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Application of the semi-analytical cavitation model to flows in a centrifugal pump

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ABSTRACT

Visualization experiments are carried out to investigate the cavitating flows in a centrifugal pump at different flow rates. The cavity lengths under different pump inlet pressure are obtained. The semi-analytical cavitation model is improved since it is not suitable for predicting large cavities full of vapor. The improved cavitation model is used to numerically study the steady and rotating cavitation in the centrifugal pump. Compared with the Zwart cavitation model, the numerical results predicted by the semi-analytical model agree much better with the experiments, especially for large cavities. The cavity lengths at the suction side are overestimated during the simulations, especially by using the Zwart model. At low flow rates, the prediction of the rotating cavitation effect is weaker and the cloud shedding frequency is smaller than those in the experiments.

1. Introduction

Cavitation is the major cause of performance degradation and damages in hydraulic machinery. Related experimental studies began in the 19th century. CFD has become an important means for the research of cavitation over the last two decades, however, it is still hard to precisely predict the cavitating flows. The cavitation model is a key factor in limiting the numerical accuracy, since both the bubble wall velocity and interfacial area concentration are difficult to be exactly calculated. Most cavitation models calculate the bubble wall velocity by using the simplified Rayleigh equation, which neglects the second-order derivative. Among them, Zwart model [1] is the most widely used [2–5], which neglects the variation of the bubble radius. Yu Zhao et al. [6] proposed a vortex cavitation model, which relates the bubble radius to vortex effects. Zhixia He et al. [7,8] and Jian Liang et al. [9] predicted the cavitating flows by using the Schnerr-Sauer cavitation model [10], which supposes the bubble number per volume of liquid is constant. This treatment in Schnerr-Sauer model is more reasonable than that in Zwart model. However, it can not be said that Schnerr-Sauer model is more accurate than Zwart model since the bubble wall velocity calculated by the simplified Rayleigh equation is far beyond precision. Roohi et al. performed numerical investigations of cavitation around a disk [11] and a hemispherical body [12] using various turbulence and cavitation models, and the Kunz cavitation model [13] was recommended. Ye and Li [14] proposed a semi-analytical cavitation model by taking the second-order derivative and bubble-bubble interaction into account. The turbulence-cavitation interaction is rather complex [4,15–18], and the turbulence was supposed to greatly inhibit the evaporation at large vapor volume fraction in Ref. [14], which is inapplicable for predicting large cavities full of vapor caused by bubble coalescence.

In this study, the semi-analytical model is improved to expand its application range. Visualization experiments are carried out to investigate the cavitation in a centrifugal pump at different flow rates, which give a deeper understanding of the cavity evolution and provide reference for the improvement of numerical models. Numerical simulations are performed towards all experimental operating conditions by using the improved semi-analytical and Zwart cavitation models. Comparisons between experimental and numerical results are made towards the pump head, cavity lengths and vapor volume fraction.

2. Numerical and experimental setups

2.1. Semi-analytical model and its improvement

The semi-analytical cavitation model [14] takes the second-order derivative and bubble-bubble interaction into account. In order to improve the numerical stability, the bubble wall velocities are obtained by integrating the modified Rayleigh equation. The bubble-bubble interaction will inhibit the phase change, especially during the condensation. The coupling strengths during the evaporation (S_E) and condensation (S_C) are calculated in quite different ways. S_C is set to be inversely proportional to the gradient of vapor volume fraction (α). Thus S_C inside the cluster is much larger than that at the cluster

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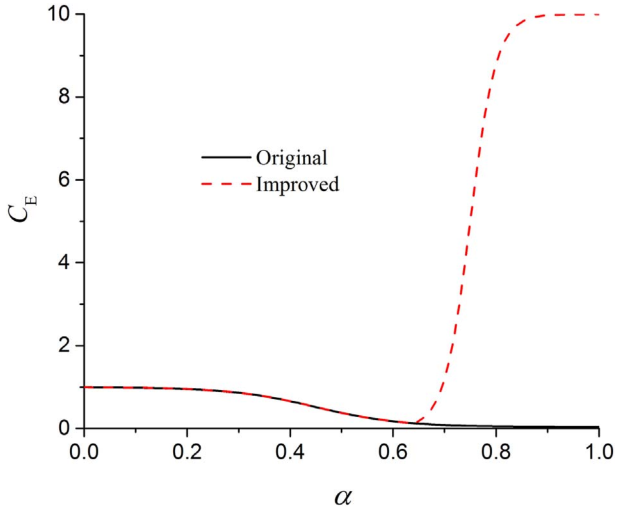

