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ABSTRACT

For industrial monitoring of fluid flows, the transition from a single-phase flow to a cavitation regime is most commonly determined by a microphone that measures the sound emitted in the vicinity of critical constrictions such as in the opening of the control valves. We have developed an alternative, analogue and robust piezoelectric detection method to observe the cavitation threshold. The evaluation of this method on the reference test orifice plate and on a chosen control valve shows that it eliminates the sound noise of an industrial environment, largely removes the subjectivity of the operator and enables a more detailed observation of the cavitation phenomenon.

1. Introduction

Cavitation occurs usually downstream the constriction of the flow where the local pressure decreases below the saturated vapor pressure of the liquid. The usual way to determine the transition from a single-phase flow to a cavitation regime is based on the sound pressure level analysis using microphones and hydrophones which are widely used and are of great importance for turbomachinery [1]-[3]. This method is also included in the standard for evaluating cavitation in valves IEC 60534-8-2:2011 [4] (hereinafter referred to as standard method). Due to its limitations, we have developed an alternative, simple and robust piezoelectric detection of cavitation threshold. To detect bubble formation in early stages, the proposed procedure uses acoustic emission (AE), which has been used previously in connection with cavitation phenomena in valves [5], since these methods were proven to be a good method for pumps and valves [6]. The AE is a useful technique also in boiling processes [7] because its frequency range is above the limit of most environmentally generated noise.

The proposed procedure makes it easier to observe cavitation without using any special digital frequency filters, such as Fourier transforms, and signal approximations, which have been used as an addition to the standard method. Moreover, a significant deficiency of the standard method is an absence of direct correlation between the cavitation phenomenon and the sound pressure signal, which is measured with a microphone. Additionally, the noise of the industrial environment has no effect on the presented method, the operator's subjective influence is removed, and it enables more comprehensive analysis of the cavitation phenomenon. This method was developed, tested and compared with the standard method on the selected control

valve, where determination of cavitation threshold is known to be challenging, and on standard orifice plate, which is clearly defined by the standard.

First, we studied different methods for detection of cavitation threshold with a distinct goal to find a clear correlation between the cavitation phenomenon and the responses of detectors. We adapted the examined control valve to optically access the place where cavitation occurs, so that we could observe cavitation with a high-speed camera, i.e., the reference method for the cavitation. Since it is difficult to define the high-speed camera's cavitation evaluator, we rather employed a laser beam deflection probe. The laser beam is transmitted through the area inside the valve where the cavitation structures are observed by the camera, and its evaluator can undoubtedly indicate the presence of cavitation in the observed control valve. However, this optical method is unsuitable for use in an industrial environment as regular valves do not have optical access.

In the beginning of this article, it is described how different physical principles (methods) are examined and compared. Later on, we explain the developed physical principle, which is tested to detect cavitation threshold with great precision, so that it becomes industrially useful.

2. Existing methods for cavitation detection

Cavitation detection in control valves according to the standard IEC 60534-8-2:2011 is based on the measurement of sound pressure level due to liquid flow through the valve. The standard focuses on the beginning of the phenomenon and less on the harmful effects that it generates.

Because in many cases the direct use of the standard method does not provide a clear value of the cavitation threshold, the standard method was further evolved in industrial practice to observe not only the acoustic signal of the microphone β , but also its filtered version β_A . The acoustic signal with the sound level β , measured with a high-frequency microphone, is first captured in the cavitationless regime of the flow and then separately when the cavitation is already present. The operator determines these two domains subjectively according to the previous experience and by listening to the valve's audible sound emission. Both signals are compared in the frequency spectrum and the frequencies that are determined by the operator not to be the result of the cavitation phenomenon are excluded. The signal β_A is thus affected only by the selected frequencies attributed to the cavitation by the subjective filtering protocol.

The presented method for determining the cavitation threshold employs the piezoelectric detection principle. Due to a direct correlation between the signal of the detector and the cavitation phenomenon, the key parameter that affects the signal is the rate of cavitation. We wanted to simplify and speed up the detection of the cavitation threshold. In addition, the microphone used in the standard method is also sensitive to the low-frequency disturbances (e.g. speech, noise of an industrial environment). On the contrary, these disturbances have no effect on the piezoelectric sensor, since they are excluded by an analogue high-pass filter. Thus, the accuracy of the measurement of the cavitation threshold detection can be greatly improved.

