STATE OF THE ART AND PERSPECTIVES ON THE STUDY OF VALVE CAVITATION

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Anno Accademico 2014 - 2015
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ABSTRACT (ENGLISH)

The purpose of the thesis is to provide a complete presentation of the cavitation phenomenon in particular for what concern the case of the valves. The idea behind this work comes from the valves manufacturer company VAG-Armaturen GmbH that has to face the occurrence of cavitation in many practical applications.

The first chapter contains information about the phenomenon in general terms and so it is not strictly connected to the case of valves. This part start from an historical background of the studies made on the issue of cavitation, starting from the end of nineteenth century. A brief description of the physical phenomenon is included in order to explain the causes that can lead to the cavitation appearance and how the cavitation develops along the flow; then some information about the dynamic evolution of spherical bubbles are presented. In the first part there are also consequences listed of the cavitation in hydraulics and the ways that are used to detect the phenomenon. Moreover, three different methods that are used in laboratory for the evaluation of the cavitation resistance of the new materials for which historical data are not available. These three methods include:

- Vibratory cavitation apparatus (ASTM G32)
- Cavitation liquid jets (ASTM G134 and variants)
- High-speed cavitation tunnels.

The conclusive argument of the first chapter is the overview of the cavitation in the case of pumps that is included in order to give a wider presentation of the cavitation, showing how the problem is faced in an application that is not the one of valves.

The second chapter deals with the topic of this thesis, which is the cavitation in valves. Introduced first are the cavitation indices used to evaluate the cavitation in valves and the cavitation limits provided by the literature. Then a presentation of the valves produced by the company VAG-Armaturen GmbH, that are considered in the present work, is made. In particular these valves are:

- Globe valve: VAG DURA glob valve
- Plunger valve: VAG RIKO plunger valve
- VAG CEREX 300 butterfly valve
- VAG EKN butterfly valve.
For each type of valve presented there is a description of the main characteristics and the principal applications in which they are used as well as a sketch of the valves.

Using the software UseCAD 7.0, provided by VAG-Armaturen GmbH, the service cavitation indices are obtained introducing in the same system three different valves: EKN butterfly valve, RIKO plunger valve and the CEREX 300 butterfly valve. The values of cavitation indices obtained in the three cases, by using the software, are compared with the analytical ones, coming from formula found in the literature, and between each other.

In this part, another kind of valve that is not produce by the company VAG-Armaturen GmbH is also introduced, the choke valve. This valve is not present in the software mentioned above. Moreover, the coefficients and the formulas used to scale the values of cavitation limits obtained experimentally with a reduced size model, are presented, as well as the practical methodology for testing the valves performance characteristics in a cavitating fluid service. Finally the techniques used to control cavitation are discussed.

The third chapter regards a new perspective in the study of cavitation in valves. In particular it is about the prediction of the cavitation index by using a numerical simulation instead of use experiments with the real valves.
ABSTRACT (ITALIAN)

La cavitazione nelle valvole è un problema con il quale le aziende produttrici, oltre che i consumatori, devono confrontarsi in numerose applicazioni. Il presente lavoro è nato in collaborazione con la ditta VAG-Armaturen GmbH con lo scopo di disporre di una raccolta esauriente sullo stato dell’arte relativo al problema e di indicare quali sono le nuove prospettive in merito.

La prima parte della tesi è composta da un capitolo relativo al fenomeno della cavitazione in termini più generali, quindi non strettamente legato solamente al caso delle valvole. Inizia facendo un breve inquadramento storico sugli studi relativi alla cavitazione iniziati alla fine del diciannovesimo secolo. Vengono presentate le cause che possono portare a cavitazione e come il fenomeno si sviluppa lungo il flusso, oltre che le formule che descrivono la dinamica delle bolle. In questa parte sono anche descritti tre metodi sperimentali che vengono utilizzati allo scopo di ottenere la resistenza all’erosione indotta da cavitazione per i nuovi materiali di cui non si dispongono ancora queste informazioni. L’ultimo argomento trattato in questo primo capitolo riguarda i cenni sulla cavitazione nel caso delle pompe. È stato inserito per mostrare come la cavitazione viene affrontata in un’applicazione diversa da quella delle valvole, allo scopo di avere una visione più ampia del problema.

Il secondo capitolo è quello che riguarda l’argomento principale dell’intero lavoro, ovvero la cavitazione nelle valvole. Prima di tutto vengono presentati gli indici utilizzati per valutare il livello di cavitazione e i limiti forniti in letteratura. Poi viene fatta una presentazione delle valvole prodotte da VAG-Armaturen GmbH che vengono considerate all’interno della tesi, in particolare queste valvole sono:

- VAG DURA control valve
- VAG RIKO control valve
- VAG CEREX 300 butterfly valve
- VAG EKN butterfly valve.

Per ogni tipologia viene fatta una descrizione delle caratteristiche principali e degli impieghi più comuni ed è una figura riportante lo schema della valvola.
Attraverso il software UseCAD 7.0 fornito dalla ditta VAG-Armaturen GmbH sono stati ottenuti gli indici di cavitazione di servizio relativi allo stesso impianto nel quale vengono introdotte tre diverse tipologie di valvola: EKN butterfly valve, RIKO plunger valve e CEREX 300 butterfly valve.

I risultati ottenuti tramite il software vengono poi confrontati con quelli ottenuti analiticamente attraverso la formula presente in letteratura.

In questa parte viene considerato anche un altro tipo di valvola che però non viene prodotta dalla ditta VAG-Armaturen GmbH e che quindi non è presente nel software sopracitato; si tratta della valvola choke.

Vengono anche descritti i coefficienti e le formule utilizzati per scalare i limiti di cavitazione della valvola (incipiente, critica, ecc.) ottenuti con modelli a scala ridotta, così come la tecnologia utilizzata per testare le valvole.

Il terzo capitolo riporta una nuova prospettiva nello studio della cavitazione nelle valvole, si tratta di un metodo di predizione dell’indice di cavitazione attraverso la simulazione numerica che può essere utilizzato al posto degli esperimenti sulle valvole reali.
1 CAVITATION

1.1 INTRODUCTION

The cavitation phenomenon appeared in the scientific literature at the end of the nineteenth century. The negative effects of cavitation (performances breakdown, erosion, vibration and noise) were initially noted on the propeller of ships by Parsons in the 1893. He also built the first cavitation tunnel: an experimental facility that strongly contributed to the first clarification of cavitation problems.

The first tunnel built by Parsons in the 1895 contained almost all components of a modern cavitation tunnel, except the impeller for water circulation. A turning mirror was installed in order to do the stroboscopic photographs of the propeller with 2 inches of diameter and to heat the tunnel water it was used an arc lamp. The atmospheric pressure inside the tunnel was removed by an air pump. A photography of the facility is shown in the figure 1.

![Image of Parsons first cavitation tunnel](image.jpg)

Figure 1: Parsons first cavitation tunnel

Around the years 1923-1925 Thoma and Leroux introduced the cavitation parameter (also called cavitation or Thoma cavitation parameter) defined by:

\[ \sigma_V = \frac{P_r - P_V(T)}{\Delta P} \]

Where \( P_r \) is the pressure at conventional reference point \( r \) where it is easily measurable (\( r \) is usually chosen in a region where cavitation inception is expected); \( P_V \) is the vapor pressure of the
fluid at the operating temperature $T$ and $\Delta P$ is the pressure difference that characterizes the system.

For example:

- In the case of gate:

\[
\sigma_v = \frac{P_{\text{downstream}} - P_v(T)}{P_{\text{upstream}} - P_{\text{downstream}}}
\]

- For a pump:

\[
\sigma_v = \frac{P_{\text{inlet}} - P_v(T)}{\rho V_p^2}
\]

Where $V_p$ is the velocity at the periphery of the runner.

