CAVITATION INDUCED VIBRATIONS IN ORIFICE PLATES AND A PARTIALLY CLOSED VALVE

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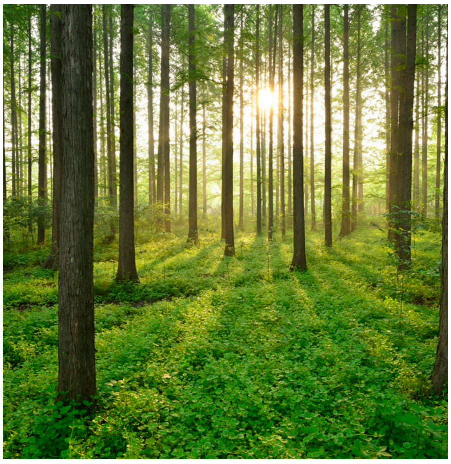

VIBRATIONS IN
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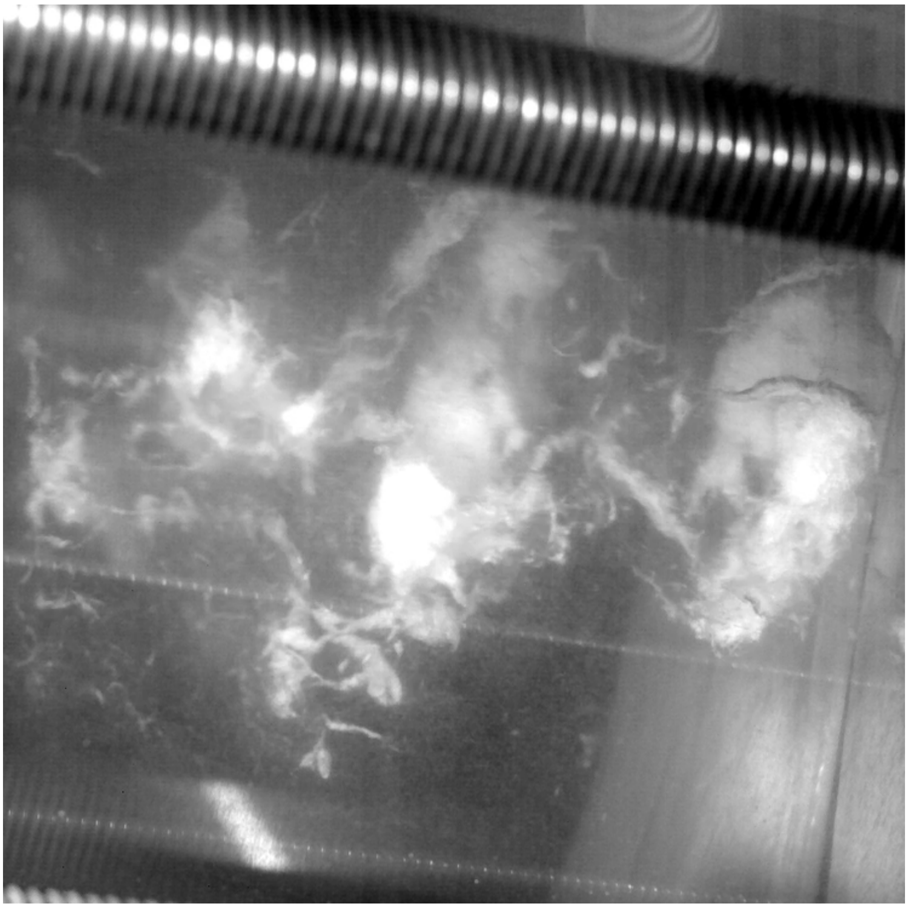

Energiforsk

Cavitation induced vibrations in orifice plates and a partially closed valve

Experimental data for CFD validation

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Foreword

Cavitation-induced vibrations in orifice plates and partially closed valves can lead to significant operational challenges and potential damage in the nuclear power plant. Cavitation can cause vibrations and erosion, compromising the integrity of critical components. Understanding and mitigating these effects is essential for maintaining safe and efficient operations.

This study aims to experimentally investigate flow-induced vibrations and cavitation in single-hole and multi-hole orifices and a partially closed Stafsjö valve. The goal is to provide experimental data for validating Computational Fluid Dynamics (CFD) models.

The results demonstrate that for higher flow rates, flow through both single-hole and multi-hole orifice plates give rise to high pressure drops and strong cavitation, but that the resulting vibration levels are lower for multi-hole plates. In addition, it was demonstrated that the risk of erosion is larger for Stafsjö valves. The data is valuable for validation of more advanced CFD models.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

The assignment includes to experimentally investigate flow induced vibrations (FIV) in orifices and partially closed valves, in order to provide experimental data for validation of CFD models.

FIV could be the result of large scale turbulent structures in the process fluid, which occurs due to major flow discontinuities such as bends, tees, bore connections, partially closed valves and orifices. If the vibration frequency is close to the structure eigen frequency this can lead to the excitation of vibration modes of the piping and connected equipment. This could potentially lead to fatigue cracking within a relatively short period of time. For large pressure losses through partially closed valves or orifices, cavitation can also appear, which can cause both vibrations but also erosion damages due to the implosion of the steam bubbles close to the walls when the pressure recovers downstream.

Today the phenomena of cavitation and FIV can be simulated using Computational Fluid Dynamics (CFD), however there are large uncertainties in the models and therefore experimental validation is needed.

The present work experimentally investigates FIV and cavitation in piping with orifices and partially closed valves, in order to provide experimental data for validation of CFD models. An existing setup with interchangeable orifice geometries was used, of which some are known to produce cavitation. In addition, a valve with different opening degrees was tested after modifying the test rig for this purpose.

Keywords

Cavitation, orifice plate, valve, flow induced vibrations, experiment, CFD validation

Sammanfattning

I uppdraget ingår att experimentellt undersöka flödesinducerade vibrationer (FIV) i strypskivor och delvis stängda ventiler, för att kunna tillhandahålla experimentella data för validering av CFD-modeller.

FIV kan induceras i strömmande media på grund av storskaliga turbulenta strukturer och uppstår på grund av stora flödesdiskontinuiteter såsom rörböjar, T-stycken, delvis stängda ventiler och strypningar. Om vibrationsfrekvensen ligger nära strukturens egenfrekvens kan detta leda till excitation av vibrationer i rörledningar och ansluten kringutrustningen. Detta kan potentiellt leda till utmattningssprickor inom en relativt kort tidsperiod. Vid stora tryckförluster genom delvis stängda ventiler eller strypningar kan även kavitation uppstå, vilket kan orsaka både vibrationer men även erosionsskador på grund av implosion av ångbubblorna nära väggarna när trycket återhämtar sig nedströms.

Idag kan fenomenen kavitation och FIV simuleras med Computational Fluid Dynamics (CFD), men det finns stora osäkerheter i modellerna och därför behövs experimentell validering.

Detta arbete undersöker FIV och kavitation i rörledningar med öppningar och delvis stängda ventiler experimentellt, för att tillhandahålla data för validering av CFD-modeller. En befintlig experimentuppställning med utbytbara strypningsgeometrier användes, av vilka några är kända sedan tidigare för att leda till kavitation. Utöver dessa testades en ventil med olika öppningsgrad efter modifiering av testriggen.

