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Criteria for jet cavitation and cavitation jet drilling

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ABSTRACT

The research history of cavitation jets is reviewed, and a mechanism that explains cavitation, methods to measure when cavitation occurs and factors that affect cavitation are introduced. The rationality of the cavitation number, which is often used to predict cavitation, is discussed. The results show that cavitation cannot be predicted using the cavitation number. The problems with the Rayleigh equation in calculating the impulse pressure under an annihilation of a cavity for explaining that a cavitation jet having more power to break rocks than that of a common jet are analyzed. A new explanation is suggested: the rock surface pressure pulses due to density changes in the cavitation jet, which makes the cavitation jet more effective. Because the static pressure at the bottom of the well is extremely high and cavitation only occurs at the vapor pressure, the pressure in the nozzle must decrease from the static pressure to the vapor pressure. Reducing the pressure in the nozzle from the static pressure to the vapor pressure is extremely difficult, and thus, much work is still required before cavitation jet drilling can be used in a practical application.

1. Research history of cavitation and cavitation jets

Great progress has been made on theory of cavitation and its applications since the cavitation phenomenon was discovered on the propeller blades in the 1850s. Although mechanisms behind cavitation and its erosive action are still uncertain, the destructive ability of cavitation is clearly detailed. With the further development of hydro-energy resource exploration, a large number of dams are being built in succession. During the operating process, high-speed flows easily result in cavitation, and the resulting erosion seriously influences the normal operation and can even result in catastrophic failures. Therefore, many studies have been performed in the fields of mechanics and hydraulics [1,2]. Subsequently, the concept of cavitation was introduced into the field of hydraulic jets by Conn [3], Johnson [4,5] and Kohl et al. [6,7], and afterwards, hydraulic cavitation jet technology was first developed. A cavitation jet was produced first by Johnson et al. [1,4,5] using a central nozzle and a spinner nozzle, which is the classic cavitation nozzle. Then, an audio-frequency, self-vibrating cavitation hydraulic jet nozzle was developed by the same authors on the basis of hydroacoustics, among which are two familiar types of nozzles, the labial nozzle and the Helmholtz quiver cavity nozzle. It is considered that the nozzle can produce strong cavitating jet, even in very deep down holes. Afterwards, a drilling nozzle with a self-vibrating cavitation jet was developed by The China University of Petroleum based on the theory of transient flow and the principle of hydroacoustics, where field tests showed good results [8–16]. This paper attempts to determine (1) if the cavitation number can predict the jet cavitation condition or not and (2) the reason making drilling rata fast while using self-vibrational cavitation jet drilling nozzle.

2. Mechanisms behind cavitation

Cavitation is a phenomenon of micro-bubbles (or gas nuclei) rapidly expanding due to liquid evaporating in a local low-pressure area (the pressure is less than the saturated vapor pressure at the current temperature) in a liquid system [2]. Liquid is not typically pure in nature; there are many tiny impurities, such as solid particulates, microbes and micro-bubbles. The radii of the micro-bubbles, referred to as vapor nuclei or cavitation nuclei, are generally less than 20 μm. When the environmental pressure is less than the saturated vapor pressure at the current temperature, the nuclei begin to expand, and cavitation occurs; when the environmental pressure is higher than the saturated pressure, the bubbles are annihilated. Fig. 1 shows cavitation occurring in a convergent-divergent tube. In Fig. 1, p_1 and p_2 are the upstream absolute pressure and the downstream absolute pressure, respectively, and v_2 is the downstream velocity. In the contracted part, p_c is the absolute pressure, and v_c is the velocity.

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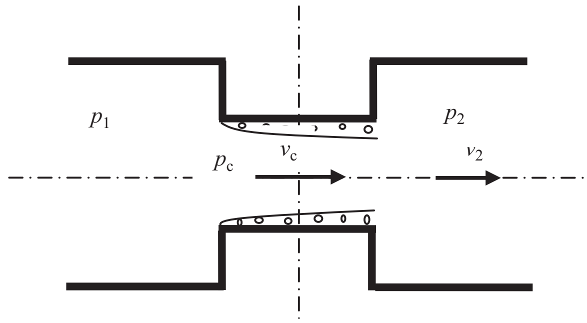

Fig. 1. Cavitation in a convergent–divergent tube.

Cavitation occurs when $p_c \le p_v$ (p_v is the absolute saturated vapor pressure of the liquid at the current temperature).

3. Measures of cavitation

Cavitation is primarily measured in the following ways [2]: (1) observing the flow field using the naked eye; when cavitation occurs, there are bubbles in the flow field that can be seen with the naked eye. (2) Detecting supersonic waves produced by cavitation bubbles in the flow field; when bubbles in the flow field are annihilated, supersonic sound is produced. (3) Detecting the photon quantum intensity captured by an electric eye passed through the flow field. (4) Use of the absorption capacity difference for γ-ray between water and bubbles. (5) Analyzing the shape of the cavitation bubble formed in the water by a laser. (6) Using the difference of schlieren between water and the cavitation bubble under a light source. At present, visual observation and noises analysis are commonly used.

