

Experimental analysis of the onset and development of cavitation in a centrifugal pump

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Abstract. Centrifugal pumps are considered as machines of high importance in a wide range of industries, hence several strategies and methods have been developed in order to ensure their optimum performance under different operating conditions. An important mechanism that can affect pump's steady and dynamic operation is cavitation, which appears in the low static pressure zone at the inlet of the impeller. Several researchers have studied experimentally the physics of the phenomenon in order to develop different methodologies for its safe detection. The aim of this paper is to study the onset and evolution of cavitation in a centrifugal pump with unshrouded impeller by performing of flow visualization and acoustic emission measurements. The results showed that the acoustic emission technique is able to detect the onset of cavitation, while the leakage backflow through the clearance affects the development of cavitation between the impeller blades.

1. Introduction

Cavitation is a hydrodynamic phenomenon that appears in hydraulic machinery, where water may be vaporized due to local pressure drop in the flow field. In centrifugal pumps water flows from areas of low pressure to areas of high pressure, so bubbles could be possibly created in the inlet of the machine and travel until a point where pressure increases again, where they are reliquified. Reliquification is a very violent procedure, where during the abrupt elimination of vapor volume and bubble implosion, shock waves are generated that could overstress solid boundaries and create unwanted noise and vibration [1]. For this reason engineers investigated different methodologies in order to be able to detect cavitation inception and its development. Mc Nulty [2] used piezoelectric sensors with resonant frequency of 130 kHz and proved that the energy of discrete high frequencies are able to monitor inception of two phase flow inside the machine. In addition, energy of noise was reduced as NPSH decreased mainly because larger cavities damped noise emitted until a point where flow became very unstable and increased again. Similar trend in their results obtained also Alfayez and Mba [3], by measuring with acoustic emission (AE) signals in a large scale pump. According to them, noise increase in low NPSH values was the result of backflow cavitation phenomenon where flow recirculation chocks pump's flowrate. Neil et al. [4] used high frequency acoustic emission (AE) sensors for the detection of

incipient cavitation. Their results showed that it is possible to quantify bubbles onset and development with the use of frequency spectrum. In addition, larger bubble areas decrease the AE root mean square (r.m.s.) value, however further NPSH reduction didn't increase the noise. Chudina [5, 6] proposed the use of microphones in the audible frequency range for the monitoring of cavitation. Despite the disadvantages introduced from the low frequency mechanical noise, they showed that there is a discrete frequency in the low frequency range related with the blade passing frequency that it is not affected from surrounding noise and was increased only when bubbles existed. Cernetic et al. [7] measured mechanical vibrations in two pumps; one with a closed impeller and a second with a semi open impeller. In the first, cavitation could be detected in the high frequency range between 1 and 10 kHz where the amplitude of this frequency increased in cavitating conditions. However in the second pump the frequency tone discussed by Chudina [5, 6] increased intensively with cavitation development and proved how geometrical characteristics of the impeller could affect noise emission. Finally, Zhang [8] et al. measured vibration response in different locations and in different frequency ranges. Similarly to Mc Nulty, showed that the onset of bubbles is detected clearer in high frequencies as well as vibration energy decreased with cavitation development until the lowest NPSH value, where noise increased again only for small flow rates. Summarizing the above works, important progress can be observed in the field of cavitation monitoring techniques. From the methods developed so far it is possible to detect the onset of cavitation with safety and predict its development depending on the transducers and frequency ranges used. However, different impellers or flowrates gave differences in the noise measurements irrespective of the methodology used. This depicts the need of deeper understanding of cavitation development and its behavior in different flow or geometrical conditions. In this paper, acoustic emission r.m.s. is measured in different flowrates in a mini centrifugal pump the casing of which is made by plexi-glass. By this way it is possible to visualize the flow with the use of high speed stroboscope and study the onset and development of cavitation as a function of noise characteristics and the NPSH value.

2. Experimental Set Up

The model of centrifugal pump that is used in this study is presented in figure 1. It is a low specific speed pump of 0.58 kW power at 12 m head with 7.5 m³/sec flow rate at its best efficiency point (BEP). Water is pumped from the tank and passes from the suction valve before it enters the semi open impeller that consists of 12 straight blades. Before impeller inlet, a 90 degrees bending pipe is installed that eradicates the axial symmetry of the flow and creates an extra pressure drop. This resulted in a non-axisymmetric pressure flow field in the inlet of impeller and as a consequence cavitation inception appeared always on the left side of the impeller eye. This is the reason that all the photos taken in this experiment are from this side of the machine, as it presented in figure 1.

