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Experimental investigation of the cavitation characteristics of jet pump cavitation reactors with special emphasis on negative flow ratios

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ABSTRACT

The flow characteristics of jet pump cavitation reactors (JPCR) were experimentally investigated for various area ratio and flow ratios varying from the maximum to −1. The focus was on the cavitation area and cavitating flow pattern for low and negative flow ratios using high-speed photography and the pressure change characteristics. This work provides a thorough understanding of the fluid dynamics and structural characteristics during cavitation such as the flow ratio, pressure ratio, area ratio and cavitation area. The results indicate that the pressure ratio has crucial effect on the change of cavitation area in negative flow ratios. The cavitation can be divided into the downstream transport cavitation stage, reflux detention cavitation stage and reverse transport cavitation stage bounded by the transition flow ratios. The flow ratio ranges are given for the various cavitation stages for various area ratios which has a significant impact on the cavitation stage. Reverse transport cavitation will not occur in the JPCR for large area ratios. When the back pressure is higher than the inlet pressure, shear cavitation strengthens significantly leading to violent collapse of the cavity, which is of potential applications as a cavitation reactor.

1. Introduction

Cavitation is a phase transition between liquid and vapor occurring within the liquid inside or at the liquid-solid interface because of the power in the flow [1]. Cavitation occurs in all kinds of fluid machinery such as propellers [2], hydrofoils [3], venturi tubes [4], external gear pumps [5], vane pumps [6], and jet pumps [7]. The most important reason for why cavitation has attracted so much attention is its frequent occurrence and undesirable effects such as noise, vibrations, material damage and performance reductions [8–11]. Much research has been conducted using various methods to understand these complex two-phase flow. Most research still relies on experiments using water tunnels, tow tanks or venturi tubes [12–15]. Numerous measurement methods have been used for cavitation research such as high-speed photography [16], PIV [17], X-rays [18] and probes [19]. Numerical simulations have also been used to predict cavitation to verify experiments, forecast the onset of cavitation and other results beyond the ability of experiments [20,21].

Jet pump are simple fluid mechanical devices to transfer energy, mass and heat by means of turbulence diffusion. Traditionally, a jet pump is usually used as a delivery device or a vacuum pump. In these cases, cavitation must be avoided to ensure the jet pump works normally with high efficiency like many other hydraulic machinery, so the previous studies mainly focused on how to increase the efficiency and avoid cavitation. However, cavitation easily occurs in water jet pumps because of the high velocities and shear flows [22–24]. The collapse of cavitation bubbles can generate very unique and precious effects such as extremely high pressures and temperatures and even highly reactive free radicals locally without significant change of the ambient environment. In these cases, cavitation is useful in cavitation reactors in various fields including food engineering, bioengineering and sewage treatment [25–27]. Although jet pumps have potential as cavitation reactors, the flow characteristics require further study to intensify the cavitation.

There have been many studies to predict the performance of jet pump. Cunningham [28] developed a formula to predict the cavitation conditions of a jet pump based on one-dimensional theory. Lu and Shang [29] deduces a more comprehensive equation using quasi-two-dimensional theory. Kudirka and Decoster [30] found that the vapor bubble occurs inside the jet boundary which was confirmed by Ran and Katz [31] who validated that cavitation begins at the vortex center of the jet. Gopalan et al. [32] found that the instantaneous pressure in a

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Nomenclature

A	cross-sectional area
C_p	pressure coefficient
D	diameter
h	total pressure difference ratio
L	axial distance
m	throat to the nozzle exit area ratio
P	total pressure
p	static pressure
z	elevation
v	cross–sectional mean velocity
Q	volumetric flow rate
q	flow ratio

Greek symbols

α	suction chamber angle
β	diffuser angle
ρ	density

Subscripts

n	nozzle exit
l	liquid
in	primary flow inlet
out	diffuser outlet
s	suction pipe
th	throat

small vortex is much lower than the average pressure in free non-submerged jets and that the initial cavitation area overlaps the vortex. Ooi [33] found that cavitation occurs in the vortex structure downstream instead of the center of the quasi-ordered structure at the nozzle outlet. Straka et al. [34] found that cavitation occurs near the nozzle outlet at a position corresponding to the vortex location. Pan and Peng [1] found that cavitation occurs not only near the nozzle outlet but also between the vortex pair downstream. Long et al. [7,35,36] divided the cavitation in a jet pump into the initial cavitation stage, developing stage, unstable limited cavitation stage and stable limited cavitation stage and experimentally investigated the influence of the area ratio and inlet pressure on the cavitation intensity in jet pump. Xiao and Long [37] studied the instantaneous pulsation characteristics of a cavitation cloud in an annular jet pump. Long et al. [38] found that absorbed gas can reduce the cavitation and the noise and vibrations caused by cavitation. However, this condition must be avoided in a cavitation reactor.

