STUDY AND ANALYSIS OF THE CAVITATING AND NON-CAVITATING JETS PART TWO
Parameters Controlling the Jet Action and a New Formula for Cavitation Number Calculation

by

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Original scientific paper
https://doi.org/10.2298/TSCI190428334H

This part of the paper presents the relation between the working conditions, nozzle geometry, nozzle diameter, and jet behavior. Experimental work has been made by impinging the submerged jets on the copper specimen as a target for a period of time. The mass loss and erosion rate at various conditions were measured, calculated and analyzed. For the visualization, a high-speed camera was used and the obtained data were processed to measure parameters which are used to characterize the clouds. Correlations among the jet dynamic power, the cavity length, erosion rate, and the pertinent experimental parameters are apparent. In addition, formulas are proposed to conveniently compare the efficiency of jetting systems based on working conditions. Based on the mathematical analyses of the obtained results a new form for cavitation number calculation is proposed.

Key words: *power, dynamic power, static power, kinetic energy, efficiency, erosion, cavitation intensity*

Introduction

Cavitation as a phenomenon occurs when the local static pressure in a fluid reaches a level below the vapor pressure of the liquid at the actual working temperature. The cavitation is considered as a common problem in fluidic equipment, such as pumps and control valves, causing serious wear, tear, and damage. Under the wrong conditions, it can reduce the lifetime of these components dramatically or can cause a drop in performance, high vibration, and noise in hydraulic systems. On the other hand, the destructive power of cavitation can be deliberately used to modify and enhance the surface or mechanical properties of target materials, *e. g.* for cleaning, cutting or peening with relatively low energy consumption. Cavitating water jets have received much attention also in the environmental industry for the possibility to use them for the decomposition of toxic substances and the water treatment [1-8].

To prevent cavitation or to effectively use it for different purposes, the investigation of this phenomenon and the study of its dynamics are essential. Until now many experimental

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studies on cavitating water jets have been made concerning jet driven pressure, shape and size of a nozzle, cavitation number, *etc.* [1, 2, 5-7]. However, the structure of the cavitating jet and the behavior of the unsteady cavitation bubbles are still in question, mostly due to the difficulty to observe the interior of cavitating flows [9-13]. With the purpose of performance prediction and efficient design of many engineering devices such as turbomachinery, turbo-pumps in rocket propulsion systems, hydrofoils, fuel injectors, marine propellers, nozzles, and cavitating jet generators, *etc.*, recently attention has also been focused on the numerical simulation of cavitating flows beside the experimental work [14].

If the relationship between the cavitation intensity and the cavitation damage of materials would be investigated precisely, the key parameter for the prediction of the cavitation damage stages (plastic, crackers, erosion, *etc.*) may be clarified [5, 7, 12]. The flow through a nozzle can be controlled by the operating conditions, orifice geometry, and flow properties. The importance of these parameters for cavitation intensity and jet dynamic power is discussed in the literature and some correlations were founded [1-3, 7, 12, 15].

This part of the paper focuses on the importance of the jet dynamic power as a parameter to measure the performance of the cavitating and non-cavitating jet; the cavitation intensity was investigated based on the jet dynamic power and other parameters. A high speed submerged cavitating jet generator was used as a tool for creating the cavitation as cavity clouds. The visualization data were processed to measure parameters which are used to characterize the clouds. The obtained results were carefully analyzed. It has been found that the structure of cavitation clouds can be used successfully as an indicator of the influences of the applied working conditions on cavitating jets characteristics, application, performance, and quality. Discussion of a new formula for cavitation number is also part of this paper. The cavitating jet test rig (generator), the experimental procedures the visualization system, and the measurements are presented in the first part of the paper. More information about the visualization procedures and equipment are in the previous publication [9].

Dependence of cavitation intensity on jet dynamic power

In this investigation, the calculation of the jet dynamic power was done based on the assumption of existing only one-phase flow (liquid phase), because of the difficulty to measure or calculate the dynamic power of the two-phase flow precisely. Consequently, the flow is defined at the nozzle exit to simplify the task. The cavitation number is calculated based on this assumption, but in fact, the cavitation number is varying from one point to another along the jet trajectory. Therefore, we must consider the used cavitation numbers shown to be averaged values. In addition, to declare the relationship between the jet dynamic power and the intensity of the created cavitation, a correlation between the cavitation cloud geometry, its action, and the jet dynamic power was deduced from the data curves presented in related figures, figs. 3-5, as it is presented later. In submerged cavitating jet, the cavitation is appearing as a cone of vapor and gas bubbles is formed around the jet (the jet is bounded) (clouds in figs. 1 and 2). This cone reduces the exchange of momentum between the jet and the surrounding water. Therefore, the decrease in jet velocity with distance occurs (while stagnation pressure increases). It can be stated that by using the terms *jet power*, the deeper the penetration of the jet into the liquid chamber is, the greater is the total jet power, *i. e.* the jet dynamic power, and consequently is lower the stagnation pressure. As the jet penetrates deeper into the chamber stagnant liquid, with sufficient dynamic power, the cavitation increases (in volume, intensity collapsing frequency, and intensity of collapse), see in figs. 1 and 2 [9]. Figure 6(a) shows the relationship

