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Experimental investigation on the performance of jet pump cavitation reactor at different area ratios

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A B S T R A C T

The present study considered a jet pump as a cavitation reactor for potential applications. Experiments were conducted on three jet pump cavitation reactors (JPCR) with three area ratios ($m = 1.78$, 2.56, 4.00) under varying operating conditions to achieve some guidance for the design and the choice of operating conditions for practical application of JPCR. As the outlet pressure decreases, the flow rate ratio increases until it reaches the cavitating flow rate ratio. Using the cavitating flow rate ratio as a boundary, the flow states can be divided into two stages, viz., the normal stage and the limited operation stage. In the normal stage, the cavitation in the JPCR is still in absence or too weak for application. In the limited operation stage, the flow rate ratio reaches the cavitating flow rate ratio and will not increase any further. Cavitation at this stage is very drastic in the form of cavity cloud and is of potential value for application. Smaller area ratio leads to smaller cavitating flow rate ratio, larger area of low pressure along the throat, larger critical nozzle cavitation number and suction cavitation number, all of which indicate that the JPCR has more effortless access to the limited operation stage. Increasing the inlet pressure will also make it easier for the JPCR to generate intense cavitation. In addition, the adjustable ranges of the inlet and outlet pressures that guarantee the limited operation stage increase with decreasing area ratio. The critical pressure ratio of the inlet pressure and outlet pressure, which indicates the beginning of violent bubble collapse stage, is irrelevant to the inlet pressure but linearly relates to m to the negative one-half power.

1. Introduction

Cavitation is an important mass transfer phenomenon and is generally defined as the inception, growth and subsequent collapse of micro-bubbles or cavities due to very low local pressure or high pressure fluctuation in a liquid [1]. Cavitation is an extremely complex phenomenon which is not yet fully understood. Thus, research on cavitation is of very high academic and application value, which attracts many scholars to design experiments on some typical structures to investigate cavitation, such as hydro foil [2,3], venturi type [4,5], and orifice [6,7]. In general, cavitation causes undesirable effects such as generation of vibration and noise, erosion and material damage [8–10]. However, physical or chemical transformation using the cavitation phenomenon, viz., cavitation reactor, is also a well-established concept. In fact, cavitation reactors have found widespread application in the areas of chemical processing, water treatment, biotechnology, crystallization, petroleum industries, etc. [11,12]. The violent collapse of micro bubbles or cavities results in the generation of extremely high temperatures and pressures locally, with the overall environment being that of normal ambient condition [13], and it can take place at millions of locations in a reactor simultaneously. Thus, physical and chemical processing requiring stringent conditions can be effectively carried out using cavitation under ambient conditions. Moreover, the generation of highly free radicals, local drastic turbulence and liquid micro-circulation can result in the intensification of various physical and chemical operations [14].

According to the principle of generation, cavitation is generally classified into four types: hydrodynamic cavitation, acoustic cavitation, optic cavitation and particle cavitation. However, only acoustic and hydrodynamic cavitation are found suitable for physical or chemical processing applications [15,16], because the required intensity of cavitation can be obtained. Acoustic cavitation reactors have been investigated over the years [17–19], but

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Nomenclature

A	cross-sectional area
C_p	pressure coefficient
D	diameter
h	ratio of total pressure difference
L	axial distance
m	area ratio of the throat and the nozzle exit
P	total pressure
p	static pressure
p_r	pressure ratio of outlet pressure and inlet pressure
$\bar{p}$	time-averaged pressure
p'	fluctuating pressure
p_v	saturation vapor pressure
Q	volume flow rate
q	flow rate ratio
q_c	cavitating flow rate ratio
v	cross-sectional mean velocity

Greek symbols

α	angle of suction chamber
β	angle of diffuser
η	efficiency
ρ	density
σ	cavitation number

Subscripts

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

their utilizations in large scale applications are still not available [20]. Hydrodynamic cavitation reactor, with careful design to avoid the erosion of surfaces, has been a comparatively recent advent. Hydrodynamic cavitation reactors usually use a multi-orifice plate, venturi tube, and high-speed or high-pressure homogenizer as the cavitation generator [21–26]. Compared with acoustic cavitation reactors, hydrodynamic cavitation reactors have been shown to be much more energy efficient for applications [27]. For some certain applications, the energy efficiency, viz., the cavitation yields per unit energy of the hydrodynamic cavitation reactor, can be one or even two orders of magnitude higher than that of the acoustic cavitation reactor [16,28]. Thus, hydrodynamic cavitation reactor is a more potential application for physical and chemical processing, and the tendency of the design of hydrodynamic cavitation reactor is to make the generation of cavitation in the reactor as easy as possible.