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1 Introduction

In the present study, cavitation and cavitation induced vibrations are studied experimentally in orifice plates (single-hole and multi-hole) and a valve. The purpose is to generate more detailed validation data for CFD-models using new advanced measurement techniques *i.e.* a high speed camera and a two-phase sensor.

An orifice plate in a pipe is characterized by the orifice diameter, d in relation to the pipe diameter, D with the ratio between them, β=d/D, Figure 1 and Table 1. The pressure loss, ΔP =P1-P5, is the difference between the pressure upstream (P1) and downstream (P5) of the orifice plate where the pressure has recovered. The pressure loss coefficient, ξ, is defined as the pressure loss normalized with the dynamic pressure, where the bulk velocity, u, is calculated as the flowrate, Q, divided by the flow cross section area upstream of the orifice, $A=\pi D^2/4$, eq. (1). The pressure loss coefficient is a function of the diameter ratio, β.

The cavitation number, σ, is often used to characterize the level or severeness of the cavitation and is defined as the local static pressure, P, minus the saturation pressure, $p_{sat.}$, normalized with the pressure loss, eq. (2). When the cavitation number is low the cavitation is strong. Strong cavitation often leads to high vibration levels as the implosion of the gas bubbles generates large pressure spikes. This can cause fatigue failure in the pipe system and also lead to erosion if the implosion of the bubbles occurs close to the pipe wall.

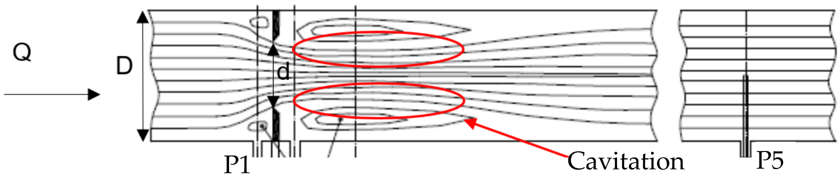


Figure 1. The flow through a single-hole orifice plate.

$$\xi(\beta) = \frac{\Delta P}{0.5\rho u^2} \quad (1)$$

$$\sigma = \frac{P - p_{sat.}}{\Delta P} \quad (2)$$

Pipe diameter, D (mm)	102.26
Orifice plate diameter d (mm)	32
β=d/D (-)	0.313
Volumetric flow rate Q (l/s)	18.3
Pressure upstream, P1 (bar a)	8.3
Pressure downstream, P5 (bar a)	2.0
Pressure loss ΔP=P1-P5 (bar)	6.3
σ_1=P1-$p_{sat.}$ /ΔP (-)	1.32

Table 1. Present single-hole orifice plate.

2 Method

2.1 TEST RIG

Within the framework of this study, the physical model from 2020 has been re-built in the Älvkarleby Laboratory to be able to study the cavitating flow downstream of flow restrictions *e.g.* orifice plates and also a valve under well-defined and controlled test conditions.

A photo of the test rig's piping and the instrumentation is shown in Figure 2. The pipe system is made in pressure class PN10. The position of the orifice plate and the downstream plexiglass pipe is also shown.

In the laboratory there is an rpm-regulated pump from Ringhals AB which takes municipal water at room temperature from a low basin of 300 m^3 and provides a flowrate of up to 300 l/s or a maximum head of about 8 bar at full speed, 1500 rpm. The speed is varied here to set the desired flow rate and upstream pressure before the orifice plate.

In order to be able to vary the downstream pressure, the test rig contains an adjustable valve downstream of the orifice plate, V5.

2.2 INSTRUMENTATION

The pressure upstream (P1) and downstream (P5) of the orifice plate or the valve is measured with 10-bar pressure sensors with an uncertainty of about ±0.5% of full scale. The position of the pressure sensors in relation to the orifice plate (x=0) is shown in both Figure 1 and Figure 2.

The volumetric flow rate (Q) is measured with a KROHNE OPTIFLUX 4000 electromagnetic flow meter with an uncertainty of about ±0.5% of full scale. This has been calibrated up to 25 l/s. The diameter of 150 mm has been chosen so that the velocity will be 1-10 m/s at the nominal flowrate tested here in order to reduce the uncertainty in the measurement. The flow meter installation meets the requirements by KROHNE for how long a straight pipe should be before (5D) and after (2D) the electromagnetic flow meter so that it is not affected by secondary flow downstream of a pipe bend.

The temperature (T1) is measured with a Pt100 sensor with an uncertainty of about 0.1°C. The temperature is needed to calculate the vapor pressure and the density. The density is 998 kg/m^3 and varies approximately 0.1% between 0-20°C.

The cavitation is visualized with a Photron FASTCAM Nova S high speed camera with a frame rate of 16000 fps. The gas phase fraction is quantified with a fiber optic A2 Photonic sensor, M2 bubble analyzer.

A measurement system with 12 channels is used for the flowrate and the pressures and the data collection is done with LabView. The sampling rate is 100 Hz and the sampling time is about 1 minute. A separate measurement system is used for the vibration measurements.

