Hydraulic characteristics of the convergent-divergent nozzle with the inner electrode in cavitating conditions

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Abstract. The knowledge of hydraulic characteristics of convergent-divergent nozzles will lead to the optimal design of a nozzle for generating a cavitation cloud. Such a nozzle is a crucial component of the CaviPlasma device, which aims to tackle the ever-growing water treatment and purification issue. To measure the characteristics, a closed hydraulic circuit was used to measure pressure differences before and behind the nozzle, and the flow rate. The characteristics were then developed based on the calculated loss coefficient ξ and the cavitation number σ. Three different nozzle designs were tested (with diameters of necks 3 mm, 4 mm, and 5 mm respectively), and multiple positions of the inner electrode were set for each design. This resulted in several characteristic curves for each design and electrode position. The study will contribute to the development of an optimal nozzle for the CaviPlasma device, enhancing its efficiency in water treatment and purification.

1 Introduction

To achieve sustainable development, it is crucial to take timely action in the face of increasing pollution of water and the environment. Removing pollutants from wastewater is a critical problem that needs to be addressed [1]. One promising solution is the use of the CaviPlasma device. Which is a patented device [2] that operates by igniting a non-thermal plasma discharge in a cavitation cloud [3, 4]. Cavitation, i.e., the transformation of liquid water into a gas phase, can be achieved in several ways. The CaviPlasma device utilizes hydrodynamic cavitation, which lowers the pressure below the saturation vapor pressure by increasing the flow velocity due to the reduction in diameter in the convergent-divergent nozzle. Therefore, the design of a suitable shape of the cavitation nozzle is crucial for the optimal functionality of the entire system with the highest hydraulic and physicochemical efficiency and the lowest economic impact.

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2 Cavitation nozzle description

For optimal operation, achieving the largest possible cavitation cloud between the electrodes is necessary, which should lead to lower demands on plasma discharge operation and create a suitable plasma discharge environment. Another important parameter is the hydraulic loss in the nozzle, which determines the parameters of the pump needed to drive the device. In this study, we will primarily focus on the hydraulic aspect of the problem. From the work [5] it follows that the size of the cavitation cloud is strongly influenced by the diffuser section of the nozzle. The gradual opening of the diffuser section positively affects the size of the resulting cavitation cloud. An angle $\beta$ of approximately $5.72^\circ$ was used for the opening of the diffuser for all measured nozzle variants, corresponding to a commercially available reamer 1:10 with a length of 70 mm. An opening angle of $\alpha = 60^\circ$ for the diffuser ensures a sufficiently gradual inlet into the neck for all variants. The nozzle inlet is a pipe with a diameter $D_1 = 15$ mm, and the outlet from the nozzle is a pipe with a diameter $D_2 = 10$ mm. Three nozzle variants were measured with neck diameters $D_n$ of 3 mm, 4 mm, and 5 mm. The inlet part of the nozzle is axially guided by an electrode with a diameter of $D_e = 4$ mm, which has an adjustable position with respect to the neck. The schematic of the dimensions of the cavitation nozzle is shown in Figure 1, where part 1 is an electrode and part 2 is a counter electrode. The flow direction is indicated by bold arrows.

![Fig. 1. The diagram of convergent-divergent nozzle dimensions](image)

3 Experimental measurement

The basis of the measuring circuit is a convergent-divergent nozzle with an axially guided electrode at the input. The electrode has a diameter of 4 mm and can be moved when the measuring circuit is shut down. The position of the inserted electrode is measured using a linear position sensor, HBM, type WA/100, range 100 mm, with absolute error $\pm 0.2$ mm. It is marked as "s" in Figure 2. The circuit is enclosed with a pressure vessel. The flow through the system is ensured by the Calpeda MXH 805 pump with a power of 1.8 kW. Flow measurement is provided by an electromagnetic flowmeter, Ela Brno, type MQI-99 CN, range 5 m3/h, with absolute error $\pm 0.007$ l/s, marked as "$Q$" in diagram 2. The pressure $p_1$ at the nozzle input is measured by an absolute pressure sensor, BD Sensors, type DMP331, range 16 bar, absolute, with absolute error $\pm 4$ kPa, and the pressure $p_2$ at the nozzle output is measured by an absolute pressure sensor, BD Sensors, type DMP331, range 2.5 bar, absolute, with absolute error $\pm 625$ Pa. The temperature in the pressure vessel marked as "$T$" is measured using a K-type thermocouple 156, Watlow, with absolute error $\pm 2.2$ °C. The pressure vessel can be operated in three modes: open to the atmosphere, with connected overpressure up to 2.5 bar, and in a vacuum mode with a connected vacuum up to -40 kPa. The pressure vessel also allows for the filling and draining of water from the circuit. The experimental circuit is shown in Figure 2.
3.1 Measurement procedure