Fig. 1. Dependences of the original and improved C_E on α.

boundary, which makes the collapse of bubble cluster proceed from its boundary towards center. The semi-analytical model is based on the vapor transport equation and the phase change rates are calculated by [14]:

$$\dot{m}^+ = 4\pi n R^2 \rho_V C_E \sqrt{\frac{\max(p_V - p, 0)}{\rho_L}\left[\frac{3}{2} + \frac{2S_E R}{3}\left(1 - \frac{\alpha_I}{\alpha}\right)\right]} \Bigg/ \left(\frac{3}{2} + S_E R\right), \tag{1}$$

$$\dot{m}^- = 4\pi n R^2 \rho_V \sqrt{\frac{\max(p - p_V, 0)}{\rho_L}\left[\left(\frac{\alpha_I}{\alpha}\right)^{2/3} - 1 + \frac{2S_C R}{3}\left(\frac{\alpha_I}{\alpha} - 1\right)\right]} \Bigg/ (1 + S_C R), \tag{2}$$

$$R = \left(\frac{3\alpha}{4\pi n}\right)^{1/3}, \tag{3}$$

$$C_E = 0.52 + 0.48\tanh[6(0.45 - \alpha)], \tag{4}$$

$$S_E = 4\pi(5 \times 10^{-4} + 0.02\alpha^2)k_E n^{2/3}, \tag{5}$$

$$S_C = \frac{C_C n\Delta}{|\nabla\alpha_C|}, \tag{6}$$

$$\alpha_C = \min(\alpha, 0.3), \tag{7}$$

Table 1
Geometric parameters of the test pump.

Inlet diameter of impeller D_1/mm	Outlet diameter of impeller D_2/mm	Outlet width of blade b_2/mm	Blade thickness s/mm	Blade number z	Inlet angle $\beta_1/^\circ$	Outlet angle $\beta_2/^\circ$	Wrap angle $\varphi/^\circ$
100	170	6	6	6	22	18	90

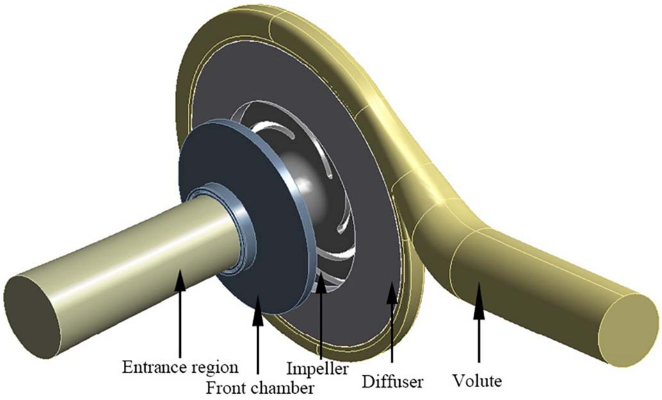

Fig. 3. Pump model.

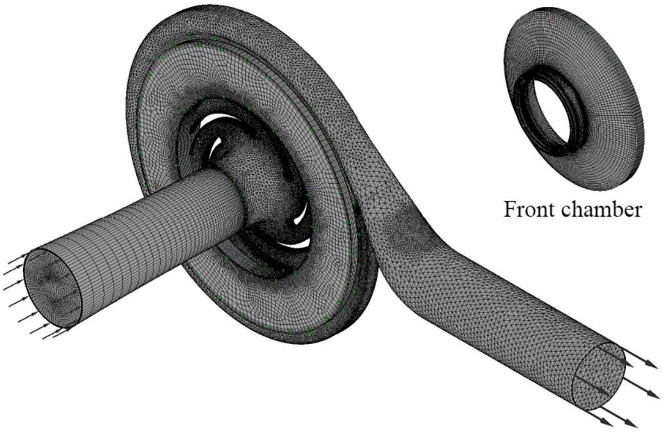

Fig. 4. Computational grid.

(a) Test pump

(b) Impeller

Fig. 2. Test pump and impeller.