Laser optical investigation of high-pressure water jets in submerged reservoir type conditions used for high-pressure jetting

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Keywords: high-pressure, jetting, laser optical measurement, back pressure, cavitation.

ABSTRACT

High-pressure jetting maybe implemented into a drilling and stimulation process for geothermal related operations. In order to facilitate a successful technology transfer to this new field of application, a good knowledge of the waterjet rock interaction has to be established first. Optical investigation of the process itself can provide relevant knowledge to enable this effective technology transfer.

For this purpose, the laser optical measurement technique particle image velocimetry (PIV) is applied to determine velocity fields of the flow in the area of interest of the jetting process. In addition to that, experiments are conducted to analyze the cavitation potential of different high-pressure nozzles. Experiments under submerged conditions and with an adjustable back pressure, imitating reservoir conditions, are conducted to examine the influence of operation parameters on the jetting performance.

The results give insights into a future water jet drilling process in a pressure-controlled environment. In particular, the effect of back pressure on the onset of cavitation for different nozzle types is observed. As cavitation erosion is discussed to be one of the rock ablation mechanisms, the findings contribute to the understanding of this type of erosion.

1. INTRODUCTION

High-pressure waterjet applications are found in many industrial applications, i.e. machine cutting or mining purposes (Summers 1995). This well-established technique can be transferred to drilling applications where the high-pressure water jet is used to effectively erode rocks and create a borehole. Although there have been several research activities in this field in the past decades, the process itself is not well understood so far and practical applications are rare (Brook and Summers 1969, Hood et al. 1990). Especially the waterjet rock interaction and the related governing erosion mechanism is not known yet. Potential erosion mechanisms after Salem Ragab and Kamel (2013) are surface erosion, hydraulic fracturing, poro-elastic failure and cavitation erosion.

Most of the research analysed the erosion effect of high-pressure jetting after the drilling process is finished. Different parameter studies varying the flow rate, stand off distance between the high-pressure nozzle and the rock surface, nozzle types, abrasives and back pressure were conducted (i.e. Liao et al. 2012, Lu et al. 2013, Stoxreiter et al. 2018). The process itself during the actual jetting process has not been investigated yet and is therefore part of current investigation (Hahn et al. 2019, Gradzki et al. 2019).

One possible method to investigate the actual jetting process is to use laser optical measurement techniques (Jasper et al. 2017). A well-established laser optical measurement technique for non-intrusive flow measurements is particle image velocimetry (PIV). PIV is a measurement technique for the observation of instantaneous velocity fields in a planar cross section of the flow, a detailed description of the method can be found in Adrian and Westerweel (2011).

As mentioned before, cavitation erosion is one possible erosion mechanism that can lead to rock ablation. Cavitation occurs if the local static pressure in the flow drops below the vapor pressure of the liquid (Ross 1977). Under those circumstances' cavitation bubbles are formed and transported with the fluid flow until the local static pressure exceeds the vapor pressure when the cavitation bubbles implode and a very short but high pressure peak is generated. This temporarily high pressure peak can cause rock ablation.

In this contribution, the effect of back pressure on the onset of cavitation in different high-pressure nozzles used for jetting is quantified by monitoring the flow rate. This indicates whether cavitation erosion is likely to occur under different operation conditions of high-pressure jetting. In addition to that, the cavitation potential of different high-pressure nozzles is evaluated. Moreover, the effect of back pressure on the development of a high-pressure water jet is analysed.

2. EXPERIMENTAL SETUP

The experiments are conducted in a high-pressure vessel (fig. 1), capable of back pressures up to 50 MPa and temperatures up to 40°C. The dimensions of the vessel are an inner diameter of 6.5×10^{-3} m (65 mm) and inner of height 0.4 m (400 mm). The back pressure in the vessel is controlled by relief valves and the corresponding back pressure and the nozzle outlet pressure are measured by pressure sensors, respectively. The flow rate is measured by inductive flow metering. A high-pressure pump with a maximum outlet pressure of 20 MPa and a maximum flow rate of 0.9×10^{-3} m^3/s (54 l/min) is used to generate the high-pressure water jet. The nozzle exit pressure is regulated by a pneumatic valve at the pump outlet. The desired pressure drop over the nozzle is then regulated by a relief valve at the vessel, by which the back pressure in the tank is controlled.

