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Experimental investigation on liquid absorption of jet pump under operating limits

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ABSTRACT

To realize the automatic quantitative control of liquid absorption, a jet pump working under operating limits is proposed and investigated. Experimental results show that the absorption amount keeps constant and is independent of the outlet pressure at the jet pump operating limits. There is an obvious interface wave in the jet pump, and the reason why the upstream pressures have not changed is because the interface wave has not arrived there. The critical pressure ratio is 0.28 at the flow ratio of 0.5%, while it is only 0.2 at the flow ratio of 19.5%. Hence, the low flow ratio produces a high critical pressure ratio, making the jet pump have a much stronger resistibility for dealing with the downstream pressure fluctuation. In addition, the jet pump has a larger bubble region length at a lower flow ratio under operating limits. The bubble diameter decreases from 0.42 mm to 0.06 mm with the flow ratio increasing at the throat cavity, while it keeps unchanged at the suction cavity, which creates a good condition for stable liquid absorption. Based on the above contributions, it is believed that the study will lay an important foundation for the large-scale application of jet pump used for automatic quantitative control.

1. Introduction

The technology of automatic quantitative control of liquid addition proportion is in a great need in many engineering fields. The conventional method of getting quantitative proportion is using the metering pump, which is not only structure complex but also cumbersome and high cost [1]. Moreover, the metering pump has potential electric leakage risk that is a fatal danger when used in some explosive places like fuel gas field or underground coal mines [2,3]. Jet pump is one kind of fluid machinery and mixing equipment that absorbs liquid automatically under the action of negative pressure [4]. With advantages of no moving parts, low maintenance, simple compact and easy to install [5], it has been widely used in oil and gas industry for producing suction to increase their production [6,7] and in the desalination of water [8,9]. However, since the liquid absorption is closely related to the negative pressure formed in the jet pump, which is affected by the downstream pressure [10], the absorption amount and proportion are variable when the downstream pressure changes.

To control the working flow precisely, many scholars have researched the cavitating venturi, which composes of a convergent nozzle, a throat and a diffuser, with a similar structure to the jet pump. When used in the rocket propulsion system, it can keep the propellant mass flow rate fixed even though the downstream pressure changes rapidly due to the start-up transient or combustion oscillations [11,12]. Taking advantage of this characteristic, the cavitating venturi was used as flow controller and flow meter with a high degree of accuracy in a wide range of mass flow rate [13]. Through keeping the upstream pressure constant and designing an 11 mm cavitating venturi, Ulas [14] provided a constant mass flow rate independent of the downstream pressure. Based on Ulas' study, Abedini [15] investigated the performance of cavitating venturi and observed a vapor–liquid flow in the device through changing the downstream pressure continuously. The critical pressure ratio was found about 0.9 when the mass flow ratio changed, which was a little higher than the critical value proposed by Abdulaziz and Dale [16,17].

However, there was no liquid absorption mentioned in the cavitating venturi/jet pump in the previous research. According to

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Kudirka' study [18], the jet pump sucked liquid under operating limits and the flow ratio was independent of the outlet pressure when it decreased to 0.1–0.2. Wang [19] designed a parallel jet adding device and found that the absorption amount was invariant when the vacuum degree reached −0.09 MPa, and a similar conclusion was also drawn by Lu [20]. Considering the cavitation adverse effect, including a sharp drop-off in efficiency, acoustic noise, component vibration and mechanical erosion [10,21], they did not use the critical condition. It was reported that the jet pump operating limit was once used to add coagulant automatically in underground coal mines [2,22]. The field operation was simple and convenient with a certain addition proportion. However, the further research on the jet pump operating limits was not mentioned.

Therefore, the performance of the jet pump operating limits was investigated and evaluated in the present paper. A purpose-built experimental testing system is used to monitor absorption amount, outlet pressure, pressure distribution and bubble region. From the experiment, we obtained the pressure characteristic of the jet pump operating limits and observed a liquid–gas interface wave on the liquid absorption process. Since the jet pump operating limits produce some cavitation inevitably, it is recommended that the anti-cavitation material is chosen to manufacture jet pump to weaken the cavitation adverse effect.

