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Cavitating flow characteristics, cavity potential and kinetic energy, void fraction and geometrical parameters – Analytical and theoretical study validated by experimental investigations

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ABSTRACT

Analytical and theoretical discussions validated by experimental investigations are presented to comprehensively study the relation between the geometrical parameters, such as the dimensionless standoff distance and nozzle geometry, and the cavity potential energy, and void fraction to improve the performance of submerged cavitating water jets. The force generated by the collapse of cavitation clouds was employed to initiate cavitation erosion in copper test samples under various hydrodynamic and geometrical conditions. The nozzle diameter and the separation distance between the nozzle and the specimen were varied in order to determine the optimal geometrical configuration, which leads to maximal erosion rate. The damaged specimens were investigated using optical and scanning electron microscopy (SEM). The obtained results – along with selected, previously published works from the literature – verify the analytically derived formulas, which emphasize the connection between the dimensionless standoff distance, and the cavitation intensity, potential energy, void fraction, and indicate the existence of an optimal dimensionless standoff distance for maximal erosion rate. Formulas to conveniently compare the efficiency of a cavitating jet based on energy consumption and dimensionless standoff distance are also presented and demonstrated. The influence of nozzle diameter and standoff distance on the kinetic energy and the specific energy consumption was clearly observed.

1. Introduction

In the design of hydraulic systems, the cavitation phenomenon is usually considered to be harmful and undesirable. Cavitation is characterized by the appearance of vapor bubbles, which appear within the flow due to the local pressure dropping below the vapor pressure of the working fluid. These formed bubbles at some point become unstable and collapse within the flow. The instabilities that occur due to bubble formation, oscillation and collapse can result in negative effects such as noise and structural damage to any component which is close to the collapsing bubbles. Cavitation is a common problem in hydraulic machines and related equipment such as turbines pumps and control valves – causing serious wear, tear and damage, its existence may lead to vibration and noise in hydraulic facilities. Under these circumstances, cavitation reduces the lifetime of components drastically. Moreover, if the cavitation bubbles replace a large volume of the liquid in a machine, performance or efficiency drop can be the result, as it frequently happens in pumps and turbines. These drawbacks of cavitation (noise, erosion and performance drop), explain why cavitation research is increasingly important for hydropower machines and equipment, pumps, turbines and valves.

Besides its obviously harmful effects, over the past few years, cavitating fluid jets have received considerable attention to understand their behavior and to determine the feasibility of using such jets for a variety of scientific and industrial applications, such as jet cutting, underwater cleaning, or for the improvement of the fatigue strength of materials [1–6]. Recently, these tests and efforts have proven that for certain applications the cavitating jet method (CAVIJET) could indeed be commercially attractive. The cavitating fluid jet is issued from one of several types of patented nozzles, each designed to stimulate the growth of un-dissolved gas nuclei,

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which exist in any fluid such as water, oil, or drilling mud. The jet subsequently carries the cavitation bubbles to the target surface, which is to be cleaned or cut. The high-pressure stagnation region causes the bubbles to collapse on or near that surface, creating concentrated, extremely high stresses over small areas in the order of micrometers. It is this localized amplification of pressure caused the cavity implosion, which provides the CAVIJET with the enhanced rates of cutting and cleaning compared to jets, which only utilize the stagnation pressure. This advantage of cavitating jets is practically useful with materials prone to cracking such as crustaceous marine life, brittle paint, cast explosives, and rocks. In such materials, the focused attack of cavitation stress impulses causes rapid fracturing which greatly enhances the erosive process. By contrast, materials lacking such brittleness, or relatively smooth and flawless surfaces, such as elastomers and wrought metals, are substantially more difficult to be eroded by cavitation. This natural selectivity of the cavitation erosion mechanism makes it useful for the cleaning of many surfaces without damage to the underlying substrate. Besides cleaning and cutting, cavitating jets can be used to either test the resistance of the materials to the cavitation damage, improve the mechanical properties of materials (e.g. shotless peening) or to modify the surface roughness of a material in the micro- or even nano level. As the cavitation bubbles collapse on the surface of specimen, the surface is deformed with time, which eventually leads to erosion and material removal, which can be quantified by measuring the weight loss in a given time [5–11].

The stages of cavitation damage are complex, especially the erosion phase, since it includes both hydrodynamic and material aspects. From the hydrodynamic point of view cavitation is characterized by the appearance of vapor bubbles in a liquid subjected to a sudden decrease in pressure below the vapor pressure corresponding to the liquid temperature. The collapse of vapor bubbles in the sub-cooled environment creates liquid micro-jets which can cause damage to solid surfaces [1–3,5,6,11].