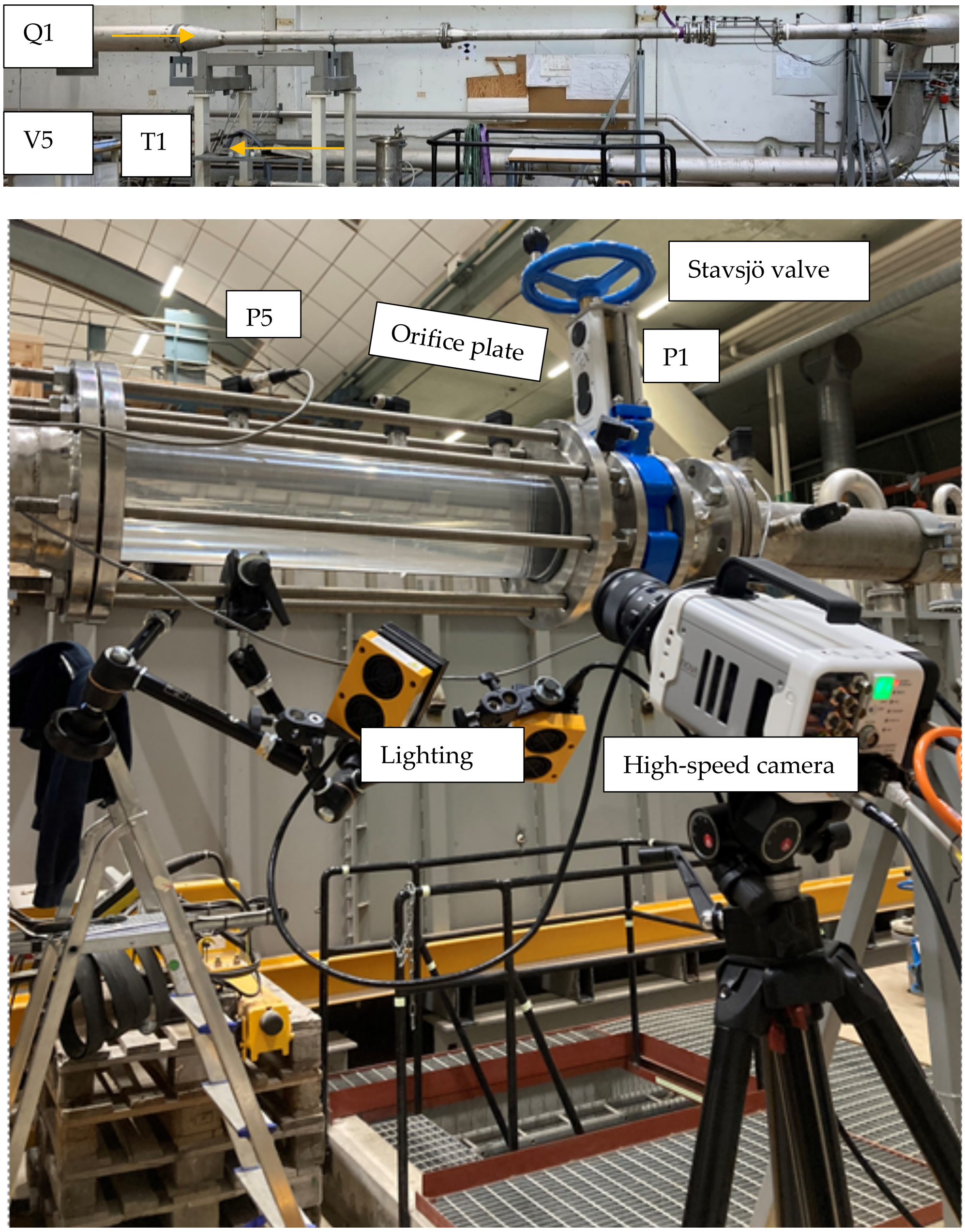


Figure 2. Photo of the test rig, Plexiglas test section, instrumentation positions and the high-speed camera.

2.3 ORIFICE PLATE GEOMETRIES

The geometry of the orifices is shown in Figure 3. The single-hole orifice plate has a single d=32 mm hole centered in the pipe.

The multi-hole orifice plate consists of 19 evenly distributed holes. Two different hole diameters have been tested, 7.2 mm and 7.4 mm with very similar total open area. The total open area for both of them is about the same as for the one-hole orifice plate. The thickness of the metal plate is 10 mm for both orifice plates.

The Stafsjö valve works by inserting a flat plate perpendicular to the flow and thereby reducing the open area in relation to the total flow cross-sectional area in the pipe, ϕ. This is fairly linear to the insertion length.

Figure 3. The single-hole orifice plate with a centered d=32 mm hole, the multi-hole orifice plate with 19 evenly distributed holes with diameters of 7.2 mm and 7.4 mm (two different plates) and the adjustable Stafsjö valve with an adjustable plate perpendicular to the flow.

2.4 TEST MATRIX AND BOUNDARY CONDITIONS

The tests are carried out with ordinary municipal water at room temperature (18°C slightly depending on the day and the ambient temperature outside the lab hall). The testing is performed in the same way as in the same tests 2020, *i.e.* for each orifice plate, tests are performed for different combinations of flow and pressure with a constant pump speed to generate different degrees of cavitation. This is then repeated for different pump speeds.

Note that the operation of the pump leads to vibrations in the pipe system, which are not flow (cavitation) induced. Relative comparisons between vibration levels can therefore only be made for the same pump speed.

3 Results

3.1. STABILITY, REPEATABILITY AND STATISTICAL UNCERTAINTY

The results from the tests show that the flow rate is stable within the measurement uncertainty. If you repeat the same test for the same conditions, you get essentially identical results in terms of measured pressures. The differences are within the measurement uncertainty. This indicates that the results are both repeatable and that the data are statistically converged with the measurement time of 1 minute.

3.1 PRESSURE LOSS COEFFICIENT

The single-hole orifice plate with d=32 mm has a diameter ratio β=d/D=0.31. If one performs tests for different flows and calculate the pressure loss coefficient ξ by a linear interpolation to the pressure drop ΔP=P1-P5 over the orifice plate, one gets the result ξ=245, see Figure 4, which is slightly lower than what the ISO standard indicates.

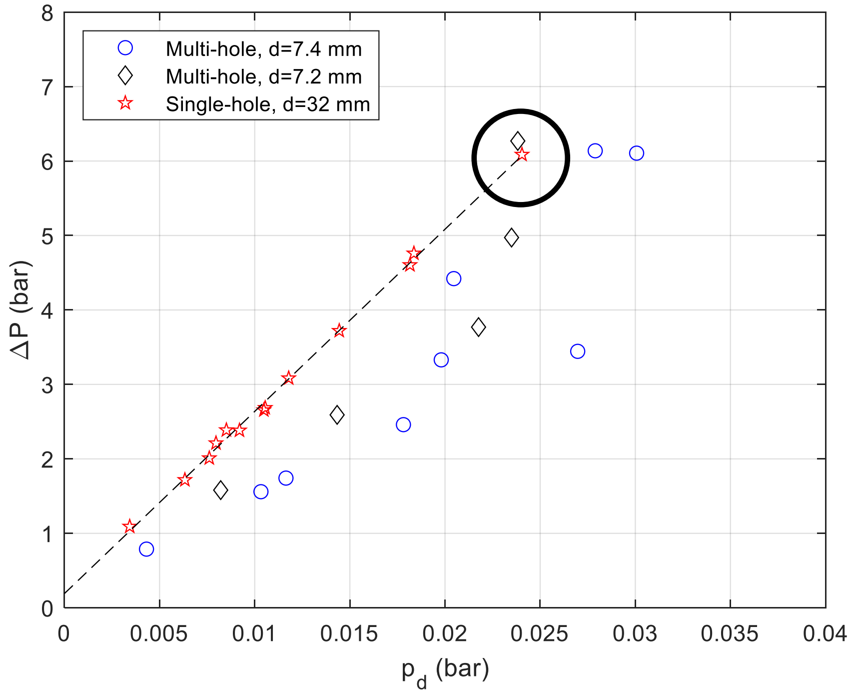


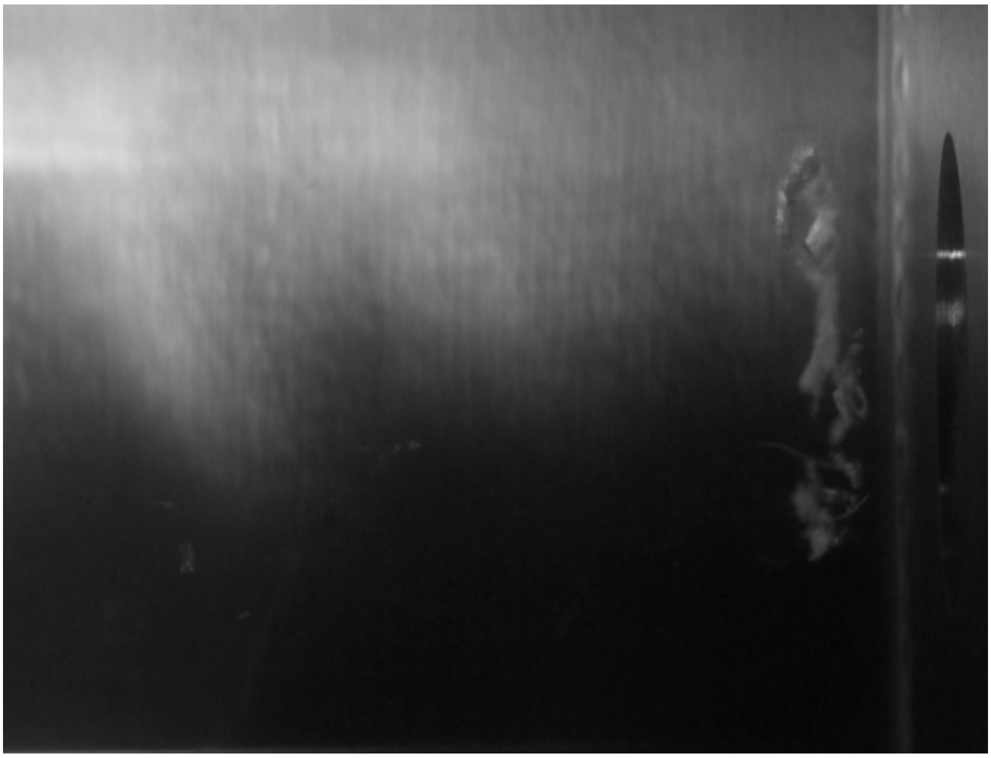
Figure 4. Pressure drop coefficient: existing single-hole orifice plate and multi-hole orifice plate.

