Numerical Modelling and Prediction of Erosion Induced by Hydrodynamic Cavitation

A. Peters*[1], U. Lantermann*, O. el Moctar*

* Institute of Ship Technology, Ocean Engineering and Transport Systems, University of Duisburg-Essen, Bismarckstr. 69, 47057 Duisburg, DE

E-mail: andreas.peters@uni-due.de

Abstract. The present work aims to predict cavitation erosion using a numerical flow solver together with a new developed erosion model. The erosion model is based on the hypothesis that collapses of single cavitation bubbles near solid boundaries form high velocity microjets, which cause sonic impacts with high pressure amplitudes damaging the surface. The erosion model uses information from a numerical Euler-Euler flow simulation to predict erosion sensitive areas and assess the erosion aggressiveness of the flow. The obtained numerical results were compared to experimental results from tests of an axisymmetric nozzle.

1. Introduction

In ship technology and maritime environments high flow velocities cause regions of low fluid pressure, which lead to the generation of vapour structures. Once these vapour structures reach regions of higher pressure, they start to rapidly collapse and are able to cause efficiency losses, vibrations and erosion.

An approach to predict cavitation erosion by [1] refers to the hypothesis of potential energy of a macroscopic vapour structure being converted into acoustic energy of pressure waves, which damage a surface directly. Krumenacker et al. [2] supposed that high values of $\partial p/\partial t$ initiate erosive bubble collapses. They state that erosion depends on the acoustic energy of pressure waves. This energy is calculated using a hybrid approach of a Reynolds-Averaged Navier-Stokes (RANS) method combined with a solver to calculate the dynamics and acoustic energies of single bubbles. Nohmi et al. [3] suggested a formula to numerically predict the aggressiveness of a flow depending on the local vapour volume, pressure and their temporal derivatives. Li [4] states that the driving erosion mechanism is the collapse of a cloud cavitation and developed a numerical erosion model, where erosion potential is qualitatively assessed by looking at the time derivative of pressure.

In a different hypothesis it is supposed that only cavitation bubbles in the direct vicinity of a surface lead to erosion. Kato et al. [5] stated an erosion model, which refers to the hypothesis, that single bubbles, which are shed from sheet cavitation cause erosion, when collapsing near a surface. A similar model was developed by Dular et al. [6]. The authors suppose that single bubbles oscillate and collapse due to the radiation of pressure waves through the fluid. It is suggested that erosion is caused once these bubbles collapse near a surface and form a liquid

[1] Corresponding author

water jet of high flow velocity, the so called *microjet*. At impact on the surface, high pressures are generated by shock impacts that are able to damage the surface. Peters et al. [7] have done further development of this erosion model to predict erosion based on the near wall behaviour of cavitation. An erosion model could be developed, which pedicts erosion based on the amount of impacts in a certain area, as well as the impact intensities.

2. Numerical Method

The flow is simulated using an implicit, pressure-based flow solver from the open source CFD package OpenFOAM. A two phase Euler-Euler flow is simulated with the Volume of Fluid (VoF) method to track the phase's interfaces. The equations of conservation of mass and momentum are solved for the homogeneous mixture of the two continuous phases. The mixture in each numerical control volume is obtained from the vapour volume fraction α, which relates the vapour volume in a control volume to the total volume of the cell. The transport equation for the volume fraction reads:

$$\frac{\partial \alpha}{\partial t} + \frac{\partial \alpha u_i}{\partial x_i} = S_\mathrm{e} - S_\mathrm{v} \,. \tag{1}$$

u_i is the velocity in coordinate direction x_i and t is the time. S_e, S_v are the source terms due to condensation and evaporation processes, respectively, which are given by a cavitation model. In this work, the cavitation model by Schnerr and Sauer [8] was used:

