Experimental study on cavitating flow in an axisymmetric system

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Abstract

We experimentally studied the cavitating flow in an axisymmetric system, aiming at finding reliable approaches to analyze cavitation. Three image post-processed approaches were applied to analyze the test data, in order to obtain the cavitation characteristics. The cavitating flow pattern was studied by high speed images. In one cavitation developing period, there could be three distinct cavitation clouds, whereas the second one is not fully developed. The first image post-processing approach was applied to obtain the mean value and standard deviation distribution, which indicate the erosion area may cover almost all the cavitation developing route and the most vulnerable erosion area locates near the cavitation collapse site. It is coincides with the erosion tests analyzed through the pit-count algorithm approach. The cavitation circulation frequency was invested via PSD analysis approach. It shows that the frequency linearly decreasing with decreasing cavitation number. Additionally, the cavitation intensity effect on cavitation erosion was quantitatively studied based. It is found that the damages are strongly enhanced when increasing the flow velocity. Moreover, the growth rate of eroded pits number is actually stepwise instead of linear (similar to our previous work in a venturi tube), which supports the idea that the cloud cavitation collapse is the primary reason for erosion. The present approaches applied here shows good potential ability of investigating cavitating flows and can be utilized for other apparatus.

Key words: Cavitating flow; Cavitation erosion; Visualization; Collapse; Orifice plate

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1. Introduction

Cavitation is defined as bubbles generation. It happens where the local pressure is below the liquid saturation pressure, and then the bubbles collapse when they are convected downstream, because of pressure recovery. If the collapse occurs in the vicinity of solid wall, the shock wave or micro jet generated during this process would erode the surface of the rigid boundary. As the energy impacting on the surface exceeds the material’s fatigue strength, then erosion happens. Such damage pattern is found almost in every hydrodynamic machines, like vessels, propellers, pumps and so on, resulting in enormous economic lose [1-6].

Remarkable attempts have been made to clarify the physical mechanism of cavitation erosion, since last century in 1917 Rayleigh discussed about the issue of cavitation erosion on ship propellers [7]. The intensity of the shock wave emitted by bubbles collapse is one of the most important factors resulting in cavitation erosion, which could reach several GPa [8-9]. Various measurement approaches are applied to obtain the impact load on solid surface. But it seems like that different approaches might get different results. Franc et al. [10] tested the cavitation generated by two parallel circular plates with a straight nozzle on one of them in the center, and the other one was placed 2.5mm away as the eroded sample. A maximum impact load of 500N was measured via a conventional pressure transducer as the cavity velocity ranges from 45m/s to 90m/s. However, Carnelli et al. [11] only got an order of 20N impact load on a same test system by using the spherical nanoindentation measurement. Also, Hattori et al. [12] obtained similar results (a maximum impact load of 20N) at flow velocity up to 184m/s by following the standard ASTM G124-95. Furthermore, Soyama et al. [13] employed the poly vinylidene fluoride (PVDF) to measure the impact load in a cavitating jet device. It turned out to be up to 200N when the jet velocity at the nozzle outlet ranges from 126m/s to 155m/s. The discrepancy between these tests was significant. One of the reasons lies in that the size of the pressure transducers adopted in these works are still larger than the tiny bubbles, although they are “micro”. The measured impact load may be caused by several bubbles collapse. And the lower sampling frequency of the pressure transducer, compared with the fast progress of collapse, could also influence the test result.

Another prevalent measurement is the pitting test, first proposed by Knapp in the 1950s [14-15]. By exposing the solid material to a cavitating flow, it is used as a transducer during the erosion incubation period, which means the material only suffers plastic deformation without mass loss. In this way, one can obtain the distribution of pits and even the number and area, but such erosion experiments still require a long exposure time [16-20]. Hutli et al. [19] tested the cavitation erosion process by exposing the copper samples to a high speed submerged cavitating jet for 30min. Rijssbergen et al. [20] tested cavitating flow around a 2D NACA hydrofoil, aiming at studying the sheet cavitation collapse behavior and related erosion mechanism. The detailed cavitation evolution structures were captured from side and top views by two high speed cameras. And the cavitation erosion was measured by oil painting method for 1 hour. Such long testing time makes it difficult to investigate the relationship between cavitation structures and erosion. A common way to solve this issue is the utilization of softer material as the transducer [21-22]. Recently, our previous work applied a thin aluminum foil attached on the solid surface as an erosion sensor. The tests only lasted few seconds to minutes, which enabled us to record the cavitation erosion progress and the cavitation evolution synchronously by high speed camera [23-25]. The results presented a strong demonstration that the cloud cavity separation and collapse are responsible for the damage.