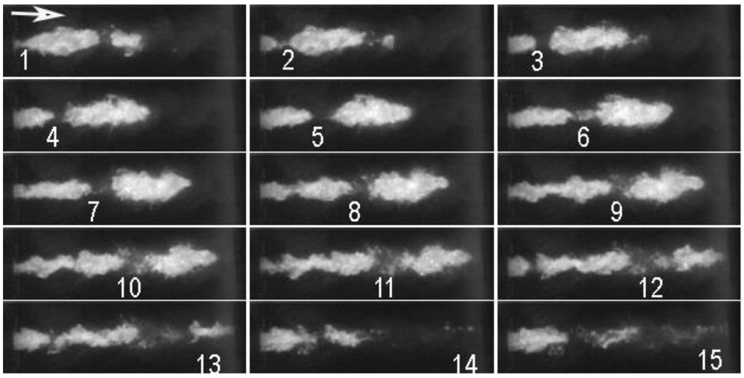

Figure 1. Tracing of cavitation clouds' dynamic behavior in consecutive frames, conditions P_1 = 105 bar, P_2 = 2.06 bar, V_J = 96.5 m/s, σ = 0.044 (frame rate = 50000 f/s)

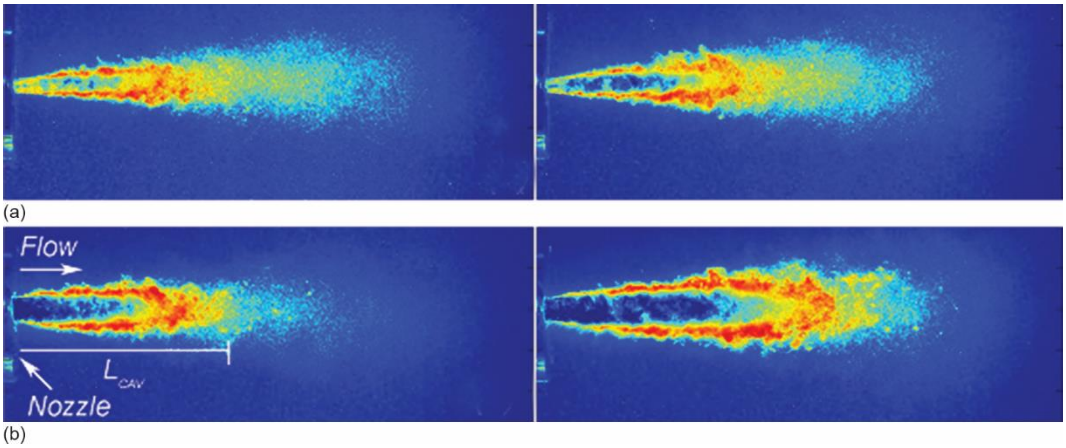

Figure 2. Processed photos show the dependency of cavitating jet composition along its trajectory on nozzle diameter – cylindrical nozzle-diameter; (a) d = 3 mm, P_1 = 30 bar, P_2 = 2.3 bar, (b) d = 7 mm, P_1 = 50 bar, P_2 = 2.3 bar, (L_{nozzle} = 20 mm, T = 21 °C) (laser illumination)
(*for color image see journal web site*)

between the jet dynamic power, P_{dyn}, and the cavitation number, σ. The cavitation number calculation was done using a classical formula based on the average exit jet velocity (assumed single-phase flow). Because of the pressure fluctuation, as well as the velocity decrease and the compressibility change along the jet trajectory co-ordinates (R, x), the cavitation number varies with the coordinates (R, x) [9, 12, 13]. In addition, the cavitation number calculated using ASTM formula ($If = P_2/P_1$) was examined against the dynamic power and against the static power. Only dynamic power is presented in fig. 6(b) and it is not a surprise that the definition indicates the same cavitation number for different nozzle geometries, but the cavitation intensity is not the same, as well as the shaping behavior of cavities and their actions. So, obviously, the ASTM definition does not adequately describe the phenomenon since in its definition the geometrical parameters are absent. The two definitions were examined here to show the reasons behind we prefer to use the general definition of the cavitation number (the classical one) in our work. Figure 6(a) shows the dependency of the cavitation number on the jet dynamic power, nozzle geometry and its dimensions (outlet nozzle diameter). As the jet dynamic power increases, the cavitation is more pronounced, figs. 1, 2, and 6(a) show that the intensity of the cavitation behavior is strongly dependent on the dynamic power. Figure 6(a) also indicates that the dynamic power of the divergent nozzle is much smaller than that of the convergent nozzle for the same injection pressure. It can, therefore, be concluded that the dynamic power is considerably more sensitive to the nozzle geometry. Figures 1, and 2 also visually demonstrate the dependency of cavitation intensity on the dynamic power and nozzle geometry. In the cavitation process, as the injection pressure increases (the input power increases), the amount of fluid subjected to cavitation will be higher and the cavitation will intensify (in both in bubble density-numbers, geometry and shedding/discharging frequencies). This is due to the presence of strong vortices because of high circulation, Γ, and a viscous core of radius, r_c. Since the minimum pressure occurs within the unsteady vortex cores, it cannot be determined by direct measurement. It is therefore assumed that the minimum pressure, P_{min}, equals to the vapor pressure, P_v, of the fluid when cavitation is observed. The value of the minimum pressure on the vortex axis, P_{min}, is estimated as $P_{min} = P_a - (\rho\Gamma/4\pi^2 r_c^2)$ [16, 17]. At high ambient pressure, P_a or P_2, it means that minimum pressure, P_{min}, will be greater than the saturation pressure for a given working temperature. This relation gives an explanation why there is a low erosion in terms of erosion area, small cavity length and width at high downstream pressure in the test chamber, more explanation is given in our previous publications [9, 12, 13].