A non-cavitating flow of liquid transitions into a cavitating one when the pressure difference (pressure drop) between the inlet absolute static pressure p_1 and outlet pressure p_2 surpasses the threshold value Δp_K . The pressure ratio x_F then takes a value known as the characteristic pressure ratio or factor x_{Fz} :

$$x_F = \frac{p_1 - p_2}{p_1 - p_v} = \frac{\Delta p}{p_1 - p_v}, \quad (1)$$

$$x_{Fz} = \frac{\Delta p_K}{p_1 - p_v} \left(\frac{p_1}{p_{1,REF}} \right)^{1/8}, \quad (2)$$

p_v stands for the saturated vapor pressure of the water and $p_{1,REF}$ the reference value of inlet static pressure. It is recommended that in the operating range of the valve, the characteristic pressure ratio x_{Fz} is as high as possible enabling high flow with no jeopardy of damage to the valve. If the pressure ratio x_F is larger than x_{Fz} , cavitation erosion may occur and consequently damage the valve [8],[9].

The static pressure may reach the cavitation threshold even under moderate operating conditions [10]. By increasing the flow rate, which corresponds to larger pressure difference in the control valve, the minimum pressure in the *vena contracta* decreases to vapor pressure of the liquid and therefore cavitation structures begin to appear. As the outlet static pressure rises above the vapor pressure, the steam bubbles implode in the vicinity of the valve [11]. The cavitation occurs in the same way also when a standard orifice plate is used, however the location of cavitation is highly specific and well determined [12]. According to the standard, the most commonly used method for determining the x_{Fz} factor is by lowering the dimensionless pressure ratio to detect the transition from cavitation to non-cavitation domain. The sound pressure level L_p is measured for each value of the ratio x_F with a microphone equipped with an octave band filter which includes the highest frequency. The measurement must be made in a sufficiently large area in a cavitation and non-cavitation domain and the data points in both are linearly approximated. The intersection of the constructed approximation lines determines the value of x_{Fz} . The procedure is repeated for other relative flow coefficients [4].

The recommended practice for evaluating control valve cavitation is also described in the standard ISA-RP75.23-1995 [13]. Among other things, the standard proposes methods for evaluating the cavitation characteristics of individual control valves and offers guidelines for selecting control valves for given applications. There is a clear connection between the two standards, as for the description of the flow regimes, the ISA-RP75.23-1995 standard defines the cavitation coefficient σ , which is the inverse value of the dimensionless pressure ratio x_F defined by the standard IEC 60534-8-2:2011. Because the σ does not convey any information about the performance of a particular valve by itself, it must be compared to benchmark σ value, also referred to as level, which can be defined in many ways that are not universally recommended. As the appropriate level to use certain application is not always self-evident, it could embrace a degree of subjectivity. Moreover, the factors such as the valve style and the opening, the duty cycle, the location, the desired life, and the operator's experience should be considered [13]. The ISA standard proposes cavitation detection with a piezoelectric or other accelerometer that has a high enough resonant frequency (> 100 kHz), which will assure consistent results for the full frequency range being analyzed (5-50 kHz). For the ease of data analysis, an optional high pass filter can be used to differentiate the low frequency noise

(< 5 kHz) resulting from background and turbulent flow and the high frequency noise resulting from cavitation [13].

Detecting vibrations with accelerometers and statistically analyzing the signals can provide potential use from real-time condition monitoring and diagnostic system for control valves. Yang et al. proposed a condition monitoring scheme using statistical feature evaluation and support vector machine (SVM) to detect the cavitation conditions of butterfly valve. The SVMs are trained, and then classify normal and cavitation conditions of control valves. This can be used to detect problems and assist in the timely scheduling of repairs to the valve before a severe failure occurs [14].

The problem of cavitation detection in control valves is also described in the patent US9423334B2 [15]. An acoustic emission sensor, i.e., an electronic sensor arranged to sense acoustic energy traveling through a solid material, which can be piezoelectric sensor, is arranged to detect the presence of cavitation inside or in the vicinity of a control valve by sensing acoustic signals. A processor is operatively coupled to the acoustic emission sensor. The processor is configured to receive acoustic information from the sensor and process the acoustic information to identify and/or monitor cavitation in the flow control device [15]. One or more filters can be configured to filter the acoustic signals to attenuate predefined unwanted frequencies above and/or below preselected respective upper and lower frequency limits. A cavitation level is determined based on the hit rate (the number of cavitation events that occur within a period of time) and the intensity (an energy unit per cavitation event). The patent predicts to track the number of times the cavitation level exceeds a predetermined threshold.

