Experimental Characterization of a Cavitating Orifice

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Abstract
Experiments on a cavitating orifice have been performed in water. The main goal was to characterize and compare three different orifice geometries. Mass flow rates and steady pressure measurements have been used to describe the hydraulic curve of the orifice. High-speed imaging has been used to characterize the cavitation evolution. Finally, special attention has been devoted to the void fraction measurements with a three pressure probes technique.

Keywords: cavitating; orifice; void fraction;

Introduction
Cavitating flows can be faced in several industrial applications where the flow undergoes sudden pressure drops such as valves, pumps and orifices. This is why, cavitation is object of several research activities, such as (1), (2), (3), (4) and (5).

This paper presents the last experimental activities conducted at the von Karman Institute on the water facility Becassine. Cavitation is induced by means of an orifice. Three different orifice geometries have been considered in this study and their hydraulic performances have been compared. Synchronized time-resolved pressure measurements and flow visualizations have been performed to characterize the different cavitating stages. In addition, the void fraction has been measured. This is a key parameter since it affects the pressure drop and heat transfer in the two-phase flow. Up to now different techniques have been developed to quantify the void fraction, but many of them are either intrusive or they require big facilities, such as (6), (7). Therefore, a non-intrusive technique has been chosen within this study. It uses three pressure sensors equidistantly placed (8) and it was validated with a known void fraction content in the work by Yenigun (9).

This report develops as follows: first, the experimental set-up and the testing procedure are detailed. The second section reviews the technique to measure the void fraction. Finally, some examples of the experimental results are illustrated and conclusions are drawn.

Experimental procedure
The test campaign was performed on the water facility Becassine. Figure 1(a) shows the corresponding experimental set-up. The water is stored in a 750 litres tank which feeds the system in a closed loop. This tank is equipped with an electrical resistance to heat the water. The maximum operating pressure is limited to 5 bar abs in order to prevent any damage to the test section built in Plexiglas. The backpressure is adjusted either slightly by a valve located downstream of the test section, or by the vacuum pump which is connected to the top of the reservoir. A minimum backpressure of 0.2 bar abs can be achieved. A smaller reservoir is located just after the pump to calm the water flow before entering the test section.

Three orifice geometries have been tested (Figure 1(b)). The first two geometries are divergent orifices in Plexiglas: one is thick with $\beta = 0.15$ and the other is thin with $\beta = 0.30$. The last one is a cylindrical sharp-edged thick orifice with $\beta = 0.17$ and thickness $s/d = 1.2$.

The mass flow rate is measured with an electromagnetic flowmeter placed upstream the test section. The static pressure upstream of the orifice and the pressure drop across the orifice are measured by two Valyldines (0.25% full-scale accuracy). The upstream pressure is measured 5D upstream the orifice and the downstream pressure is measured 16D downstream the orifice. D is the test section diameter equals to 4 cm. The test-section is also instrumented with three unsteady pressure transducers (XTL-M Kulites 0.1% full-scale accuracy). They are positioned downstream of the orifice at 4.8D, 6.4D and 7.9D, respectively. The spacing of 6 cm between consecutive transducers and the acquisition

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frequency of 100 kHz have been set according to the previous calculations for the three-pressure probes technique validation (9).

Figure 1: (a) Schematic of the facility; (b) Orifice geometry: thin divergent orifice (top), thick divergent orifice (center) and cylindrical thick orifice (bottom)

The flow is visualised at two different locations of the test section. A first camera records ~5000 images at 14 kHz just downstream the orifice. A second camera is positioned 4D downstream the orifice at the position of the three-pressure transducers. It records flow images at 1 kHz. The two cameras are synchronized between them as well as with the time-resolved pressure measurements. The water temperature is measured in the calming reservoir with a thermocouple type K. The dissolved amount of oxygen in the water is also measured in the calming reservoir with a Vernier Optical DO probe.

