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p.291:14 – p.292:10	p.373:07 – p.374:10
p.292:Fig.1	p.373:Figure 2
p.292:11 – p.293:02	p.374:14 – p.375:14
p.293:Fig.2	p.376:Figure 4

ON CAVITATION IN FLUID POWER

Timo KOIVULA
Tampere University of Technology
Institute of Hydraulics and Automation
P.O.Box 589
33101 Tampere
FINLAND
e-mail: timo.koivula@tut.fi

Cavitation consists of evaporation and condensation of a liquid. Cavitation normally occurs when liquid at constant temperature is subjected to vapour pressure. In fluid power applications the evaporation pressure is reached when flow velocity is increased sufficiently. The occurrence of cavitation in fluid power is mostly detrimental. One of the devastating consequences of cavitation is the mechanical degradation of a solid material (cavitation erosion). Because cavitation is mostly harmful to the system it is to be avoided as far as possible. When actions for preventing cavitation are considered, it is essential to recognise the existence of cavitation and location of cavitation inception point. Direct detection of cavitation is often impossible due to the complicated constructions of fluid power components. Due to restrictions of direct detection of cavities, various indirect methods can be used.

In this paper, cavitation phenomenon is explained and effects of cavitation on the system are dealt with. Cavitation erosion mechanisms are described and parameters affecting the degree of formed cavitation erosion are discussed. Various methods for cavitation detection are presented.

Keywords: Fluid power, Cavitation, Cavitation erosion, Detection of cavitation

1 INTRODUCTION

Cavitation may appear to be a problem in fluid power systems. Cavitation affects fluid power systems and components in various ways, which are usually undesirable. For example efficiency of a system is reduced due to cavitation and vibrations as well as noise level of a system is increased. One of the remarkable consequences of cavitation is cavitation erosion. Cavitation erosion is formed when cavitation is violent enough and occurs close to adjacent material surfaces. Cavitation erosion is always very harmful as it causes fluid contamination, leakage, blockages and undesired operation of system. When actions for preventing cavitation are considered, it is essential to verify the existence of cavitation and locate the cavitation inception point. The existence of cavitation is often very difficult to detect because cavitation occurs typically locations where the access for measuring instruments is limited. There are however a few means to detect cavitation in fluid power components.

Proc. of 1st FPNI-PhD Symp. Hamburg 2000, pp. 371-382

2 CAVITATION PHENOMENON

Cavitation is a term used to describe a process, which includes nucleation, growth and implosion of vapour or gas filled cavities. These cavities are formed into a liquid when the static pressure of the liquid for one reason or another is reduced below the vapour pressure of the liquid in current temperature. When cavities are carried to higher-pressure region they implode violently and very high pressures can occur.

When the local pressure of a liquid is reduced sufficiently dissolved air in oil starts to come out of solution. In this process, air diffuses through cavity wall into the cavity. When pressure in the liquid is further reduced, evaporation pressure of the liquid is achieved. At this point the liquid starts to evaporate and cavities start to fill with vapour. When this kind of a cavity is subjected to a pressure rise cavity growth is stopped and once the pressure gets higher cavities start to diminish. Cavities disappear due to dissolution of air and condensation of vapour. When a cavity is mostly vapour filled and subjected to a very rapid pressure rise it implodes violently and causes very high pressure peaks. Implosion is less violent if the gas quantity of a cavity is great. This requires relatively slow nucleation of a cavity.