Multi-hole orifice plates have no unambiguous pressure loss coefficient, and the pressure drop depends on how much it cavitates. The pressure drop for the cases where it does not yet cavitate is significantly lower than for the single-hole orifice plate, even though the total open area is the same. However, for the measurement points that are around the operating point σ=1.32 (marked with a ring), see Table 1, the pressure drop and thus the flowrate (which is almost choked) will be more or less the same as for the single-hole orifice plate.

3.2 VISUALIZATION OF THE CAVITATION

Figure 5 shows the cavitation in the single-hole orifice plate. The bulk velocity downstream of the orifice plate is 23 m/s based on the measured flowrate and d.

The high-speed camera has a temporal resolution of 0.0625 ms, which corresponds to a movement of about 1.6 mm (16 pixels). This is high enough to resolve and capture the instantaneous vortex structures and follow their development downstream of the orifice plate. One can observe how the cavitation varies greatly in time and space. However, at the same time, it consists of coherent large-scale axi-symmetric vortices that are generated regularly (with a separation in the flow direction approximately equal to d)



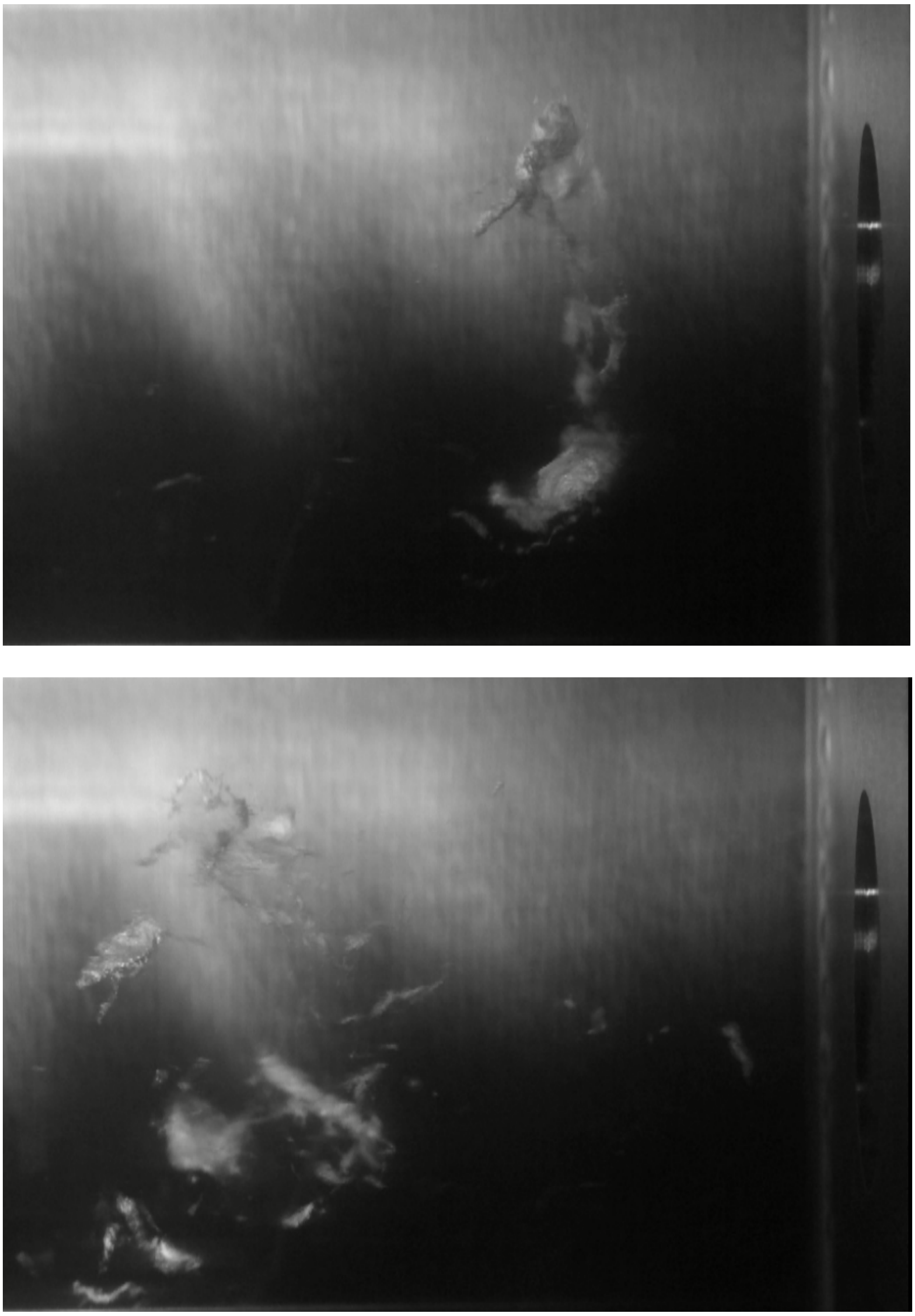


Figure 5. Incipient cavitation in the single-hole orifice plate, σ=1.7. t=0.2, 1.2, 2.5 and 4.5 ms.

in the shear layer between the jet and the recirculation zone. The vortices are transported approximately at the bulk velocity. In the center of the vortex ring, the pressure is locally lowest, which gives rise to cavitation. The vortex is stretched in the flow direction, becomes unstable, less symmetrical, and secondary longitudinal vortices are generated, which are sucked in from behind through the primary vortex. The vortex breaks up and fall apart into smaller vortices, which eventually implode further downstream as the pressure recovers.