Figures 3(a) and 3(b) show a range of variation of dimensionless average cloud length (jet length) with dynamic power and with cavitation number. The relation between the average cloud length and the tested parameters are of a power function relationship form. This power function relationship was also presented in the literature, but they were presented only for the cavitation number and cloud length [9, 13, 15]. In this work, we tested the other parameter – dynamic power of the jet. The relationship between the cloud length and jet dynamic power is presented here because we believe that the use of dynamic power is more convenient as the cavitation number is still not defined sufficiently well, while the dynamic power is well understood and is well defined.

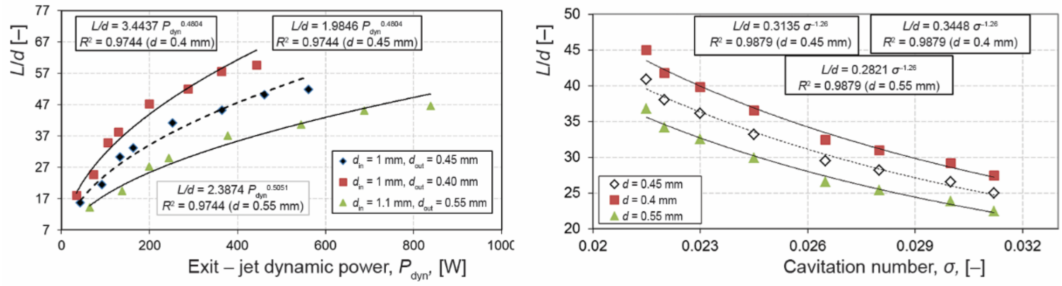

Figure 3. Dependence of cavitating jet length, *L*/*d*, for the convergent nozzle on (a) jet dynamic power, P_{dyn}, and (b) on cavitation number, *σ* (for each point the average of 10 measurements is used in the graphs)

The correlation between the dimensionless length of cavity clouds and the cavitation number has the form:

$$\frac{L_{cloud}}{d_{out}} = 0.3131\sigma^{-1.26} \quad \text{with} \quad R^2 = 0.93$$

For convergent nozzle ($d_{\text{in}} = 1$ mm, and $d_{\text{out}} = 0.45$ mm), the cloud length is decreasing with increasing cavitation number. This is logical as it was explained earlier.

The correlation between the dimensionless length of cavity clouds and the jet dynamic power has the form:

$$\frac{L_{\text{cloud}}}{d_{\text{out}}} = 1.989 P_{\text{dyn}}^{0.4885} \quad \text{with} \quad R^2 = 0.9486$$

For the same nozzle, the cloud length is increasing as the jet dynamic power is increasing, as it was also explained earlier. Each point of the curve represents the average cloud length and appears in ten consecutive frames.

Accordingly, we assume a general relation as:

$$\frac{L_{\text{cloud}}}{d_{\text{out}}} = A\sigma^{-N_1} \quad \text{and} \quad \frac{L_{\text{cloud}}}{d_{\text{out}}} = BP_{\substack{\text{dyn}\\ \text{n}}}^{N_2}$$

Both A and B are dependent on the nozzle diameter, while N_1 and N_2 are not. The parameter A has no unit, while B has [W^{-1}] as a unit [9, 13, 18, 19]. Figure 4 demonstrates the relationship between the erosion rate and the jet dynamic power for divergent and convergent nozzles. The relationship is in both cases $ER = CP_{\text{dyn}}^K$, the constants C and K are depending on the nozzle geometry. The reasons for the differences between the cases (divergent and convergent) are previously mentioned. The tested specimens were eroded by cavitating jets with different dynamic power (different jet velocity V_{J}) at constant cavitation number. This was accomplished by changing the upstream pressure, P_1, adjusting downstream pressure, P_2, and keeping the working fluid temperature constant in order to have the same cavitation number for all tests. Figure 5 presents the relationship between erosion rate and cavitation number for convergent and divergent nozzles. The relation is also a power relation and the nozzle diameter is playing a role. The obtained relationships between the dimensionless cloud length (jet length), jet dynamic power, and the erosion rate might be used to define the relationship between the erosion rate and dimensionless cloud length. This relationship can make the importance of the dimensionless stand-off distance (x/d) in the determination of the performance of cavitating jets obvious. Cavitation intensity can be regulated in several ways to obtain desired cavitating jets.