$$\begin{aligned} S_\mathrm{e} &= \frac{\rho_\mathrm{v}\rho_\mathrm{l}}{\rho}\frac{3\alpha(1-\alpha)}{R_\mathrm{b}}\sqrt{\frac{2}{3}\frac{p_\mathrm{b}-p}{\rho_\mathrm{l}}}\,, \quad \text{for } p < p_\mathrm{v}\,, \\ S_\mathrm{c} &= \frac{\rho_\mathrm{v}\rho_\mathrm{l}}{\rho}\frac{3\alpha(1-\alpha)}{R_\mathrm{b}}\sqrt{\frac{2}{3}\frac{p-p_\mathrm{b}}{\rho_\mathrm{l}}}\,, \quad \text{for } p \geq p_\mathrm{v}\,. \end{aligned} \tag{2}$$

ρ_v and ρ_l are the densities of vapour and liquid, respectively, and ρ is the density of the mixture. R_b is the radius of a cavitation bubble and p_b the inner bubble pressure. p_v is the vapour pressure. The cavitation model is based on a simplified Rayleigh-Plesset equation for bubble dynamics. To enable the simulation of unsteady sheet and cloud cavitation, a turbulence correction is applied, which considers the reduction of turbulent kinetic energy due to high compressibility in the mixture region.

3. Erosion Model

The developed erosion model is based on the microjet hypothesis [6] and was derived as explained in [7]. An erosion is supposed to happen, when two conditions are fulfilled: 1. It is possible that a microjet process takes place near the surface. 2. The velocity of the microjet needs to exceed a critical velocity, to damage a given material. The microjet velocity can be related to the pressure caused by a microjet, while the critical velocity depends on the stress needed to plastically deform the regarded material. For a dimensionless stand-off distance of $\gamma = 1.1$ the local jet velocity can be estimated by the following formula, as written in [7]:

$$v_\mathrm{jet} \approx 10.8\sqrt{\frac{p-p_\mathrm{v}}{\rho_\mathrm{l}}}\,. \tag{3}$$

An expression for the critical velocity velocity can be derived from a one-dimensional impact of a liquid mass onto a solid boundary [9]. The Tait equation was used to relate pressure and density of liquid water. The formula for the critical velocity is given as:

$$v_\mathrm{crit} = \sqrt{\frac{p_\mathrm{y}}{\rho_\mathrm{l}}\left(1-\left(1+\frac{p_\mathrm{y}}{B}\right)^{-1/n}\right)}\,. \tag{4}$$

$B = 300$ MPa and $n = 7$ are standard coefficients for liquid water in the Tait equation of state. To evaluate the generation of microjets on a surface, the presence of single cavitation bubbles in the vicinity of the solid boundary needs to be predicted. Therefore, the control volumes near a face of the surface are checked for a minimum volume of vapour. Afterwards, it is evaluated, whether the local jet velocity is higher than the critical velocity. When both conditions are fulfilled, an erosion impact for this time step on the regarded face is supposed to happen. For each impact, an intensity coefficient is calculated:

$$c_{\text{intensity}} = \frac{v_{\text{jet}}}{v_{\text{crit}}} \,. \tag{5}$$

With the given method, it is difficult to quantify the amount of bubbles of different shapes and to estimate, which bubbles are able to form erosive microjets. A dimensionless deformation coefficient is therefore introduced to predict erosion qualitatively. It is assumed that the number of impacts, as well as their intensities, are the main factors to assess erosion potential. For each face of a regarded surface, the number of impacts, weighted with their intensity coefficients, is summarized and related to the total erosion impacts. The deformation coefficient is introduced, which is a measure of the erosion taking place in one face, compared to the total erosion:

$$c_{\text{def}} = \frac{\sum_t^T c_{\text{intensity},t}}{\sum_n^N (\sum_t^T c_{\text{intensity},t})_n} \,. \tag{6}$$

Here, t is the time step index and T the total calculated time of the erosion model. n is the index of a face and N the total number of all eroded faces.

