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RESEARCH PAPER

Bubble dynamics characteristics and influencing factors on the cavitation collapse intensity for self-resonating cavitating jets

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Abstract: Based on bubble dynamics theory, a mathematic model describing the cavitation bubble size variation in the flow field of self-resonating cavitating jet was developed considering the pressure field and mass and heat exchange between cavitation bubble and ambient fluid. With this model, the influence factors on the cavitation intensity are investigated. The results show that the destructiveness of cavitating jet in breaking rocks depends on the bubble's first collapse, with decreasing intensity in the subsequent collapses. The self-resonating effect significantly enhances the cavitation intensity by promoting the collapse pressure and elongating its duration. Hydraulic parameters are proven to be the dominating factors influencing cavitation intensity: while collapse intensity monotonously increases with jet velocity, there exists an optimum ambient pressure where highest collapse intensity can be achieved. Conversely, the fluid properties show minor influences: cavitation intensity only slightly decreases with the increasing of fluid's density and barely changes with the variation of viscosity and surface tension. The results from this investigation help to uncover the mechanism of the enhanced erosion potential of self-resonating cavitating jet. The conclusions can be used to further improve the performance of self-resonating cavitating jet in field applications.

Key words: self-resonating cavitating jet; cavitating bubble; collapse intensity; hydraulic parameters; fluid properties

Introduction

Based on transient flow and hydroacoustic theory, self-resonating cavitating jet (SRCJ) technology modulates jet flow field to strengthen the coherent structures originated in the jet's shear layer. That strengthening leads to larger pressure drop inside the vortices and thus promotes stronger cavitation inception in situ[1]. As the collapse of cavitation bubble emits enormous pressure pulse and temperature peak, the jet's erosion potential can be significantly enhanced[2]. This technology has been widely used in petroleum engineering including oilfield drilling[3, 4], formation plugging removal[5], halite cavity construction[6], and water injection[7]. A series of patented tools have been developed and the operation procedures involving this technology have been standardized[8]. Field application demonstrated that SRCJ increases ROP by 40.7% on average [9] and enhances rock permeability by 45%[10], showing its superior treatment efficiency. Previous researches about SRCJ generally cover the nozzle design, rock erosion efficiency evaluation, and application optimization. Whereas, there are no reports about cavitation bubble dynamics, especially details about the collapse process, in the flow field of SRCJ. The variation of cavitation intensity under different jet hydraulic conditions and drilling fluid properties is also unclear. These issues are crucial for understanding the mechanism of enhancing jet's erosion potential by cavitation effect and predicting the treatment efficiency of SRCJ in different application conditions. These issues are examined in this study and the results can be used for optimizing designs of this technology in field applications.

1. Mathematical model for cavitation bubble dynamics

1.1. Bubble dynamic equation

To describe the variation of bubble radius R with the pressure outside the bubble $p(t)$, the Keller-Miksis equation was adopted[11]:

$$\left(1-\frac{\mathrm{d}R}{\mathrm{d}t}\frac{1}{c}\right)R\frac{\mathrm{d}^2R}{\mathrm{d}t^2}+\frac{3}{2}\left(1-\frac{\mathrm{d}R}{\mathrm{d}t}\frac{1}{3c}\right)\left(\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2=\left(1+\frac{\mathrm{d}R}{\mathrm{d}t}\frac{1}{c}\right)\times \frac{p_{\mathrm{b}}(t)-p(t)}{\rho}+\frac{R}{\rho c}\frac{\mathrm{d}p_{\mathrm{b}}(t)}{\mathrm{d}t}-\frac{4\mu}{\rho R}\frac{\mathrm{d}R}{\mathrm{d}t}-\frac{2S}{\rho R} \tag{1}$$

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It assumes that the bubble maintains sphericity during variation and considers the influences of fluid density ρ, viscosity μ, surface tension S, and fluid compressibility. For water, these parameters were taken as: $\rho=1.0\times10^3$ kg/m^3, $\mu=0.798\times10^{-3}$ P·s, $S=0.072$ N/m, $c=1481$ m/s.

The gas inside the bubble consists of air and other gases besides water vapor. These gases enter the bubble by diffusion during bubble inception and expansion and are treated as non-condensable during bubble variation. The pressure inside the bubble p_b was determined using the van der Waals state equation:

$$p_{\mathrm{b}}=\frac{\left(N_{\mathrm{va}}+N_{\mathrm{nc}}\right)R_{\mathrm{g}}T}{\frac{4\pi}{3}\left(R^3-h^3\right)} \tag{2}$$

where h is the van der Waals hard core radius, $h=R_0/8.86$, and R_g is the gas constant. The temperature T is affected by heat transfer mode between the bubble and the outside flow field. The quantities of water vapor N_{va} and non-condensable gas N_{nc} vary due to the mass change with the ambient fluid, and were calculated by the heat transfer and mass transfer equations below.