In the meantime, great effort has been made on the prediction of cavitation erosion, based on various mechanisms [26-31]. And most of them were conducted by CFD method. A recent study performed by Gavaisses et al [32] predicted the cavitation area in an axisymmetric geometry (similar to the current work) via both visualization and CFD approaches, in order to correlate the eroded location with the location of cavitation development. The simulation results had great agreement with the visualizations.

In the present study, we performed jet flow cavitation tests through two adjacent parallel plates with a nozzle—orifice plate. Aiming at providing insight into the details of the correlation between cloud cavitation collapse and cavitation-induced erosion, and establishing fully experimental methods for investigating different cavitating
devices, three image post-processing approaches were employed to analyze the cavitation characteristics. The prediction results were validated by cavitation erosion tests.

2. Experimental setup

All the experiments were conducted in a cavitation loop test platform in the Laboratory for Water and Turbine Machines, University of Ljubljana. As seen in Fig. 1, the entire closed test system was driven by a loop pump, a downstream tank which can be used for water heating, a vacuum pump for controlling the system pressure, a test section composed of two parallel plates, an electromagnetic flow meter, ABB WaterMaster V with a measurement uncertainty of 2% and two pressure transducers, ABB 266AST with ±0.04% measurement uncertainty. Hence, the measurement uncertainties due to instruments was estimated less than 3%. The detailed test rig facilities can be referred in [25]. In the attempt of obtaining the full cavitation erosion data from the very beginning of the cavitation being generated, two valves are mounted upstream and downstream from the test section, far enough for avoiding disturbance. To assure the test repeatability, the dissolved gases were measured by the Van-Slyke method [33] after running the test rig for 30 min at a low pressure, since the dissolved gases have significant influence on cavitation. In the presented work, the gas content of 15 mg/L in water was maintained.

The test section was manufactured by Plexiglas for visualization. As mentioned above, it consists of two square parallel plates with a dimension of 150mm×150mm. The flow comes through a nozzle tube at the center of the upstream plate, where the cavitation generates at the throat. And then it moves downstream through four symmetrical outlet holes on the periphery. The downstream plate is used as the eroded target. The distance between two plates is controlled by a washer with a thickness of 3mm. The profile of the test section is illustrated in Fig. 2, as well as the real model.

![Fig. 2 Profile of the orifice plate (a) and the real model (b)](image)

The high speed camera, Fastec Imaging HiSpec4 2G, was placed in the front of the downstream plate. It has a maximum resolution of 3Mpixel with a sampling frequency of 523fps. The cavitation evolution under different cavitation number in the first place. The cavitation number is a dimensionless parameter defined as: \( \sigma = \frac{p_\infty - p_v}{0.5 \rho \upsilon^2} \).

Here \( p_\infty \) stands for the reference pressure, measured 200mm upstream from the test section. \( p_v = 3170\text{Pa} \) is the water saturation pressure, \( \upsilon \) denotes the velocity at the nozzle.
throat and $\rho = 998.2 \text{kg/m}^3$ means the water density.

During the cavitation erosion tests, the pump was firstly operated at a low frequency to get the water circulating in the system at a low velocity without any cavitation. Then, the desired operating condition was set by closing the upstream valve and switched the pump operating frequency. At the end, the desired operating condition was achieved by opening the upstream valve rapidly. The cavitation damages were measured by a 10μm thick aluminum foil attaching on the downstream plate. The eroded progress was also recorded by high speed camera, since the exposure time only lasts for 5min. The whole test section is symmetrical, so the foil only covers part of the surface, as shown in Fig. 3.

Fig. 3 Aluminum foil attached downstream plate

Fig. 4 shows the instantaneous cavitation structures under various cavitation numbers. These successive images were recorded by high speed camera at a shooting frequency of 2773fps for 2min.

As seen, the cavitation structure is annular, and the size increases with the decreasing cavitation number. For $\sigma = 3.36$, the length reaches 26.9mm (from the cavitation inception point to collapse point), while it is only 6.1mm at $\sigma = 5.15$. Also, because the distance between two plates is only 3mm, we can note that the generated cloud cavitation is composed of numerous tiny bubble clusters.

For predicting the eroded areas, the successive images of the cavitation structure were post-processed by calculating the standard deviation value. Each image is treated as matrix, within which every each element

3. Results and discussions

Fig. 4 Cavitation structure under various cavitation numbers
Fig. 5 Mean value (upper) and standard deviation distribution (below) under various cavitation numbers.

\[ \sigma = 4.56 \]
\[ \sigma = 3.80 \]
\[ \sigma = 3.57 \]
\[ \sigma = 3.41 \]
\[ \sigma = 3.37 \]
\[ \sigma = 3.21 \]
indicates one pixel. More details concerning to the applied post-processing approach can be found in ref. [34].