2. Design and theoretical analysis of jet pump

2.1. Design of jet pump

Fig. 1 illustrates the structural view of jet pump. It consists of a convergent nozzle and a mixing chamber. The flow process in the convergent nozzle is assumed to be one dimensional isentropic flow. The density is assumed to be constant and equal to the liquid density at the operating temperature. Accordingly, the Bernoulli's equation between Sections 1-1 and 2-2 can be written as:

$$\frac{P_1}{\rho} + \frac{v_1^2}{2} = \frac{P_2}{\rho} + \frac{v_2^2}{2} \tag{1}$$

where P_1 is the inlet pressure, Pa; P_2 is the nozzle exit pressure, Pa; v_1 is the inlet velocity, and v_2 is the nozzle exit velocity, m/s; ρ is the liquid density, kg/m^3; Since v_1 is far less than v_2, v_1 is neglected. Then the nozzle diameter can be expressed as:

$$d_2 = \sqrt{\frac{4m}{\pi\sqrt{2\rho(P_1 - P_2)}}} \tag{2}$$

where m is the mass flow rate, kg/s.

To produce operating limits, the nozzle exit pressure P_2 should reduce to the water saturated vapor pressure, which is about −97 kPa–(−99 kPa) [13,14]. Here, the inlet pressure P_1 is taken as 500 kPa and the mass flow rate m is taken as 0.44 kg/s (1.6 m^3/h). If all these values are inserted in Eq. (2), the nozzle exit diameter d_2 is calculated as 4.0 mm. The throat diameter d_3 and throat length L_{th} are taken as 6.0 mm and 20.0 mm, respectively. Referring to related studies [14,23], a converging angle α of 13.30° and a diverging angle β of 14° are taken for minimum pressure losses.

2.2. Pressure distribution along the jet pump

Masses of bubbles are produced in the jet pump under operating limits, while they coalesce and break with moving downstream [24]. As shown in Fig. 1, a liquid–gas interface forms between the bubble region in the upstream and liquid region in the downstream, and so the pressure distribution along the jet pump should be divided into two parts by the interface. In the upstream, the bubble pressure is close to the water saturated vapor pressure. The downstream liquid is still taken as one dimensional isentropic flow, so the Bernoulli's equation between Sections 3-3 and any Section x-x in the downstream can be expressed as:

$$\frac{P_x}{\rho} + \frac{v_x^2}{2} = \frac{P_d}{\rho} + \frac{v_d^2}{2} + \xi\frac{v_d^2}{2} \tag{3}$$

According to the continuity equation:

$$(1+q)m = \rho v_d A_d = \rho v_x A_x \tag{4}$$

where q is the flow ratio of absorption amount and working flow rate; P_x is the pressure at Section x-x, Pa; P_d is the pressure at Section 3-3, Pa; A_x is the area of Section x-x, m^2; A_d is the area of Section 3-3, m^2; v_d is the outlet velocity, and v_x is the velocity of Section x-x, m/s; ξ is the resistance loss coefficient.

Substituting v_x and v_d calculated from Eq. (4) into Eq. (3), we can get:

$$P_x = P_d - \frac{m^2}{2\rho}\left(\frac{1}{A_x^2} - \frac{1+\xi}{A_d^2}\right)(1+q)^2 \tag{5}$$

Substituting the mass flow rate m from Eq. (2) into Eq. (5), we can get:

$$P_x = P_d - \frac{\pi^2 d_2^4}{16}\left(\frac{1}{A_x^2} - \frac{1+\xi}{A_d^2}\right)(P_1 - P_2)(1+q)^2 \tag{6}$$

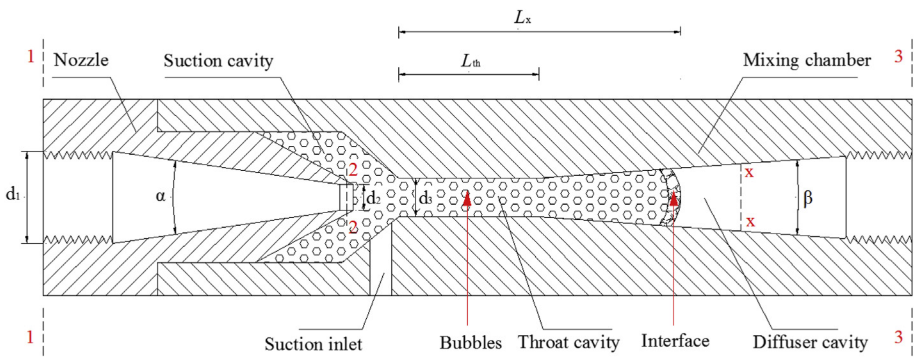

Fig. 1. Structural view of the jet pump.