Numerical study of the reentrant jet and twin vortex flow regimes in the ventilated cavitation.

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Abstract. Ventilated cavitation is generated artificially by injection of air through very precise openings in the profile. The main parameters of a ventilated cavitation are the gas supply injected rate and the gas leakage rate at rear of the cavity. The unsteady ventilated cavitation is characterized by gas regimes, of which there is three types [3]: portion gas-leakage, twin vortex gas-leakage, gas-leakage from pulsating surpercavities. The experimental observations show, in the twin vortex gas-leakage case, for low ventilation air flow coefficient it is the reentrant jet regime which appears. The present numerical study concerns the twin vortex gas leakage regime around the conical head bodies. The study is based on the 2D numerical code IZ models unsteady cavitating flows. In the present work, dissolved non-condensable gas is taken into account in the transport equation-based model in this numerical code. The numerical results are compared and validated with experimental measures [1] and an analysis of the transition between the reentrant jet and twin vortex is presented.

1. Introduction:

The cavitation is characterized by the formation of vapor pocket within a liquid submitted to a local pressure drop. This process called natural cavitation [2], is often synonymic of damage and loss of performance (erosion, emissions of sound, effects on lift and drag…) in many industrial devices (projectile, submarine propellers, hydraulic systems…). One of the solutions consists by injecting of air in the pocket, this process is called ventilated cavitation [1]. This model which is controllable allows to reduce the damage due to the cavitation. The main parameters of the ventilated cavitation are the gas supply rate and the gas-leakage.

The cavitation is mostly unsteady and turbulent flow. The unsteady ventilated cavitation is characterized by gas regimes, which there is mainly tree types [3]: portion gas-leakage, twin vortex gas-leakage, gas-leakage from pulsating surpercavities. In the experimental study [1] the photographs show, in the twin vortex gas-leakage case, for low ventilation air flow coefficient it is the reentrant jet regime which appears.

With the computing development, to move forward in the understanding of the physical phenomena we have more and more resort to numerical simulations. It is in this objective that the code IZ, which is the 2D numerical code models unsteady cavitating flows, was developed. The process of evaporation or condensation is control through a barotropic state law or the transport equation-based model [2, 4].

In the present work, dissolved air is taken into account in the transport equation-based model in this numerical code IZ. The model is applied to ventilated cavitation around conical head bodies. In this study we are particularly interested in the gas-leakage by vortex tubes case of the ventilated cavitation. The numerical results are compared and validated with experimental measures of [1].

Our work is divided into two parts. The first part of the paper is dedicated the theoretical formulation, where the IZ code governing equations, cavitation model and turbulence model are presented. The second part is dedicated to the results and discussion.
2. Theoretical formulation:

2.1. Governing Equations:

The code uses the in one-fluid models, where the two phases (liquid/vapor) are treated as a single continuous fluid, homogeneous, with an average density. The system is governed by the Navier-Stokes equations:

\[
\frac{\partial \rho_m}{\partial t} + \nabla \left( \rho_m \bar{U}_m \right) = 0
\]

\[
\frac{\partial}{\partial t} \left( \rho_m \bar{U}_m \right) + \nabla \left( \rho_m \bar{U}_m^2 \right) = \nabla \pi_m
\]

with \( \rho_m \) is the mixture density, \( \bar{U}_m \) is the mixture velocity and \( \pi_m \) is the tensor for the external forces. These equations are coupled with a cavitation model to determine the mixture density.

2.2. Cavitation model:

By considering a control volume \( V \) we have:

\[
\alpha_v = \frac{\text{Vapour volume}}{\text{Total volume}}
\]

\[
\alpha_{ng} = \frac{\text{Non-condensable gas volume}}{\text{Total volume}}
\]

With \( \alpha_v \) the vapor volume fraction and \( \alpha_{ng} \) the non-condensable gas volume fraction. The mixture density \( \rho_m \) is given by:

\[
\rho_m = \alpha_v \rho_v + \alpha_{ng} \rho_{ng} + \left( 1 - \alpha_v - \alpha_{ng} \right) \rho_l
\]

\[
\alpha_l + \alpha_v + \alpha_{ng} = 1
\]

\( \rho_l \) density of liquid, \( \rho_v \) density of vapor, \( \rho_{ng} \) density of non-condensable gas and \( \alpha_l \) the liquid volume fraction.

The vapor and non-condensable gas volume fractions are governed by the transport equations:

\[
\frac{\partial \alpha_v}{\partial t} + \nabla \left( \alpha_v \bar{U}_m \right) = \dot{m}^- + \dot{m}^+
\]

\[
\frac{\partial \alpha_{ng}}{\partial t} + \nabla \left( \alpha_{ng} \bar{U}_m \right) = 0
\]

The term source \( \dot{m}^- \) and \( \dot{m}^+ \) of the vapor volume fraction transport equation governs the evaporation and condensation of the vapor. There are several models [5, 6, 7], in this study we use the Singhal model [7]:

\[
\dot{m}^- = C_v \nu_0 \rho_l \rho_v \left[ \frac{2 \rho_v - p}{3 \rho_l} \right]^{1/2} \left( 1 - \alpha_v - \alpha_{ng} \right)
\]

\[
\dot{m}^+ = C_c \nu_0 \rho_l \rho_v \left[ \frac{2 \rho_v - p}{3 \rho_l} \right]^{1/2} \alpha_v
\]

With \( C_v \) and \( C_c \) empirical constants, \( \nu_0 \) free-stream velocity, \( p_v \) the saturated vapor pressure.