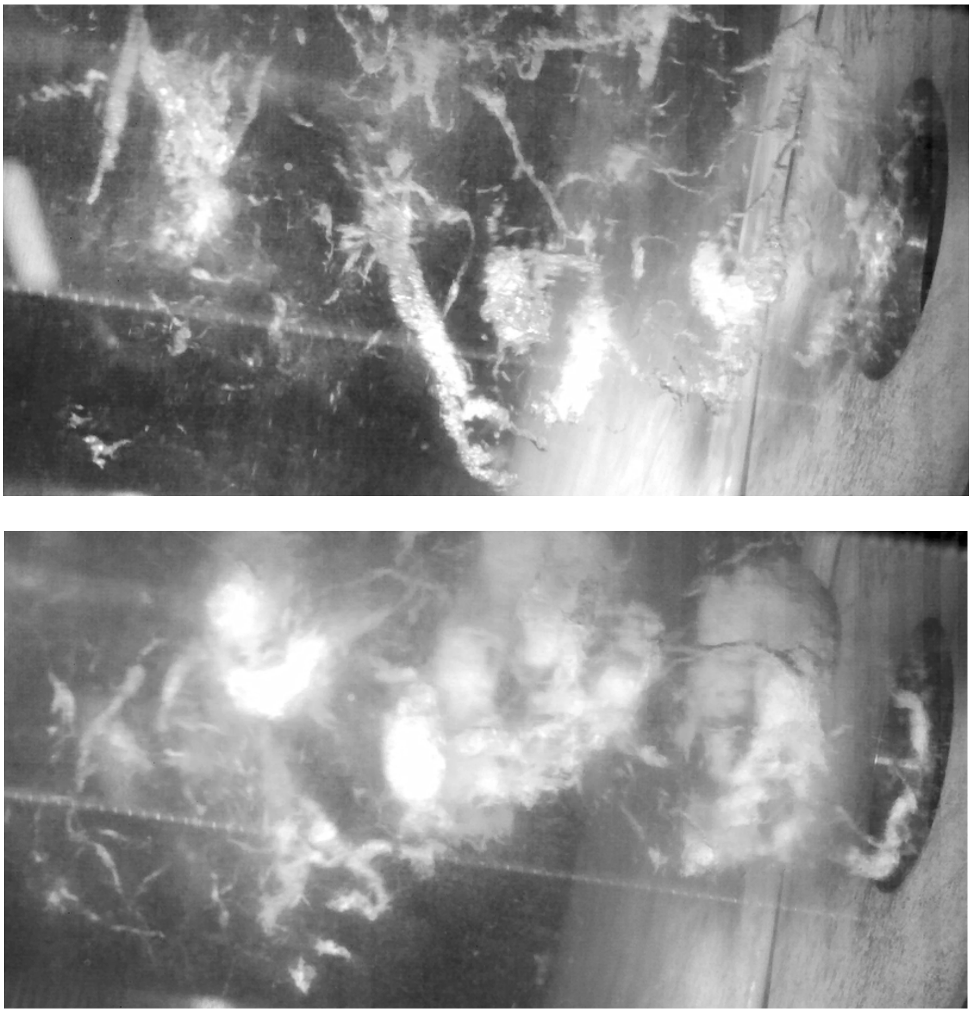


Figure 6. Instantaneous coherent vortical structures with cavitation for the single-hole orifice plate. Top: σ=1.4 and bottom σ=1.3.

The lower the cavitation number, the more cavitation, more powerful vortices and a higher fraction of vapor gas phase, see Figure 6 where σ=1.4 and 1.3.

The results from averaged movies with a longer sampling time also show that the vortices are coherent to x/D=0.5 (equivalent to about 1-2d) downstream of the orifice plate before they start to break up, see Figure 7.

In the direction across the pipe and the flow, there is a radial profile with the largest amount of cavitation in the shear layer between the jet and the recirculation zone and the smallest amount of cavitation in the recirculation zone where the velocity locally is lower and the static pressure is higher. The cavitation gradually decreases downstream as bubbles implode, see Figure 7.

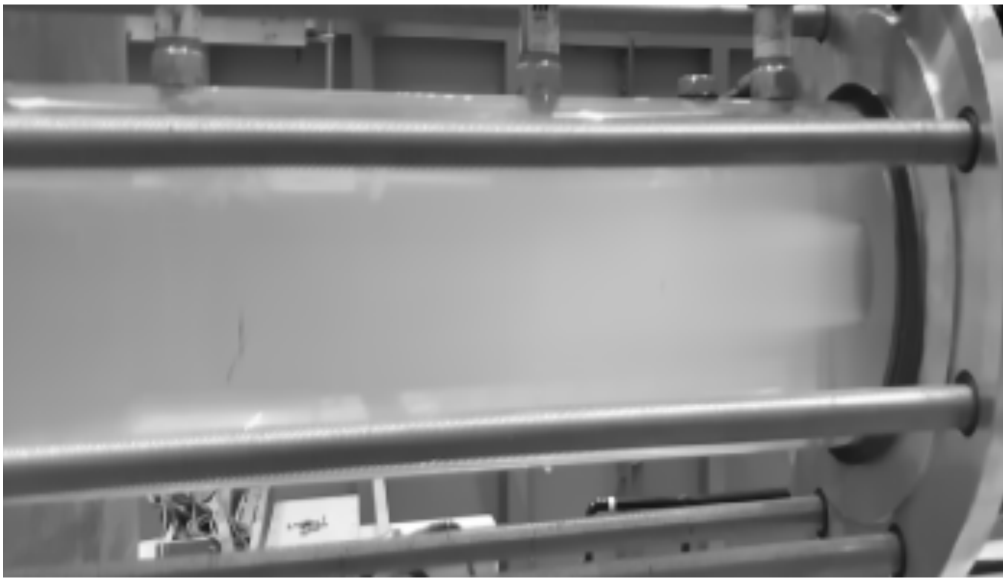


Figure 7. Mean cavitation field for the single-hole orifice plate.

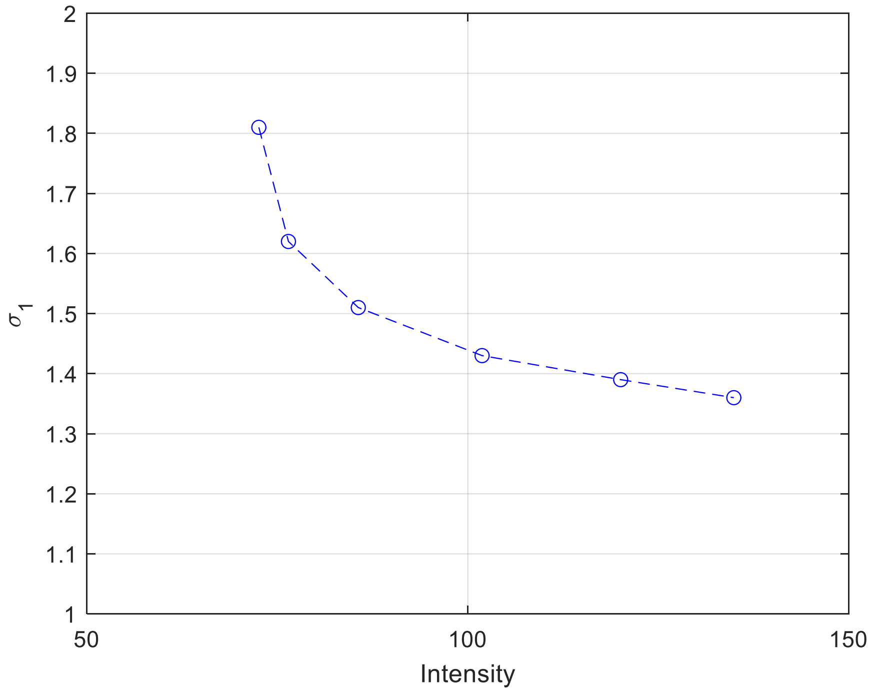


Figure 8. The cavitation number as a function of light intensity in the movies.