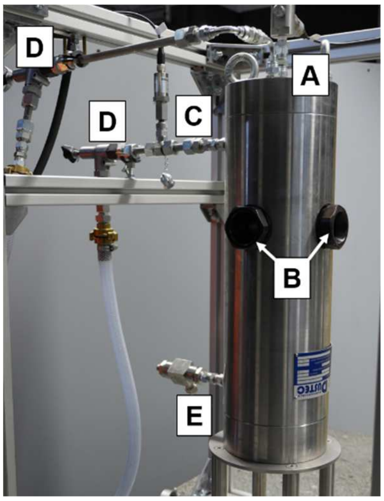

Figure 1: High-pressure vessel with fluid inlet (A), sapphire windows (B), pressure sensor (C), relief valves (D) and additional fluid outlet (E).

Table 1: Parameters of different high-pressure nozzle types used for the experiments.

Name	Type	Manufacturer
N1	Sapphire	MVT
N2	Sapphire, with flow straightener	MVT
N3	Sapphire	Spraying Systems
N4	Stainless Steel	Lechler

The experiments to examine the onset of cavitation are conducted with different types of high-pressure nozzles, the parameters are given in table 1. All nozzles have the same outlet diameter of 1,8 $\times 10^{-3}$ m (1.8 mm). The main difference is the material and geometry of the smallest diameter, i.e. the nozzle outlet diameter. Nozzles N1, N2 and N3 have a sapphire insert whereas nozzle N4 is made of hardened stainless steel. Nozzle N2 has an additional flow straightener. All nozzles are new at the beginning of the experiments (zero hours of operation) and had about two hours of operation at the end of the experiments. A change of the nozzle performance during the experiments was not observed.

Optical access to the high-pressure vessel is realized by three sapphire windows with an optical diameter of 35×10^{-3} m (35 mm), which are positioned in a 90° angle each. The applied experimental setup for PIV measurements in the high-pressure vessel is illustrated in figure 2. A 16 bit sCMOS camera (LaVision sCOMS, 2550x2160 pixels) with a Zeiss Yashica macro lens and the illumination source, a Nd:YAG double pulse-laser (Quantel Evergreen 200, repetition rate 15 Hz, wave length 532 nm, pulse length 5 ns), are synchronized by a timing unit. The recorded images have a dimension of $15.0 \times 10^{-3} \times 7.0 \times 10^{-3}$ m (15.0 x 7.0 mm) with a scaling factor of 6.4×10^{-6} m/pixel, corresponding to a spatial resolution of the optical investigation of 6.4×10^{-6} m (6.4 µm).

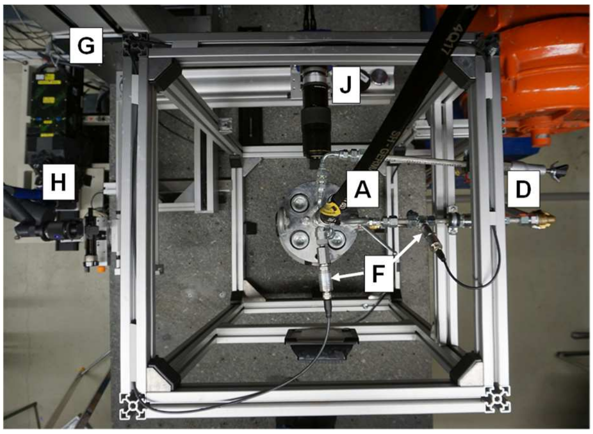

Figure 2: Top view of the test setup for PIV measurements in the high-pressure vessel. The camera with macro lens (J) is positioned in a 90° angle to the laser optics (H). Camera and laser are positioned by a linear unit (G). The fluid inlet (A) is realized through the top of the vessel. The nozzle outlet pressure and the back pressure are measured by pressure sensors (F), respectively. Relief valves are used to regulate the back pressure (D).

3. RESULTS

The results of the experiments are divided into two parts. Firstly, the effect of back pressure on the onset of cavitation is discussed. Secondly, the effect of back pressure on the development of a free high-pressure water jet is presented.

To make the results comparable even if different nozzle outlet pressures are applied, a non-dimensional parameter P^* is introduced. The non-dimensional pressure ratio P^* is defined as the ratio between the back pressure in the vessel P_{vessel} and the nozzle outlet pressure P_{nozzle}:

$$P^* = P_{vessel} / P_{nozzle} \quad [1]$$

3.1 Effect of back pressure on the onset of cavitation for different high-pressure nozzle types

The effect of back pressure on the onset of cavitation is visualised in figure 3. The upper brass coloured part is the nozzle, the surrounding water is black background and cavitation clouds are white coloured due to light scattering. When no back pressure is applied, the cavitation clouds are clearly visible. Increasing the pressure ratio P* and therewith the back pressure leads to a shortening of the cavitation cloud length until it disappears completely.

