CAV2021
11th International Symposium on Cavitation
May 10-13, 2021, Daejon, Korea

NUMERICAL PREDICTION OF CAVITATION EROSION IN A CENTRIFUGAL PUMP

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Abstract: Many types of cavitation erosion prediction methods have been proposed by researchers worldwide. In CFD based prediction methods, numerically computed cavitation aggressiveness are coupled with data base of cavitation erosion resistance of each material. Once the cavitation aggressiveness are calibrated with erosion rate of the specific material experimentally, quantitative prediction of cavitation erosion can be practicable. In this study, cavitation aggressiveness functions are newly proposed. The new cavitation aggressiveness are utilizing the product of local pressure and time derivative of void fraction considering the velocity of collapsing bubble surfaces. For evaluation and calibration, cavitation erosion experiments for a centrifugal pump were carried out. The location of the erosion in the experimental results showed relatively good agreements to the area with high value of computed cavitation aggressiveness.

Keywords: Computational Fluid Dynamics; Cavitation Erosion; Centrifugal Pump; Cavitation Aggressiveness

1. Introduction

Cavitation causes many kinds of troubles in pumping machineries such as head breakdown, noise and vibration and so on. Among these drawbacks, the prediction of erosion is still very challenging due to its complicated nature with multi physics of fluid and material. Many types of cavitation erosion prediction methods have been proposed by many researchers worldwide [1-8]. In CFD based prediction methods, numerically computed cavitation aggressiveness those quantify erosion risk are coupled with data base of cavitation erosion resistance of each material. Cavitation aggressiveness are sometimes called cavitation intensity, erosion indices or some other similar terminologies. Once the cavitation aggressiveness are calibrated with erosion rate of the specific material experimentally, quantitative prediction of cavitation erosion can be practicable. Of course this strategy is not sufficient and metallurgy, microscopic fracture mechanics and fluid material interaction based prediction method is also very important, though early implementation of even premature method looks significant for making design works better.

In this study, some cavitation aggressiveness functions are newly proposed. The new cavitation aggressiveness are utilizing the product of local pressure and time derivative of void fraction considering the velocity of collapsing bubble surfaces. For evaluation and calibration, cavitation erosion experiments for a centrifugal pump were carried out [9].

2. Proposals of Cavitation Aggressiveness

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One of the authors had already proposed four types cavitation aggressiveness as written in functions (1),(2),(3),(4)[8]:

$$\frac{1}{T_c}\int_0^{T_c} \alpha \cdot max\left[\frac{\partial p}{\partial t}, 0\right] dt \tag{1}$$

$$\frac{1}{T_c}\int_0^{T_c} \alpha \cdot max[(p - p_v), 0]\, dt \tag{2}$$

$$\frac{1}{T_c}\int_0^{T_c} max[(p - p_v), 0] \cdot max\left[-\frac{\partial \alpha}{\partial t}, 0\right] dt \tag{3}$$

$$\frac{1}{T_c}\int_0^{T_c} max\left[-\frac{\partial \alpha}{\partial t}, 0\right] dt \tag{4}$$

where T_c is characteristic period of cavitation such as one cycle of cloud shedding, pump rotation etc. p, p_v , α and t are static pressure, saturation vapor pressure void fraction and time respectively. Physical meaning of functions are (1) many bubbles are exposed to rapid pressure rise, (2) many bubbles in high pressure, (3) rapid collapse of bubbles in high pressure and (4) rapid collapse of bubbles. These formulae are implemented in commercial CFD software SCRYU/Tetra.

In this study new cavitation aggressiveness are proposed. Three strategies for development of new functions are constituted. First, the unit of functions is the power per unit area to relate to the local rate of erosion. Second, to simplify the calculation, only the physical quantity of the object surface is used, and the volume average and volume integral of the fluid region are not used. Third, the dependence of the calculation result of function on the physical models and CFD schemes should be reduced as much as possible. From the first strategy, functions (1) and (3) can be candidates for prototype. In the previous researches by LEGI group, derivative of cavity volume is considered important and pressure derivative is neglected[3,4]. In this study, LEGI's examination is referred and function (3) is focused.