Qualitatively, the amount of cavitation, estimated as the average light intensity in the movies, is proportional to the cavitation number, see Figure 8, implying that σ is indeed a good measure of cavitation intensity. The amplitude of the measured sound level, just like the light intensity, is also a good indirect measure of how severe the cavitation is, as was shown in 2020.

The two-phase sensor, see Figure 9 placed on the centerline of the pipe at x/D=2, can quantify the fraction of the gas phase as well as measure the size and velocity of spherical gas bubbles. In this case, the gas phase close to the orifice plate consists of large vortical structures rather than small spherical bubbles, making size and velocity difficult to measure. However, the vortices can be quantified from the videos with the high-speed camera. The fraction of the gas phase, on the other hand, can only be judged qualitatively from the movies, *i.e.* that it cavitates more with a lower cavitation number, but not how much higher the fraction of the gas phase is. However, this has now been quantified with the new two-phase sensor. Figure 10 shows that the cavitation number is indeed an appropriate measure of how much it cavitates, *i.e.* how large the fraction of the gas phase is. The probe could not handle the flow for the 32 mm single-hole orifice plate and broke. This indicates that the cavitation is somehow more violent and severe for the single-hole orifice plate.

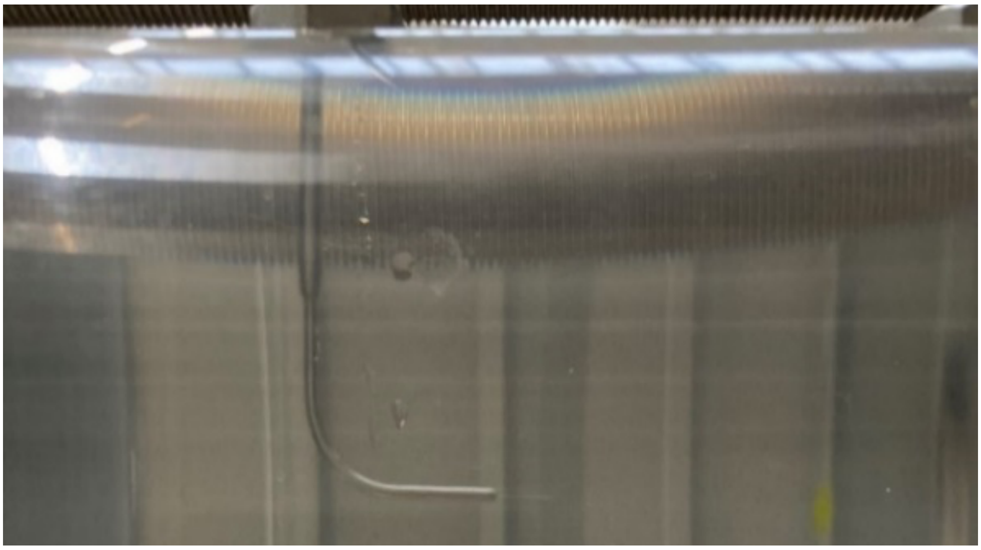


Figure 9. The two-phase sensor positioned at the pipe center line r/R=0 at x/D=2.

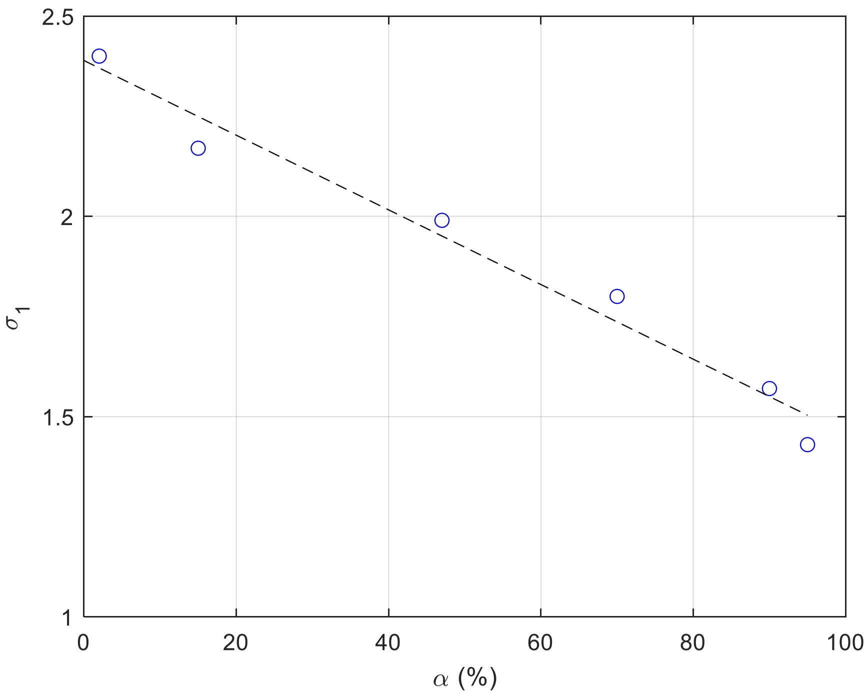


Figure 10. The correlation between the gaseous void fraction and the cavitation number for the multi-hole orifice plate at x/D=2 and r/R=0.

The multi-hole orifice plate breaks up the large vortical structures into several smaller ones and the pressure recovery is shorter in the flow direction, Figure 11. The vortices in the different holes are not synchronized. These mechanisms might explain the reduced vibration level for the multi-hole orifice compared to the single-hole orifice plate, see next section.

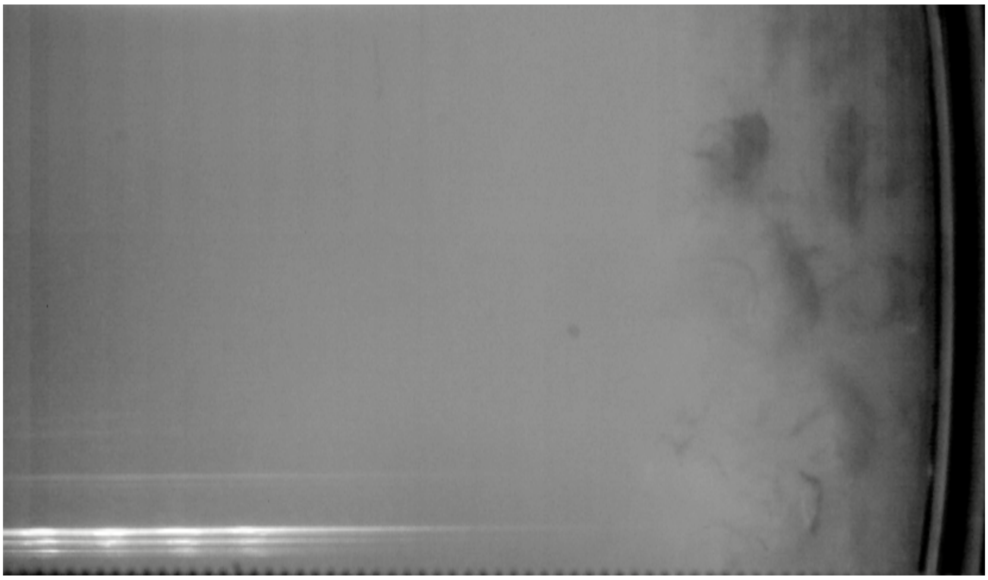


Figure 11. The multi-hole orifice plate produces smaller vortices.