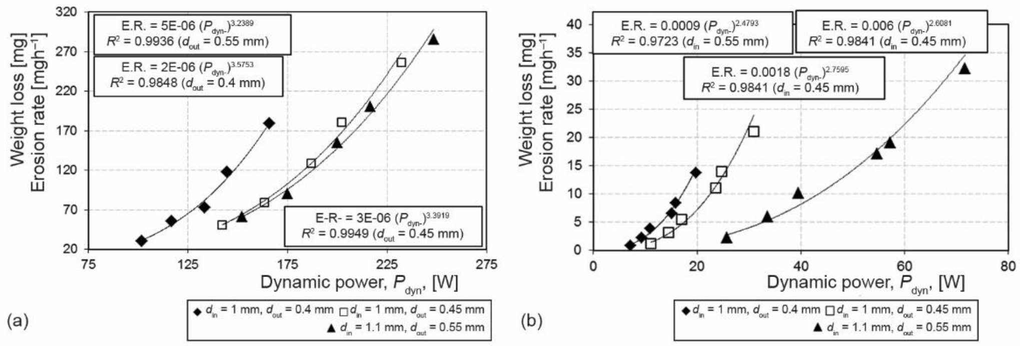

Figure 4. Dependence of cavitation erosion rate on jet dynamic power; (a) convergent nozzle, (b) divergent nozzle

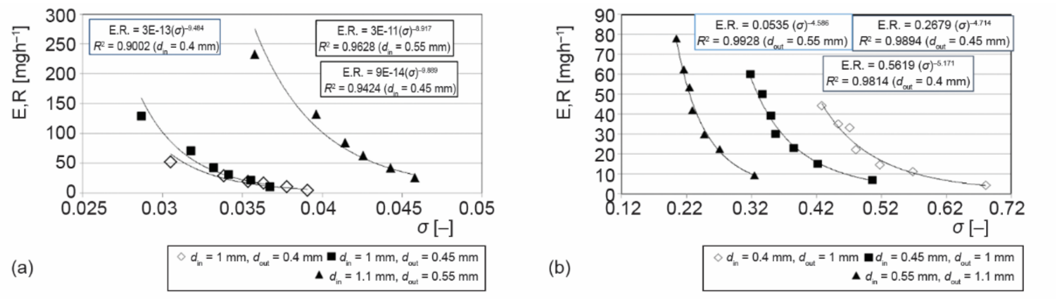

Figure 5. Dependence of cavitation erosion rate on cavitation number, σ; (a) convergent nozzle, (b) divergent nozzle

One of these is achieved by changing P_2 (downstream pressure). As P_2 is decreased, the cavitation number also decreases, and the cavitation intensity increases. Here, the jet velocity, V_J, is kept constant, by adjusting P_1. (Note: $P_1 \gg P_2$). The range of change in P_2 was limited for both convergent and divergent nozzles arguably, a greater range of P_2 could have been used, but the choice was determined by optimizing for the maximum specimen erosion with the experimental parameters available, more information can be found in previous publications [12, 13]. The spreading angle of the jet is dependent mainly on the surrounding *i. e.* downstream pressure, P_2, for a given nozzle geometry. Thus, pressure P_2 can be assumed to be an important parameter governing the performance of the cavitating jets when other control parameters are kept constant [18-20]. The ambient pressure, $P_{amb} = P_2$ is acting as a force against continuous rolling up of shear layers that are created as the jet passes through the surrounding stationary fluid. This could also be explained as the influence of static power: as the static power decreases, the cavitation increases in both bubbles' volume and intensity, but again ambient pressure or downstream pressure, P_2, has a limited range of variation compared with that of injection pressure, P_1. In other words, the variation of static power is small compared with that for dynamic power.

Cavitating jet efficiency and nozzle geometry

A key measure of the performance of the erosion process is the energy required to remove a unit mass of a given target material. For overall performance, this can be expressed as the cumulative mass of material removed per unit energy consumed. When plotted against time, this represents a running value of the erosion efficiency. Thus, the cavitating jet generator efficiency can be calculated based on the erosion rate calculation as a result of its action on the target specimen, as eq. (1), at a working power, P_{Work}, where:

$$\eta_{ER} = \frac{W(t_0) - W(t)}{tER_{max}} = \frac{ER}{ER_{max}} \tag{1}$$

For each operating condition, there is an optimum dimensionless stand-off distance, x/d, for gaining maximum erosion rate. The ER_{max} [mgh^{-1}] could be achieved with available or expended power, P_{work}, where $W(t)$ is the weight of the specimen (target) after a certain exposure time, t, (after cavitation treatment, t is exposure time), $W(t_o)$ – the initial weight of the specimen (before cavitation treatment, zero exposure time) and P_{total} is the total power delivered by the pump.