Subsequently, many experiments were carried out to study the physical aspects of the phenomenon and to examine its effects on industrial systems. Theoretical and numerical approaches were widely used. [6]

There were two main fields of research: the first focused on bubbles dynamics (Rayleigh 1917, Lamb 1923, Cole 1948, Blake 1949, Plesset 1949) and the second related to supercavities. The simplicity of the spherical shape made the study of the dynamics of bubbles relatively easy. This simple model demonstrates the main features of many practical cases such as bubble collapse, bubble formation from a nucleus, bubble oscillations, etc. Experience shows that more complicated situations can be approximately dealt with using this model. [6]

Several equations have been developed and applied to the problems of the bubble growth and the bubble collapse.

Regarding supercavitation it is considered the case in which a cavity attached to a hydrofoil extends and becomes longer and longer due to the decreasing of the parameter $\sigma$. Anyway the studies of supercavitation are related to underwater rockets and torpedos: cavitation effects are used to produce a bubble of gas inside the liquid large enough to surround an object travelling through the liquid in order to greatly reduce the friction drag and so reach very high speeds. An example of this is shown in the following figure 2.
More recently vortex cavitation was considered (1983). Rotational structures generate low pressure regions inside the liquid itself, whereas the minimum pressure occurs at the liquid boundary for irrotational flows. Such pressure drops can be very intense, so that vortex cavitation often starts for high values of the cavitation number in comparison with other types of cavitation.

Vortex cavitation is present along the leading edge of delta wings, downstream of the propeller hub and at the tip of the propeller blades. The following figures, 3 and 4, show the case of vortex cavitation on a propeller and on delta wings.
Figure 4: Delta wings vortex cavitation
1.2 THE PHYSICAL PHENOMENON

Cavitation is the rapid vaporization and subsequent violent condensation of a fluid. The process is somewhat analogous to boiling, where vapor bubbles are created when, by heating the liquid, the vapor pressure reaches the atmospheric pressure (or to be more general the pressure of the surrounding ambience).

For the case of cavitation the driving mechanism is not the temperature change, but the pressure change: when there is a local pressure lowering and the vapor pressure is reached, vapor bubbles appear.

In order to better clarify the situation consider the phase diagram of a substance that is the curve that separate solid, liquid and vapor phases of the substance at different temperatures. Any process that raises the temperature or reduces the pressure by a sufficient amount will produce a phase change from liquid to vapor. In figure 5 the phase diagram for the case of water is presented.

![Phase diagram of water](image)

Figure 5: Phase diagram of water [4]

When a fluid passes through a narrow restriction it accelerates because of the reduction of the section and the pressure may drop below the vapor pressure of the liquid. Over the vena contracta the velocity decreases as the flow area expands and the pressure built again. The figure 6 is the scheme of this situation.
As a vapor bubble is formed in the vena contracta, it travels downstream until the pressure recovery causes the bubble to implode. This two-step process: the formation of the bubble in the vena contracta and its subsequent implosion downstream, is called cavitation. [1]

In general some conditions must be present to produce cavitation:

- the liquid must contain some entrained gases or impurities, which act as “hosts” for the formation of the vapor bubbles; these hosts are also called nuclei. The quantity and the size of the nuclei present in the flow depend on the history of the water, usually water contains enough nuclei that cavitation will occur when the local pressure drops to vapor pressure;
- the pressure somewhere in the liquid must drop to or below the vapor pressure;
- the ambient pressure outlet must be greater than the vapor pressure in order for the cavity to collapse.

The creation and implosion of the cavitation bubbles involve five stages:

- the velocity increase through the restriction and the liquid’s pressure drops below the vapor pressure.
- the liquid expands into vapor around the nuclei host (particulate or entrained gas);
the bubbles grow until the flow move away from the vena contracta and then the increasing pressure recovery inhibits the growth of bubbles;

as the flow moves away from the vena contracta, the area expands and so there is a reduction of the velocity and an increase of the pressure. This increased pressure collapses or implodes the bubble vapor back to a liquid;

if the bubbles are near the surface of the valve or of the hydraulic machinery (pumps, turbines), the force of the implosion is directed toward the surface wall, causing damages. Researches have indicated that the collapse must occur approximately one bubble diameter from the boundary in order to cause erosion damage.
1.3 OVERVIEW ON THE DYNAMICS OF SPHERICAL BUBBLES

In this chapter information are presented about the dynamic evolution of a spherical bubble with a fixed center.

The main assumptions are as follows:

- the liquid is incompressible;
- gravity is neglected;
- the air content of the bubble is constant, its inertia is neglected as is any exchange of heat with the surroundings. This adiabatic assumption is valid when considering rather large bubbles;
- the bubble is saturated with vapor whose partial pressure is the vapor pressure at the liquid bulk temperature. [6]

The functions that we are to determine in the liquid domain $r > R(t)$ are the velocity $u(r, t)$ and the pressure $p(r, t)$ induced by the evolution of the bubble. $R(t)$ is the radius of the cavity. The following figure 7 shows the situation.

![Figure 7: Bubble in a liquid domain](image.png)
The mass transfer through the interface is neglected so that the liquid velocity at the interface $u(R, t)$ is equal to the interface velocity:

$$\dot{R} = \frac{dR}{dt}$$

The mass conservation equation for incompressible fluid (the divergence of the velocity is 0, $\nabla u = 0$) gives:

$$u(R, t) = \dot{R} \frac{R^2}{r^2}$$

The pressure on the cavity interface is given by:

$$p(R, t) = p_v + p_{g0} \left( \frac{R_0}{R} \right)^{3\gamma} - \frac{2S}{R} + 2\mu \frac{\partial u}{\partial r} \bigg|_{r=R}$$

Where $p_g$ stands for the partial pressure of the gas inside the bubble, $p_{g0}$ initial pressure, $R_0$ initial radius, $S$ surface tension, $\mu$ viscosity of the fluid and $\gamma$ ratio of the gas heat capacities.

Doing some passages we can arrive to the Rayleigh-Plesset equation:

$$\rho \left[ R \dot{R} + \frac{3}{2} R^2 \right] = p_v - p_{\infty}(t) + p_{g0} \left( \frac{R_0}{R} \right)^{3\gamma} - \frac{2S}{R} + 4\mu \frac{\dot{R}}{R}$$

Where $p_{\infty}(t)$ is the pressure in the surrounding liquid and $\rho$ the density of the liquid.

This equation allow us to determine the evolution in time of the radius of the bubble $R(t)$.

Before the initial time ($t < 0$), the bubble is supposed to be in equilibrium with under pressure $p_{\infty,0}$ which is equal to the vapor pressure $p_v$. From the instant $t = 0$ a constant pressure $p_{\infty}$, higher than $p_v$ is applied to the liquid. It result in the collapse of the bubble in a characteristic time $\tau$ called Rayleigh time:

$$\tau = \sqrt{\frac{\pi}{6} \frac{\Gamma(5/6)}{\Gamma(4/3)}} \frac{R_0}{\sqrt{\frac{\rho}{p_{\infty} - p_v}}} \equiv 0,915 \frac{R_0}{\sqrt{\frac{\rho}{p_{\infty} - p_v}}}$$

The value of $\tau$ is in good agreement with the experimental values for a large range of initial values of the bubble diameter. As an example, in the case of water, a bubble with an initial radius of 1 cm collapses in about one millisecond under an external pressure of 1 bar. [6]
1.4 THE EFFECTS OF CAVITATION IN HYDRAULICS

The consequences of the presence of cavitation bubbles in the flow are well known. When cavitation develops in a hydraulic machinery: turbine or pumps, involves a reduction of efficiency. For example, measurements have been done on the Francis turbines and they show that the efficiency of the machinery decrease directly with the cavitation coefficient. Moreover there is a production of noise that at early stages is described as a popping or cracking noise, while extensive cavitation produces a steady hiss or sizzling noise. Some describe the noise as a gravel rolling down the piping.