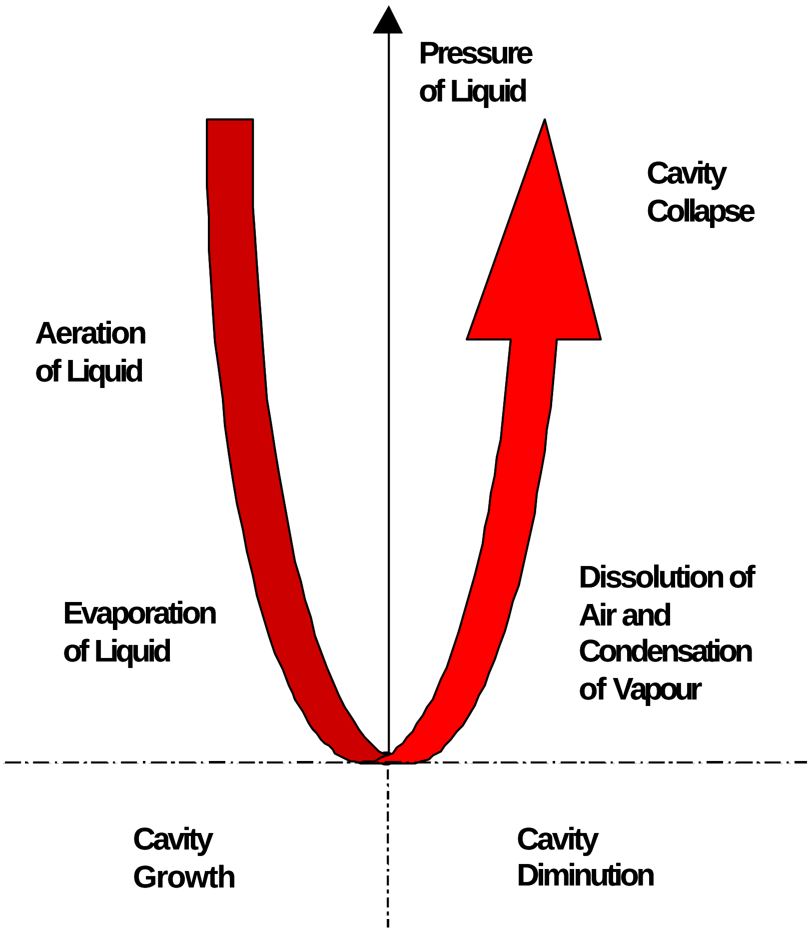

Figure 1. Cavitation process

3 CAVITATION IN ORIFICES AND VALVES

Flow rate through an orifice is affected by a number of factors. First of all, the flow rate is a function of pressure difference across the orifice. Also the geometry of an orifice has a significant effect on the flow characteristics. Diameter and length of an orifice, as well as the shape of inlet corner determines the flow path of the liquid. The behaviour of oil is dependent on its properties, including viscosity, density, and additive packages.

When the pressure difference across an orifice is increased sufficiently, cavitation occurs in the exit flow. Cavitation starts when the inlet corner of an orifice is sufficiently sharp and the flow detaches from the orifice walls. At this stage a vapour region is formed inside the orifice. A schematic presentation of the formation of the vena contracta is seen in Figure 2. When the downstream pressure behind the orifice is reduced sufficiently, the cavitation intensifies and the vapour region is extended beyond the exit of orifice.

The pressure distribution at steady state flow in ideal orifice is presented in Figure 2. The set of curves shows, how pressure in vena contracta changes when downstream pressure (p_d) is varied. Due to increased velocity of flow in vena contracta, dynamic pressure head is increased and hence static pressure head is decreased. When static pressure in vena contracta is decreased to the evaporation pressure of a liquid, cavitation starts to occur. Cavities travelling along the flow collapse when they enter to higher pressure region of flow. The solid lines in Figure 2 indicate cavitation free flow and dotted lines indicate the presence of cavitation. When downstream pressure is decreased further the cavitating region becomes longer. The faster the pressure recovery behind the orifice is the more violent are cavity implosions.