The energy per unit time per unit volume imparted to the liquid was used as an appropriate parameter for measuring the system efficiency. Power calculations for the jet action can be based on the total hydraulic power provided by the pump. However, in our case (cavitating jet generator) only a small portion of the pump power is used for the erosion process, as the nozzle geometry is not matched with the pump power. Therefore, the dynamic power of the jet can be used as the parameter to assess the cavitation erosion action (jet dynamic power estimate was based on the exit jet velocity – assuming single-phase flow only liquid). However, even without matching this, we will have a higher jet power because of cavitation (two-phase flow). The smaller cavitation number shows a significant increase in the erosion rate. This could be explained by a larger volume of cavitation bubbles when the cavitation number is low. The decrease of cavitation number can be achieved by using high dynamic power (high injection pressure enhancing the jet dynamic power directly) keeping the downstream pressure constant or, secondly, by decreasing the downstream pressure and keeping the injection pressure constant. However, this is usually limited by a small range of values of P_2. As it was published in a previous work [12, 13], an increase in dynamic power can be achieved with an increase in the injection pressure, (*i. e.* power delivered to the fluid) and/or nozzle geometry [21-23]. Increasing the jet dynamic power for a given nozzle geometry will lead to a reduction in the cavitation number but will reach the maximum erosion rate without also controlling the distance between the nozzle exit and target. Note that for each working condition there is a certain optimum stand-off distance, see figs. 6(a) and 6(b), more information is given in previous publications [13, 21].

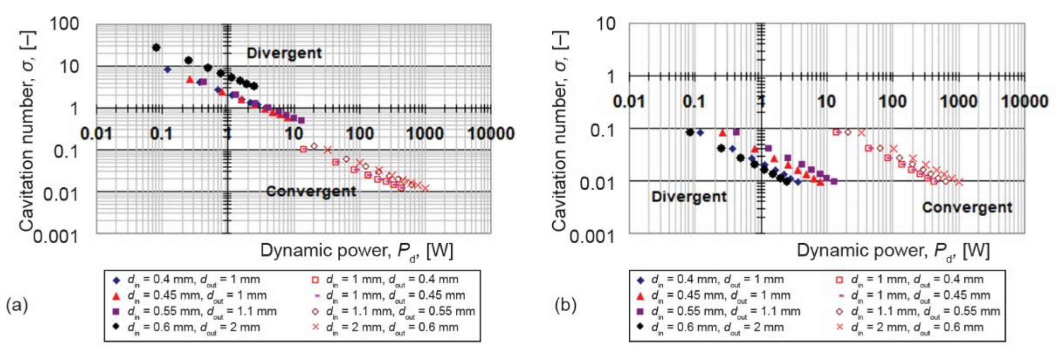

Figure 6. Variation of cavitation number with the jet dynamic power; (a) the classical definition, (b) the ASTM definition

Equations (2) and (5) are proposed new relationships for cavitation erosion efficiency calculation:

$$\eta_{(\mathrm{ER})_{\mathrm{dyn}}} = \frac{ER_{P_{\mathrm{dyn}}}}{ER_{P_{\mathrm{dyn(max)}}}} \tag{2}$$

where $ER_{P_{\mathrm{dyn}}}$ is the erosion rate at applied jet dynamic power, and $ER_{P_{\mathrm{dyn(max)}}}$ – the erosion rate which could be achieved at maximum jet dynamic power:

$$\eta_{(\mathrm{ER})_{\mathrm{Stand\ of\ distance}}} = \frac{ER_{(x/d_{\mathrm{out}})}}{ER_{(x/d_{\mathrm{out}})_{\mathrm{optimum}}}} \tag{3}$$

where $ER_{(x/d_{\mathrm{out}})}$ is the the erosion rate at any dimensionless standoff distance, and $ER_{(x/d_{\mathrm{out}})_{\mathrm{optimum}}}$ – the erosion rate at an optimum dimensionless stand-off distance.

The previous two expressions may be used for fixed nozzle geometry and dimensions as in eq. (2). In eq. (2), when N_{ref} represents a reference nozzle or the *best* nozzle (in terms of geometry and dimension) which is used for given working conditions and test rig characteristics and N_{tested} represents the nozzle to be tested:

$$\eta_{(ER)} = \frac{ER_{N_{tested}(x/d_{out})_{optimum}}}{ER_{N_{ref.}(L/d_{out})_{optimum}}} \tag{4}$$

where $ER_{N_{tested}(x/d_{out})_{optimum}}$ is the maximum erosion rate achieved by tested N_{tested} at optimum distance and $ER_{N_{ref.}(L/d_{out})_{optimum}}$ – the maximum erosion rate achieved by reference nozzle $N_{ref.}$ at the optimum distance.

In addition, eqs. (3)-(5) may be used to calculate the nozzle jet efficiency based on the dynamic power of the jet:

$$\eta_{P_{dyn}} = \frac{(P_{dyn})_{N_{tested}}}{(P_{dyn})_{N_{ref.}}} \tag{5}$$

Equation (7) represents the efficiency of the nozzle based on the cavitation intensity:

$$\eta_{I_{cav}} = \frac{(I_{cav})_{N_{tested}}}{(I_{cav})_{N_{ref.}}} \tag{6}$$

$$I_{cav} = fE_{cloud} \tag{8}$$

where f is the shedding frequency, and E_{cloud} is the potential energy of the cavitation cloud, defined by eq. (8) [13].

$$E_{cloud} \cong V_{cloud}\Delta P \tag{8}$$

$$V_{cloud} = \frac{\pi}{4} d_{out}^2 L_{cloud} C_1 v \tag{9}$$

$$\Delta P \cong P_{amb.} - P_{cloud} \tag{10}$$

where C_1 is a correction factor ($C_1 > 1$), since the average cloud diameter is larger than the nozzle diameter, and it depends on the nozzle geometry, mainly on the outlet nozzle diameter, d. More information about cavitation intensity determination is presented in [8].