Measurements were performed for each of the three designs of the cavitation nozzle over a wide range of electrode insertions into the nozzle. For variants with neck diameters of 3 and 4 mm, measurements were taken for electrode insertion ranging from 13 mm upstream of the neck to an insertion depth of 1 mm from the wall of the convergent part of the nozzle. For each of these variants, a total of 13 electrode insertion positions were measured with a step of 1 mm. The nozzle with a neck diameter of 5 mm offers the possibility of guiding the electrode through the neck, which creates a space for a wider range of insertion states. For this variant, the electrode insertion range was measured from 13 mm upstream of the neck in the convergent part to 8 mm downstream of the neck in the divergent part of the nozzle with a step of 1 mm. In this nozzle mode, a total of 30 characteristics were measured. For each pair of neck diameter and electrode insertion settings, the entire hydraulic characteristic was measured. Flow parameters were adjusted by changing the pressure in the pressure vessel, in the range of +150 000 Pa to -40 000 Pa relative pressure. Flow parameters were also influenced by a frequency converter connected to the pump motor. The motor frequency was changed in the range of 8-70 Hz. Each operating point on the characteristic was always set by changing only one of the parameters (pressure/frequency). Each characteristic for the measured pair of neck diameter and electrode insertion settings consists of 20 measured operating points.

During the measurements, the temperature of the system was always monitored to ensure it did not exceed the limit of 30°C, as the pressure of saturated vapor, which is an important parameter for cavitation inception, is strongly dependent on temperature. Whenever the temperature approached the limit, the water in the system was exchanged to decrease the temperature. The new water was circulated in the system for several minutes to allow it to stabilize and any dissolved air to be released. Finally, the entire system was de-aerated prior to the actual measurements.

3.2 Evaluation procedure

After setting a specific operating point, the measured values were allowed to stabilize before recording the data. The sensors provided data at a sampling frequency of 1000 samples per second. The data from the sensors were processed using MATLAB software. A 30-second data set was saved in every operating point, from which the mean values of the input pressure, output pressure, flow rate, and temperature were calculated. Firstly, the density value and the saturation vapor pressure were determined based on empirical formulas 1 and 2 [6, 7] as a function of temperature.

\[
\rho = \frac{99983952 + at + bt^2 + ct^3 + dt^4 + et^5}{1 + ft}
\]  
(1)
Where \( a = 16,945176, b = -7,9870401\cdot10^{-3}, c = -46,17041\cdot10^{-6}, d = 105,56302\cdot10^{-9}, e = -280,54253\cdot10^{-12}, f = 16,897850\cdot10^{-3} \) and \( t \) is a temperature in °C.

\[
p_v = 610,94 \cdot e^{\left(\frac{17,625}{t+243,04}\right)}
\]  

(2)

Furthermore, the calculation of the cavitation number \( \sigma \) was performed, which characterizes the state of cavitation flow. The definition of this parameter varies, and in this paper used definition is given by equation 3 [8]. To calculate the parameter, the pressure at the nozzle outlet \( p_2 \), the density \( \rho \), the saturation pressure of vapor \( p_v \), and the average flow velocity in the nozzle throat \( v_n \) were used. The loss coefficient \( \zeta \), which characterizes the degree of hydraulic losses in the nozzle, was calculated from the difference in pressure before and after the nozzle \( (p_1 - p_2) \) using the formula 4 [8].

\[
\sigma = \frac{p_2 - p_v}{\frac{v_n^2}{\rho}}
\]  

(3)

\[
\zeta = \frac{p_1 - p_2}{\frac{v_n^2}{\rho}}
\]  

(4)

\[
v_n = \frac{4\cdot Q}{\pi\cdot D_n^2}
\]  

(5)

Where \( Q \) is the flow rate in the system and \( D_n \) diameter of the neck of the nozzle. The hydraulic characteristics were created from these parameters.