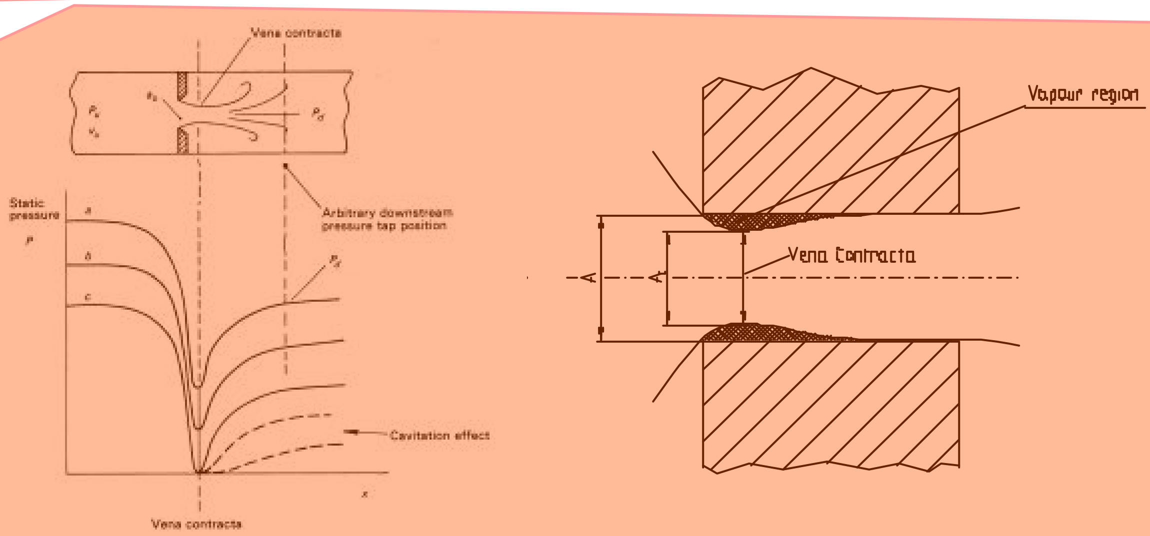

Figure 2. Pressure distribution at steady state flow in ideal orifice flow. At certain stage flow separates in orifice inlet corner and a vena contracta is formed.
[McCloy and Martin (1973), Koivula et al (1992[b])]

When cavitation is intensive enough the flow rate through an orifice does not increase when the downstream pressure is decreased. This phenomenon is typically referred as “saturation” or “choking”. The presence of cavitation is clearly seen in Figure 3, where the measured and calculated flow rates are compared. The degree of cavitation can be estimated with the aid of a non-dimensional parameter typically referred as cavitation number, K.

$$K = \frac{2 \cdot (p_d - p_v)}{r \cdot v^2} \quad (1)$$

The numerator in the equation above corresponds to the static pressure, which resists cavitation, and denominator corresponds to the dynamic pressure, which promotes cavitation. When cavitation starts to occur the cavitation number is called incipient or critical cavitation number. Usually the critical cavitation number for orifices is between 0.2 and 1.5 [Lamb (1987)].

In the Figure 3, it can be seen that the visual observation of cavitation inception matches quite close to the point of flow saturation. The cavitation inception was determined visually when the first cavities was seen at the orifice.

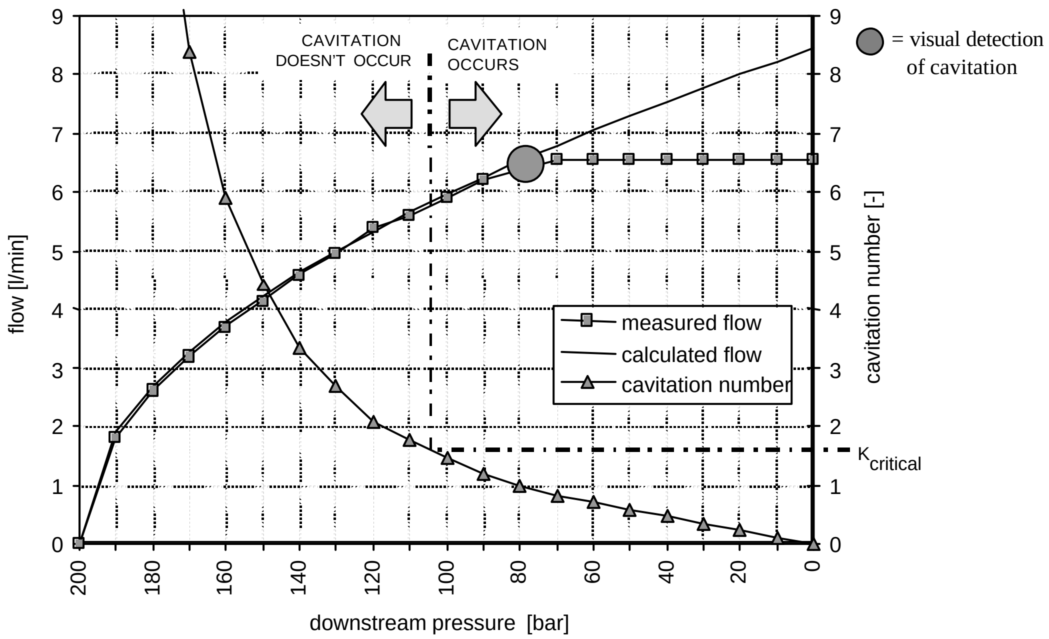

Figure 3. Comparison of measured and calculated flow rates through an orifice.