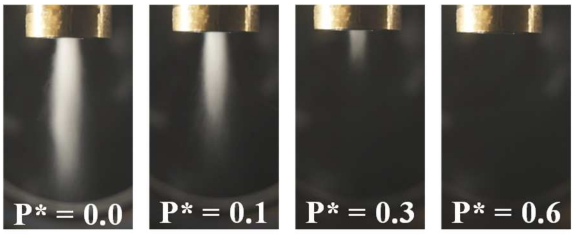

Figure 3: Cavitation behaviour of high-pressure nozzle N1 as a function of increasing pressure ratio P*.

Complementary to the optical observation, the flow rate is monitored. If gas bubbles due to cavitation or degassing are formed in the nozzle outlet, the resulting fluid flow can be choked. This phenomenon occurs due to the lower speed of sound of the two-phase flow compared to the corresponding single-phase flow (Kieffer 1977, Radovskii 1973). In a choked flow regime, the flow rate is no longer a function of the pressure drop at the nozzle outlet but reaches a maximum. Therefore, the onset of cavitation in a high-pressure nozzle can be determined by observing the flow rate for different pressures. If the flow rate is a function of the pressure, the flow is not choked and thus no cavitation is occurring.

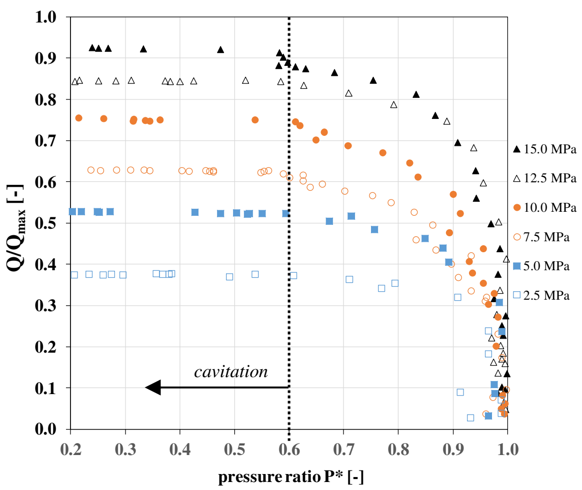

Figure 4: Cavitation behaviour of nozzle N1 as a function P* for nozzle outlet pressures from 2.5 - 15.0 MPa, flow rate normalized by maximum flow rate.

One form of presentation to examine the cavitation behaviour of different nozzles is shown in figure 4. Here, the dependency of the normalized flow rate from the pressure ratio P* of nozzle N1 is shown. For different nozzle outlet pressures from 2.5 - 15.0 MPa, the tendencies are the same and no dependence on the nozzle outlet pressure can be found. First, the flow rate is independent of the pressure ratio up to P* = 0.6 for all nozzle outlet pressures. Subsequent, the flow rate decreases with increasing pressure ratio. This indicates that cavitation is suppressed if the pressure ratio exceeds P* = 0.6 for this nozzle type. This outcome is in accordance with the optical observations shown in figure 3, where the cavitation clouds become invisible if the pressure ratio reaches P* = 0.6.

Figure 5 shows the cavitation behaviour of the different tested nozzles N1-N4 for a nozzle outlet pressure of 10.0 MPa, respectively. For nozzles N1, N2 and N3 the curves look similar. Again, for pressure ratios up to P* = 0.6 the flow rate is independent of the pressure, indicating cavitation to occur. After a pressure ratio of P* = 0.6 the flow rate is dependent on the pressure, indicating cavitation to be suppressed. The similarity is because all those three nozzles are of the same type, meaning they have a sapphire insert. On the contrary, the curve of Nozzle N4 shows a major difference to the other nozzles. For all tested pressure ratios, the flow rate is dependent on the pressure. This indicates that the cavitation potential of this nozzle is lower than the other nozzles.