Fig. 5 presents the mean value and standard deviation distribution under various cavitation numbers. From which, we can identify the cavitation covering area via the mean value distribution, and predict the potential eroded area through the standard deviation distribution. One can notice that the size of the mean value and standard deviation distributions are almost identical with each other. However, the contours are not that analogous when the cavitation number drops below 3.41. The standard deviation indicates that the most potential erosion region locates on the periphery with highest deviation value, while the most covered cavitation region given by the mean value lie in the middle of the contour (The scales of the standard deviation and mean value are used for better image contrast to identify the cavity covered region and potential erosion region). When the cavitation number goes above 3.57, the distributions are nearly the same. The reason is that as the cavitation number decreases, the cavitation evolution process becomes more distinct and regular. As a result, the likely eroded area concentrates at the sites where collapse occurs, making it prone to be damaged by emitted shock wave or jet flow. Whereas the cavitation evolution is a little irregular as the cavitation number is higher. Besides, one may find that the distribution is not strict symmetrical. We reckon that it is probably caused by the uneven screw intension.

Fig. 6 shows the damaged aluminum foil after being exposed in cavitation for 5min, at \( \sigma = 3.41 \). A ring-type eroded area can be seen directly by naked eyes. The diameter is approximately 40mm, identical with the predicted standard deviation distribution in Fig. 5.

![Erosion Diameter](image)

**Fig. 6 Cavitaiton damaged aluminum foil at \( \sigma = 3.41 \)**

The cavitation erosion progress on the aluminum foil was recorded by high speed camera. We employed pit-count algorithm to detect the erosion pits [25, 35]. Fig. 7 shows the recorded instantaneous raw images of aluminum foil in pairs and the post-processed images by pit-count algorithm, where the brighter area implies overlapping pits.

The chosen operation condition is \( \sigma = 3.41 \) and the time interval between each pair is 900\( \Delta t \), here \( \Delta t = 43.5 \) ms. The brighter area indicates the damaged pits, compared with the original image at \( t = 0 \). As seen from the experimental images, the pits are growing gradually in the region where cavitation collapses. Much clearer pits can be observed in the post-processed images, benefited from the pit-count algorithm, which eliminates the disturbances from illumination reflections or system vibration, resulting in more sharp contrast. One can see great agreement between experimental images and measured images. At the beginning of the exposure, the pits scatter nearby the collapse sites without many overlaps. However, since the cavitation tends to erode the place where has already been damaged or has surface defect [23], some of the erosion pits overlap each other consequently, giving rise to higher brightness after long exposure.

To investigate the cavitation intensity effect on erosion, two more tests were carried out by keeping the cavitation number constant as 3.41. Under this circumstance, the cavitation size remains unchanged, but the nozzle throat velocities are different. Based on the case in Fig. 8, where \( v = 12.9 \) m/s, the higher velocity condition was accomplished by increasing both the flow rate and upstream pressure, while the lower velocity was achieved in an opposite approach. The test results are given in Fig. 14. It is implied that the cavitation intensity has profound impact on cavitation induced damage. We can see considerable distinction after enhancing the cavitation intensity – more damages are produced. Even so, the diameter of the eroded ring area nearly stays the same. On the contrary, reducing the cavitation intensity leads to lower damages and what’s more, the damaged area is not annular.
Fig. 7 Raw images of recorded aluminum foil (upper), post-processed images (middle) and predicted results of the eroded area at this instant (down) at $\sigma=3.41$

Fig. 8 Cavitation erosion tests under different velocity at constant cavitation number $\sigma=3.41$

On the basis of the pit-count algorithm, the pits number accumulation as a function of time is obtained, as plotted in Fig. 9(a). It obviously indicates that the cavitation intensity significantly increase the damage process. The growth rate increases linearly with increasing velocity when keeping the cavitation number constant. To be more precise, we focus on a smaller time range from 43.5s to 48.5s. The case of $v=12.9$m/s is selected, as shown in Fig. 9(b). We can find that instead of a straightly linear pits increment, it presents a stepwise growth pattern. The reason lies in that the pits are mainly caused by the periodic cavitation collapse [25, 30], during the cavitation growing time, only a few pits could be generated.
Fig. 9 Erosion pits number as a function of time (a) 1 min (b) 5 s

References


