Numerical prediction of the gas content effect on the cavitation characteristics of the pump using the simplified Rayleigh-Plesset equation

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Abstract. The paper presents the ongoing research on cavitation modelling so far which includes validation studies of the gas content effect on the cavitation characteristics of the pump. Cavitation flow characteristics are modeled by performing Computational Fluid Dynamics (CFD) simulations using Schnerr–Sauer cavitation model implementing empirical coefficients. As a result, it was found that the inclusion of the third phase into the cavitation model significantly affects the cavitation characteristics of the pump and the NPSH.

1. Introduction
Cavitation is a hydrodynamic phenomenon consisting of intensive formation and subsequent collapse of gas bubbles in a moving liquid (Figure 1). Cavitation affects the characteristics of the pump. Developed cavitation makes the head, pressure and efficiency of the pump decreasing, and then leads to a complete breakdown of its operation.

Figure 1. The cavitation in the pump.
Nowadays the problem of improving the cavitation qualities of the pump equipment is very urgent because cavitation and cavitation erosion damage the most critical pumping equipment: energy pumps, special purpose pumps, etc. Numerous researches are devoted to study the process of cavitation [1].

For example, in article [2], the cavitation model was tested experimentally for a pump with a radial impeller. The volume of fluid (VOF) model was chosen as a cavitation model for the calculation of multiphase flow. To study the cavitation characteristics at the inlet boundary, the pressure was decreased until the failure occurred. After the experiment, the results were compared (Figure 2).

![Figure 2: Comparison of numerical simulation and test results.](image)

In study [3] the model was compared with experimental data for different flow rates. According to the graphs in the Figure 3, the difference between experimental data and numerical simulation results is considerable.

![Figure 3: Comparison of numerical simulation and test results for various flow rates:](image)

- a) $Q = 168 \text{ m}^3 / \text{h}$; b) $Q = 210 \text{ m}^3 / \text{h}$; c) $Q = 226.8 \text{ m}^3 / \text{h}$

The experimental studying of cavitation can be carried out in various ways. One of the most common used is ultrasonic. For example, this method can be used to study the resistance of different materials to cavitation [4, 5]. Whereas the cavitation tests of the pump are carried out on special stands with the subsequent plotting of cavitation characteristics. [6]

With the invention of computational fluid dynamics methods it became possible to calculate the partial cavitation characteristics of pumps by numerical methods, but this approach is collocated with many difficulties. The main problem is the complex physical nature of the phenomena, therefore, it is
necessary to take into account a large number of factors in the mathematical model. During the simulation of cavitation in [7], a simplified Rayleigh–Plesset equation was used, which led to applying of the additional empirical coefficients (Figure 4).

![Figure 4: Volume fraction of vapour at the NPSH 2 m.](image)

As a result, the cavitation model including certain empirical coefficients showed a very good agreement with experimental data (Figure 5).

![Figure 5: Cavitation characteristics of the pump for different coefficients.](image)
Actually, the use of a simplified Rayleigh–Plesset model leads to the necessity of correction this equation by introducing empirical coefficients. Probably, it is due to the fact that this model does not take into account many factors, such as the presence of undissolved air in the liquid, the surface tension of the gas bubble, acceleration and others.

In the current article it was supposed that the dissolved air has a greater influence on cavitation than other factors. Therefore, the aim of the study was to find out whether gas content has an influence on cavitation characteristics obtained by numeric calculations or does not have any.

2. Mathematical models

Experiments were carried out with the pump which 3D model and volume mesh are represented in Figure 6.

![Figure 6. 3D model (left) and volume mesh (right) of the considering pump.](image)

In order to numerically predict cavitation CFD simulation was used [8,9]. The effectiveness of such method was validated by numerous researches and publications [10,11]. Flow field was simulated by the standard k–ω two-equation turbulence model and multiphase flow model [12,13].

Regarding the process of cavitation, it was performed by Schnerr–Sauer [14] model which is widely used in numerous cavitating flow simulations in literature [15,16]. This model is based on the Rayleigh–Plesset equation [17,18,19,20].

\[
\frac{p_v - p_0}{p_1} = R \frac{d^2R}{dt^2} + \frac{3}{2} \left( \frac{dR}{dt} \right)^2 + \frac{2\sigma}{\rho_1 R} \tag{1}
\]

Neglecting acceleration, surface tension and viscosity, a simplified form is obtained:

\[
\frac{dR}{dt} = \sqrt{\frac{2}{3} \left( \frac{p_v - p}{p_1} \right)} \tag{2}
\]

The boundary conditions adopted in this calculation are the total pressure at the input and speed at the output. An important point is that such boundary conditions are preferable to set in the calculation of the cavitation phenomena, as in this case, the inlet pressure is a calculated value and pulses during the solution. So, the inlet pressure is a fixed value in the considered problem. By decreasing (changing) reference pressure the intensity, distribution area and cavitation characteristics were obtained.

After finding the suitable method to simulate cavitation process, besides water and vapour, the third phase consisting of undissolved air was included to study the gas content effect on the cavitation characteristics.
3. Numerical simulation and flow field analysis
Figure 7 shows the difference between two-phase and three-phase simulation of cavitation.

Several models with different gas content were considered in the course of the study: with 1, 3 and 5% of undissolved air in liquid. The numerical simulation results are represented in the Figure 8, the change in the intensity of cavitation with increasing gas content is shown.

Figure 7. Volume fraction of vapour at pressure 40 kPa, 20 kPa.

Figure 8. Volume fraction of vapour with the gas content of 1, 3, 5% and without gas at all.
Cavitation flow characteristics for various gas content are shown in the Figure 9.

![Figure 9. Cavitation characteristics of the pump for various gas content.](image)

Based on above the results of numerical simulation, Table 1 is made.

| Dissolved air content, % | NPSH, m |
|-------------------------|---------|
| 0                       | 1.8     |
| 1                       | 2       |
| 3                       | 2.6     |
| 5                       | 3.2     |

According to table 1, NPSH of 5% model is much higher than without gas at all. Inspite of the fact that such amount of gas is rather small, the inclusion of the third phase into the cavitation model significantly affects the cavitation characteristics of the pump and the NPSH. The same difference between NPSH results is obtained by using a simplified Rayleigh–Plesset model without insertion of the empirical coefficients. What is more, such amount of undissolved air is always contained in the liquid during the pump tests. Thus, the characteristics obtained during such tests will incorporate the gas content.

4. Conclusions

Despite numerous research efforts cavitation modelling is rather a difficult task and it is necessary to model it much more accurately. The standard model for numeric simulation of cavitation is Schnerr–Sauer one, which is based on the simplified Rayleigh–Plesset equation. Unfortunately, this simplification doesn’t allow to take into account the surface tension of the liquid, acceleration and, especially, the undissolved air according to the results of this study.

In order to find out whether the model of pump with undissolved air differs from the standard Schnerr–Sauer one, the third phase was inserted. The current paper mainly analyzes the difference of cavitation development between two-phase and three-phase flow on the condition of the same pressure...
boundary conditions at both ends and other settings. From the above results of flow field analysis, it is shown that the intensity of cavitation increases with the rising of gas content. As a result, undissolved air in liquid significantly influences on the NPSH of the pump.

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