The cavitation in the Stafsjö valve forms a tongue-like structure downstream of the crescent-shaped gap between the curved lower edge of the valve plate and the curved bottom of the pipe. Since the cavitation and implosion occur along the pipe wall, the risk of erosion damage is probably greater than for an orifice plate, where the cavitation takes place at the center of the pipe, Figure 12.

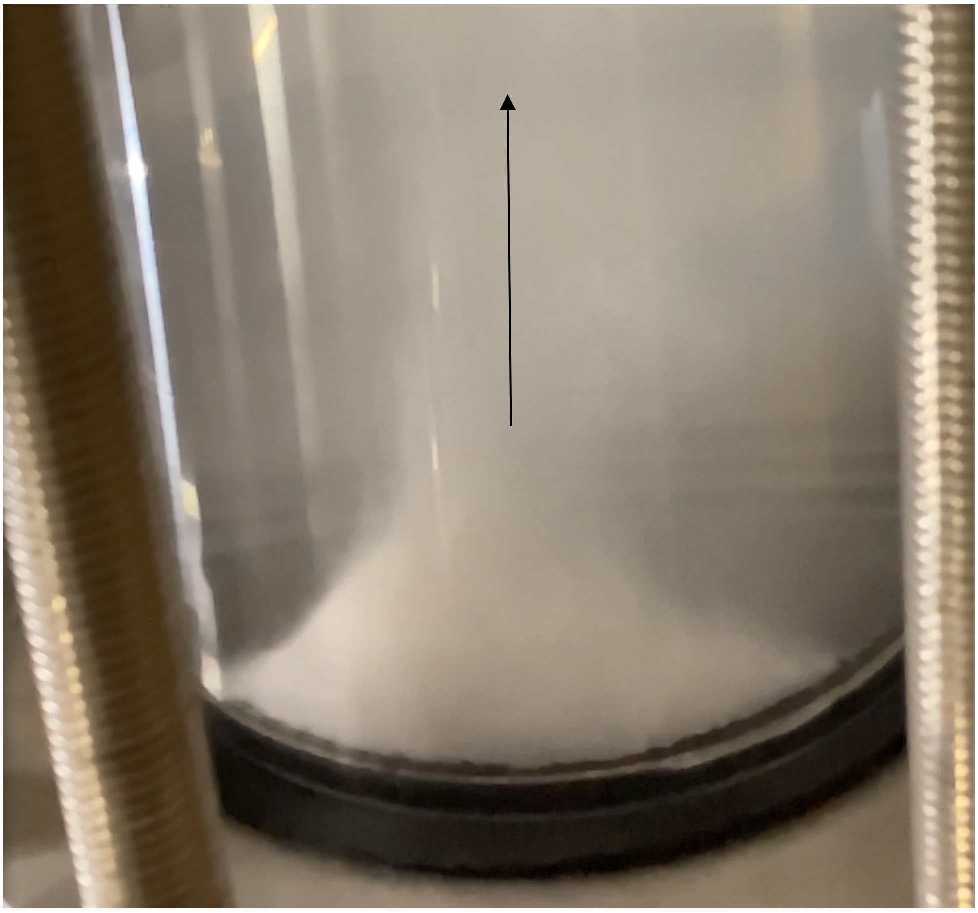


Figure 12. Cavitation downstream of the Stafsjö valve seen obliquely from below (the flow upwards in the image), ϕ=0.12 and σ=1.4.

The calculated pressure drop coefficient depends on the proportion of open area in a similar way to other types of flow restrictions such as the orifice plate and a perforated plate, Figure 13. This suggests that the detailed geometry of the flow restriction is of secondary importance to the pressure drop. When the gap for the Stafsjö valve is 7 mm at the bottom of the pipe and the proportion of open hole area is about 0.12, the pressure drop coefficient and cavitation number becomes equivalent to that of the single-hole orifice plate.

The more you close the Stavsjö valve (reducing the open area) and increase the pressure drop by lowering the pressure downstream, the higher the pressure drop coefficient will become and the stronger the cavitation will be, *i.e.* a lower cavitation number, σ, see Figure 14.

When plotting the variation of the cavitation number for all the flow restrictions together against the downstream pressure normalized with the pressure drop, they all end up on the same line, Figure 15.

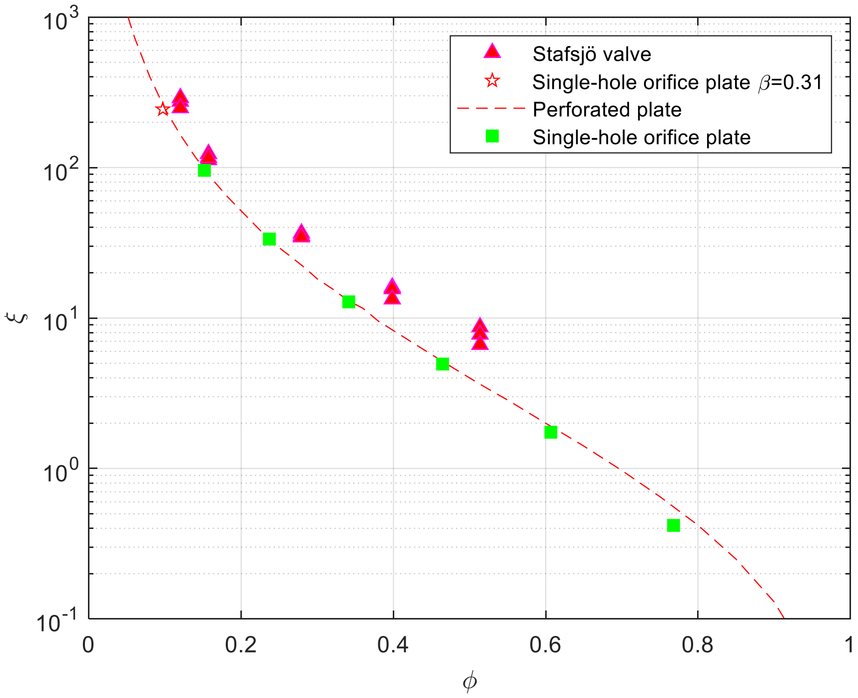


Figure 13. Pressure loss coefficient as a function of the open area's share of the total cross-sectional flow area.

