation was recorded by a high-speed camera, see fig. 8. The total interval of sensing the initial cavitation is < 253.5 ms, 255.875 ms >, each frame is shifted by the 0.125 ms, and the repeatability of the bubble is on every 7 frames, i.e. every 0.88 ms, corresponding to the frequency of the bubble formation 1142 Hz. As it is a slow flow, there is no significant displacement of the bubble, but the bubbles arise individually and do not affect each other excessively. Remarkably, the bubbles are noticeable only after the narrow section.

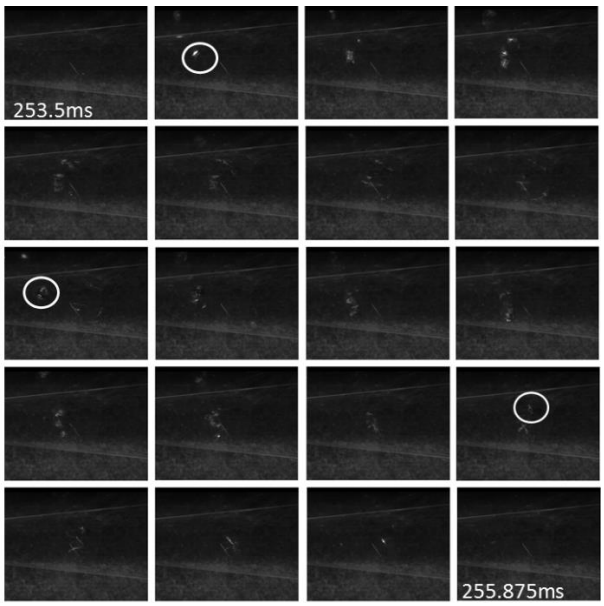


Fig. 8. Images from high speed camera for variant B - initial cavitation.

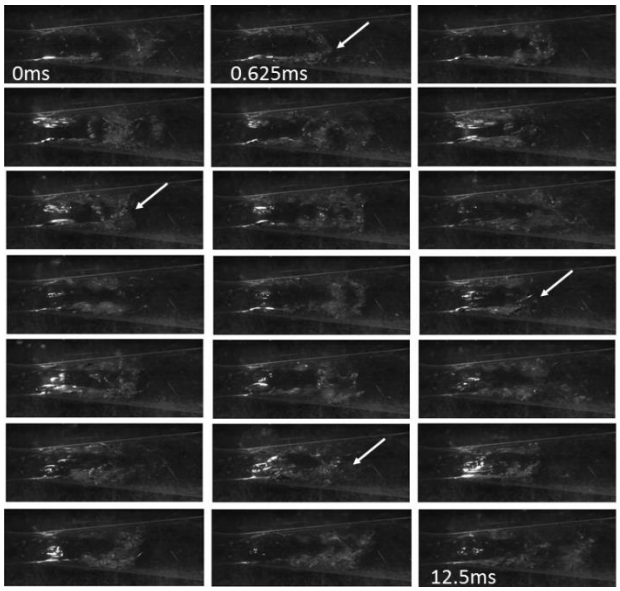


Fig. 9. High-speed Camera images for variant C – fully developed cavitation.

The development of cavitation cloud and bubbles in fully developed cavitation is evident from fig. 9. The first image is at a time of 0 ms, the last frame is at a time of 12.5 ms. Every fifth frame is displayed, so the time interval between frames is 0.625 ms. The repeatability of the bubble, or the disappearance of the cloud, is on every 4 frames (the image with an arrow that tracks the extinction of the cloud), i.e. every 2.5 ms, which corresponds to the frequency of the extinction (creation) of the air cloud 400 Hz. Individual bubbles cannot be observed at this time.

6 Conclusion

In the article, the hydraulic parameters of the formation of cavitation in the flow of oil are examined using the transparent nozzle of the circular cross section and the subsequent evaluation is performed. First of all, attention is paid to the development of cavitation depending on the temperature of the flowing medium. A critical cavitation number is specified for the given geometry.

In variant B, after the extinction of the bubble, a faint fog is observed. The air in the bubble causes suspension and the emergence of a new bubble. If there was no air in the bubble, then the cavity would disappear, and no new bubble in that spot would emerge. This phenomenon is also described in literature [1]. It is therefore clear that this will only be the case for air cavitation. It is likely that neither in the C variant the steam cavitation has been achieved, which will subsequently be verified by the mathematical model.

Cavitation depends on the amount of air in the oil (which cannot be easily determined). This is related to the oil temperature, pressure in the liquid and the dissolution rate. The results of the physical experiment will be used to create a mathematical model of air cavitation in the oil. Measured hydraulic quantities will be used as boundary conditions, the amount of air in the oil will be estimated subsequently, then specified more accurately by numerical calculations.

Acknowledgement

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References

1. Noskievič, J. Kavitace. Praha: Academia (1969).
2. Brennen, C. E. Cavitation and bubble dynamics. Cambridge University Press, USA (2014).
3. Himr, D., Habán, V., Hudec, M., Pavlík, V. Experimental investigation of the check valve behavior when the flow is reversing. EPJ 114 doi: 10.1051/epjconf/201714302036 (2016).
4. Li, W. Modeling Viscous Oil Cavitating Flow in a Centrifugal Pump. J. Fluids Engineering 138 (1) (2015).
5. Kopáček, J. Vzduch v minerálním oleji a jeho měření. Strojírenství 36 (1986).
6. HYDAC. Fluid Control Contamination Handbook [online]. [CIT. 2019-05-10]. Available from: https://www.hydac.fi/wp-content/uploads/2018/08/EN7603-9-04-18_Fluid-Control-Contamination-Handbook-web.pdf.
7. Jablonská, J., Kozubková, M. Visualization of gas bubbles during cavitation in the nozzle. AIP 1889, 020014 (2017) DOI: 10.1063/1.5004348.
8. Bureček, A., Hružík, L., Vašina, M. Determination of undissolved air content in oil by means of a compression method. Strojniski Vestnik – J. Mechanical Engineering, 61, 7-8 (2015) DOI: 10.5545/SV-JME. 2015.247.
9. Parish, J. Controlling cavitation [Online]. Valve magazine, 2009 [cit. 2019-05-10]. Available from: https://www.pro-quip.com/images/proquip/PDFs/Controlling%20Cavitation.pdf