Noise is normally complemented by excessive vibration, which can cause metal/piping fatigue, miscalibration, or malfunctioning of sensitive instrumentation. In some cases, the vibration can be minimized by anchoring the piping securely to floors, walls, etc.\[1\]

Another important effects is the wall erosion that occur when the collapse is very near or on the surface.

There are two suggested mechanism by which damage occurs at solid boundaries. The first is the high-pressure shock waves generated by collapse of the cavities, these pressures have been estimated to be over $10^6$ psi, which is sufficient to damage any material. The other source of potential damage is due to what is called a microjet. When a bubbles collapse near the boundary, the pressure distribution around the bubbles is unsymmetrical due to the presence of the boundary. As the bubble collapses, the side of the bubble away from the wall reaches a higher velocity and the bubble collapse inward, forming a jet shooting through the center of the bubble. This jet reaches high velocities and creates a local pit when it impacts the wall.

Cavitation erosion is strongly dependent upon the flow velocity for two major reasons: one is that the number of bubble nuclei increase with the flow velocity, the second is that the impulsive pressure pulses induced by collapsing bubbles also increase with the flow velocity. This latter effect is due to two factors: larger velocity results in a larger pressure drop and in larger pressure gradient, so the bubble nuclei reach larger size and then encounter a larger pressure gradient at collapse, causing an increase of the collapse intensity and pressure pulses. Measurements generally indicate that cavitation erosion damage increases as a power between 4 and 9 of the flow velocity.\[4\]

Linked to cavitation erosion damage there is corrosion: since cavitation removes oxidized material from the surface, fresh material is exposed and this greatly accelerates corrosion. So it can be said that cavitation magnify the effect of corrosion.
Cavitation can also accelerate the erosion caused by the presence of the sediments in the flow. This is because the surface weakened by the cavitation is more easily eroded by the abrasive action of the sediment.
1.5 CAVITATION DETECTION

Laboratory experiments are used to explore the physics and develop empirical relationships for predicting various levels of cavitation. The purpose is to give some knowledge of how cavitation is detected and how data are analyzed.

Since cavitation causes noise, pressure fluctuations, vibrations, pitting and loss of efficiency, any device that is sensitive to one of these can be used to detect cavitation. Several electronic instruments, including sound level meters, pressure transducers, accelerometers and hydrophones have been used in the laboratory to measure cavitation. [2]

Hydrophones are a kind of microphones designed to be used underwater in order to measure the noise coming from there. Usually they are made with a transducer that produce electric energy whenever there is a pressure change (noise is a pressure change in a fluid).

Accelerometer is device that measures the acceleration and it must be rigidly mounted on the test specimen downstream pipe wall. In the further chapters the test procedure, especially for valves, will be discussed.

Other methods of detecting cavitation are visually and aurally. In particular if a transparent section can be installed, cavitation events can be seen by the naked eye or with stroboscopic lighting. If is not possible to visualize the flow, a trained ear can usually heard cavitation except in cases where there is an extremely high background noise level. A trained observer can be quite precise in detecting early stages of cavitation visually or aurally.
1.6 LABORATORY TESTING METHOD OF CAVITATION EROSION

The aim of this chapter is to present the cavitation erosion testing methods commonly used in the laboratory. These laboratory experimental studies have the purpose of obtaining an evaluation of the cavitation resistance of the new material in a short time period, whereas in the real field, cavitation erosion, may occur after a long duration of exposure. This is very useful for the evaluation of the resistance to cavitation erosion of new materials for which historical data are not available.

In this chapter three different laboratory testing methods that are used to generated the erosion data are presented. They are: vibratory cavitation apparatus (ASTM G32), cavitation liquid jets (ASTM G134) and a high-speed cavitation tunnel. ASTM is the American Society for Testing and Materials that standardized the first two methods.

1.6.1 Vibratory cavitation apparatus (ASTM G32)

In the ultrasonic cavitation tests, the cavitation is generated by a vibratory device employing an ultrasonic horn. The high frequency oscillations of the horn, typically tens of kilohertz, induce cyclic formation of very high and very low pressure, which generate high negative tension in the liquid.

This can be understood easily if one considers the acoustic field generated by the imposed amplitude motion of the tip of the horn given by:

\[ X(t) = A \cos(2\pi f t) \]

Where \( X(t) \) is the vertical position of the tip of the horn at instant \( t \), \( A \) the amplitude and \( f \) the frequency of the tip vibratory oscillations.

The resulting acoustic pressure is given by:

\[ p = \rho_i c_i \dot{X} = -2\pi f \rho_i c_i A \sin(2\pi f t) \]

Where \( \rho_i \) is the liquid density and \( c_i \) is the sound speed in the liquid.

Typically, the vibratory devices operates at 20 kHz and the amplitude of the horn tip motion, \( A \), is maintained at 25 μm.

This gives for water:

\[ p = -4.7 \times 10^6 \ (2\pi f t) \ [Pa] \]
Since the amplitude of the pressure oscillations is much larger than the ambient pressure, this results in pressure drops during the negative pulse cycles much below the critical pressure of most liquid. Nuclei critical pressure is the value at which, if the local pressure goes below, explosive bubbles grow and so cavitation is created.

A sample “button” of the material being tested is affixed to the end of the horn and is subjected to the cavitation resulting from the vibration of the horn. [7]

The vibratory cavitation apparatus (G32) is described with its two variants: the direct method and the alternative method.

For the direct method the ASTM the technical features are: samples diameter of 16 mm, vibration frequency of 20 kHz and an amplitude peak-to-peak of 50 μm. The container is a 2000 ml beaker filled with distilled water and tip of the horn is submerged 8 mm beneath the free surface. The temperature is controlled by immersing the beaker in a water bath maintained at 25 ± 2°C.

In the alternative configuration, that is also known as the stationary specimen method, the sample is placed at distance typically of 0,5 mm below the vibrating horn tip made of a cavitation resistant button, for example in titanium.

In figure 8 there are two configurations presented.

![Figure 8: ASTM G32 direct method and the alternative method [7]](image)

Deviations from the ASTM G32 method as to be documented.

The alternative method is especially useful for testing materials difficult to be made into threated. [7]
Experiments show that the erosion patterns using the two methods are significantly different, in particular in the case of the direct method there is a large eroded area concentrated mainly in the central part of the sample, whereas in the case of alternative method the erosion is more spread. This difference is shown in figure 9; the samples are made in aluminum alloy Al 7075 for 900 minutes of exposure to cavitation and with a button samples diameter: 12.7 mm.

![Figure 9: Erosion in samples tested with direct method (left) and with alternative method (right) [7]](image)

The difference in the erosion patterns is due to the shape of the bubble cloud that is generated in the two cases: in the direct method the cavitation bubble cloud collapses in a hemispherical way towards the tested sample, in the alternative method, it collapses in a cylindrical way. This can be seen in figure 8.