4 Results

In Figures 3-5, we can see individual \( \zeta-\sigma \) characteristics for various nozzle throat diameters. The black cross indicates the cavitation inception point. As inception of cavitation was considered a point, where cavitation bubbles were visible to the naked eye. For the nozzle with a throat diameter of 5 mm, only the part of the characteristic where the electrode is in the convergent part is shown in Figure 5 to allow for better comparison with the other nozzle variants. We can observe that all three nozzle variants exhibit the same behavior trend, with the loss coefficient remaining constant as the cavitation number decreases until the point of cavitation inception. From there, after a slight decrease, the loss coefficient starts to significantly increase. Another observed phenomenon is that the electrode's depth of insertion into the nozzle throat has no significant effect until the point 2 mm away from the throat, where the whole characteristic starts to shift towards higher loss coefficients. An interesting fact is that each characteristic for the nozzle with a throat diameter of 4 mm has higher losses than the characteristic for a similar electrode depth for the other two diameters. This is the case where the nozzle throat and electrode have the same diameter.

The following two figures, 6-7, depict the state where the electrode is being inserted through the nozzle throat. The value of \( s = 0 \) mm corresponds to the state where the electrode is aligned with the inlet of the throat. Negative values of the variable \( s \) indicate insertion through the electrode. It can be seen that inserting the electrode causes a sudden increase in the loss coefficient in the nozzle, which continues to increase with further insertion up to a depth of 5 mm. Further insertion in the throat region does not lead to significant changes in the characteristics. We can see that the effect of electrode insertion on nozzle loss is enormous. At the maximum, the loss coefficient is more than four times greater than the maximum value of the loss coefficient in the convergent part of the nozzle. At a depth of electrode insertion greater than the length of the throat, there is a change in the shape of the
characteristics. In the non-cavitating region, the $\zeta$ value is no longer constant but decreases with decreasing cavitation number. However, the level of loss is comparable to the electrode region in the throat.

**Fig. 3.** Hydraulic characteristic of convergent-divergent nozzle with neck diameter $D_n = 3$ mm

**Fig. 4.** Hydraulic characteristic of convergent-divergent nozzle with neck diameter $D_n = 4$ mm
Fig. 5. Hydraulic characteristic of convergent-divergent nozzle with neck diameter $D_n = 5$ mm

Fig. 6. Hydraulic characteristic of the nozzle with $D_n = 5$ mm – neck section

Fig. 7. Hydraulic characteristic of the nozzle with $D_n = 5$ mm – divergent section

5 Conclusion

For the future optimal design of a water cleaning and treatment device based on hydrodynamic cavitation, it is important to understand the hydraulic behavior of its main component - the convergent-divergent nozzle. Three different nozzle designs with throat diameters of 3, 4, and 5 mm were tested. For each design, a wide range of axial electrode insertion into the nozzle was measured. For nozzles with throat diameters of 3 and 4 mm, the range was 1-13 mm before the throat. For the nozzle with a throat diameter of 5 mm, which allows for electrode insertion through the convergent section, throat, and into the divergent section of the nozzle, the range was measured from 13 mm before the throat in the convergent section to 8 mm after the throat in the divergent section of the nozzle. The nozzle displacement was done in increments of 1 mm. For each nozzle design and specific electrode insertion, the pressure before and after the nozzle, flow rate, and water temperature in the system were measured. From the measured data, the cavitation number $\sigma$ and loss coefficient...
ζ were calculated. These two parameters were used to construct hydraulic ζ-σ characteristics, which were used for subsequent evaluation.

From the measured data, it can be concluded that the insertion has no influence on the nozzle characteristics up to a value of 2 mm before the throat. Similarly, there are no significant changes in the characteristic in the area where the nozzle is inserted beyond the throat into the diverging part of the nozzle. If we focus on the convergent region of electrode insertion, the nozzle with a throat diameter of 4 mm shows the highest losses. This may be due to the fact that the throat size is the same as the electrode size. When the electrode is inserted into the throat, there is a sudden increase in the loss coefficient, which is caused by partial blockage of the flow area by the electrode. Further increase in losses occurs by inserting the electrode into the throat up to a distance of 5 mm from the beginning of the throat. Beyond this insertion, the loss values remain approximately the same.

The obtained characteristics will aid in the future optimal design of the CaviPlasma device. Based on the acquired knowledge, it currently appears advantageous to use a cavitation nozzle with a throat diameter of 5 mm and electrode insertion in the convergent section near the throat. In this arrangement, the nozzle shows relatively low losses and a low cavitation number, which corresponds to the fully developed cavitating flow regime, a desirable phenomenon for the proper functioning of the device. In further experiments, it would be appropriate to focus on the cavitation characteristic and behavior of the nozzle and continue the design of the CaviPlasma device with consideration to the distribution of the phase field in the flow.

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