4. Factors that influence cavitation

The primary factors that influence the beginning and development of cavitation in water are the border shape of the flow, absolute pressure and flow velocity (see Fig. 1). Other factors include the liquid viscosity, surface tension, gas nuclei, vaporization property, impurity of water, surface environment of the wall and pressure-gradient [2]: (1) The influence of the liquid viscosity is actually the influence of the Reynolds number, which is related to boundary layer separation and affects the position of the minimum pressure position on the wall. (2) When cavitation bubbles are annihilated, surface tension increases the velocity and decreases the frequency and amplitude of the vibrations. (3) Although many particulates exist in a liquid system, it is the micro-bubbles that affect the occurrence and development of cavitation and not micro-solids or organic microorganisms. (4) The roughness of the wall plays an important role in the beginning and development of cavitation. Generally speaking, cavitation occurs more easily when the wall is rough than when it is smooth because flow is separated more easily behind a rough convex, which makes the negative pulse increase. (5) The distribution of the pressure directly influences the beginning of cavitation because cavitation is only caused by low pressure. (6) Because a high molecular polymer affects the flow profile and restrains the pulse phenomenon of the boundary layer, the cavitation number consequently decreases. (7) The thermodynamic characteristics of the liquid influence the beginning of cavitation; cavitation occurs when the liquid pressure is equal or less than its vapor pressure, which is a function of the temperature.

5. Criterion of cavitation

5.1. Existing theory—Cavitation number

The critical state at which the first tiny cavity randomly appears in a small area of the flow field when the flow velocity is fixed and the pressure decreases (or the pressure is fixed and flow velocity increases) is denoted as a cavitation occurrence. In actual applications, whether to prevent or to use cavitation, the conditions of cavitation must be given attention. Although there are many factors that influence cavitation, the absolute pressure and flow velocity are the most dominant factors. Thus, absolute pressure and flow velocity are used to define the cavitation parameter.

In classical cavitation theory, the saturated vapor pressure is regarded as the critical pressure at which cavitation occurs in a liquid system. The cavitation number is defined as [2,6]

$$\sigma = \frac{p_2 - p_v}{\rho v_c^2/2} \tag{1}$$

where σ is the cavitation number, p_v the saturated vapor pressure of the liquid at the current temperature and ρ is the liquid density.

For a submersed jet with a high environmental pressure, because p_2 is much greater than p_v in Eq. (1), p_v can be neglected. Using the expression, $\rho v_c^2/2 = p_1 - p_2$, the cavitation number can be expressed as [6]

$$\sigma = \frac{\text{Downstream pressure}}{\text{Total pressure drop of nozzle}} = \frac{p_2}{p_1 - p_2} \tag{2}$$

Cavitation should occur if $\sigma \le 1$ and should be steady when $\sigma \le 0.5$. Even if the environmental pressure is on the order of several dozens of MPa, if the jet-velocity is large enough, cavitation should occur [2,10].

5.2. Existing problems

There is a large scatter in cavitation number in actual applications, i.e., the cavitation number cannot be used to accurately determine if cavitation will occur. In hydromechanics, the energy balance and continuity equation are

$$\begin{aligned} &P_c + \frac{1}{2}\rho v_c^2 = P_2 + \frac{1}{2}\rho v_2^2 + \frac{\xi}{2}\rho v_c^2 \\ &A_c v_c = A_2 v_2 \\ &\xi = \left(1 - \left(\frac{A_c}{A_2}\right)\right)^2 \end{aligned} \tag{3}$$

where ξ is the local drag coefficient of the cross-section of the abruptly expanding tube, A_c is the area of the cross-section of the contracted tube, and A_2 is the area of the cross-section downstream of the tube. Consequently,

$$p_c = p_2 + \rho v_c^2 \left[\left(\frac{A_c}{A_2}\right)^2 - \left(\frac{A_c}{A_2}\right) \right] \tag{4}$$

If $A_c/A_2 = 0.5$ is assumed, then p_c is at its minimum when

$$p_c = p_2 - \frac{1}{4}\rho v_c^2 \tag{5}$$

Certainly, this result is derived under the optimal condition of the cavitation structure. When the cavitation number $\sigma = 1$, then $p_2 = p_v + (\rho v_c^2/2)$ and $p_c = p_v + (\rho v_c^2/4) > p_v$, and cavitation would not occur. When the cavitation number $\sigma < = 0.5$, then $p_2 < = p_v + (\rho v_c^2/4)$ and $p_c < = p_v$, and cavitation would occur because the physical requirements are satisfied.

Therefore, when using the cavitation number to determine if cavitation will occur, two requirements must be satisfied: (1) $A_c/A_2 = 0.5$ and (2) $\sigma < = 0.5$. Thus, from this result, the cavitation number has no value in universal application.