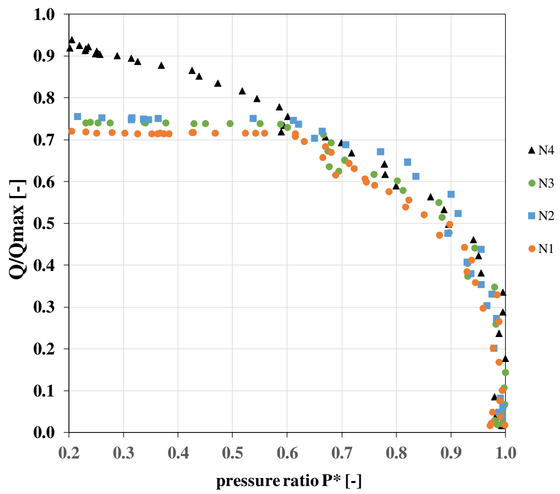

Figure 5: Cavitation behaviour of different nozzles as a function P* for a nozzle outlet pressure of 10.0 MPa each, flow rate normalized by maximum flow rate.

Applied to high-pressure jetting the results give an indication if cavitation is likely to occur under specific operation conditions. Meaning, if nozzles N1-N3 are used for jetting and the pressure ratio exceeds P* = 0.6, cavitation erosion does not happen and thus can not be the governing erosion mechanism. This is an important aspect because for deep-drilling the hydraulic pressure alone can be several hundred bars, not considering the rock pressure. Therefore, the nozzle outlet pressure delivered by a high-pressure pump must be very high to drill in the cavitation regime of such type of high-pressure nozzle. Cavitation does not only erode the rock but also the high-pressure nozzle itself. Thus, it might be preferable to operate in the non-cavitating regime to ensure a longer lifetime of the high-pressure nozzle. From this point of view nozzle N4 appears to be advantageous as there is no cavitation regime. But nozzle N4 is made of hardened stainless steel which wears out faster than a sapphire nozzle. Which nozzle type is better should be examined in future field tests.

3.2 Effect of back pressure on the development of a high-pressure water jet

The effect of back pressure on the development of a high-pressure water jet is examined for nozzle N1 and nozzle N3. For this, the two-dimensional velocity distribution is obtained from PIV analysis. For PIV analysis, a multi-pass decreasing interrogation window is applied. Initial window size of 64 x 64 pixels is calculated once followed by a final window size of 32 x 32 pixels which is calculated twice with an overlap of 50%. The results are averaged over 1000 statistically independent experiments. This results in a 2D velocity distribution with velocity data every 100 µm and a spatial averaging of the velocity data over 200x200 µm^2. Afterwards, the centreline velocity distribution is analysed via MATLAB. The centreline is defined as the position where the centre of the nozzle outlet is located, which is illustrated in figure 6. Hence, the centreline velocity represents the maximum velocity distribution along the axial distance. Here, the axial position is given as non-dimensional distance D from the nozzle outlet:

$$D = D_{axial} / D_{nozzle} \qquad [2]$$

Figure 6 shows the normalized centreline velocity along the non-dimensional distance from the nozzle outlet for different pressure ratios P* and a fixed nozzle outlet pressure of 10 MPa for nozzle N1. Because the pump outlet pressure is fixed to 10 MPa, the pressure ratios can also be interpreted as back pressure.

As expected, the centreline velocity decreases with increasing distance from the nozzle outlet for all pressure ratios. For lower pressure ratios, namely P* = 0.4 and P* = 0.5, the centreline velocity drops faster compared to higher pressure ratios. Here, nozzle N1 is still in the choked flow regime, i.e. cavitation bubbles are formed at the nozzle outlet.

Figure 7 shows the normalized centreline velocity along the non-dimensional distance from the nozzle outlet for different pressure ratios P* and a fixed nozzle outlet pressure of 10 MPa for nozzle N3. Again, the centreline velocity decreases with increasing distance from the nozzle outlet for all pressure ratios. Like nozzle N1, the lower pressure ratios show a faster drop of the centreline velocity compared to higher pressure ratios. Like nozzle N1, nozzle N3 is in the choked flow regime for these pressure ratios.