3. Correlation between optical detection of cavitation and microphone/PZT detection

As an alternative to the standard method for cavitation detection, we experimented with new optical and contact methods. It is of great importance that some of them may be used as a reference to compare other methods; but above all, that they have a direct connection with the cavitation phenomenon. Detection method with a piezoelectric sensor proved to be the most suitable for detecting cavitation threshold, thus this method has been further developed. The experimental setup with all examined methods for cavitation detection is shown in Fig. 1.

Fig. 1. Top-down view of the experimental setup including four different methods for cavitation detection: visual observation by a high-speed camera, laser beam deflection probe, microphone and piezoelectric contact sensor.

To visualize the cavitation volume within the control valve as a reference for further measurements we used a Photron FastCam SA-Z with a macro lens and proper back-illumination with a fiberglass LED lamp. The fast camera provides high time resolution to observe light transmission through cavitation structures. We can spot various cavitation structures with different intensity (Fig. 2) depending on the pressure drop in the control valve.

Fig. 2. Snapshots acquired by a high-speed camera at different stages (a-d) of cavitation. The circle indicates the path of a laser beam through the valve.

The next optical method is the laser beam deflection probe (BDP) that linearly converts the light power into the output voltage with a single silicon photodiode [16]. When the laser beam traveling through the liquid inside the valve gets obscured by the cavitation structure (bubble, vapor cloud), the output voltage from the photodiode is reduced proportionally to the transmitted amount of light. At the early stages of cavitation (Figs. 2a and 2b) there are just a few cavitation bubbles which become larger and appear with greater ratio (Figs. 2c and 2d) when the pressure ratio increases [17]. As the cavitation bubbles deflect the laser light away from the photodiode, less and less light reaches it until the beam is fully dispersed by the cavitation structures so that the photodiode becomes unilluminated. The cavitation evaluator for the signal of the laser BDP was defined by calculating the average value of the signal over time and expressing this value relatively to the maximum value.

$$C_{\text{BDP}} = \left(\frac{1}{t_z} \int_0^{t_z} U_{\text{BDP}}(t) dt \right) / C_{\text{BDP, max}} \quad (3)$$

The high-frequency microphone proposed by the standard IEC 60534-8-2:2011 is another non-contact method for cavitation detection. It was placed 10 cm above the control valve head. The measuring sensor contains a single stage amplifier. The signal has a zero DC offset of 5 V and the frequency spectrum of the microphone is in the hearing range from 50 Hz to 20 kHz. The cavitation evaluator is determined also for the microphone signal by first subtracting the DC value of 5 V from the time dependent signal of the microphone signal, then calculating its absolute value and finally averaging over the whole time of recording t_z . Finally, it is expressed relatively to the maximum value.

$$C_{\text{MIC}} = \left(\frac{1}{t_z} \int_0^{t_z} |U_{\text{MIC}}(t) - 5 \text{ V}| dt \right) / C_{\text{MIC, max}} \quad (4)$$

Fig. 3. Comparison of cavitation evaluators as a function of a non-dimensional pressure ratio. The letters from a to d indicate the corresponding high-speed camera frames presented in Fig. 2.

The contact piezoelectric sensor is an out-of-plane displacement sensor intended primarily to detect frequencies above the hearing range, however it is also sensitive to frequencies below 10 kHz. The sensor has a flat response in the range up to 2 MHz and the noise-equivalent displacement of 1 pm. To further process the signal of the piezo sensor and eliminate the unwanted frequencies that are not significant for measurements, we used low- and high-pass filters. Though it is almost impossible to completely remove certain frequencies, we can greatly reduce their amplitude, so they have no substantial effect on the value of the output signal. The piezoelectric sensor was positioned at various locations on and around the valve. We defined

the cavitation evaluator for the signal by averaging the absolute value of the signal on entire sampling time interval and expressing it relatively to the maximum value.

$$C_{PZ} = \left(\frac{1}{t_z} \int_0^{t_z} |U_{PZ}(t)| dt \right) / C_{PZ, \max} \quad (5)$$

We compared the dependence of the previously defined cavitation evaluators of laser BDP C_{BDP} , microphone C_{MIC} and piezoelectric sensor C_{PZ} on the dimensionless pressure ratio (Fig. 3). For each detection method, two sequential measurements with identical conditions were performed. At a certain value of pressure ratio (approximately 0.48) which is known as characteristic pressure ratio, the evaluator C_{BDP} starts to fall as the laser beam path gets increasingly obscured with cavitation bubbles. We can observe that the evaluator C_{PZ} responds even a bit earlier due to some of the first cavitation vibrations. It is challenging to clearly notice the beginning of the cavitation from the microphone's evaluator C_{MIC} , though this evaluator also responds to increasing presence of sound that is not related to cavitation. At larger values of pressure ratio, the C_{PZ} reaches the maximum value since the sensor saturates at such intensive vibrations.