In the control volume adjacent to the surface of an object, the power of the surrounding liquid when the cavitation volume is reduced is expressed in equation (5).

$$power = -(p - p_v)\frac{V\Delta\alpha}{\Delta t} = -V(p - p_v)\frac{\partial \alpha}{\partial t} \qquad [\mathrm{w}] \tag{5}$$

$$V \approx \Delta x \times \Delta y \times \Delta z = A \times \Delta y \tag{6}$$

where V, Δx, Δy, Δz and A are volume of control volume cell, grid size of x direction, grid size of y direction, grid size of z direction and contact area of control volume to the object respectively. The y direction is normal to the object surface. Partial derivative of α in equation (5) has the component of bubble size change due to collapse and the component of bubble convection, however in this study the latter component is assumed negligible. Because the control volume exists on the bottom of boundary layer and velocity is small. Resultant instantaneous cavitation aggressiveness ICA_1 is as follows.

$$ICA_1 = -\eta(p - p_v)\frac{V}{A}\frac{\partial \alpha}{\partial t} = -\eta(p - p_v)\Delta y\frac{\partial \alpha}{\partial t} \qquad [\mathrm{w}/m^2] \tag{7}$$

where η is efficiency of fluidic power that contributes to erosion. In this study η is independent on the physical properties of the material. The grid size of Δy in equation (7) is grid dependent. So equation (7) is modified.

$$ICA_2 = -\eta(p - p_v)\delta y\frac{\partial \alpha}{\partial t} = -\eta'(p - p_v)\frac{\partial \alpha}{\partial t} \qquad [\mathrm{w}/m^2] \tag{8}$$

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$$\text{Ideal C.F.L. number} = \frac{C \times \Delta t}{\delta y} \tag{9}$$

where η', δy and C are dimensional efficiency, ideal cell height and sound speed of liquid velocity.

There are many considerations for static pressure in cavitation calculations. Consider the transient process of a single cavitation bubble collapse. Maximum of instantaneous static pressure just after the collapse is highly dependent on the physical modeling. If the liquid around the bubble is assumed compressible, maximum pressure could be in the order of water hammer pressure of $\rho C\Delta u$ and pressure wave propagates from the collapse point where ρ, C and Δu are density of liquid, sound speed of liquid and characteristic velocity of bubble collapse. On the other hands, if the liquid is assumed incompressible, maximum pressure is infinite and its duration is infinitesimal. There is no pressure wave propagation. Another issue is pressure distribution of static pressure around the bubble. When conventional cavitation model and finite volume method, ordinarily only one pressure value is defined in one numerical cell, and static pressure of the cells those contain vapor phase would be close to saturation vapor pressure. Therefore, it is difficult to consider the effect of high pressure generated during / after the bubble collapse by the current function (3), because static pressure and void fraction in one cell are counted simultaneously in function (3). To follow the second and the third strategies, moving averaged static pressure p_{mavg} can be adopted instead of instantaneous static pressure p as seen in equation (10)

$$p_{mavg}(t) = \frac{1}{\Delta t_1 + \Delta t_2} \int_{t-\Delta t_2}^{t+\Delta t_1} p(\tau) d\tau \tag{10}$$

where Δt_1 and Δt_2 are interval time for moving average. τ is time variable for integration. More simply ordinary time averaging is recommended because of the minimum dependency of physical modeling.

$$\bar{p} = \frac{1}{T_C} \int_0^{T_C} p(t) dt \tag{11}$$

In original function (3), terminal stage of bubble collapse can be taken account for theoretically due to the high value of pressure. However by adopting equation (11), the terminal stage that is most risky for erosion cannot be detected. To take account for this stage, some weighting might be effective. In this study weighting is performed by the normalized collapse velocity of a bubble referring to the Mach number. Cavitation in the control volume is modeled as a single spherical bubble of equal volume. Then:

$$\frac{4\pi}{3} R^3 = V\alpha \tag{12}$$

$$v_{nbc} = \frac{1}{C}\frac{dR}{dt} = \frac{1}{C}\left(\frac{3V}{4\pi}\right)^{\frac{1}{3}} \frac{1}{3} \alpha^{-\frac{2}{3}} \frac{\partial \alpha}{\partial t} \tag{13}$$

where R and v_{nbc} are bubble radius and normalized collapse velocity. Considering equations (8), (11) and (13) the following new functions are proposed.

$$ICA_3 = -\eta'_3(\bar{p} - p_v)\frac{\partial \alpha}{\partial t} \quad : \bar{p} > p_v \ , \quad \frac{\partial \alpha}{\partial t} < 0 \quad [\mathrm{w}/m^2] \tag{14}$$

$$ICA_4 = \eta'_4 \alpha^{-\frac{2}{3}} \frac{\partial \alpha}{\partial t}(\bar{p} - p_v)\frac{\partial \alpha}{\partial t} = \eta'_4(\bar{p} - p_v)\alpha^{-\frac{2}{3}}\left(\frac{\partial \alpha}{\partial t}\right)^2 \quad : \bar{p} > p_v \ , \quad \frac{\partial \alpha}{\partial t} < 0 \quad [\mathrm{w}/m^2] \tag{15}$$

where η'_3 and η'_4 are dimensional efficiency. For the pump impeller case, equations are calculated with the relative coordinate system fixed to the rotating body.