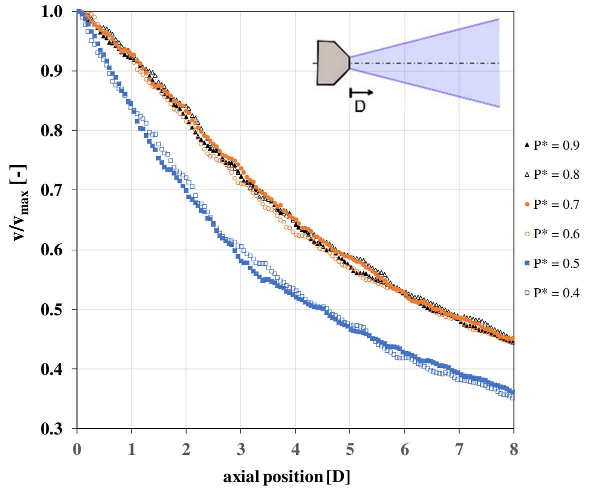

Figure 6: Velocity distribution at the centreline of a high-pressure jet created with N1 as a function of P*, velocity normalized by maximum axial velocity, nozzle outlet pressure 10 MPa.

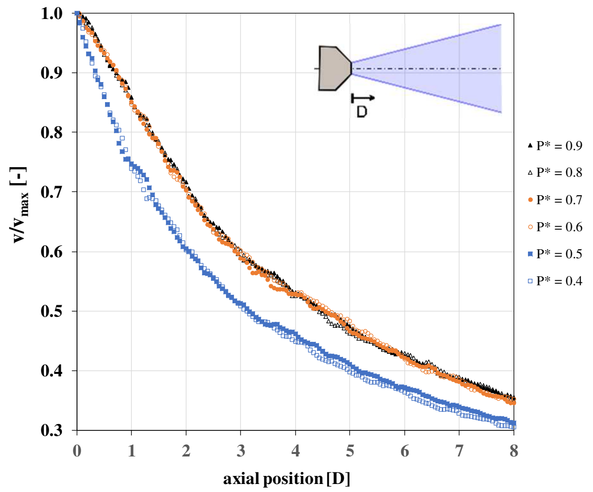

Figure 7: Velocity distribution at the centreline of a high-pressure jet created with N3 as a function of P*, velocity normalized by maximum axial velocity, nozzle outlet pressure 10 MPa.

The centreline velocity is an indication for the maximum possible energy that can be delivered to the rock surface during jetting. The higher the velocity the higher the energy input on the rock. The results show clearly that for a higher back pressure, i.e. downhole for deep-drilling, the energy is lower if the nozzle outlet pressure is maintained constant for the non-cavitating regime.

Moreover, comparing the slope of the centreline velocity decay, nozzle N3 shows a greater slope. This means that the conservation of the velocity along the centreline is worse. Applied to high-pressure jetting this means that for the same standoff distance between the nozzle outlet and the rock surface, a high-pressure jet from nozzle N1 would provide more energy impact on the rock surface than a high-pressure jet from nozzle N3. Thus, the effectiveness of a nozzle can have a great influence on the jetting performance.

4. CONCLUSIONS

In this contribution, the cavitation potential of different high-pressure nozzles as a function of back pressure was examined. Optical investigation of the process gave insight into the occurrence of cavitation clouds. Moreover, by monitoring the flow rate a cavitation and a non-cavitation regime could be identified. In contrast to the examined sapphire nozzles, the nozzle made of hardened stainless steel did not show a cavitation regime.

In addition to that, the laser optical method PIV was applied to analyse the two-dimensional velocity distribution of a high-pressure water jet and its dependency from the back pressure. Here, a clear dependence of the centreline velocity from the back pressure could be proven for both the cavitating and the non-cavitating regime. The higher the back pressure the lower the centreline velocity.

All in all, if jetting is applied for deep-drilling the probability of occurrence of cavitation is strongly depending on operation conditions. If the pressure ratio of surrounding pressure downhole, i.e. back pressure, and nozzle outlet pressure is below a critical value, cavitation is suppressed. This critical value has to be evaluated individually for each nozzle type, as the experiments showed. If the pressure ratio is below this critical value, the likelihood of cavitation erosion is very low and thus will not be the governing erosion mechanism. From a practical point of view, this would exemplary mean that in a depth of 3000 m with a hydraulic pressure of 30 MPa the nozzle outlet pressure must not exceed 50 MPa (nozzle outlet velocity of approximately 200 m/s) to ensure suppression of cavitation in the nozzle. The results also give an indication that there is a clear reliance on jetting performance and the applied high-pressure nozzle.

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Acknowledgements

This work is being funded through the “FH-Struktur” venue for universities of applied sciences by the ministry for innovation, science and research of the state of Nordrhein-Westfalen, Germany (AZ: 322-8.03.04.02 - FH-Struktur 2016/04) and partly funded from the European Union’s Horizon 2020 research and innovation programme project “SURE” under grant agreement No. 654662.