Cavitation clouds collapsing cylindrically were found to be much less erosive than the hemispherically collapsing cavitation clouds. Mass loss versus time curves on the same material (aluminum alloy Al 7505) for the two methods are presented in figure 10, which illustrates a mass loss rate by the direct method being almost twice that of the alternative method. [7]
The conventional test procedure using the ultrasonic vibrating horn method is to expose the sample to cavitation for a selected period of time, interrupt the test, remove the sample, and record weight to enable calculation of weight loss as a function of time. The sample is then returned to the exact same position on the horn for additional time intervals of erosion. Other erosion characteristics such as volume of erosion imprint, maximum width and depth can also be recorded, together with photographs of the evolution of the eroded region as a function of time [7].

Erosion tests using ultrasonic cavitation provide reproducible cavitation within a laboratory environment, but the cavitation thus generated is different from that on a propeller or a rudder in a number of ways. The cavitation bubbles are of nearly uniform sizes and are excited by the horn at a fixed frequency, while real cavitation fields have a distribution of bubble nuclei sizes and cavitation forms and vastly different exciting frequencies. The most important discrepancy is the presence in the ultrasonic method of a cavitation bubble cloud always at the same location. [7]
1.6.2 Cavitation Liquid Jets (ASTM G134 and variants)

The cavitation bubble clouds created in this case are more realistic than the ones when using the ultrasonic horn testing (G32). There is a distribution of micro bubbles with various sizes which collapse on the sample.

Cavitation intensity produced by cavitating jets can be varied in a wide range through adjustment of the type of the jet, the jet velocity, the jet diameter, the jet angle, the standoff distance, and the ambient pressure in which they are discharged. [7]

The test consists of a jet discharged at high pressure and velocity from a cavitating jet nozzle in a cell whose pressure may be controlled: the test chamber can be pressurized, or at atmospheric pressure. A sample holder is present in order to allow to take of the sample for measurements and then replace it correctly for the subsequent tests.

The overall test procedure is similar to that used in the G32 tests other than using a cavitating jet.

A normal test procedure for a sample is as follows: (a) the sample is exposed to the cavitating jet for a predetermined period of time, (b) the test is interrupted, (c) the sample is taken out from its holder for examination, and (d) the erosion is characterized by weight and depth measurement.

Photographs of the progression of the erosion patterns are taken at selected times. The sample is then returned for additional testing, and the process is repeated. [7]

1.6.3 High-speed Cavitation Tunnels

Cavitation erosion tests can also be conducted in high-speed cavitation tunnels. In order to be able to characterize the resistance to cavitation erosion of hard materials within reasonable exposure times, cavitating flows of sufficiently high aggressiveness are required. As aggressiveness increases with flow velocity, cavitation erosion tunnels are often designed for high velocities and consequently high pressures.[7]

A pump provides a certain flow rate, and a heat exchanger can be used in order to limit the increase in temperature during long tests.

Several pressure sensors are used to control the operating point. A flow meter measures the flow rate \( Q \) in the test section and two pressure sensors give the upstream and downstream pressures \( P_1 \) and \( P_2 \) respectively.

The cavitation parameter is evaluated with the relationship:

\[
\sigma = \frac{P_2 - P_v}{P_1 - P_2}
\]
Different types of test sections have been used to investigate cavitation erosion in high-speed tunnels such as a Venturi with or without a central body, slot cavitator, cylindrical specimen spanning the tunnel or radial divergent. As an example, the radial divergent test section used in the LEGI (‘’Laboratoire des Écoulements Géophysiques et Industriels’’, Grenoble, France) facility is presented in figure 11. [7]

![Figure 11: Schematic view of the radial divergent test used at LEGI laboratory [7]](image)

The quantity measured in this test is the depth of the erosion caused by the cavitation on the sample.

For the experiments in the LEGI laboratory the tunnel is operated with a cavitation number around 0.9. The figure 12 represents a typical example of a profile of a sample eroded in the cavitation tunnel at LEGI laboratory. The test section is made of stainless steel A2205, the upstream and downstream pressures are respectively 40 bar and 18.9 bar, flow rate: 8.2 l/s and the exposure time: 161 h.

![Figure 12: Typical example of a sample eroded [7]](image)
Damage is concentrated in an annular region extending roughly between radius 20 mm and radius 26 mm. The radial location of this region is controlled by the value of the cavitation number. This region moves downstream when the cavitation number is decreased and follows the increase in cavity length. [7]
1.7 OVERVIEW ON CAVITATION IN PUMPS

In order to have a more general view of the cavitation phenomenon, this chapter presents an overview about the problem of the cavitation in pumps.

In particular at the impeller input there is a restriction of the section and so the pressure decreases. If the pressure reaches the value of the vapor pressure, cavitation can begin.

The consequences of cavitation in pumps are very significant on the performances because it may causes erosion damages and because large quantities of vapor can reduces the efficiency even before the erosion occurs. Naturally the other consequences are noise and vibration.

Care has to be taken on the corrosion since it causes financial losses due to downtime and repair, or replacement.

In figure 13 a scheme of the situation is presented.

Where:

\[
\frac{p_0}{\gamma} : \text{total absolute head in the reservoir;}
\]

\[
z_e + \frac{p_e}{\gamma} + \frac{v_e^2}{2g} : \text{total head at the pump input;}
\]
\( Y \): losses in the suction pipe;

\( D \): diameter at the impeller input;

\( \Delta \): losses from the pump input section to the vena contracta section.

In the figure 1 the red line is the energy grade line (EGL) and the green line is the hydraulic grade line (HGL).

By doing the equilibrium at the two sections: the one at the pump input and the other one at the one where there is the minimum value of pressure (vena contracta downstream the impeller input):

\[
\frac{p_0^*}{\gamma} = z_e + \frac{p_e^2}{2g} + Y = z_e + \frac{D}{2} + \frac{p_{\text{min}}}{\gamma} + \Delta + \frac{v_e^2}{2g} + Y
\]

And so:

\[
\frac{p_0^*}{\gamma} = z_e + \frac{D}{2} + \frac{p_{\text{min}}}{\gamma} + \Delta + \frac{v_e^2}{2g} + Y
\]

Severally users don’t know the single values \( \frac{v_e^2}{2g} \), \( Y \) and \( \Delta \)

The manufacturers provide the sum of these three terms, the so called: net positive suction head \( NPSH \).

By doing a simple substitution:

\[
\frac{p_0^*}{\gamma} - z_e - Y - NPSH = \frac{p_{\text{min}}}{\gamma}
\]

In order to avoid cavitation the minimum pressure must not reach the vapor pressure and so it can be written:

\[
\frac{p_0^*}{\gamma} - z_e - Y - NPSH > \frac{p_v}{\gamma}
\]

\[
\frac{p_0^*}{\gamma} - z_e - Y - \frac{p_v}{\gamma} > NPSH_r
\]

In the last equation the subscript \( r \) means that \( NPSH_r \) is the net positive suction head required.

Looking at the last relationship it’s easy to understand that the terms on the left side with the sign minus ahead are “harmful” and have to be limited.
The vapor pressure $p_v$ depends on the altitude of the system and on the temperature of the water, we can only take into account of this.

On the term $Y$, which represents the losses along the suction pipe, it’s possible to operate: the pipe is designed as short as possible and, in order to reduce the localized losses, curves try to be avoided. Moreover is possible to consider larger diameter and smaller roughness, in particular for the case of short pipe where the increase of the cost is not so high. Another solution is to put beside it another parallel pipe in order to reduce the velocity maintaining the same flow.

On the term $z_e$ we can easily act lowering the altitude of the pump when it is possible.

Obviously a pump with a lower $NPSH_r$ can be chosen, but it is more expensive and more cumbersome.
2 VALVE CAVITATION

2.1 INTRODUCTION

Cavitation is a common problem for valves, it develop when the flow passes through a partially open valve and at the low-pressure zone downstream to the restriction the vapor pressure is reached by the water.