Multi-orifice plates and venturi tubes are the most commonly used hydrodynamic cavitation reactors. Cavitation in reactors using multi-orifice plate is shear cavitation induced by shear flow due to the high velocity gradient [6,7,29]. In reactors using venturi tube, cavitation is caused by the surge of velocity, which reduces the local pressure to the critical pressure owing to the sharp decrease of the flow channel section area [30,31]. The integrated utilization of these two mechanisms can predictably make cavitation more effortless to be generated. The jet pump is such a device whose principle of cavitation generation can be considered as the combination of these two mechanisms owing to its special structure. The conception of using the jet pump as the cavitation reactor follows the tendency of the design of hydrodynamic cavitation reactors. Predictably, the jet pump is of more potential as a cavitation reactor. However, the use of a jet pump as a cavitation reactor is still unreported except for our granted patent [32]. Before the application in any physical/chemical processing, the performance of the jet pump as a cavitation reactor must be studied carefully, which is of particular concern in this study.

Several theoretical studies have been conducted to predict the performance of jet pump. Cunningham [33] put forward the calculation formula of the cavitation condition of a jet pump based on the one-dimensional theory. Lu [34] deduced a more comprehensive equation using the quasi-two-dimensional theory. More studies were concentrated on the flow mechanism of cavitation in jet pump. Kudirka [35] suggested that the vapor bubble first occurs inside the jet boundary. Ran's [36] experimental result confirmed Kudirka's suggestion and validated that the cavitation inception appeared at the vortex center of the jet. Xiao [37] then considered the vortexes to be induced by the shear layer based on visualization of cavitation captured by a high speed camera. Long [38] noted that the adverse pressure gradient caused by the convergent suction chamber was another reason for cavitation inception, he divided the cavitation stages into four stages, viz. the incipient cavitation, developing cavitation, intensive cavitation, and intensive two-phase cavitation under the operating limit, based on the images captured. Following Long's research, Wang [39] conducted further study on the propagation characteristics of the closure region of the cavity cloud in a jet pump with experiments. These studies were mainly concentrated on the mechanisms of the cavitation inception and the cavitation flow due to the aim was to seek methods to restrain the occurrence of cavitation. Even some supplementary measures, such as air supply [40,41], were explored to destroy cavitation. However, when a jet pump is used as a cavitation reactor, the aim is to the contrary. The cavitation inside must be developed cavitation with sufficient intensity so that it can be utilized in physical/chemical processing. The cavitation intensity in the jet pump used as a cavitation reactor and its influence factors should be investigated, which is the necessary pioneer work before its application.

Therefore, series of experiments were conducted to gain a more comprehensive understanding of the jet pump as a cavitation reactor. The influences of area ratios and inlet pressures on the cavitation intensity were analyzed. By monitoring the static pressures along the jet pump, the pressure distribution characteristics were studied. Two cavitation numbers were defined to investigate the cavitation performance. The adjustable ranges which can guarantee intense cavitation were also explored. The critical pressure ratio is proposed to judge the beginning of the violent bubble collapse stage, and its calculation formula was sorted out. This study will enhance the knowledge of the application of hydrodynamic cavitation reactors and is especially important for the jet pump cavitation reactor from the design to the choice of operation conditions.

2. The principle and design procedure of JPCR

2.1. The principle of JPCR

The structure of a JPCR is based on the conventional jet pump which mainly consists of five parts, namely, inlet pipe, nozzle, suction chamber, throat and diffuser, as shown in Fig. 1. The high pressure primary flow runs through the nozzle exit with very high