The water is deaerated before each test. First, the water is slightly heated at 30°C while it circulates in the closed loop at the minimum pump speed. After, the vacuum pump is activated in order to liberate the oxygen. The dissolved oxygen concentration is expressed as a percentage of the maximum amount of oxygen that water can hold at a given temperature, specifically

\[
\%\text{saturation} = \left( \frac{\text{actual DO reading mg/L}}{\text{saturated DO reading mg/L}} \right) \cdot 100
\]  

Eq.1

Figure 2 depicts the reduction of this percentage during eight hours. The cavitation tests start when the measured dissolved oxygen content is below the 10% of the saturated dissolved oxygen at the testing temperature. During the tests, this value changes of only 2.5%. For each orifice, an average of thirty testing conditions have been recorded. Different flow rates have been tested by varying the upstream pressure. The downstream pressure was set either at ambient or at two different vacuum conditions, i.e. 0.2 bar abs and 0.5 bar abs, in order to cover the whole range from fully liquid up to the super cavitation regime.

Figure 2: Evolution with time of the dissolved oxygen content

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Void Fraction Measurement Technique

The void fraction has been measured during the cavitation tests by means of the three-pressure transducers technique, which was developed in 1970s by Brown and Margolis (8). This method relies on the assumption that pressure waves propagate through a pipe without changing their amplitude (10), (3). The strategy of this technique is to place three pressure sensors equidistantly. The transducer in the middle is taken as the reference one. For each location the relations reported in Eq.2 can be written

\[ p_1 = p(-L, f) = C_1(f)e^{-\beta L} + C_2(f)e^{\beta L} \]

\[ p_2 = p(0, f) = C_1(f) + C_2(f) \]

\[ p_3 = p(L, f) = C_1(f)e^{\beta L} + C_2(f)e^{-\beta L} \]  

Eq.2

A transfer function can be built from these three pressure signals in the frequency domain. This function is directly linked to the speed of sound. Thanks to the equal distance among the sensors, the transfer function reduces itself to a cosine signal and the speed of sound can be retrieved.

This velocity is the speed of sound confined to the pipe environment, \((c_{\text{conf}})\). This means that this value depends on the hydraulic and mechanical characteristics of the pipe. In order to retrieve the free sound velocity \(c_{\text{free}}\), an additional equation is needed. Eq.3 takes into account the mixture density \(\rho_M\), the pipe diameter \(D\), the elasticity of the pipe \(E\), its thickness \(e\) and finally the pipe Poisson’s ratio \(\nu\). These terms related to the pipe and the material properties are considered to be constant. Assuming a homogeneous two-component mixture, the fluid density \(\rho_M\) is calculated as the weighted average of the vapor and liquid phase density, \(\rho_{\text{gas}}\) and \(\rho_{\text{liq}}\) respectively. In Eq.4 \(\alpha\) stands for the void fraction.

\[ c_{\text{free}} = c_{\text{conf}} \sqrt{\frac{1 + \frac{D}{e} (1 - \nu^2)}{E}} \cdot \rho_M \]  

Eq.3

\[ \rho_M = \alpha \cdot \rho_{\text{gas}} + (1 - \alpha) \cdot \rho_{\text{liq}} \]  

Eq.4

Finally, to close the system of equations, a relation between the speed of sound and the void fraction is needed. This can be obtained by deriving pressure over density (11), as in Eq.5.

\[ \left(\frac{1}{c_{\text{free}}}\right)^2 = \alpha \cdot \rho_M \cdot \left(\frac{1}{\rho_{\text{gas}}}\right)^2 + \left(\frac{\rho_M}{\rho_{\text{liq}}}\right)^2 - \alpha \cdot \rho_M \cdot \frac{\rho_{\text{gas}}}{\rho_{\text{liq}}} \left(\frac{1}{c_{\text{liq}}}\right)^2 \]  