1.2. Heat transfer between cavitation bubble and ambient fluid

It is generally accepted that the bubble translation velocity is much smaller than the inward velocity of bubble wall during collapse. Thus the heat convection between the bubble and the surrounding fluid was ignored in the calculation. Heat conduction and radiation were determined with the model proposed by Qin et al.[12]. Their model simplifies the conduction as the heat transfer between two plane surfaces separated by a water layer. The layer thickness is taken as the bubble radius. For calculating the heat transfer due to radiation, the Stefan-Boltzmann law was employed. Taking the above two heat transfer processes into consideration, the temperature variation inside the bubble during the time step Δt is calculated as:

$$\Delta T=\frac{1}{C_{\mathrm{va}}N_{\mathrm{va}}+C_{\mathrm{nc}}N_{\mathrm{nc}}}\left[-p_{\mathrm{b}}\Delta V-\frac{\kappa A\left(T-T_{\infty}\right)}{R}\Delta t-e\sigma A\left(T^4-T_{\infty}^{\ 4}\right)\Delta t\right] \tag{3}$$

where C_{va} and C_{nc} is the specific heat of water vapor and non-condensable gas, respectively. κ is the thermal conductivity, $\kappa=0.6$ W/(m·K) , and e is the emissivity, $e=0.95$. σ is the Stefan–Boltzmann constant, $\sigma=5.67\times10^{-8}$ W/(m^2·K^4).

1.3. Mass transfer between cavitation bubble and ambient fluid

During bubble expansion, water vaporization occurs on the wall due to the lowered pressure inside the bubble. Conversely, the vapor will condense into water and expel out of the bubble in the bubble collapse process. The quantity of non- condensable gases also changes as a result of mass transfer due to the concentration unbalance inside and outside of the bubble. To account for the mass change of both water vapor and non-condensable gases inside the bubble, the quantity of gas is updated in the calculation. Storey and Szeri[13] proposed that the mass transfer was dominated by diffusion for cavitation bubbles and could be described as:

$$\frac{\mathrm{d}N}{\mathrm{d}t}=4\pi R^2 D\frac{C_{\mathrm{wi}}-C_{\mathrm{i}}}{l_{\mathrm{d}}} \tag{4}$$

where D is the diffusion coefficient. $D=2.8\times10^{-6}$ m^2/s and 2.5×10^{-9} m^2/s for water vapor and non-condensable gases, respectively. l_d is the diffusion length and is calculated by:

$$l_{\mathrm{d}}=\min\left(\sqrt{\frac{RD}{\left|\mathrm{d}R/\mathrm{d}t\right|}},\frac{R}{\pi}\right) \tag{5}$$

1.4. Calculation and initial conditions

The calculation model introduced in Section 1.1–1.3 is closed by the 5 equations. Solving the equation set gives the variation of bubble radius R with the pressure outside of the bubble $p(t)$. To illustrate the calculation process, consider the calculation of the unknown parameters at step i from those having been obtained from step i–1: the bubble radius R_i was first obtained by solving equation 1 with the known bubble radius R_{i-1} and pressure inside bubble $p_{b,i-1}$. Then, the temperature and mass change during the time step were obtained using equations 3 and 4, respectively. In this way, the pressure inside the bubble $p_{b,i}$ at step i was calculated with Equation 2. This same process was adopted as calculation time proceeded. To solve the second order differential Equation 1, the high-precision Runge-Kutta method was used. The radius of cavitation nuclei and its change rate were input as initial condition for the calculation. For cavitation nuclei in the water, the radius was in the range of 5−100 μm and the initial change rate was generally assumed as 0[14].

1.5. Numerical validation

To validate the numerical model established in the above section, the experimental data from Lauterborn et al.[15, 16] was compared with the results calculated by the model (Fig. 1). Lauterborn et al. used a piezoelectric transducer to generate a standing sound field in the water. The pressure varied sinusoidally with an amplitude of 132 kPa and a frequency of 21.4 kHz. Cavitation inception and bubble oscillation were recorded with a high-speed camera. The bubble size variation was reproduced numerically by the calculation model developed in this study with the initial nuclei radius of 6 μm. The results are displayed in Fig. 1, which show excellent agreement with the experimental data within the first three oscillation cycles, but in the bubble's subsequent variations, however, the numerically produced bubble radius is slightly smaller than that measured in the experiment. The reason is probably that the bubble was affected by the vessel wall in the experiment, but the bubble in the calculation was assumed to be in an infinite flow field, ignoring the effect of the vessel wall. Overall, the comparison proves high precision and reliability of the mathematical model.