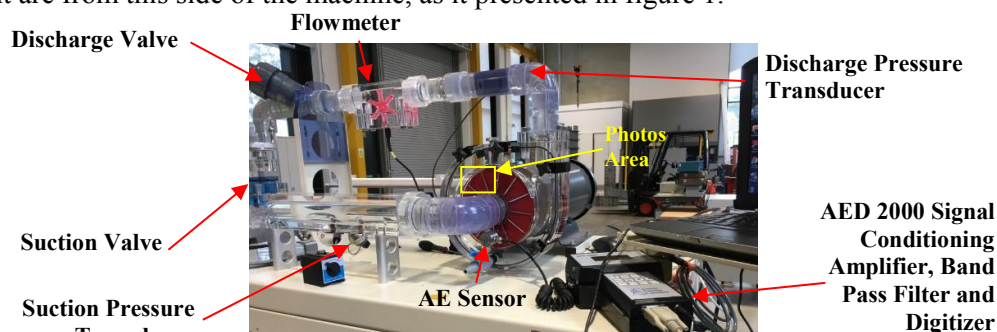


Figure 1 Pump test rig

After the pump, water passes from the flow rotometer and from the discharge valve, which controls the flowrate and returns to the tank. For cavitation experiment, NPSH value is decreasing in order to study its inception and development. This is done by throttling the suction valve in order to increase the losses and reduce the total suction pressure, while properly regulating the discharge valve to retain the flow rate. However, this resulted in cavitation inception far before the pump's inlet, in the suction valve, for the lowest NPSH value irrespective of the flowrate. Four different flowrates have been tested for an

impeller with straight blades and rotational speed has been chosen at 1800 rpm. According to McNulty [2], Neil [4] and Zhang [8], cavitation affected more intensively high frequency ranges no matter the physical quantity measured. As a consequence, acoustic emission sensor is used in order to validate the ability of detecting bubbles inception as well as to associate noise emitted with cavitation behaviour by the study of the photos of the flow field obtained. The sensor is connected with AED 2000 in order to filter, amplify and digitize the signal. After signal digitization, conditioner transfers in laptop, every second, the average of 90 volt r.m.s. values. The AE r.m.s. results presented here deal with the average value of AE obtained during two minutes of measurement at each operating point. For flow visualisations a stroboscope has been used and photos were taken with a DSLR camera. Tests were performed three times in order to ensure repeatability both at the measurements of flow quantities but also for cavitation inception and development. Repeatability error for flowrate and total head calculations was 0.2% and 0.5% respectively. Quantitative repeatability is not expected for AE measurements as well as in visual observations. However, the trends of noise as a function of the NPSH were repeatable as well as the photos of cavitation inside the impeller.

3. Experimental Results

Four different flowrates are tested in order to derive the NPSH - H_{TOT} and NPSH - AE r.m.s. graphs that are presented in figure 2. As the flow rate increases, it is more difficult to approach low NPSH values mainly because of the use of the valve as the mean of total suction pressure drop. As a result, total head drop is much clearer in lower flow rates than in higher flow rates such as 159 lt/min. Another limitation introduced by the suction valve is the inability to obtain measurements and photos between the two lowest NPSH values. At the last point pressure dropped heavily in the suction of the pump and cavities were created in the valve and travelled inside the impeller. Measurements at this point present high interest because differences are obtained in noise trends between already published studies [2, 3, 4 & 7]. However, flow visualization approach provides interesting conclusions, which are discussed afterwards.