The following figure 14 shows the situation for a butterfly valve. In particular this figure clarifies where the cavitation develops downstream of a partially open butterfly valve: is the cone of low pressure downstream of the disc.

![Figure 14: Cavitation zone downstream of a butterfly valve [3]](image)

As already said in the introductory chapter, cavitation has several negative consequences: objectionable noise, vibration, erosion and decrease of the useful life of the valve and of the nearby piping components.

Another “side-effect” of cavitation is an apparent decrease in the efficiency of the valve [4]. This happens when there is a choked flow condition that is presented in the following chapters.

For these reasons it is important to consider the possibility to have cavitation when a valve is included in a system. The personnel responsible has to understand the nature of the cavitation phenomenon and the fundamental abatement technology in order to limit the negative consequences.

Briefly cavitation can be controlled and eliminated by one of these three basic method: a) by modifying the system, b) by making certain internal body parts out of hard or hardened materials, c) by installing special devices in the valve that are designed to keep cavitation away from valve surface or prevent the formation of the cavitation itself [1]. These techniques will be presented more in detail.
2.2 CAVITATION INDICES

To predict the possibility of having cavitation, experts adopted a single parameter that was introduced by Thoma and Leroux in the years 1923-1925.

\[ \sigma = \frac{P_r - P_V(T)}{\Delta P} \]

Where \( P_r \) is the pressure at conventional reference point \( r \) where it is easily measurable (\( r \) is usually chosen in a region where cavitation inception is expected); \( P_V \) is the vapor pressure of the fluid at the operating temperature \( T \) and \( \Delta P \) is the pressure difference that characterizes the system.

In particular the parameter chosen for this document is:

\[ \sigma = \frac{P_1 - P_V}{P_1 - P_2} \]

Where \( P_1 \) is the absolute pressure upstream of the valve, \( P_2 \) is the absolute pressure downstream of the valve and \( P_V \) is the absolute vapor pressure of the fluid at the inlet temperature.

In general terms, the parameter \( \sigma \) is a ratio of “forces” that resist cavitation to “forces” that promote cavitation [1].

Different parameters have been introduced in order to define the cavitation in valves:

\[ K = \frac{P_1 - P_2}{P_1 - P_V} = \frac{1}{\sigma} \]

Or:

\[ \sigma_2 = \frac{P_2 - P_V}{P_1 - P_2} = \sigma - 1 \]

As shown in the equations above the parameters \( K \) and \( \sigma_2 \) are related to the index \( \sigma \) by simple relationships.

In the applications, this cavitation index evaluated for the operating conditions, is compared to the value of cavitation limit established for the specific valve.
2.3 CAVITATION LIMITS

The cavitation index $\sigma$ quantifies only the service conditions. By itself it does not convey any information about the performance of a particular valve in a particular application. Different valves can tolerate different levels of cavitation, and different applications are concerned about a different aspects of cavitation (for instance, noise versus vibration versus damage). Therefore $\sigma$ must be evaluated at the service conditions and then compared to a benchmark for the valve that reflects the permissible degree of cavitation (cavitation limit) for the application [4].

In particular these benchmarks are:

- incipient cavitation;
- constant or critical cavitation;
- incipient damage;
- choking cavitation.

**Incipient cavitation $\sigma_i$**

This is the first level of cavitation considered. It’s a very conservative design limit and it’s used only where noise or other disturbances cannot be tolerated and so it is considered only for a few valves.

Selecting incipient cavitation as a limit restricts all operation to a cavitation-free regime. Incipient cavitation is extremely mild, and often cannot be heard over the flow noise and vibration produced by other components in a piping system.[4]

**Constant or critical cavitation $\sigma_c$**

Next there is a higher cavitation limit known as constant. This level is considered a conservative application limit, generally, no objectionable noise, vibration, or damage occurs at this condition.[4]

For most applications, constant cavitation, is recommended for what might be termed “cavitation-free operation”.

The values of incipient and constant cavitation are usually evaluated by plotting the accelerometer output versus the cavitation index $\sigma$ on log-log coordinates.

The figure 15 shows a typical situation.
In figure 15 the points A, B and C represent:

- A: point defining incipient cavitation index;
- B: point defining constant cavitation index;
- C: point defining choking cavitation index.

Incipient and constant cavitation are determined by the intersection of straight-line portions of the figure. A few valves tested have significantly different cavitation characteristics and produce different accelerometer curves.[2]

It must noticed that even if in figure 15 the choke cavitation is present, the normal method of evaluating the onset of choking is different and will be presented subsequently.

**Choking cavitation** $\sigma_{ch}$

As the valve begins to choke (point C) there is a sudden drop in the cavitation intensity because as the length of the vapor cavity downstream of the valve increases, the collapse of the cavity occurs farther from the valve. [2]
Choking cavitation is the severe level of cavitation and is appropriate only for valves that operate for short periods of time. For example, erosion damage may not be the deciding factor in pressure-relief valves that operate infrequently. In general a valve can operate choked when the system is designed to tolerate heavy vibration and if noise is not a consideration.

Under “fully chocked” flow conditions an additional decrease in the downstream pressure will not increase the flow rate through the valve at a given inlet pressure. The value of $\sigma$ associated to this condition may be estimated from the following equation:

$$
\sigma_{ch} = \frac{P_1 - P_v}{\Delta P_{choked}} = \frac{P_1 - P_v}{F_L^2(P_1 - F_F P_v)}
$$

Where $F_L$ is the liquid pressure recovery factor and $F_F$ is the liquid critical pressure ratio factor. $F_L$ is calculated as follows:

$$
F_L = \frac{q_{max}}{C_V \left( \frac{P_1 - 0.96 P_v}{G_f} \right)^{1/2}}
$$

Where $q_{max}$ is the maximum flow rate (choked flow conditions) at a given upstream condition, $P_1$ is the pressure at the upstream pressure tap for the $q_{max}$ determination, $G_f$ is the liquid specific gravity at upstream conditions (ratio of density of liquid at flowing temperature to density of water at 15,6°C) and $C_V$ is the valve flow coefficient:

$$
C_V = q \left( \frac{G_f}{\Delta P} \right)^{1/2}
$$

Where $q$ is the volumetric flow rate and $\Delta P$ is the pressure differential $(P_1 - P_2)$.

The liquid critical pressure ratio factor, $F_F$, is ideally a property of the fluid and its temperature. It is the ratio of the apparent vena contracta pressure at choked flow conditions to the vapor pressure of liquid at inlet temperature [5]. It is calculated as follow:

$$
F_F = \frac{1}{P_v} \left( P_1 - G_f \left( \frac{q_{max}}{F_L C_V} \right) \right)
$$

The following figure 16 shows how the flow rate doesn’t increase even if the differential pressure increases, when the flow is choked.
Figure 16: Evaluation of choking cavitation [2]

As shown in figure 16, the value of $\Delta P_{choked}$ can be obtained by intersecting the two straight lines.

**Incipient damage cavitation $\sigma_{id}$**

Incipient damage is the level of cavitation in which an increase in cavitation intensity first produces any detectable damage to either the valve or the downstream piping. It is much more difficult to detect since it cannot be determined from acceleration or vibration curves as seen for the case of incipient and constant cavitation.

The method used in this case is to measure the pitting rate of damage on samples of soft materials, for example aluminum. In particular soft aluminum is used as test material to minimize testing time.

At this level of cavitation, objectionable noise and vibrations may be produced and their intensity varies depending on the test device.

Pitting rate generally exhibits a strong increase with flow velocity for the same cavitation number $\sigma$. Several investigations have shown that pitting rate increases with a power of velocity generally between 5 and 6.