Thus, previous research has mainly focused on normal operating conditions for a jet pump, with few studies of reversed flow conditions. Normal operating conditions refer to the suction flow in the jet pump being greater than zero. For these conditions, the jet flow in the nozzle entrains the suction flow and the mixed fluid flows downstream through the throat. Reversed flow conditions refer to the suction flow jet pump being less than zero. In this case, the flow sprays into the throat and then flows backwards into the suction chamber, so the flow direction is opposite to that for the normal operating conditions. In general, the local pressure at a point in a jet pump can be divided into the average pressure and the fluctuating pressure. When the local pressure approaches the vapor pressure, the flow is vulnerable to cavitation. For low and negative flow ratios, the suction flow velocity is very small and may even be in the opposite direction to the jet flow. The velocity gradient is then so large at the nozzle exit that the shear is very intense in the jet flow. Kelvin-Helmholtz instability theory states that the shear layer is very unstable, which give rise to the Kelvin-Helmholtz waves that contain many vortexes [39]. The vortexes significantly expand the fluctuating pressure amplitude; thus, the local pressure can decrease to the vapor pressure for an instant even when the average pressure is still much higher than the vapor pressure. Cavitation then occurs as in the flow behind a multi-orifice plate [40]. Violent cavitation in a jet pump for these conditions can be useful if well understood. In addition, jet pump with different area ratios has different cavitation characteristics, which need to be further understood.

Therefore, the present study presents a series of experiments conducted to obtain more understanding of the flow characteristics in JPCR for low and negative flow ratios. The JPCR global characteristic curves are given for various area ratios and various inlet pressures. The cavitation areas and cavitating flow patterns are investigated using high-speed photography with measurements of the pressure change characteristics for the same conditions.

2. Experiment setup

2.1. JPCR structures

A JPCR includes an inlet pipe, nozzle, suction chamber, throat and diffuser, as shown in Fig. 1. The high pressure inlet flow passes through the nozzle exit at high speed with suction flow entrained due to the low pressure in the suction chamber. The two flow streams mix intensively in the throat and then flow out through the diffuser with some pressure recovery. In general, there is no cavitation in a traditional jet pump which is referred to as the no cavitation stage. The suction flow increases to maximum as the outlet pressure decreases which also leads to cavitation, which can be divided into various cavitation stages. As the outlet pressure increases, the suction flow rate decreases from the no cavitation stage and can even become negative flow with cavitation again appearing but with variations which need further study.

The JPCR performance can be characterized by the area ratio (m), flow ratio (q), and pressure ratio (h) defined as follows.

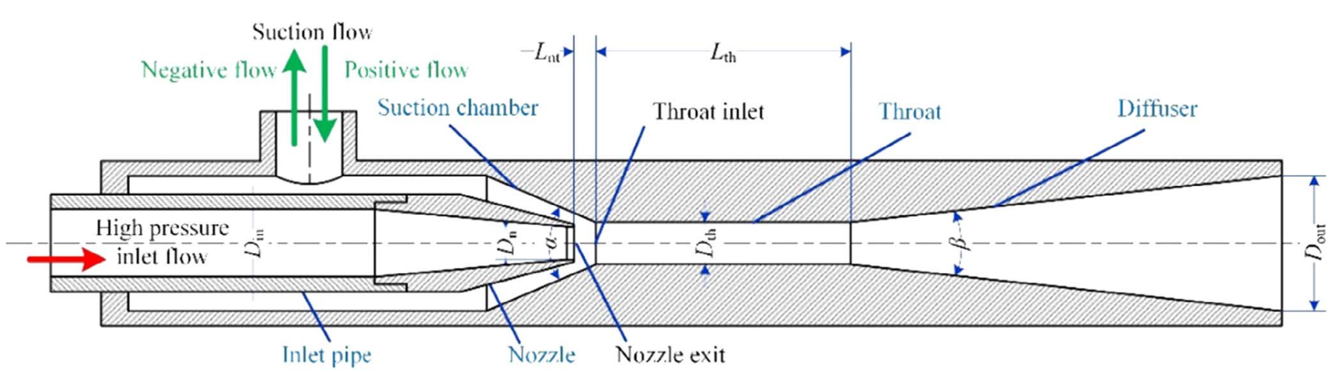

Fig. 1. Schematic drawing of JPCR.