Flow rate for turbulent flow through an orifice is typically calculated using the following equation.

$$Q = C_q \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{r}} \quad (2)$$

where: C_q = flow coefficient

A = cross-sectional area of flow path

Δp = pressure difference across the orifice

ρ = density of liquid

In practice, when calculating the flow through a valve, a problem arises when determining the flow coefficient. The flow coefficient is dependent on the geometry of orifice and the properties of the liquid.

Schmidt and Corradini (1997) present a simple model to calculate the flow coefficient (C_q) for cavitating orifice flow. In this model, a constant value of flow coefficient is used for non-cavitating flow and for cavitating flow C_q is calculated as follows.

$$C_{q\,cav} = C_c \cdot \sqrt{K_s} \qquad K_s = \frac{p_u - p_v}{p_u - p_d} \tag{3}$$

As shown in Figure 2, when cavitation occurs, the vapour region occupies a fraction of the orifice cross-sectional area (A) and the flow passes through vena contracta (A_c). The contraction coefficient C_c represents the ratio of areas A_c and A. C_c is a strongly geometry-dependent parameter.

$$A_c = C_c \cdot A \tag{4}$$

Lichtarowicz et al (1965) show that for cavitation free flow at sharp edged orifices (l/D ≈ 2) values for the flow coefficient and contraction coefficient are 0.84 and 0.61, respectively.

4 CAVITATION EROSION

Mechanical degradation of a solid material caused by cavitation is called cavitation erosion. Cavitation erosion can be formed when cavity implosions are violent enough and they take place near enough to the solid material. Cavitation erosion can be identified from a specific rough mark in surfaces of component flow paths.

Despite the great deal of research the actual mechanism of cavitation erosion is still not fully clear. At present it is considered that there are two possible mechanisms to cause cavitation erosion. When a cavity collapses within the body of liquid, the collapse is symmetrical. The symmetrical collapse of a cavity emits a shock wave to the surrounding liquid (see Figure 4). When a cavity is in contact with or very close to the solid boundary, the collapse is asymmetrical. In asymmetrical collapse the cavity is perturbed from the side away from the solid boundary and finally the fluid is penetrating through the cavity and a micro-jet is formed (see Figure 4).

However, it has been stated [Hansson and Hansson (1992), Preece (1979)] that each of these mechanisms has features that do not give a full explanation to the observed cavitation erosion phenomena. The shock wave is attenuated too rapidly and the radius of the cavity micro-jet is too small to produce the degree of the overall cavitation erosion. Nevertheless, when a cloud of cavities collapses, the cavities do not act independently, but in concert (triggering each other's collapse). The collapse of the cavity cloud enhances the effects of the cavities adjacent to or in contact with the solid boundary.

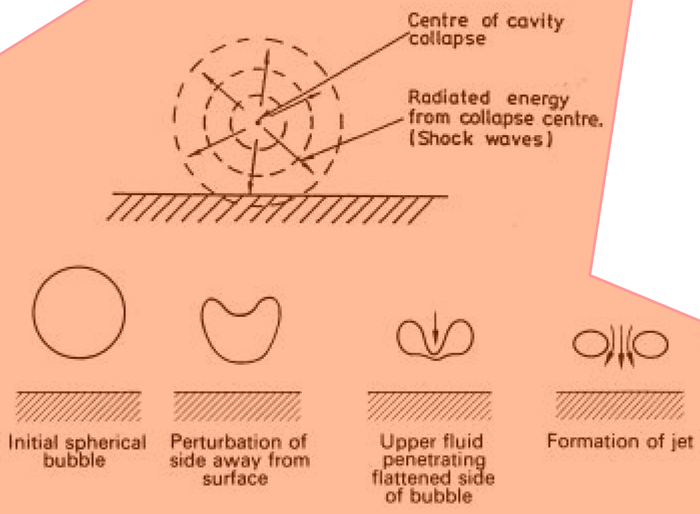

Figure 4. The shock-wave mechanism and micro-jet mechanism of cavitation erosion. [Lamb (1987), Knapp et al. (1970)]