Equation (11) shows the relation between the efficiency of the nozzle based on the cavitation intensity to jet efficiency based on the dynamic power:

$$\eta = \frac{(I_{cav.}/P_{dyn})_{N_{tested}}}{(I_{cav.}/P_{dyn})_{N_{ref.}}} = \frac{1}{\eta_{(P_{dyn})}} \frac{(I_{cav.})_{N_{tested}}}{(I_{cav.})_{N_{ref.}}} = \frac{\eta_{(I_{cav.})}}{\eta_{(P_{dyn})}} \tag{11}$$

Figures 7-10 show the relations between the erosion rate, nozzle geometry, cavitation number, efficiency, and jet dynamic power based on these proposed formulas.

The analysis of obtained results reveals this general concept; for practical applications it is valuable to use an optimum nozzle geometry (mainly the nozzle diameter, as the aggressive intensity of cavitation can simply be increased by controlling a dimensionless standoff distance without the need for additional power, this concept was already proved experimentally as it is presented in our previous publications [12, 13].

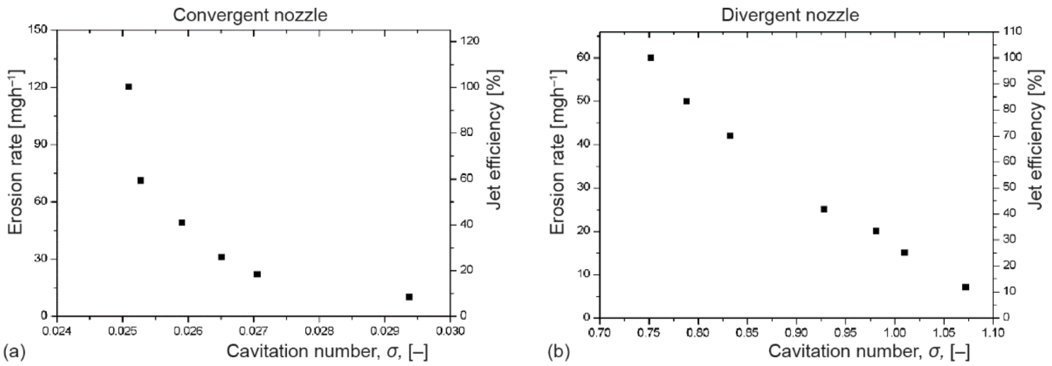

Figure 7. The dependency of jet efficiency (a) and the erosion rate (b) on the cavitation number; the jet efficiency for each nozzle was calculated based on the maximal erosion obtained by the nozzle itself for a certain test

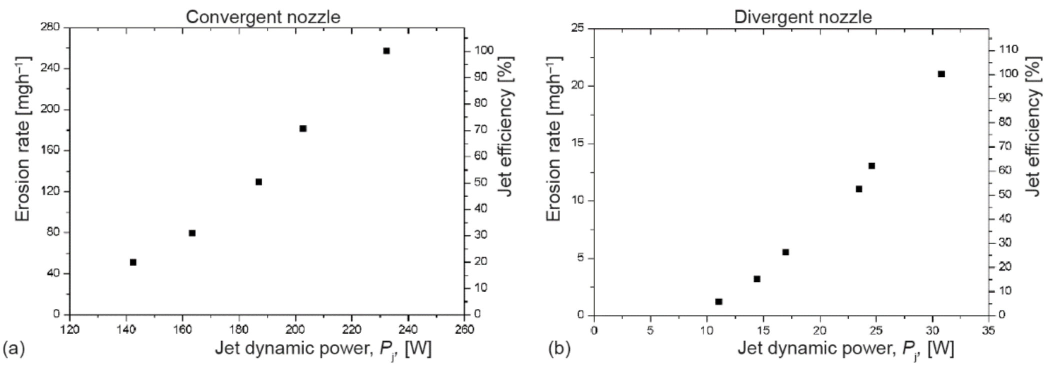

Figure 8. The dependency of jet efficiency (a) and the erosion rate (b) on the jet dynamic power, P_{dyn}; the maximum erosion rate obtained with each nozzle was used as a reference to calculate the efficiency

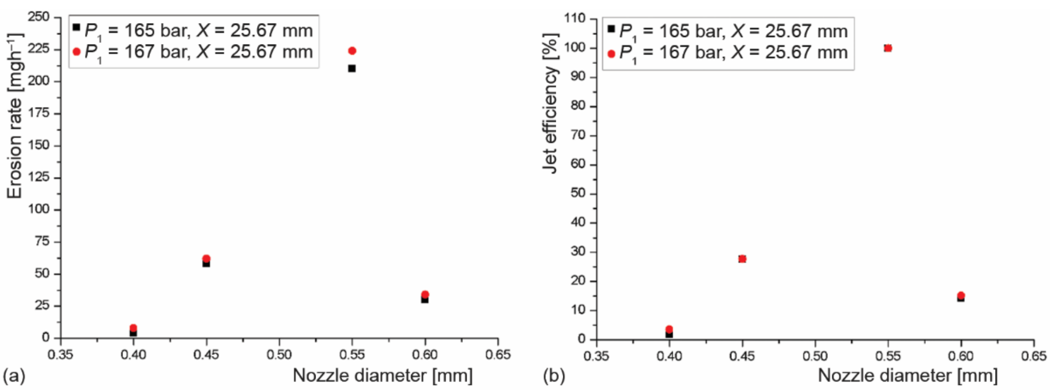

Figure 9. The dependency of erosion rate (a) and jet efficiency (b), on the nozzle diameter. The jet efficiency for each nozzle was calculated based on the erosion obtained by an optimal nozzle (d = 0.55 mm)