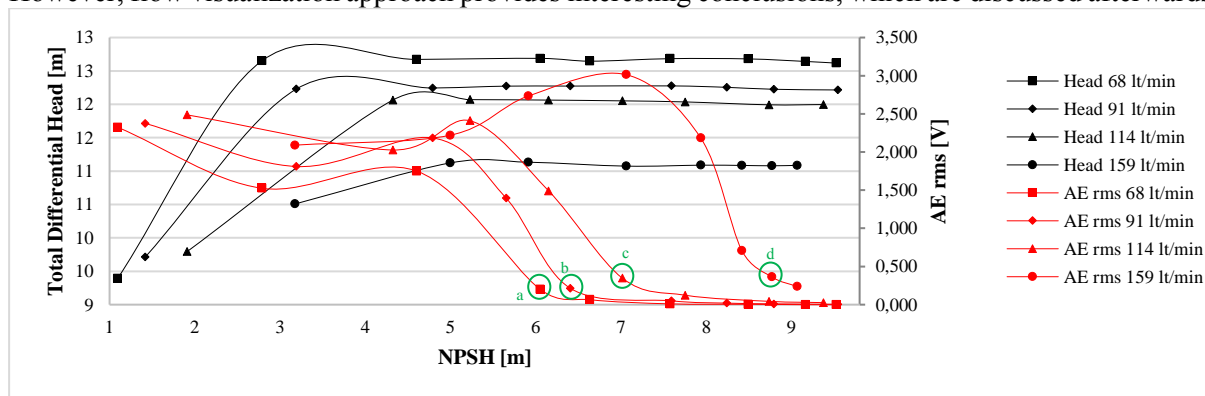


Figure 2 Total head and AE curves in red impeller for four flow rates

The AE analysis confirmed that the increase of flowrate increases the NPSH value where cavitation started due to the higher velocity field inside the impeller. Also it was validated that the increase of noise coincides with cavitation inception by observing the flow with the use of a stroboscope.

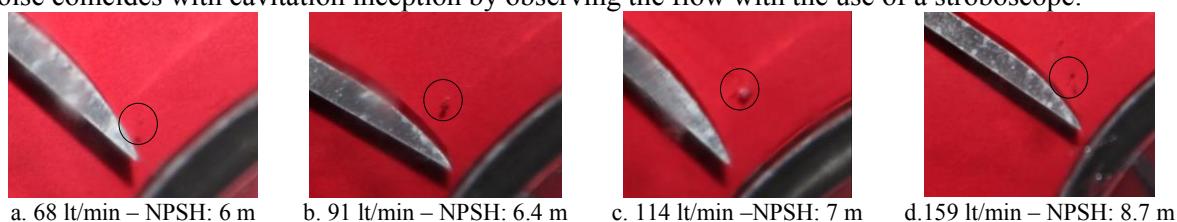


Figure 3 Cavitation inception that corresponds to visual inception point in different flow rates

In figure 3 the appearance of the first bubble in the flow field is presented. As it is expected, vapour is formed in the suction side of the leading edge (LE) of the blade, irrespective of the flowrate studied. It is very interesting that AE r.m.s. value increases just after the appearance of the first small cavity, as it can be seen in figure 2, for points a-d, for all the flowrates. This is the result of correct use of band pass filtering that allows only frequencies in the range of 100 to 150 kHz to pass and removes all the surrounding low frequency environmental noise of the motor and the pump. A further decrease of NPSH value results in an increase of the number and magnitude of cavities for all flow rates, as can be observed in figure 4. At this NPSH value, AE r.m.s. reaches a local maximum value, similarly to the majority of the results presented in other works [2-4]. Until this point the shock pressure waves generated from bubble implosion travel without resistance through the liquid flow and they are transferred to pump casing and to the sensor.

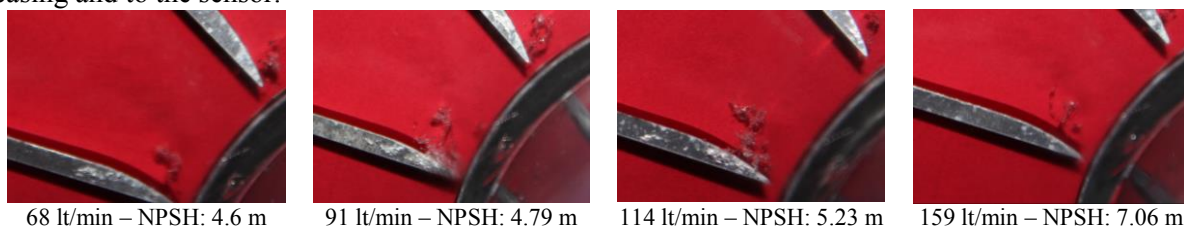


Figure 4 Photos that correspond to local maximum value of AE r.m.s. in different flow rates

However, further decrease of total suction pressure increases the two phase flow area thus resulting in some decrease of noise emission. Gulich [9] has noticed that NPSH decrease creates large cavities that absorb the pressure waves created. Figure 5 presents the flow field inside the impeller when noise is decreasing. For all flowrates, cavitation area has increased and close to the blades inlet two phase flow extends in a large part of the blade passage. In addition the sharp shape of LE blade accelerates locally the flow and deteriorates vapour creation.

