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Numerical analysis of bubble dynamics in the diffuser of a jet pump under variable ambient pressure*

Xin-ping Long (龙新平) [1,2], Qing-qing Wang (王晴晴) [1,2], Long-zhou Xiao (肖龙洲) [1,2], Jun-qiang Zhang (章君强) [1,2], Mao-sen Xu (徐茂森) [1,2], Wei-feng Wu (吴伟烽) [3], Bin Ji (季斌) [1,2]
1. *State Key Laboratory of Water Resources and Hydropower Engineering Science, School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, China, Email: xplong@whu.edu.cn*
2. *Hubei Key Laboratory of Waterjet Theory and New Technology, Wuhan University, Wuhan 430072, China*
3. *School of Energy and Power, Xi'an Jiaotong University, Xi'an 710049, China*

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Abstract: Recent studies have shown that the collapse of cavitation bubbles in a jet pump can generate an extremely high pressure with many potential applications. The dynamics of the bubble is governed by the Rayleigh-Plesset equation. With the bubble dynamics equation and the heat and mass transfer model solved with the Runge-Kutta fourth order adaptive step size method, the oscillations of the bubble in the diffuser of the jet pump are assessed under varied conditions. To obtain the pressure variation along the diffuser, the Bernoulli equation and the pressure measured in experiment are coupled. The results of simulation show that a transient motion of the bubbles can be obtained in the diffuser quantitatively, to obtain the pressure and temperature shock in the bubble. Moreover, increasing the outlet pressure coefficient would result in a more intense bubble collapsing process, which can be used in the subsequent studies of the cavitation applications. The predictions are compared with experiments with good agreement.

Key words: Cavitation, jet pump, bubble collapse

Introduction

The cavitation occurs in industrial structures, such as the rotating machinery, the injectors, the jet pumps, and other hydraulic devices. Most of the time, it is accompanied with serious effects like the erosion, the noise and the decrease of the fluid-machinery efficiency. However, owing to the generation of hot spots, highly reactive free radicals and turbulence associated with liquid circulation currents, in industrial applications, biological engineering[1], water disinfection[2], and even food industry, like milk sterilization, the cavitation has attracted much of attention during past several decades, and our understanding of the cavitation has been greatly improved. Recent reviews were made by Gogate and Kabadi[3], Luo et al.[4] and Peng and Shimizu[5].

To understand the fundamental mechanism of the cavitation phenomena[6], experiments were carried out for the growth and collapse of individual bubbles[7-12].

For numerical modeling of gas bubbles oscillating in liquids, the first analysis of cavitation and bubble dynamics was made by Rayleigh. Plesset further considered the influence of the physical characteristics of fluid viscosity and surface tension and derived the Rayleigh-Plesset equation. For many real physical problems, the shape of a bubble is unlikely to remain to be spherical, especially during the collapse phase of its motion, or when the bubble is near the boundary of the fluid. In this case, the velocity potential of the bubble motion is usually determined by the boundary element method[13].

In simulating the bubble collapse, the processing under the ambient pressure can be divided into two approaches, i.e., the constant and variable forms.

The constant pressure model is considered as able to simplify the calculation in investigating the motion

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Biography: Xin-ping Long (1967-), Male, Ph. D., Professor
Corresponding author: Bin Ji, E-mail: jibin@whu.edu.cn

of a bubble. Rayleigh, as mentioned above, took the ambient pressure as a constant. Plesset and Chapman simulated two specific cases of initially spherical bubbles collapsing near a plane solid wall, a bubble initially in contact with the wall and a bubble initially a distance of half its radius away from the wall at the closest point, with the assumption of the constant ambient pressure. Other researchers such as Popinet and Zaleski[14], Dular and Coutier-Delgosha[15] and Li et al.[16] also assume that the ambient pressure is constant in the simulation domain.