4. Results

The flow through an axisymmetric nozzle was investigated by Franc et al. [10, 11]. Water is flowing through a cylinder of 8 mm radius from top to bottom. The cylinder is connected to a radial divergent outflow part via a 1 mm radius. Cavitation is generated at the radius and travels further downstream. The cavitation structures mostly collapse in specific regions, which leads to a characteristical ring of erosion on the bottom target plate, within a given distance from the rotational axis. Figures 1 and 2 show a momentary snapshot of the numerical simulation of internal flow through the nozzle. Cloud and sheet cavitation collapse within a characteristic distance from the radial axis. This leads to the high erosion potential predicted on the bottom boundary in this region.

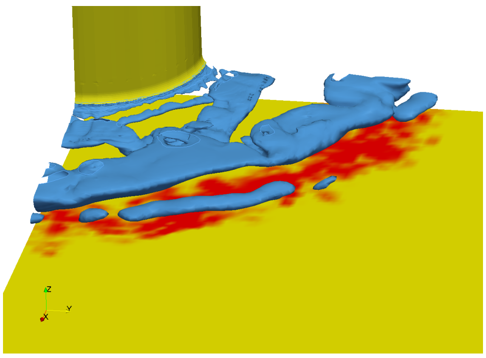

Figure 1. Cavitation structures travelling downstream from the radius. The predicted erosion on the bottom boundary is marked in red.

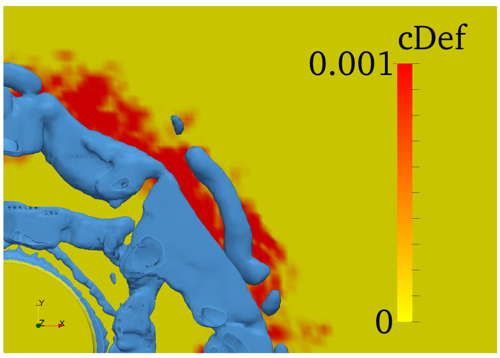

Figure 2. Top view of the correlation between cavitation and predicted erosion.

The numerical erosion prediction is compared to the experimental results from top view in Figure 3. The eroded target sample from the experiment is shown on the left and the numerical erosion prediction on the bottom boundary is shown on the right. The black circle marks the area, where the highest erosion damage was measured during experiments [10, 11]. It is apparent that the numerical method is well able to identify the area of highest erosion potential.

A statistical comparison of experiment and simulation is shown in Figure 4. To enable a qualitative comparison, the dimensionless damage distributions are shown, which were normalized by the maximum values of predicted erosion (simulation) and surface deformation (experiment), respectively. The numerical erosion model is able to give a good prediction of the position of maximum erosion potential, but predicts a larger total area to be eroded.

5. Conclusions

The developed erosion model predicts erosion based on the microjet hypothesis stated by Dular et al. [6]. The numerical method is able to simulate cavitating flows and predict erosion based on the present flow conditions. A comparison of the numerical prediction and the experimental results shows good agreement.

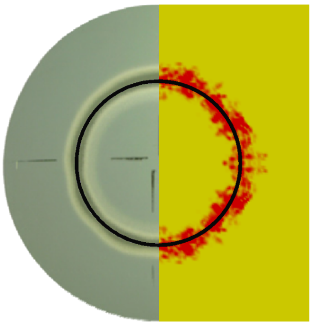

Figure 3. Top view of eroded target sample from experiment (left) and the numerical erosion prediction (right).

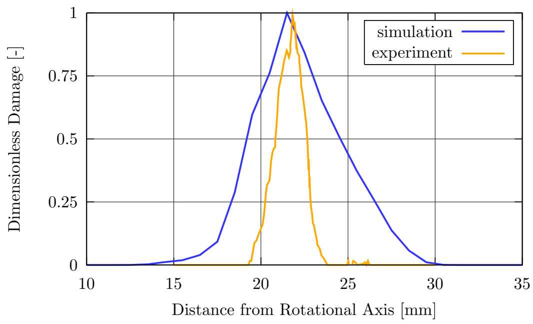

Figure 4. Comparison of dimensionless damage distributions from experiment and simulation.

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