2.3. Turbulence model:

The natural or ventilated cavitation is a turbulent phenomenon. The k-epsilon turbulence model is used to calculate the turbulent viscosity:
\[
\frac{\partial (\rho_m k)}{\partial t} + \nabla (\rho_m U_m \cdot k) = \nabla \pi_k \tag{2.11}
\]
\[
\frac{\partial (\rho_m \varepsilon)}{\partial t} + \nabla (\rho_m U_m \cdot \varepsilon) = \nabla \pi_{\varepsilon} \tag{2.12}
\]
\[
\mu_e = \rho_m C_\mu \frac{k^2}{\varepsilon} \tag{2.13}
\]

For more details on the code IZ see [2, 3].

3. Results and comparison with the experimental measures of Stinebring and Holl [1]:

In the experimental study [1], three models conical head bodies were tested (45° apex angle, 1.0 inch diameter conical head). The model I and II have respectively afterbody of diameter 0.5 and 1 inch and the model III is without afterbody. The observations of the model I and II show the stable cavity. The observations of the model III show the unstable cavity where we observe the transition between the reentrant jet and twin vortex flow regimes. This very interesting observation is used to validate the numerical model. See figure 1a and 1b experimental model III and numerical grid distribution model.

![Experimental Model III and Numerical grid distribution model](image)

**Fig. 1:** (a) Experimental Model III, (b) Numerical grid distribution model

The main similarity parameters are:
- \(\sigma\) the natural cavitation number:
  \[
  \sigma = \frac{p_\infty - p_e}{1/2 \rho_l V_{\infty}^2}
  \tag{3.1}
  \]
- \(\sigma_c\) the ventilated cavitation number:
  \[
  \sigma_c = \frac{p_\infty - p_c}{1/2 \rho_l V_{\infty}^2}
  \tag{3.2}
  \]
- \(C_Q\) the ventilation air flow coefficient:
  \[
  C_Q = \frac{\dot{Q}}{V_{\infty} D^2}
  \tag{3.3}
  \]
- \(\dot{Q}\) the volume flowrate of air and \(D\) the model diameter.
- \(F_r\) the Froude number:
  \[
  F_r = \frac{V_{\infty}}{\sqrt{gD}}
  \tag{3.4}
  \]

For three different velocity (30 ft/sec, 45 ft/sec and 50 ft/sec), we compared the experimental measures and the numerical results. The figure 2a shows the cavitation number versus cavity length and the figure 2b shows the ventilation air flow coefficient versus cavitation number. The cavity length and ventilated cavitation number predicts by the model are in agreement with the experimental measures.
For $V_\infty = 30$ ft/sec, the figures 3a and 3b represent the evolution of the ventilated cavity (the reentrant jet region case) and of the vortex for $C_Q = 0.014$ and the figures 4a and 4b represent the evolution for $C_Q = 0.051$ (the twin vortex regime case), we notice that the model predicts the two modes of cavity closure for flow behind a conical ventilated cavitator experimentally observed: reentrant jet regime and twin vortex regime.

Fig. 2: (a) Ventilated cavitation number versus cavity length, (b) Ventilation air flow coefficient versus ventilated cavitation number.

Fig. 3a: Evolution of the ventilated cavity for $C_Q = 0.014$ and $V_\infty = 30$ ft/sec

Fig. 3b: Evolution of the vortex for $C_Q = 0.014$ and $V_\infty = 30$ ft/sec
After this validation with the experimental measures we were interested in the transition phase between the reentrant jet and twin vortex flow regimes. Thus, the transition ventilation air flow coefficient \( C_Q \) was estimated. It is estimated equal to the average of the ventilation air flow coefficient \( C_Q \) of the jet reentrant case and of the twin vortex case in the transition. We notice on the figure 5, which represents the transition ventilation air flow coefficient \( C_Q \) function of the Reynolds number, two evolution phases the transition coefficient function of the Reynolds number. In the first phase, for Reynolds number less than \( 4.5 \times 10^6 \), the transition coefficient \( C_Q \) varies linearly with the Reynolds number. In the second phase the transition coefficient remains almost constant.
Fig. 5: Evolution of the transition ventilation air flow coefficient versus Reynolds number.

4. Conclusion:
In this study the 2D numerical code IZ models unsteady cavitating flows was developed, where the dissolved non-condensable gas is taken into account in the transport equation-based model in this numerical code.

The numerical results are compared with the experimental measures of [1] in the reentrant jet and twin vortex flow regimes ventilated cavitation. The cavity length and ventilated cavitation number predicts by the code are in agreement with the experimental measures.

An analysis of the transition phase between the reentrant jet and twin vortex flow regimes shows that for the Reynolds number less than $4.5 \times 10^6$ the transition ventilation air flow coefficient $C_Q$ varies linearly with the Reynolds number and the transition coefficient remains almost constant.

References

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