The degree of cavitation erosion is affected by various factors. The intensity of cavitation determines the load, which is subjected to a solid surface. Geometry of flow paths, pressure distribution in a system, and properties of fluid, including cleanliness level of the fluid determine the intensity of cavitation. The solid material itself does not affect the existence of cavitation. When cavitation exists, the formed cavitation erosion is dependent on material properties like hardness, work hardening capability, and grain size. Also stress state and corrosion resistance of a material affect the degree of cavitation erosion.

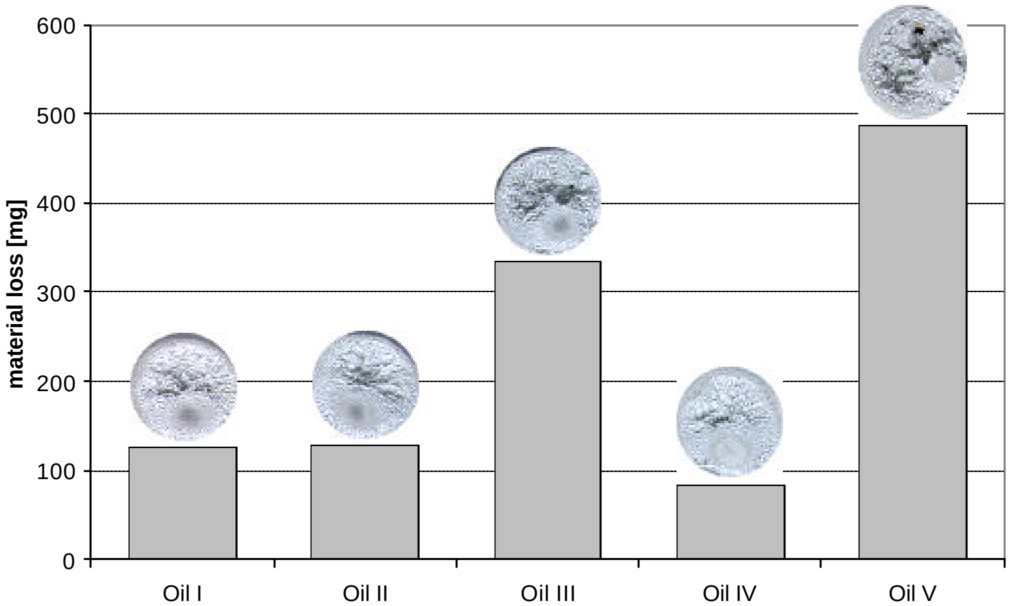

Figure 5. Material loss due to cavitation erosion with different oil types [Koivula et al. (1999[a])].

In travelling cavitation, where cavities travel with stream flow, cavitation erosion is not formed in the place where cavitation incepts, but further downstream. This often leads to wrong conclusions when the reasons for cavitation are discussed and preventive actions are often targeted to wrong locations.

5 DETECTION OF CAVITATION

When actions for preventing cavitation are considered, it is essential to recognise the existence of cavitation and location of cavitation inception point.
Detection of cavitation can be done directly only by verifying the existence of cavities. Direct detection is possible by observing visually the population of developed cavities in flow passages. However, fluid power components encompass usually complicated constructions and cavitation can occur in various locations where the access for visualisation instruments is limited. Due to restrictions of direct detection of cavities, various indirect methods can be used. In these indirect methods the measurements are typically targeted to the shock waves generated by cavity implosions.

When detecting cavitation from an operating machine, environmental disturbances make the indirect measurements difficult. Indirect measurement methods are especially useful if the measurement data from non-cavitating circumstances is available. Cavitation generates typically high frequent vibration from which the existence of cavitation can be recognised.
At the Institute of Hydraulics and Automation, IHA (Tampere University of Technology) several cavitation detection methods have been studied. In the studies, controlled cavitation was created with a cavitating-jet apparatus, where cavitation starts when static pressure head at high velocity flow reduces in the vena contracta of the jet and a cloud of cavities is ejected around the emerging jet.