Eq.5

Results

The first measurements concern the mass flow rate through the orifice. As an example, Figure 3 shows the hydraulic curve for the cylindrical orifice with \(\beta=0.17\). Here, the mass flow rate is plotted versus the pressure drop through the orifice. A non-dimensional representation of this curve is used. The theoretical choked flow rate \((Q_{\text{chok}})\) and choked pressure drop \((\Delta P_{\text{chok}})\) have been used at this purpose. In fact, these values are unique for a certain upstream pressure condition and different upstream pressures correspond to different hydraulic curves. The linear part of the theoretical curve in Figure 3 corresponds to a fully liquid behavior and it is derived by Chisholm’s correlation for thick orifices (12). The choked flow is computed by modelling the hydraulic system in EcosimPro and considering an isentropic expansion (13).

Figure 4 depicts different stages of cavitation at four pressure drops \((\Delta P = \sqrt{\Delta P/\Delta P_{\text{chok}}})\). \(\Delta P = 0.7\) corresponds to initial stage where cavitation is barely visible and no significant deviation from the linear trend are noticed. \(\Delta P = 0.9\) and \(\Delta P = 1\) correspond to a developing cavitation. As the pressure drop increases, large vaporous structures coexist with thin bubbles which are responsible of most of the noise. Finally, the super-cavitation stage is reached for \(\Delta P = 1.2\). Super-cavitation is the evolution of the choked flow. The submerged liquid jet becomes visible at the center of the test section. A thick vapor cavity surrounds it. On the walls of the test section a film of water is falling down.

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Void fraction has been measured and these values have been related to the cavitation parameter \( \sigma = \left( P_{up} - P_{sat} \right) / \Delta P \). An example is illustrated in Figure 5(a) for the thick cylindrical orifice. The images on Figure 5(b) are those recorded in the upper part of the test section for the cylindrical thick orifice. They show the flow topology at three different flow conditions, namely \( \sigma = 1.8 \), \( \sigma = 1.15 \); and \( \sigma = 1 \). The \( \sigma \) values higher than 1.8 correspond to a fully liquid flow. In this range, a correct speed of sound couldn’t be calculated. In fact, this technique would require an acquisition frequency higher than 100 kHz to capture such high speeds of sounds as those in a fully liquid flow (around 1500 m/s in water) (9). At \( \sigma = 1.8 \), cavitation is barely visible at the exit of the orifice but the flow appears completely liquid in the region of the transducers (Figure 5(a)). However, a constant whistling can be heard at this condition and a free speed of sound of 1381 m/s has been computed. It corresponds to a void fraction of 3.8E-7. Figure 5(b) shows the case of \( \sigma = 1.15 \). The vapor phase appears well dispersed in the liquid, which satisfies the homogeneous two-phase flow assumption. The void fraction is estimated at 0.0003. Finally, the highest value of void fraction (i.e. 0.0013), has been measured at \( \sigma = 1 \). From this point, the flow starts choking and the cavitation cloud extends itself farther and farther from the orifice. In fact, the front of this cavitation cloud starts appearing in the frame as we can see on Figure 5(c). Reducing the cavitation parameter, super-cavitation appears and the technique is no longer applicable.
Conclusion

An experimental study on cavitation has been carried out. Three different orifice geometries have been analyzed, two divergent orifices, thin and thick, respectively, and a thick cylindrical orifice. The hydraulic behavior of these orifices has been observed from the fully liquid to the super-cavitation. Moreover the effect of the orifice geometry on the flow topology has been examined. Special attention has been given to the void fraction, which has been estimated by means of time-resolved pressure measurements. These results have been linked to the cavitation parameter in order to correlate the cavitation intensity to the void fraction and to question the influence of the orifice geometry on these correlations.

References


4. Experimental and numerical study of the flow characteristics in a cryogenic valve with liquid nitrogen and water. Peveroni, Laura and Pinho, Jorge and Steelant, Johan and Strengnart, Marc and Vetrano, Maria Rosaria. 2015.