The understanding and control of cavitation involves a multitude of geometrical, hydraulic and chemical factors, as well as thermodynamic parameters and material properties. A number of these parameters are extremely difficult to accurately quantify, although their influence is discussed in the literature. Generally it was found that, these tested parameters such as injection and downstream pressures, velocity, cavitation number, fluid temperatures, gas contents (dissolved gases in the working fluid) etc. has significant effect on the flow behavior, cavitation phenomenon and its side effects such as efficiency, vibration, noise and erosion etc. [5–11].

As well known, the fluid jet works by forcing a large volume of fluid through a small orifice in the nozzle. The constant volume of fluid travelling through a reduced cross sectional area causes the particles to rapidly accelerate. This accelerated stream leaving the nozzle impinges the material situated in its path. There are two kinds of liquid jets. One is called a free jet, which is surrounded by air with no cavitation occurring. The other kind which involves the cavitation phenomenon is called a high speed submerged cavitating jet, and it is normally produced by injecting high speed water into a water filled chamber. The cavitation clouds are appearing as a result of shear stress, which is exerted by the injection of the water and which takes place between the jet and the surrounding stagnant liquid [12–15]. Recently some modifications were made, based on the idea of the shear stress between fluids with different flow velocities, and the result was named cavitating jet in air. In this kind of cavitating jet generator, two concentric nozzles are used. In this artificial submerged jet cavitation is created by injecting a high-speed water jet into a concentric low-speed water jet. The big outer nozzle has flow with low pressure, while the inner one is a high pressure jet, thus the cavitation clouds appear due to the shear stress between the two jets [15]. Regarding the effect of hydrodynamic conditions, in the case of a submerged cavitating jet in a water filled chamber it was found, that the difference between the downstream pressure (i.e. the pressure in the test chamber) and the upstream pressure (i.e. injection pressure) is the most influential concerning the performance of the jet (shedding/discharging of cavitaion clouds). While, in the case of the cavitating jet in air, the injection pressure of the low speed jet might affect the overall performance of the jet [2,9,10,12,13,15,16].

However, when the hydrodynamic conditions are kept constant, geometrical parameters, such as the nozzle geometry and standoff distance are the most important factors which influence the jet shape, behavior and its performance. These geometrical factors play an important role in the cavitation damage process in both micro and macro level. In micro level previous works show the importance of the distance between the surface and the center of the collapsing bubble, where damage can be observed when the bubble is generated at a distance from a solid boundary, which is less than twice than its maximum radius [17].

In macro level, previous experimental works indicated that at fixed hydrodynamic working conditions geometrical factors such as the sample standoff distance (X, which is the distance between the nozzle outlet and target surface), nozzle outlet diameter (d) or the so called dimensionless standoff distance (X/d) severely influence the performance of the jet and thus the erosion rate or the effectivity of any surface treatment with cavitation [2,16,18,19]. Therefore the principal aim of our paper is to point out the importance of these geometrical parameters – especially the dimensionless standoff distance – regarding the performance of the cavitation jet, by analytically derived formulas, which are validated with several experimental results. Our derived formulas and the proposed methods, which are based on these, can help users optimize the performance of their cavitating jets by finding the optimal standoff distance.

2. Theory and mathematical derivation of the relation between X/d and Jet performance

Until now, many experimental studies on cavitating water jets have been made concerning many parameters, such as the driving pressure, nozzle geometry, exit jet velocity, cavitation number, and Reynolds number [4–6]. Even the frequency of shedding and the discharging of cavitation clouds could be determined based on the driving pressure and nozzle geometry, yet the structure of cavitating jets and the behavior of unsteady cavitation bubbles are unclear due to the difficulty of observing the interior of cavitating flows [12,20]. With the purpose of performance prediction and the efficient design of high-speed cavitating jet generators, much attention has been focused on the theoretical, experimental and numerical simulation of cavitating flows.

The standoff distance (X) is defined as the measured distance from the exit of the nozzle to the surface of the test specimen, which is an adjustable parameter in most cases. The aim of the work is to demonstrate theoretically and experimentally the major importance of the dimensionless standoff distance parameter (X/d, where X is the distance between the sample and the nozzle and d is the output diameter of the nozzle), which was used in tests with cavitating and non-cavitating jets in our previous works [16,21]. In the following section we discuss the parameters which effect the process of cavitation and show the influence of X/d on the erosion rate from a theoretical point of view.

Although in general the efficiency of any system is defined as the output relative to the input, our discussion will not cover the overall system but only the segment starting from the nozzle outlet to the target surface. Here the input is defined as the jet