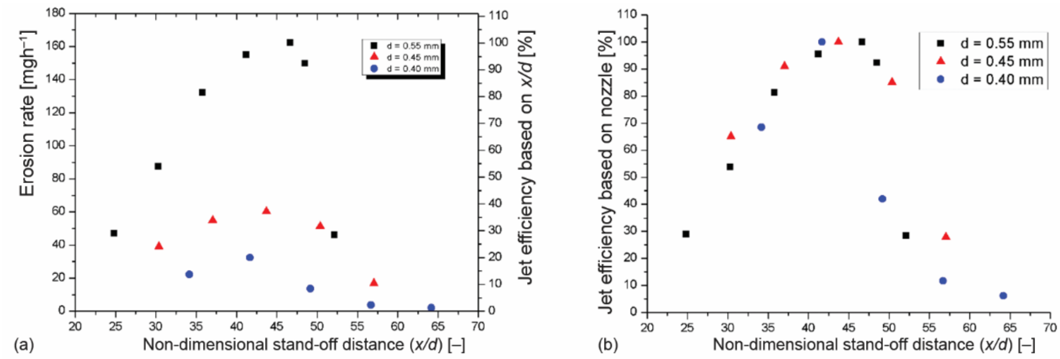

Figure 10. The dependency of jet efficiency and erosion rate on the dimensionless stand-off distance (*x*/*d*); (a) the jet efficiency for each nozzle was calculated based on the erosion rate obtained by an optimal nozzle (*d* = 0.55 mm), (b) the jet efficiency for each nozzle was calculated based on its maximum erosion. The working conditions are given in tab. 1.

Table 1. Hydrodynamic conditions for the x/d_{out} investigations with 1800 seconds exposure time

d_{out} [mm]	P_1 [MPa] ±0.1	P_2 [MPa] ±0.1	V_J [ms^{-1}] ±0.5	σ [–] ±0.001	T [°C] ±1
0.40	12.36	0.309	101.1	0.040	19
0.45	12.1	0.31	101.4	0.040	19
0.55	14.54	0.31	101.3	0.040	19

Proposed formula for the cavitation number

According to the obtained results in this work and in the previous work, the cavitation number σ can be expressed using dynamic and static power as parameter terms by multiplying and dividing the classical cavitation number formula by flow rate, Q:

$$\sigma = \frac{P_{\text{ref.}} - P_V}{\frac{1}{2}\rho u_{\text{ref.}}^2} = \frac{P_{\text{ref.}} - P_v}{\frac{1}{2}\rho u_{\text{ref.}}^2}\frac{Q}{Q} = \left(\frac{P_{\text{stat.}}}{P_{\text{dyn}}}\right)_{\text{at the point of measurement}} \tag{12}$$

Since the variation range of $P_{\text{ref.}}$ (P_2 represents the downstream pressure – the average of the pressure in the test chamber usually used as reference pressure, $P_{\text{ref.}}$) is too small as compared to the variation range of injection pressure, P_1, the downstream pressure, P_2, could be assumed as constant. In addition, vapor pressure, P_v, is constant for prescribed working temperature and therefore the difference in the numerator is constant compared with dominator as in eq. (12). Thus, the cavitation number is decreasing with increasing the dynamic power, *i. e.* the cavitation intensity is increasing with dynamic power.

But this formula and the classical one are not enough to describe the phenomenon. Accordingly, a new formula is proposed in this work for calculating the cavitation number. Based on the classical formula for cavitation number, we introduce the geometrical factor as a term which characterizes the shape and dimensions of the object (nozzle, hydrofoil, *etc.*) as in eq. (13):

$$\sigma = \frac{P_{\text{ref.}} - P_V}{\frac{1}{2}\rho u_{\text{ref.}}^2} = \frac{P_{\text{ref.}} - P_v}{\frac{1}{2}\rho u_{\text{ref.}}^2}\frac{Q}{Q}GF = \frac{P_{\text{stat.}}}{P_{\text{dyn}}}GF \tag{13}$$

where *GF* represents the geometrical factor, which could be a formula or a ratio including d_{in}, d_{out}, L_{nozzle}, taper angle, surface roughness, *etc.* The nozzles with the same *GF* should create a cavitation phenomenon with the same intensity and behavior. In the case of cavitation tunnels, the curvature shape, leading and trailing edges, chord length, the angle of attack, surface roughness, and the chamber geometry are essential parameters to determine the GF. Thus, GF can be used to determine the cavitation inception. More work is needed to determine the correct GF.

