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Experimental study on the influence of geometrical parameters on the cavitation erosion characteristics of high speed submerged jets

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ABSTRACT

The influence of the geometrical working parameters on the cavitation erosion process was experimentally investigated by exposing the surfaces of copper samples (as a kind of Face Centred Cubic material (FCC)) to a high speed submerged cavitating jet for various time periods using a cavitating jet generator. The resulting erosion rate and eroded area is discussed in detail. Influences of the non-dimensional standoff distance, the non-dimensional aspect ratio and the angle of attack is experimentally determined. The results show that the erosion rate and weight loss are strongly depending on these separately investigated parameters. With this test rig facility and applied hydrodynamic parameters the maximum erosion was found to take place with a non-dimensional standoff distance varying between 42 and 48 (depending on the nozzle diameter), with a non-dimensional aspect ratio of 11 and with 105° angle of attack. A model to explain the influence of the angle of attack on the erosion rate based on the cavity bubble and target surface interaction is presented. In addition, the obtained results demonstrate that the used small-diameter (0.4–0.6 mm) water cutting nozzles could be applied for metal machining by cavitation and cavitation cutting with low power consumption and high cutting efficiency.

1. Introduction

Cavitation is a well-known phenomenon in the field of high speed flows and it is generally considered to be an undesired, sometimes even harmful process in hydraulic systems. However, there are several scientific and industrial applications where cavitation jets are used purposefully e.g. for jet cutting, underwater cleaning and for the improvement of fatigue strength of materials, etc. In these cavitating jets, vortex cavitation is initiated in the low-pressure region of the vortex core, which occurs in the shear layer around a high-speed water jet. The vortex cavitation forms a big cavitation cloud, which shedding is a periodical phenomenon with a frequency in the order of several kHz [1–5]. When the cavitating jet hits the surface of a target material shock waves and micro jets are produced as the consequence of the bubble collapse, which cause a significant force of impact ($\geqslant 1500$ MPa) [6,8]. For the applications where the erosive capabilities of the cavitating jets are utilized it is very important to have high energy impacts, and thus to produce erosive vortex cavitations with the highest possible efficiency [9,10,4].

Maximizing the efficiency of cavitating jets is not trivial since many parameters have an influence on the erosion process, such as: hydrodynamic conditions, geometrical conditions (nozzle, test chamber and the target), fluid and material properties [2,5,9,7,12,11]. Therefore an exact solution by either analytical or experimental methods has been out of reach for a long time [13].

If the relation between the cavitation intensity in a cavitating jet and the erosion rate of materials would be investigated precisely, the key parameter for the prediction of the cavitation erosion rate may be clarified [9,14,15]. From the erosion point of view, the behaviour of the severely erosive cavitation depends on the pressure gradient in the jet nozzle, the jet geometry and the material of the target [5,9,7,14]. Macroscopically, the erosion rate depends on the ratio of the cavitation intensity and the cavitation resistance.

Based on that the fact that cavitation damage can occur only if the cavitation intensity created by the flow field exceeds the cavitation resistance of the material, therefore the damage mechanism can be expected to depend on the ratio of cavitation intensity and

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Nomenclature

σ	cavitation number – defined as: $\sigma = \frac{p_{\text{ref.}} - p_v}{\frac{1}{2}\rho u_{\text{ref.}}^2}$
p_{ref}	reference pressure (Mpa) = P_2
$p_v\ (T)$	saturation (vapour) pressure (Mpa)
$\rho\ (T)$	density of the liquid (kg/m^3)
T	temperature (°C)
x	stand-off distance (mm)
A	nozzle cross-section area (m^2)
L_n	nozzle length (mm)
d_{in}	inlet nozzle diameter (mm)
L_n/d_{out}	non-dimensional aspect ratio
$h_{1,2,3}$	distance between the bubble centre and target surface
$u_{\text{ref}} = Q/A = V_J$	reference velocity (m/s)
P_1	upstream pressure (Mpa)
P_2	downstream pressure (Mpa)
ΔW	weight loss (mg)
Δt	exposure time (h, s)
Q	$k * \sqrt{(P_1 - P_2)}$ (m^3/s)
K	constant, depends on the nozzle diameter and geometry; (m^3/s Pa$^{0.5}$)
d_{out}	outlet nozzle diameter (mm)
x/d_{out}	non-dimensional standoff distance

cavitation resistance. As this ratio increases above non-damaging levels the damage mechanism starts from a fatigue-like process over plastic deformation to a failure mechanism, when the cavitation intensity exceeds the tensile strength of the material. At a low cavitation impact intensity elastic deformation is taking place (e.g. vibratory cavitation system), while a higher intensity produces plastic deformation and surface hardening (e.g. high speed submerged cavitating jet). When the full hardening has occurred, further exposure to cavitational stresses eventually causes fatigue cracking on the surface [26,27].