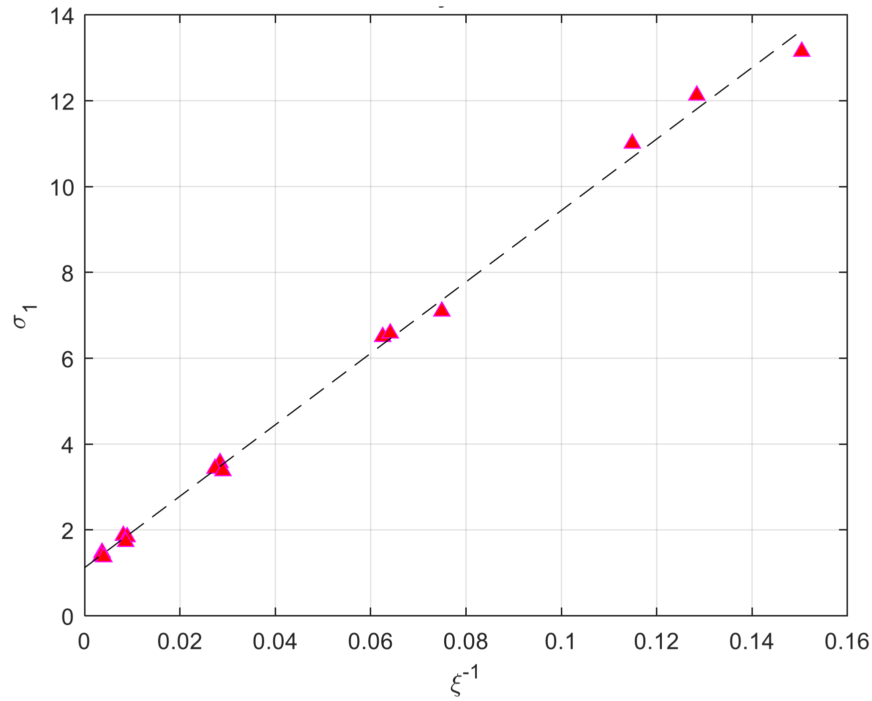


Figure 14. Cavitation number for the Stavsjö valve as a function of the inverse of the pressure loss coefficient.

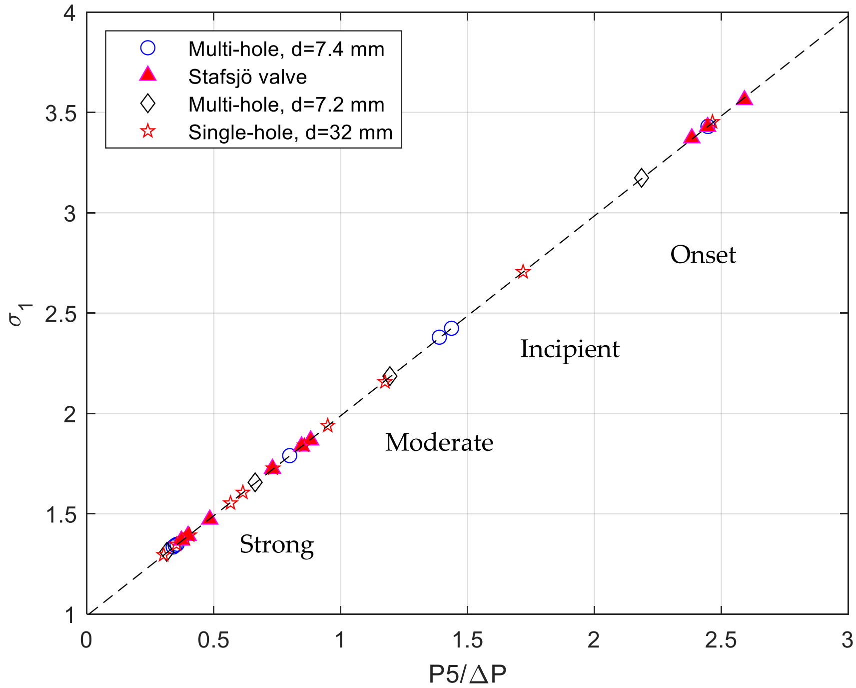


Figure 15. Cavitation number for all flow restrictions.

3.3 VIBRATION MEASUREMENTS

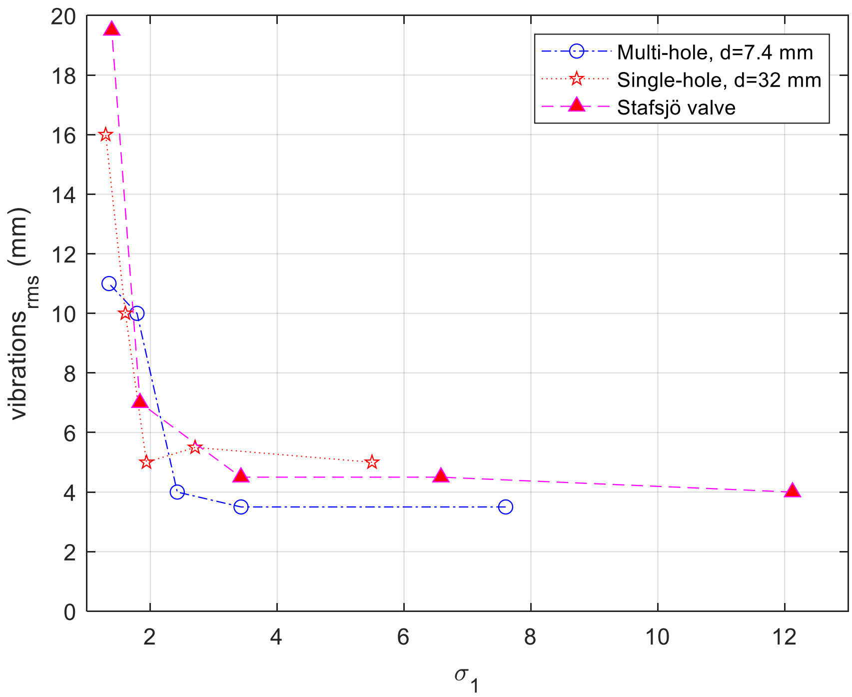


Figure 16. Vibration level as a function of the V5-valve position for single-hole and multi-hole orifice plates.

The results from the vibration measurements with accelerometers show that the vibration level increases with increasing cavitation and is dampened for the multi-hole orifice plate compared to the single-hole orifice plate.

4 Conclusions

The flow through a single-hole orifice plate leads to very high pressure drop and strong cavitation for larger flowrates. The cavitation, in turn, leads to high vibration levels.

A multi-hole orifice plate with roughly the same open area has the same pressure drop and amount of cavitation for higher flowrates, however, the vibration level is lower. It is conjectured that the damping of the vibration level is related to the fact that the synchronized large scale vortical structures constituting the cavitation for the case of the single-hole orifice plate are split into smaller vortical structures for the multi-hole orifice plate, which are not synchronized.

The pressure drop and cavitation in a Stafsjö valve is similar to the orifice plates with the distinction that the risk for erosion is larger since the cavitation and implosion occurs adjacent to the pipe wall.

Detailed time resolved measurements have been conducted with a high speed camera at 16000 fps shedding new light on the vortical structures constituting the cavitation and their break down process.

Novel data for the gaseous void fraction has been acquired and it has been showed that there is a strong correlation to the cavitation number, commonly used to quantify the level of cavitation.

These new data can be used for the validation of more advanced CFD models.

CAVITATION INDUCED VIBRATIONS IN ORIFICE PLATES AND A PARTIALLY CLOSED VALVE

For flows through orifices or partially closed valves at large pressure losses, cavitation can appear, which can cause both vibrations and erosion damages due to the implosion of the steam bubbles close to the pipe walls when the pressure recovers downstream.

Today the phenomenon of cavitation can be simulated using Computational Fluid Dynamics (CFD), however there are large uncertainties in the models and therefore better experimental validation is needed.

The present work experimentally investigates cavitation induced vibrations in pipes with orifices and partially closed valves using modern measurement techniques, e.g. a high-speed camera and a two-phase sensor, in order to provide new experimental data for validation of CFD models.