5.1 Monitoring of Steady-State Flow Behaviour

The presence of cavitation can be detected by monitoring steady-state flow behaviour of a fluid power component. When pressure downstream from a valve is reduced sufficiently, flow rate does not increase with the increasing pressure drop across the valve. By measuring the characteristic curve of a valve, a cavitating range can be determined (see for example Figure 3).

In addition, in the case of pumps, cavitation in suction line reduces the efficiency of the pump. When pressure is reduced in the suction line, pump chambers do not fill completely due to air-release in suction line. Measurement of the flow rate on pump outlet reveals the reduction in pump flow and hence cavitation. [Myllykylä (1999)]

5.2 High-Speed Monitoring of Pressure and Vibrations

When detecting cavitation indirectly, the question is typically about measuring the shock waves induced by cavity implosions. Cavity inception is at first seen in very high frequencies, and therefore very fast transducers are needed. Shock waves can be recorded in the cavitating fluid with high-speed pressure transducers. The propagation of shock waves continues from fluid to the surrounding component body and measurement of the acceleration of the component surface reveals the presence of cavitation. In Figure 6, high-speed pressure transducer is used to record pressure peaks due to cavitation. In the left, no cavitation is present and only pump fluctuations can be seen. In the second figure, cavitation has just incepted and when cavitation has developed extensively (in the right), the pressure peaks get higher. In the Figure 6, also the vibration (acceleration) of the test block surface is presented. The difficulty in acceleration measurements is the isolation of disturbing vibration sources of the component.

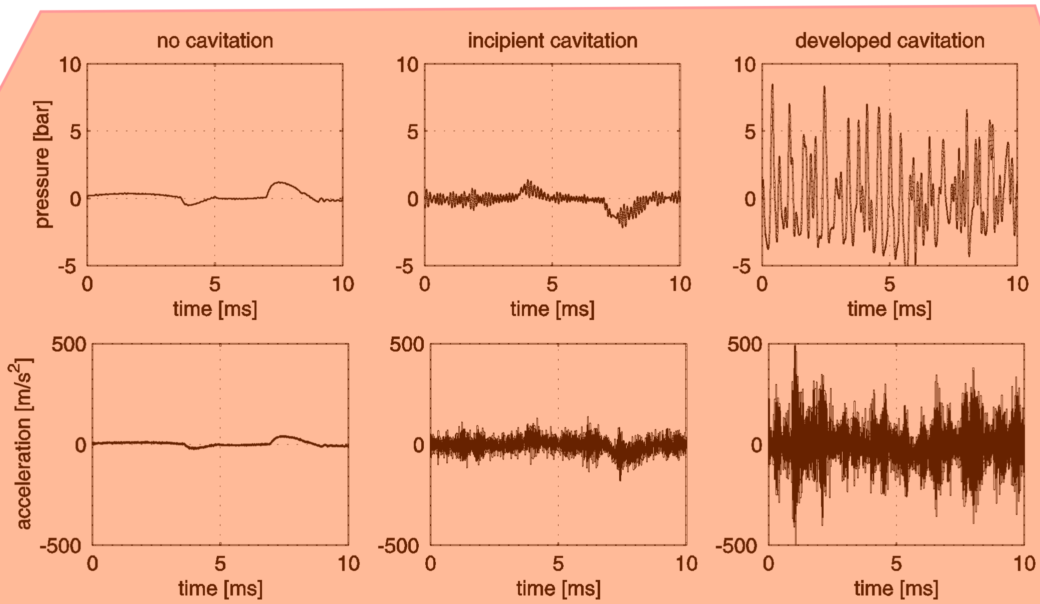

Figure 6. Pressure in downstream chamber and acceleration of the test block. Cavitation intensifies from left to right. [Koivula et al. (2000)]

5.3 Monitoring of Acoustic Pressure Emission

Cavitation produces broadband high-frequent noise. Noise is emitted when the cavities collapse violently and high pressure peaks are generated. Incipient cavitation may not be audible to human ear but developed cavitation can be identified from distinct sizzling or crackling noise. Using microphones and sound level meters, also incipient cavitation can be recorded.