The relation between erosion rate and cavitation aggressiveness is expressed simply as follows.

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$$ER = \kappa(CA - CA_{th}) \quad : \quad CA > CA_{th} \qquad [m/s] \tag{16}$$

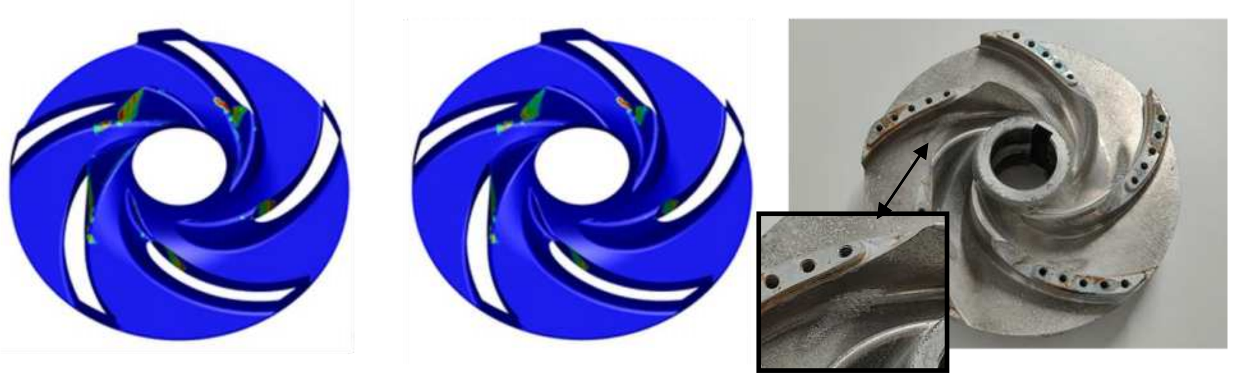
where ER, κ , CA and CA_{th} are local erosion rate, erosion susceptibility, time averaged cavitation aggressiveness and threshold of cavitation aggressiveness respectively. From the experimental results $\kappa\eta'$ and κCA_{th} are calibrated for specific materials. More complicated erosion functions in which incubation period is concerned for example can be established in further study.

3. Experiments

A test pump was a split case pump with double suction casing. The transparent window installed in the suction casing enabled the observation of cavitation flow characteristics. The objective shrouded impeller was made of pure aluminum for the acceleration of erosion. The impeller had detachable shroud in order to assess the eroded surface on the internal flow passages. The eroded surfaces were characterized quantitatively in every predetermined measurement timing in order to determine the cumulative erosion rate of each material. The replication method using the silicon rubber material was applied to obtain the replicas of the eroded surfaces because the direct measurement was difficult due to the geometry of the impeller. The transcribed eroded surface on the replicas were measured by the 3D optical profiler.

4. Results

The developed cavitation flow occurred on the suction surface of the impeller blade in experiments. The cavitation bubbles collapsed inside the impeller and eroded the flow passages. Unsteady simulation of cavitation flow in the test pump was carried out with the commercial software, ANSYS Fluent. The SST k-ω model and the Zwart-Gerber-Belamri model were adopted as turbulence model and cavitation model. In Figure (1) time averaged cavitation aggressiveness and erosion of the impeller were compared. The location of the erosion in the experimental results showed relatively good agreements to the area with high value of computed cavitation aggressiveness. The difference of CA_3 and CA_4 are not significant. Calibration is now underway. Similarity rules of erosion are also examined experimentally. 6th power low of rotational velocity was reported in the literatures. If the similarity rule are not reproduced enough in the proposed aggressiveness, some additional terms such as $(\omega/\omega_0)^l(D/D_0)^m$ shall be multiplied explicitly to the aggressiveness functions.



(a) CA_3 (b) CA_4 (c) Photograph of the eroded impeller

Figure 1 Comparison of cavitation aggressiveness and eroded impeller in experiment

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Acknowledgments: The authors would like to express their sincere thanks to Mr. Naoki Kodama and Mr. Tsutomu Kakisu for significant CFD contribution.

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