On the other hand, for bubbles under a variable ambient pressure condition, however, there is no direct, exact or accepted expression for the ambient pressure expression, $p_\infty(t)$, as a controversial issue. However, it is a crucial parameter for the mechanism of the bubble motion. Several simplified functions were suggested for the ambient pressure for convenience. A harmonic functional form is expressed as $p_\infty = p_0(1 \pm \varepsilon \sin\omega t)$, where ε is the amplitude of the oscillation, ω is the frequency and t is the time, as suggested by Zhang and Li[17]. Furthermore, the expression for the pressure induced by the external sound field on the outside of the bubble wall, $P_S = P_A \mathrm{e}^{\mathrm{i}\omega t}\sin[(kR)/kR]$, is reduced to $P_S = P_A \mathrm{e}^{\mathrm{i}\omega t}$. For small values of kR_0, $\sin(kR_0) \approx kR_0$ and the pressure outside the bubble could be treated as uniform[18], where P_A is the amplitude of the acoustic wave, k is the wave number, ω is the angular frequency of the acoustic wave. The equation, $p_\infty(x,t) = p_0 + p_a \sin(kx - \omega t + \varphi)$ is employed by Wang and Manmi[19] with consideration of both the phase position and the wave velocity, where p_0 is the hydrostatic pressure, t is the time, and k, p_a, ω and φ are the wave number, the pressure amplitude, the angular frequency, and the phase shift of the ultrasound, respectively. Since these pressure expressions are based neither on the measurement nor on the calculation for a real flow, the results obtained can not adequately explain the cavitation related phenomena accurately such as the thermal and pressure shock in the bubble. Qin[20] developed a numerical methodology for the calculation of the ambient pressure, i.e., the pressure distribution around the bubbles in a convergent-divergent nozzle by a CFD code, based on the RNG k-ε model of the turbulent flow. In this paper, in the Rayleigh-Plesset equation, a position dependence is added, $\Delta x = v \cdot \Delta t$, from the original time dependent form. Based on the above treatment of the ambient pressure, Qin et al.[21] employed a heat transfer model, including the effects of conduction plus radiation, to describe the thermodynamics of the non-condensable gas inside the bubble and the results of this heat transfer model match the previously published experimental data well. Kumar and Moholkar[22] used the approach of discrete calculations while modeling the pressure variation in the nozzle flow based on the Bernoulli equation between consecutive points. As shown in the above description, the calculation of the ambient pressure was improved by Qin and Kumar significantly. Nevertheless, the calculated ambient pressure can still not well reflect the real flow. For many cavitation applications, an accurate control of cavitation is highly desirable. For example, the milk sterilization based on the cavitation needs a high sterilization efficiency to reduce the protein inactivation. As shown in the above reviews, the ambient pressure in the simulation is still a crucial parameter, and there is no efficient method describing the pressure diffusion in a real flow.

In the present paper, the gas bubble dynamics in the liquid under the hydraulic excitation in a jet pump is numerically studied to calculate the nonlinear oscillations of the bubbles. For a thermal analysis, the heat transfer model of Qin et al.[21,23] is adopted with consideration of the energy carried by the vapor. In addition, the effect of mass diffusion is considered based on the study of Kumar and Moholkar[22]. According to our experimental results, the cavitation is induced in the outlet of the nozzle, then develops in the throat shear layer, and collapses in the diffuser finally if the cavitation number is small enough. In other word, the upstream flow of the jet pump would influence the flow in the diffuser. However, in a common diffuser, the cavitation state is absolutely different, for example, the bubble might collapse at the boundary. To sum up, the paper, considers a single bubble in the diffuser of the jet pump. The description of the ambient pressure variation is based on the pressure measured in experiment and the Bernoulli equation, which can reflect the ambient pressure variation along the diffuser in a real flow accurately. On this premise, based on the Rayleigh-Plesset equation and combined with the mass-diffusion and thermal effects, we can evaluate the pressure and temperature variations in the bubble quantitatively, which can serve as a reference for the subsequent cavitation application studies in the jet pump.

1. Mathematical formulation

In this paper, based on the concept of the confined co-axial jet cavitation, we integrate the structure of the orifice and the venturi tube with the jet pump theory. Strong vortex cavitation will be induced by using a high-speed jet to entrain the low-speed secondary flow in a confined space. This sort of confined co-axial jet cavitation is different from the traditional form of cavitation, which can induce cavitation under a relatively high environmental pressure due to the vortex in the shear layer. Moreover, the contained