There are two reasons for this strongly non-linear effect of the flow velocity. One reason is that the amplitude of the impulsive loads increases with flow velocity. This is because when the
velocity is increased at constant $\sigma$, the ambient (downstream) pressure has also to be increased in order to conserve the cavitation number. (Note that an increase of flow velocity causes a decrease of the cavitation number. In order to maintain a constant cavitation number when there is an increase of the flow velocity, the downstream pressure has to be increased).

The bubbles then experience a higher pressure during their dynamic process, resulting in a stronger bubble collapse and an impulse load of higher amplitude. The second reason is that the bubble production rate also increases with flow velocity so that the frequency of pressure pulses increase too. When combined, both effects induce a rapid increase of pitting rate with flow velocity.[7]

The effect of flow velocity on pitting rate is illustrated in figure 17 where the reference pitting rate is plotted versus flow velocity, for three different materials: aluminum alloy Al 7075, nickel aluminum bronze NAB and stainless steel A2205. Results are obtained with a constant cavitation number: $\sigma = 0.9$.

![Figure 17: Effect of flow velocity on reference pitting rate](image)

For each case, the expression of the trend line is shown. All three curves follow approximately the same power law $V^5$ with the flow velocity $V$. 

$y = 1E-08x^{5.0787}$

$y = 1E-08x^{4.7835}$

$y = 3E-09x^{4.8508}$
Manufacturer’s recommended limit $\sigma_{mr}$

The manufacturer’s recommended limit for cavitation is an operational limit supplied by the valve manufacturer for a given valve. It may or may not coincide with other cavitation coefficients already discussed. The evaluation of this limit can be based on factors other than the laboratory test, such as accumulated experience with a particular design in a particular application or understanding of the specific design features.

This limit concept has been introduced to allow the most effective use of available control valve hardware and knowledge. The valve user should seek clarifications from the valve manufacturer of the information used in this evaluation. [4]
2.4 VALVES CONSIDERED

The aim of this chapter is to present the type of valves that are considered in the document, in particular the valves produced by the company VAG-Armaturen GmbH, for which the software UseCAD 7.0, provided by the same company, gives cavitation data output in terms of cavitation parameters.

The valves that are presented are:

- Globe valve: VAG DURA control valve
- Plunger valve: VAG RIKO control valve
- Butterfly valves: 1)VAG CEREX 300 butterfly valve, 2)VAG EKN butterfly valve

For each kind of valve presented there will be a description of the main characteristics and the principal applications in which they are used. In addition, a sketch of the valves produced by VAG-Armaturen GmbH, will be shown.

Moreover another kind of valve is presented, the so called choke valve. This type of valve is not produced by VAG-Armaturen GmbH and outputs from the software UseCAD 7.0 are not available.
2.4.1 GLOBE VALVE

This type of valve is used in a wide variety of applications for manual or automatic control. The following figure 18 shows the section of a typical globe valve.

![Manual globe valve](image1)

**Figure 18: Manually operated globe valve [1]**

The control of flow is obtained by moving the closing member up and down in the seat, the position of this member determines the opening of the valve. The globe valve can be activated manually or automatically.

These valves can be considered as high-resistance valves because they can withstand high pressure thanks to their shape which makes them very strong. Their resistance can also be increased by increasing the wall thickness of the body or by using flanges, bolting and internal parts built-up with stronger materials.

Although the globe body design can handle high-pressure classes, manual globe valves are usually applied to lower-pressure applications because of the thrust limitations of the hand operator [1]. In fact significant stem forces are required by the throttling process. High-pressure applications will require the use of a gear operator.
An important advantage of globe valves is that they can be designed with a particular cage or retainer that are useful in avoiding cavitation, flashing, vibration, erosion, or high noise level. These equipment are presented in the chapter 2.8 (Controlling cavitation) focusing on the cavitation’s aspect.

The principal disadvantage is that this kind of valve has large losses also in full open position and this is due to their complicated flow path. The losses are increased if the special cages mentioned above are present in the valves.

Moreover, globe valves are larger, heavier and more expensive when compared to the other valves (for example rotary valves).

In figure 19 the globe valve produced by VAG-Armaturen Gmbh called: DURA Control Valve is presented.

![Figure 19: VAG DURA control valve](image-url)
2.4.2 PLUNGER VALVE

This type of valves is characterized by an annular flow cross-section in any position. Because of this it can be called a straightway control valve. These valves are used for continuous regulation of pipeline system in case of high pressure drop and flow rate.

The following figure 20 shows the plunger valve produced by VAG-Armaturen GmbH called: RIKO Plunger Valve:

![Diagram of a plunger valve](image)

Figure 20: VAG RIKO control valve

Inside the body there is a plunger (piston) that is moved axially in flow direction by a crank gear toward the sealing seat. The regulation of the flow rate is done thanks to this motion.

In order to have a good corrosion protection, as well as excellent performances and long service life, the plunger and the shaft are equipped with bearings.

Between the body and the plunger is placed a quad O-ring that guarantees a permanent tightness even under high stress cycles.
The main fields of application of VAG RIKO plunger valves are: conveyance of water in catchment basins and dams, bypass lines of hydropower stations, long distance pipelines, water treatment in waterworks, water supply in pumps stations, supply control of elevated tanks, drinking water networks and cooling water circuits of industrial and power plants.

The outlet of the RIKO valves can be chosen between these different types:

- Type “E” with cut-off edge;
- Type “SZ” with slotted cylinder;
- Type “LH” with orifice cylinder.

**Type “E” with cut-off edge:**

This is the “standard version” that usually is used as a pump start-up valve and also in bottom outlets. The following figure 21 shows a picture and a scheme for this kind of outlet solution.

![Figure 21: Picture (left) and scheme (right) of the standard version "E"](image)

**Type “SZ” with slotted cylinder:**

The version SZ is preferably used as a control valve in the case of considerable pressure differences. Moreover it is good for water containing suspended matter, but for what the concerns of this document, it is used to prevent cavitation. The following figure 22 shows a picture and a scheme of this kind of outlet solution.
Type “LH” with orifice cylinder:

Also this solution is preferably used as a control valve in case of considerable pressure differences. It has to be noted that this solution is an optimum prevention of cavitation. The following figure 23 shows a picture and a scheme of this kind of outlet solution.

Now a comparison of the cavitation limits related to the RIKO valves with these different types of outlet solution is made. The valve considered is a RIKO plunger valve with nominal diameter $DN = 300 \text{ mm}$. 
The figure 24 shows the comparison of the cavitation limits: $\sigma$ beginning cavitation and $\sigma$ full cavitation, that is provided by the software UseCAD 7.0 for the different types of outlet solution.

![Different outlet types for RIKO valve](image)

**Figure 24: Cavitation limits for a RIKO valve with different outlet solutions**

Form this graph (figure 24) it is demonstrated how the outlet solutions “SZ” and “LH” involve lower cavitation limits than the outlet solution “E” with cut-off edge. This means that “SZ” and “LH” solutions are much better in avoiding cavitation than the simple type “E”.

Moreover, in order to have a more clear representation of the comparison, figure 25 presents the cavitation limits related to the outlet type solutions “SZ” and “LH”.

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The graph above (figure 25) shows that in terms of cavitation, the outlet solution “LH” is better than the solution “SZ” since it involves lower values of cavitation limits.