For any flow under any conditions regardless of the existence of the cavitation phenomenon, both formulas, the classical one and that from ASTM (standard test method for erosion of solid materials), provide a cavitation number. Therefore, these two formulas are not enough to indicate the existence of cavitation phenomenon. This applies to the case of fluid flow in two systems under the same hydrodynamic working conditions but geometrically (shape and dimensions) differing the cavitation number will be the same but the cavitation intensity will not.

If we use the ASTM formula, we can easily have the same cavitation number for two systems. If we have two systems and in one of them at certain cavitation number ($\sigma = P_2/P_1$) the cavitation exists, then in the second system (for the same cavitation number), we will meet two possibilities. The first possibility is that we will have the phenomenon in two systems but surely the cavitation will not have the same intensity and strength. The second possibility is that we will not get cavitation in the second system at all. If we use the classical formula, the situation is more complicated since it is not easy to have the same hydrodynamic working conditions and the same cavitation number for two systems. But if we use the first system as a reference for the second system and we use the same cavitation number of the first system (reference one) for the second system, as a result, we will have the same outcomes as that in the ASTM formula case. This proves the importance of introducing another parameter in the existing formulas for the cavitation number in order to have a reliable indicator.

The GF (parameter), is proposed as an additional parameter in the cavitation number formulas, introduced after multiplying and dividing the formula by flow rate.

In the case of cavitating jet generators, the GF (parameter) is related to the nozzle inlet and outlet diameter, the nozzle throat, nozzle length, taper angle. These parameters have a big influence on the discharge coefficient of the nozzle, *i. e.* the nozzle power (jet dynamic power, P_{dyn}) since it depends on the discharge coefficient. The influences of these parameters were already presented in various publications [12, 13, 15, 22]. While in the cavitation tunnel, the hydrofoils are used, therefore the GF (parameter) is related to the leading-edge geometry (leading edge radius), location and value of maximum thickness, the location of maximum camber, chord length, chord line, mean camber line, maximum camber, and trailing edge. Also, the surface roughness has a significant effect on the cavitation when the other parameters are kept fixed as mentioned in many publications [23, 24].

The GF should encompass somehow all the parameters. It is including into the formula would provide also recognition of a restricted border between the existing and non-existing cavitation, *i. e.* between the cavitating and non-cavitating flow. The authors believe that the proposed formula which can be considered as a modification of the two existing formulas (classical and ASTM), is the first step to achieve the reliable indicator formula.

It can be discussed why do we concentrate only on the geometrical parameter. What about the size and the flow velocity scale effects, the gas content, viscosity, surface tension, pH level, *etc.* The answer is that, for the size and flow velocity scale effects, this GF can be considered to encompass them. Concerning the rest of the parameters (such as fluid properties, gas content, and pH level, *etc.*), in most of the time there is no way to control or to modify these parameters (it is not easy to change the environment of the work such as working fluid and environment), so there is no need for their influence in formula. While the geometry of different cavitation systems parts (such as nozzles, hydrofoils, and propellers) can easily be modified to increase the efficiency, the geometry and shapes are in our hands even if we are limited with some restrictions. The literature presents that the geometry and shape of those parts play the main role in the creation process of cavitation, its strength and its action [12, 13, 15 , 22, 23]. We believe that, if the geometrical parameter is defined well and inserted in the classical cavitation number formula as in eq. (13), the result is a cavitation number that describes the cavitating and non-cavitating flow more precisely. It will be an efficient parameter, such as Reynolds number and other dimensionless numbers used in fluid mechanics. More precise determination of the GF as a correction tool needs further investigation.

Conclusions

The result of the analysis associated with the experimental work which was carried out to enhance the performance of the cavitating and non-cavitating jet and related parameters can be concluded as following.

- The relevant parameters controlling the jet were determined. The obtained results support the presented, analytically derived formulas, which can be used to predict and estimate the jet action for various conditions.
- The effect of nozzle geometry dominated over all other parameters of jet performance and quality.
- For cavitating jets, considering the geometrical parameters, the dependence of the cavitation action on the jet dynamic power was also declared.
- The cavitation erosion rate as a kind of cavitation action could be used as a good indicator for cavitating jet generator performance.
- The classical definition was preferred to be used in this paper because it is more reliable for describing the cavitation phenomenon than the ASTM definition – both of them do not consider the GF.
- A formula shape to express the cavitation number including GF is proposed. Further work is needed to define precisely the GF.
- Although the cavitating jet efficiency may be determined in several ways, the common underlying parameter is the GF as established in this study. Also, appropriate expressions to conveniently compare the efficiency of the cavitating jet and its behavior is also presented and demonstrated.

Acknowledgment

The first author is also grateful for the Ministry of Science in Libya for support during his research activity. Libyan government paid to EPFL-LHM for using some equipment.

The authors would like to express their thanks to the International Active Swiss Company (mvt AG) for permission to use their data in this paper. Also, they would like to express their thanks to Prof. Gergely Kristof at Department of Fluid Mechanics and Prof. David Legrady at NTI-BME for their valuable comments for the first author during the writing of the paper.

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Paper submitted: April 28, 2018
Paper revised: August 29, 2018
Paper accepted: Septembar 3, 2018