More information is obtained when cavitation noise is measured with wide range of high frequencies and results are plotted as frequency spectrum the inception and development of cavitation can be seen clearly. Frequency spectrum of acoustic pressure measured from the cavitating-jet apparatus is presented as 3D-chart in Figure 7. At the time of 3s, the inception of cavitation is clearly seen in sudden increase of acoustic pressure at high frequencies (> 8 kHz). When cavitation is developing, acoustic pressure extends to the lower frequencies as well. Same kind of trends can be seen when frequency spectrums of pressure and vibration measurements are analysed.

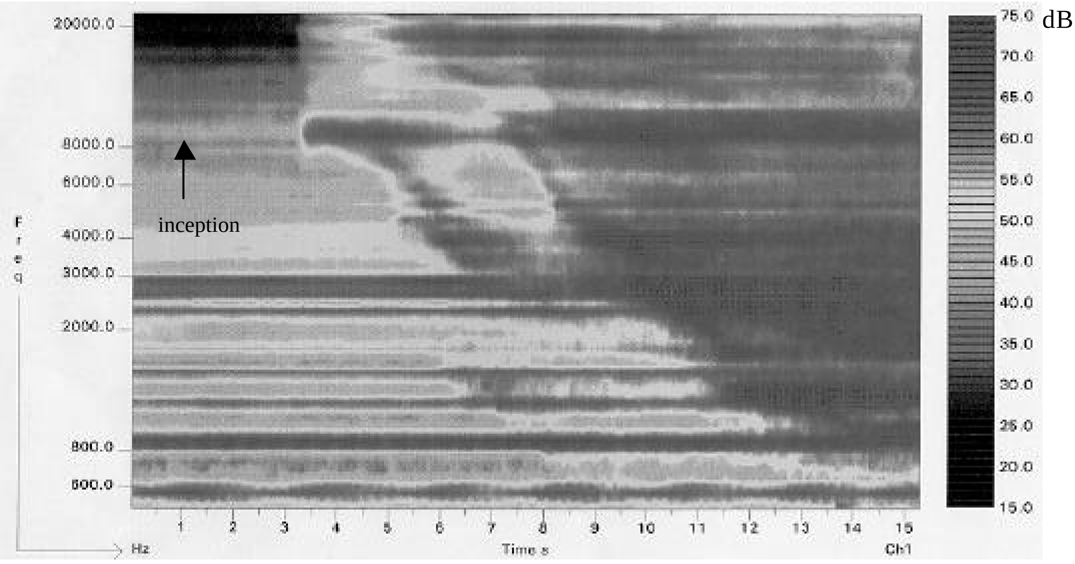

Figure 7. Frequency spectrum of acoustic pressure. Cavitation is developing when downstream pressure is decreased with time. [Koivula et al. (2000)]

5.4 Detection of Cavities by Flow Visualisation

Direct detection of cavitation is possible with flow visualisation. Gas or vapour filled cavities can be detected visually only if the fluid is somewhat transparent and visual devices can access the cavitating flow region. Visual observation of cavities was studied in the cavitating-jet device as well (Figure 8). Sapphire-windows were mounted at the cavitating flow. When lighting and observation is done both through one window the light does not scatter from the cavities and visualisation is poor. Two windows are needed in order to get successful visualisation of cavities. However, arrangements for two visualisation windows are often difficult. In the test system, light to the downstream chamber was supplied through one window and observation was done through another window. Light scattering from the cavities was optimised by mounting the windows in 140° angle.