Finally, in order to have a more complete analysis, a comparison of the noise level reached in the three different solutions with respect of the opening angle expressed in percentage, are also executed. The values are provided from the software UseCAD 7.0. It must be noted that the noise level in the case of the outlet types “SZ” and “LH” is exactly the same as shown in the table 1 where the noise levels in decibel are listed.
Table 1: Noise level value from the three outlet solutions

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>Type E</th>
<th>Type SZ</th>
<th>Type LH</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>55.39</td>
<td>50.93</td>
<td>50.93</td>
</tr>
<tr>
<td>20</td>
<td>61.18</td>
<td>53.94</td>
<td>53.94</td>
</tr>
<tr>
<td>30</td>
<td>64.78</td>
<td>56.94</td>
<td>56.94</td>
</tr>
<tr>
<td>40</td>
<td>67.32</td>
<td>59.61</td>
<td>59.61</td>
</tr>
<tr>
<td>50</td>
<td>68.75</td>
<td>61.36</td>
<td>61.36</td>
</tr>
<tr>
<td>60</td>
<td>69.46</td>
<td>62.92</td>
<td>62.92</td>
</tr>
<tr>
<td>70</td>
<td>69.73</td>
<td>64.26</td>
<td>64.26</td>
</tr>
<tr>
<td>80</td>
<td>69.79</td>
<td>65.42</td>
<td>65.42</td>
</tr>
<tr>
<td>90</td>
<td>69.76</td>
<td>66.25</td>
<td>66.25</td>
</tr>
<tr>
<td>100</td>
<td>69.72</td>
<td>66.65</td>
<td>66.65</td>
</tr>
</tbody>
</table>

The graphical representation of the noise level values listed in the table 1 is showed in the following figure 26.

![Noise level comparison](image)

**Figure 26: Noise level comparison of the three types of outlet**

From the previous graph (figure 26) it is clear how the noise level curve, relative to the output solution “E”, is above the curve related to the types “SZ” and “LH” for the whole stroke of the valve. This means that they are also better in terms of noise produced.
2.4.3 BUTTERFLY VALVES

The butterfly valve is a quarter-turn (0° to 90°) rotary-motion valve that uses a round disk as the closure element. When in the fully open position, the disk is parallel to the piping [1]. There are several alternatives for the design of the disk.

The butterfly is a popular valve because of its light weight, compact size, satisfactory performance, and low cost. With certain disk designs, the flow capacity of a butterfly valve can approach that of a gate valve in the full open position. A variety of materials can be used for the body, disk, and seat to make it suitable for use with almost any liquid [2].

The following figure 27 presents a type of butterfly valve produced by VAG-Armaturen GmbH, the so called: CEREX 300 butterfly valve.

In this type of valve, the shaft, is attached to the disk in correspondence to the exact centerline of the disk and so it is called a “concentric disk”. With this solution, the shaft and the middle of the disk, are centered in the valve so there is always contact between the disk and the seat for the
whole stroke. In particular when the valve is closed (0° open) there is full contact between the two parts, in any other position the disk will touch the seat in two points. For this reason butterfly valves with a concentric disk design has the tendency to wear, especially in the points of contact. In some cases, when the valve moves only within small ranges, there will be an important wear in the points of contact which will allow leakage at those points when the valve is closed.

To overcome this problem of constant contact between the seating surfaces, butterfly-valve manufacturers developed the “eccentric cammed disk” design [1].

In figure 28, the eccentric disk valve produced by VAG-Armaturen GmbH named EKN butterfly valve, is presented.

![Figure 28: VAG EKN butterfly valve](image)

Such design allows for the center of the shaft and the disk to be slightly offset down and away from the center of the valve. The disk and the seat are in full contact when the valve is closed, but when the valve opens the disk lifts off the seat, avoiding any unnecessary contact.
2.4.4 CHOOSE VALVE

The last kind of valve considered in this part is the so called “choke valve”. As already said, this valve is not produced by VAG-Armaturen GmbH and so it is not present in the software UseCAD 7.0.

This type of valve is widely used in case of very high pressure systems (hundreds of bars) as is the case of gas and oil company.

The choke valves are divided with respect of the design into two principal categories:

- Cage and (external) sleeve
- Plug and cage

Cage and sleeve

The structure of a choke valve with a “cage and sleeve” is shown in the following figure 29.

![Figure 29: Sketch of the choke valve [11]](image)

The flow arrives to the valve from the pipe at the top that has an inner diameter that decreases gradually. Then the water enters in a cylindrical chamber in which it is located a fixed cylindrical cage which has a certain number of holes depending on the valve considered. The sleeve is a device that determine the flow that can pass through the holes sliding back and forth and overlapping the cage.

The following figure 30 shows the situations in which the valve is fully opened and fully closed.
In the figure 30(a) that is the case of the fully open setting, the holes are not covered at all by the sleeve, on the other hand in case of fully closed figure 30(b) the holes of the cage are completely covered by the sleeve.

The percentage of the travel that the sleeve element runs with respect of the cage gives the opening degree of the valve. Since there is a minimum travel rate at which the fluid starts flowing, the valve is actually closed until a certain valve opening (for example 19%) is reached [11].

With this design the flows enters in the cage in the forms of several jets and then it continues through the outlet pipe which has an inner diameter that slowly increases.

**Plug and cage**

In this design solution the plug is the controlling element that moves in the internal diameter of the cage. In the following figure 31 it is presented the sketch of the plug and cage trim.
From the figure above it is possible to observe that in this case the regulation of the flow depends on the position of the plug with respect to the cage. Similarly at the external trim, also the position of the internal plug determines the degree of occlusion of the holes in cage and so the flow rate that can continue in the outlet pipe.

**Choke valves typical application: wellhead**

The choke valves common utilization is as wellhead in oil and gas well where they have to contain the pressure that arrive from the drilling equipment in order to do not have problems at the production equipment.

An important problem that engineers have to face, in the wellhead choke vales, is the presence of solid particles in the fluid that is extracted from a reservoir. When the fraction of solids in the flow is low there are not substantial variation with respect of the single-phase flow case. On the other side, a consistent amount of solids particles may alter the flow control characteristics in a remarkable way, this is the case of the extraction of heavy oils from the sand [11].

The problems that can arise are: the wear due to the impact of the solid particles on the internal part of the valve, the change of regulation and dissipation characteristics of the device and the risk of occlusion due to sand accumulation.

In order to avoid the negative aspects correlated to the presence of the solid particles in the flow, in particular the erosion, in the past, sand exclusion system were installed to protect the devices.

Anyway the experiences in the extraction of heavy oils demonstrate that if the sand is allowed to pass through the system the production is improved of about the 40% with respect of the solution with the sand exclusion system installed. For this reason, the strategy that does not consider the exclusion of the sand from the flow that arrives to choke valve installed on the well, becomes more economically attractive. This demonstration took place in the oil sands and heavy oil fields of eastern Alberta and western Saskatchewan in Canada.

After this discovery, Canadian petroleum industry has successfully developed and implemented a production approach for heavy oil which involves the deliberate initiation of massive sand influx and the continued production of substantial quantities of sand. This technique that started from the already mentioned regions of Alberta and Saskatchewan, is slowly expanding worldwide [11]. It is called CHOPS (Cold Heavy Oil Production with Sand) technique and its physical mechanism is not discussed here since it is beyond the topic of this document.
The effects of the solid particles present in flow have been also evaluated by S. Malavasi, G.V. Messa and G. Ferrese [11] who focused their attention on the dissipation effect induced, in particular the solid particles determine an increase of the pressure losses through the device and their result allow to provide the following simple formula for a priori rough estimation of this parameter:

$$\Delta p = CV_{sp}^2 Q^2 \left[ (1 - C) + C \frac{\rho_p}{\rho_f} \right]$$

Where $Q$ is the flow rate, $C$ is the delivered solids concentration, $CV_{sp}$ is the flow coefficient in the single-phase case, $\rho_f$ the density of the fluid phase and $\rho_p$ the density of the solid phase.