The dependence of the damage mechanism on the test conditions (e.g. geometrical parameters) is one of the reasons why a unique material property alone is not appropriate to correlate and fully describe the cavitation resistance. Besides, it is difficult to simulate and understand the reaction of a material which is exposed to highly localized, non-stationary impact loading. Furthermore, it is also expected that the microstructure plays a role in this reaction too.

The aim of this study is to investigate the influence of geometrical conditions of a high speed cavitation jet generator, such as the non-dimensional standoff distance, the non-dimensional aspect ratio, the nozzle diameter, and the angle of attack on the cavitation erosion process in commercial copper as the test material, with an aim to maximize erosion efficiency in this target.

2. Experimental procedures

The experimental setup is described in our pervious publication [16]. The schematic diagram of the test chamber and nozzle geometry is presented in Fig. 1. The same protocol, which was used in our previous work [16] for determining the cavitation erosion parameters, erosion quantification and accuracy of the measured quantities is also employed here.

The apparatus in the facility (including the cavitating jet generator) was calibrated in order to obtain results with high accuracy. The pressure transducers used to measure the upstream and downstream pressures were calibrated precisely with a reference pressure transducer (HUBER). The temperature sensors in the test rig were calibrated perfectly by the use of a NORMA type digital thermometer as the reference in the calibration process, the uncertainty was of in the order of ±1 °C. The upstream pressure (P_1) and the downstream pressure (P_2) were measured at the inlet and outlet of the test chamber, respectively. The pressure transducers were calibrated by the manufacturer and accuracy certificates were issued for a maximum error of ±0.2/±0.21% FS (Full Scale), respectively. Since the flow rate was determined by using the P_1 and P_2 values from a previous nozzle calibration, the uncertainty of the determination was also in the order of ±0.3% FS.

Since the test rig does not contain a flowmeter, the flow rates were measured manually by measuring the amount of collected water for a given time period for different nozzles and up- and downstream pressures. Based on these the volumetric flow rate curve (Q [m^3/s]) can be plotted (Eq. (1)) against the pressure difference, where k is the discharge constant for a given nozzle, which can be obtained as the slope of the curve.

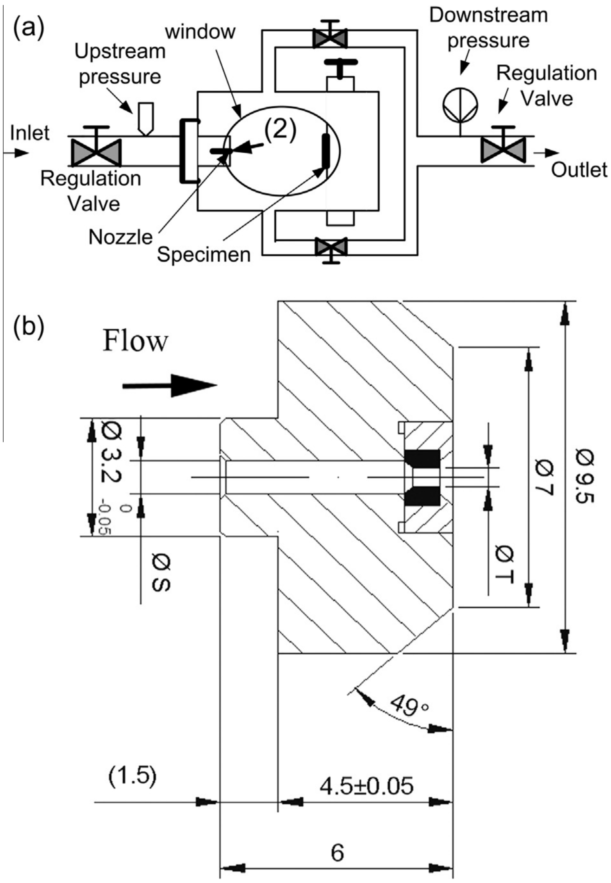

Fig. 1. Schematic diagram of (a) the test chamber, (b) nozzle body geometry (mm).

$$Q = k\sqrt{P_1 - P_2} \tag{1}$$

By knowing k for the used nozzles, the exit jet velocities (V_j) can be calculated for any applied hydrodynamic and geometrical working conditions, based on Eq. (1). In our experiments this was automatically done by a custom Labview software based on the measured pressure differences.

The tested specimens were machined from commercial Cu (99.9% purity copper). For each specimen, the desired experimental