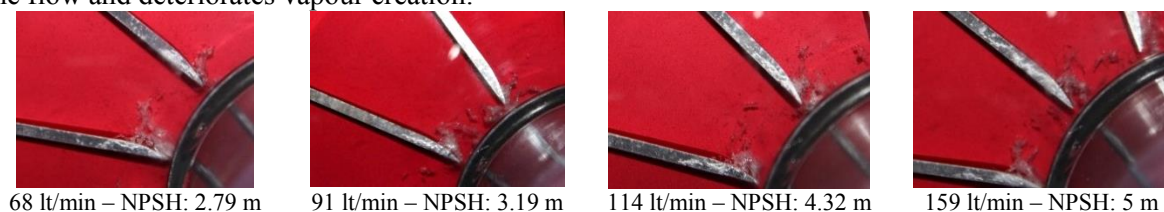


Figure 5 Photos from impeller that correspond to AE r.m.s. decrease in different flowrates

Finally, figure 6 shows the photos taken for the lowest NPSH value of point 4 of figure 2, where the discharge valve was almost fully opened and the suction valve was throttled. For the majority of the flowrates this was the operating point with the most intensive noise and vibration. At this point the flow becomes very unstable and exhibits intensive recirculation and separation regions. In addition, cavitation due to leakage flow recirculation can be observed at the yellow brackets marked in Fig. 6, where bubbles exist in the space between the impeller and the casing. Alfayez [3] and Brennen [1] discussed the same phenomenon and noted it as backflow cavitation. Also, the thickness of the clearance of this impeller ranges from 1 mm in the trailing edge (TE) to 1.3 mm in the LE, introducing high volumetric losses and reducing pump efficiency. The corresponding blade height ranges from 3.2 to 7 mm, respectively. As a consequence, part of the flow that already consists of bubbles enters the clearances, where it is further accelerated, thus increasing cavitation. This flow is driven in the low pressure area of the impeller and it is re-joined with the two phase flow already established in the suction of the pump. At this point, cavitation dominates at the impeller inlet, vapour blocks the flow, pump's head drops, and noise increases heavily. However, this phenomenon becomes less extended as the flow rate takes higher values, as can be observed in figure 6 (green boundary lines), as also in the AE r.m.s. results of figure 2. This happens because, as the pump flow rate is growing, the percentage fraction of the flow that is passing through the clearance becomes lower. As a result, recirculating flow affects more the flow characteristics in low flowrates.

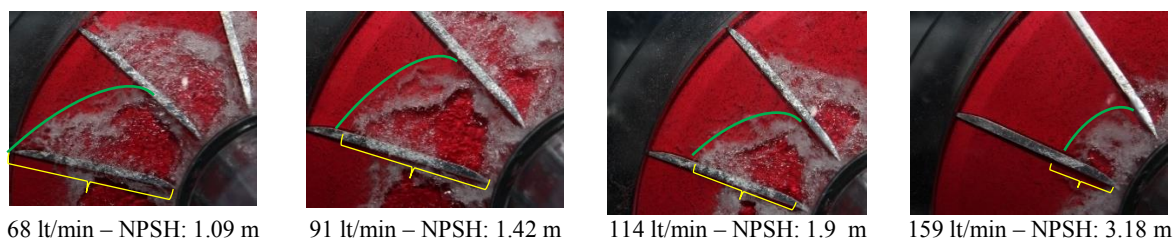


Figure 6 Photos from impeller that correspond to the lowest NPSH point for different flowrates

4. Conclusions

This study investigates the inception and development of cavitation in a centrifugal pump with unshrouded impeller and straight blades. In order to detect and study the cavitation behaviour, one AE sensor is placed close to the suction side of the pump. Furthermore, the casing of the machine is made from plexi-glass in order to be able to visualize the flow between the blades and validate noise measurements. The obtained total head curves confirmed that intense cavitation in low NPSH values can block the flow rate of the machine and reduce its ability to maintain water head. In addition, the AE signal is found to increase exactly at the point of the onset of cavitation, and this was validated by flow observations. Also, the emitted noise r.m.s. decreases when cavitation is increased, irrespectively of the flow rate. Finally, interesting observations have been made at the lowest NPSH value, where backflow cavitation dominates the flow and creates a very turbulent and noisy environment that was depicted both in photos taken from the impeller, as well as in the AE results. The obtained results aim to contribute to the deeper understanding of cavitation inception and evolution in such pump configurations. In addition, the flow visualisation validates the effective and reliable use of AE measurements as cavitation inception detection methodology. However, more research could be done in order to study the effect on cavitation of other critical geometric characteristics, such as the blade shape and inlet angle, as also the effect of different clearances.

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