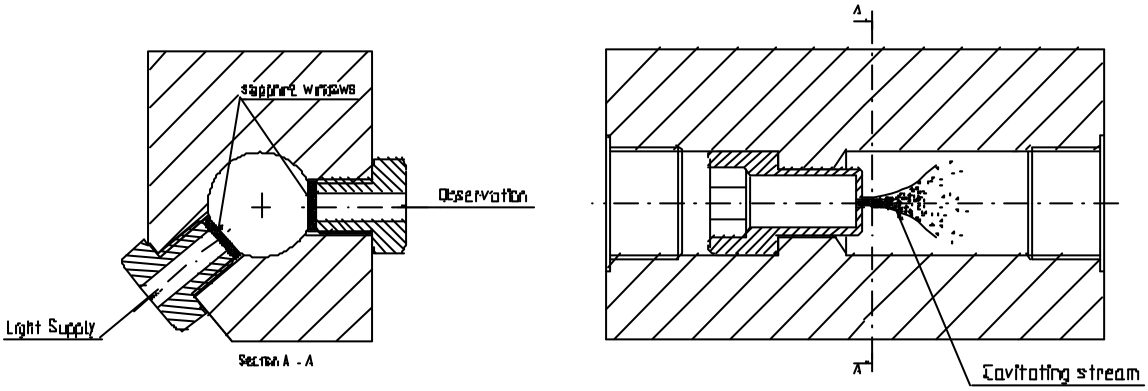

Figure 8. The arrangement of flow visualisation in the cavitating-jet apparatus.
[Koivula et al. (2000)]

At first, the chamber was lit by halogen light and observation was carried out with human eye, camera or video camera. The population of cavities emerging the orifice is seen as a homogenous foggy jet due to relatively long exposure time (Figure 9). The measurement of the intensity of light scattered from the cavities gives information of the intensity of cavitation.

When pulse light and high-speed photography is implemented, the motion of cavities can be arrested. This enables, for example, the analysis of the cavity size distribution. In the test installation, a xenon-discharge light and CCD-camera was used. A close-up view of cavitating flow is presented in Figure 9. A population of cavities can be seen clearly in the oil flow.

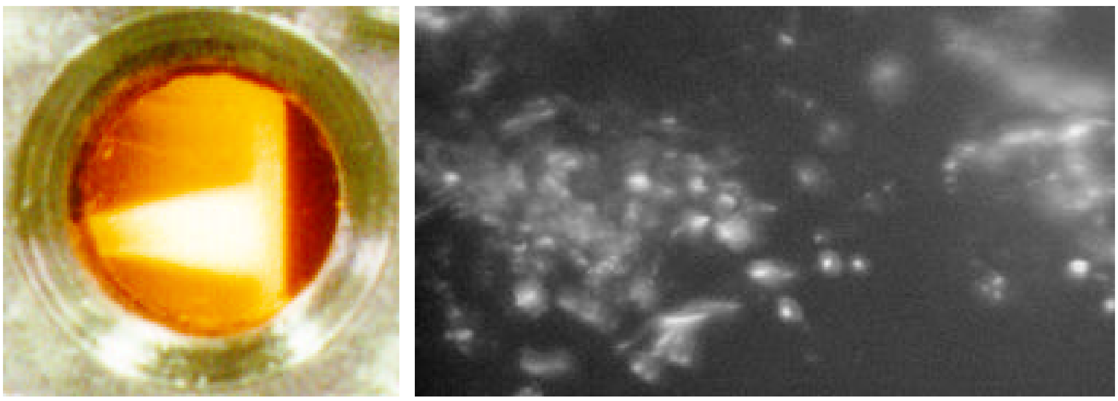

Figure 9. Photographs of cavitating oil flow. Left: halogen light and film-camera. Right: Close-up view with xenon-discharge light and CCD-camera.
[Koivula et al. (2000)]

6 SUMMARY

Cavitation as a phenomenon was described and the effects of cavitation on fluid power systems and components were dealt with. Mechanisms of cavitation erosion were described and reasons for various erosion rates were discussed. Several cavitation detection methods were illustrated.

7 LIST OF NOTATIONS

r	Fluid density	kg/m^3
Dp	Pressure difference	bar
A	Cross-sectional area of flow path	m^2
A_c	Cross-sectional area of vena contracta	m^2
C_c	Contraction coefficient	-
C_q	Flow coefficient	-
K	Cavitation number	-
K_s	Cavitation parameter	-
p_d	Downstream pressure	bar
p_u	Upstream pressure	bar
p_v	Evaporation pressure	bar
Q	Flow rate	l/min
v	Flow velocity	m/s

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