It is evident that the piezoelectric sensor clearly indicates the cavitation threshold since the transition from the single-phase flow to the cavitation regime is very abrupt and can be undoubtedly discriminated. The laser beam detects bubbles in a very narrow zone inside the valve, thus the difference in the value of its signal evaluator between the two executed measurements is much greater than the variation of measurements with piezoelectric sensor. This is especially evident at lower pressure ratios when bubbles form stochastically.

The comparison between optical and microphone/piezoelectric cavitation threshold detection methods gives a clear correlation between the methods. Now we can safely claim that the signal of both, the standard microphone method as well as the newly developed piezoelectric method truly responds to the increase of cavitation structures in the vicinity of the valve opening, visible by the optical methods.

4. Development of the piezoelectric method

The piezoelectric method for cavitation detection proves not only suitable due to the sharp transition to cavitation regime but also for its practical use in industrial environment. The initially used piezoelectric sensor was later on replaced with a cheaper piezoelectric polyvinylidenefluoride (PVDF) film. The sensor operates reciprocally, as the change in the length or thickness of the film generates the corresponding charge which results in a voltage difference on the film electrodes. The converter acts as an active capacitor, so we must consider the input impedance of the measuring device.

In order to amplify, filter and otherwise process the sensor output signal (Fig. 4a), an appropriate electronic circuit, which also enables to monitor the signal at different stages of analogue processing, has been developed. The initially digitally defined signal evaluator (Eq. (5)) that was used in the initial measurements was later performed analogously as an output of the analogue electronic circuit. The signal from the piezoelectric film is amplified and filtered through the high-pass and the low-pass filter to reduce the unwanted (disturbing) frequencies in the output signal

(Fig. 4b). Thus, the resulting signal contains the frequencies between 10 kHz and 1 MHz. The signal is amplified again and finally, the cavitation evaluator C is determined by setting the absolute value to the signal (Fig. 4c) followed by a signal integration with a discharging characteristic time constant of 0.1 s (Fig. 4d).

Fig. 4. Schematics of the analogue signal processing chain. The raw voltage signal from the PVDF sensor that is fed into the processing circuit (a) is first band-pass filtered (b), then the absolute value of the signal is preformed (c) and finally, its integration gives an analogue output, called the cavitation evaluator C (d).

5. Results and Discussion

First, the detection of the cavitation threshold was tested on a standard orifice plate [4]. The geometric characteristics of the orifice plate are clearly defined by the standard; thus, such test site is very suitable for analyzing different effects on the measurements. Following that, we

studied the cavitation threshold on a more complex circuit element—a control valve whose threshold changes with different valve opening, static pressure and temperature. Moreover, this control valve is also known to emit whistling sound at specific operating parameters. To study the new method, we have performed different measurements of cavitation detection with a piezoelectric sensor. The microphone signal β and its modified (filtered) version β_A are compared with the cavitation evaluator C on the same graph.

Fig. 5. Typical cavitation threshold measurement on the standard orifice plate (a) and on a selected control valve (b) by a standard microphone method (β and β_A) and the presented piezoelectric approach (C).

The essential difference between the cavitation within the control valve to the cavitation behind the standard orifice plate is the increased complexity of the phenomenon which makes it challenging to determine the cavitation threshold. It is evident (Fig. 5) how difficult it is to notice the cavitation threshold according to the standard method, especially in the basic version of the sound level signal (β signal). The new method works incomparably better since it determines the exact beginning of cavitation even without the use of any mathematical tools. In both measurements using the piezoelectric method, a slow buildup of the cavitation evaluator signal is observed due to the intensification of the acoustic background (see the zoomed inset in Fig. 5b).

Another characteristic difference between among the tested methods is seen by observing Fig. 5a. Slightly above the pressure ratio of 0.3, we have intentionally produced an external noise by clapping hands. As a response to the hand clap, both microphone signals significant increased, while the cavitation evaluator remained unchanged. We can conclude that the noise of industrial environment can have a significant impact on the measurements performed by the standard method. On the other hand, the cavitation evaluator C is independent of such acoustic background, which turns out to be one of the advantages of the piezoelectric approach.

The piezoelectric detection method enables us to measure cavitation not only at the site of occurrence but also in the near surroundings, especially on the inflow and outflow pipes, since mechanical vibrations are transmitted from the cavitation site by the structures and flowing medium. We carried out measurements at various places around the standard orifice plate and the chosen control valve. According to the expectations, the largest amplitude of the cavitation

evaluator's signal was detected in the vicinity of the control valve. The amplitude decreased by 30-times when the contact measurement was performed at the distance of 0.5 m from the cavitation site on the connecting pipe. The signal was noticeable both up- and downstream from the orifice plate or control valve (the measuring points are marked in Fig. 1). By performing the measurements downstream and upstream equally away from the valve, one could also determine the presence of flashing.

Hysteresis, the phenomenon at which the output signal (cavitation evaluator) varies at the same value of x_F depending on whether x_F increases or decreases, was observed in some measurements that were carried out at the different rates of increasing the pressure ratio [18]. During every measurement, the pressure ratio is increasing linearly with time from zero to its maximum value and then at the same rate falling back to zero. Hysteresis is noticeable in measurements at higher rates (faster increase/decrease of flow velocity with time). With slowly increasing pressure ratio, there are much more cavitation acoustic bursts detected, since it takes a longer time to sweep over the desired values of x_F . As hysteresis occurs both in the microphone and the piezoelectric sensor signal, it cannot be assumed that it is only a result of the sensor.

The piezoelectric detection is a contact method, thus it is difficult to achieve the repeatability of sensor attachments. It has been shown, that the positioning of sensors is crucial for optimal observations at a given state [19]. Although the attachment has a noticeable effect on the amplitude of the signal (the measurements vary by 25 %), we did not observe any influence on the value of the cavitation threshold. Further improvement of the sensor's attachment brought the repeatability below 5 %. This was achieved by fixing the PVDF sensor on a short waveguide that can be repeatedly reattached to the pipes.

We also investigated the effect of high-pass filter's cut-off frequency on the cavitation evaluator. The amplitude of the evaluator is reduced by approximately 5 times with the selected cut-off frequency at 30 kHz compared to the 10 kHz. The effect is observed in both, the orifice plate and the control valve. The difference between the two elements is examined at a 100 kHz cut-off frequency, when only signal from the control valve can be detected but with a much lower amplitude. It is worth adding that the measurements on the standard orifice plate were performed on a PMMA [poly(methyl methacrylate)] pipe, while they were performed on metal pipes when using the valve.

6. Conclusion

We have developed a simplified piezoelectric contact method to accurately determine the transition from a non-cavitating to a cavitating flow. This method was tested on a standard orifice plate and on a selected control valve and compared to the microphone-based methods proposed in the IEC 60534-8-2:2011 standard.

The presented method is sensitive to the acoustic waves emitted by the cavitating structures. A piezoelectric sensor transforms the acoustic signature of the cavitation into a broadband voltage signal. This signal goes through an online data processing by the dedicated analogue electronic circuit. The output from the circuit is a simple analogue cavitation evaluator, a voltage signal whose DC value reports on the degree of cavitation. This signal can be further digitalized or displayed using an analogue gauge.

Simultaneous measurement of the degree of cavitation with optical and acoustic approaches clearly demonstrates direct correlation between the visual presence of the cavitation phenomenon and the sound pressure signal, which is measured with a microphone, or the ultrasound captured by the piezoelectric sensor.

A series of experiments were performed using the newly developed piezoelectric cavitation sensor. We have studied various effects, e.g., detecting the signal at different measuring points close to the origin of cavitation, measuring the cavitation hysteresis, the effect of sensor's attachment and the change of the high-pass filter's cut-off frequency. We have compared the piezoelectric detection to the acoustic method proposed by the IEC 60534-8-2:2011 standard. In contrast, the proposals of the ISA-RP75.23-1995 standard are obviously more appropriate as they are similar to the solutions which we implemented in the developed detection system.

This piezoelectric detection system provides sharp and evident transition to cavitation regime. Moreover, there is no effect of industrial environmental vibrations and noise on the measured signal. We are foreseeing the transition from the current microphone-based cavitation detection method to the simplified piezoelectric approach, since the latter proved to be more objective, as well as cheaper to construct and use.

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