In this work we only present this formula without demonstrate it because this goes beyond the purpose of this chapter that is only a general presentation of the choke valves.

**Cavitation in choke valves**

The common method used to detect cavitation in this valve is to graph the value of the flow rate $Q$ with respect of the square root of the pressure drop $\sqrt{\Delta P}$. The following figure 32 shows a typical trend of this graph.

![Figure 32: Flow rate versus the square root of the pressure drop](image)

As it is possible to see from the figure above, in correspondence of a certain point (A), there is no more direct proportionality between $Q$ and $\sqrt{\Delta P}$. From this point the flow affected by cavitation, and so noise and vibration are produced.
Continuing along the graph, once the point B is reached, the flow rate does not increase even if there is an increase of the pressure drop. This is the condition of choked flow.

The simultaneously presence of a dense fluid and corrosion due to cavitation, produces a important damages on the devices.
2.5 CAVITATION INDEX $\sigma$ WITH THE SOFTWARE UseCAD 7.0

The aim of this chapter is to compare the cavitation index evaluated with the software UseCAD 7.0 provided by the company VAG-Armaturen Gmbh, with the ones obtained with the formulas available in literature:

$$\sigma = \frac{P_1 - P_V}{P_1 - P_2}$$

$$K = \frac{P_1 - P_2}{P_1 - P_V} = \frac{1}{\sigma}$$

$$\sigma_2 = \frac{P_2 - P_V}{P_1 - P_2} = \sigma - 1$$

The values of the vapor pressure of the water with respect to the temperature are shown in the following table 2:

<table>
<thead>
<tr>
<th>T [°C]</th>
<th>Pv[mmHg]</th>
<th>Pv[mWC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4,579</td>
<td>0,062</td>
</tr>
<tr>
<td>10</td>
<td>9,205</td>
<td>0,125</td>
</tr>
<tr>
<td>20</td>
<td>17,51</td>
<td>0,238</td>
</tr>
<tr>
<td>30</td>
<td>31,71</td>
<td>0,431</td>
</tr>
<tr>
<td>40</td>
<td>55,13</td>
<td>0,749</td>
</tr>
<tr>
<td>50</td>
<td>92,3</td>
<td>1,255</td>
</tr>
<tr>
<td>60</td>
<td>149,2</td>
<td>2,028</td>
</tr>
<tr>
<td>70</td>
<td>233,5</td>
<td>3,174</td>
</tr>
<tr>
<td>80</td>
<td>355,1</td>
<td>4,828</td>
</tr>
<tr>
<td>90</td>
<td>525,8</td>
<td>7,148</td>
</tr>
<tr>
<td>100</td>
<td>760</td>
<td>10,332</td>
</tr>
</tbody>
</table>

Note that:

1 mWC = 73,5559 mmHg
1 mmHg = 0,0136 mWC

Table 2: Vapor pressure with respect of temperature

All the calculations present in the following cases are referred to a flow temperature equal to 20°C.

Three types of valves have been considered: EKN butterfly valve, RIKO plunger valve and CEREX 300 wafer butterfly valve.

Presented in the final part of the chapter is a comparison of the results obtained for each case.
2.5.1 CASE 1: EKN Butterfly Valve

Project scheme:

![Diagram of project scheme](image)

Figure 33: Project scheme

Input data:

Pipes:
- $H_1$: 20 mWC
- $H_2$: 10 mWC
- $DN_1$: 200 mm
- $DN_2$: 200 mm
- $\zeta_1$: 5,374
- $\zeta_2$: 5,374

Valve:
- EKN butterfly valve
- Pressure rate PN: 10
- Nominal DN: 200 mm

The table 3 reports the calculations obtained with the software UseCAD 7.0:

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>$\zeta$ Valve</th>
<th>Ke Valve</th>
<th>$\zeta$ All</th>
<th>v(m/s)</th>
<th>Q(m³/s)</th>
<th>Q(m³/h)</th>
<th>H1 (mWC)</th>
<th>H2 (mWC)</th>
<th>$\Delta P$ (mWC)</th>
<th>$\sigma$ pipe</th>
<th>$\sigma$ full Cav.</th>
<th>$\sigma$ beg. Cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>400,0</td>
<td>79,20</td>
<td>410,7</td>
<td>0,690</td>
<td>0,0217</td>
<td>78,07</td>
<td>19,87</td>
<td>10,13</td>
<td>9,74</td>
<td>2,08</td>
<td>0,800</td>
<td>1,80</td>
</tr>
<tr>
<td>20</td>
<td>125,0</td>
<td>141,7</td>
<td>135,7</td>
<td>1,20</td>
<td>0,0376</td>
<td>135,5</td>
<td>19,61</td>
<td>10,39</td>
<td>9,21</td>
<td>2,21</td>
<td>1,50</td>
<td>2,40</td>
</tr>
<tr>
<td>30</td>
<td>42,00</td>
<td>244,4</td>
<td>52,74</td>
<td>1,91</td>
<td>0,0600</td>
<td>216,1</td>
<td>19,00</td>
<td>11,00</td>
<td>8,00</td>
<td>2,58</td>
<td>1,80</td>
<td>2,75</td>
</tr>
<tr>
<td>40</td>
<td>16,00</td>
<td>396,0</td>
<td>26,74</td>
<td>2,66</td>
<td>0,0835</td>
<td>300,8</td>
<td>18,06</td>
<td>11,94</td>
<td>6,13</td>
<td>3,40</td>
<td>1,98</td>
<td>3,00</td>
</tr>
<tr>
<td>50</td>
<td>7,00</td>
<td>598,7</td>
<td>17,74</td>
<td>3,24</td>
<td>0,102</td>
<td>365,9</td>
<td>17,13</td>
<td>12,87</td>
<td>4,27</td>
<td>4,79</td>
<td>2,10</td>
<td>3,25</td>
</tr>
<tr>
<td>60</td>
<td>3,49</td>
<td>847,8</td>
<td>14,23</td>
<td>3,59</td>
<td>0,113</td>
<td>405,9</td>
<td>16,47</td>
<td>13,53</td>
<td>2,95</td>
<td>6,56</td>
<td>2,15</td>
<td>3,40</td>
</tr>
<tr>
<td>70</td>
<td>2,09</td>
<td>1094</td>
<td>12,83</td>
<td>3,77</td>
<td>0,118</td>
<td>425,9</td>
<td>16,12</td>
<td>13,88</td>
<td>2,24</td>
<td>8,11</td>
<td>2,10</td>
<td>3,60</td>
</tr>
<tr>
<td>80</td>
<td>1,26</td>
<td>1413</td>
<td>12,00</td>
<td>3,89</td>
<td>0,122</td>
<td>439,4</td>
<td>15,87</td>
<td>14,13</td>
<td>1,74</td>
<td>9,68</td>
<td>2,00</td>
<td>3,75</td>
</tr>
<tr>
<td>90</td>
<td>0,754</td>
<td>1824</td>
<td>11,49</td>
<td>3,96</td>
<td>0,124</td>
<td>448,2</td>
<td>15,70</td>
<td>14,30</td>
<td>1,40</td>
<td>11,08</td>
<td>1,90</td>
<td>3,90</td>
</tr>
<tr>
<td>100</td>
<td>0,550</td>
<td>2136</td>
<td>11,29</td>
<td>4,00</td>
<td>0,126</td>
<td>451,9</td>
<td>15,63</td>
<td>14,37</td>
<td>1,26</td>
<td>11,81</td>
<td>1,80</td>
<td>4,15</td>
</tr>
</tbody>
</table>

Table 3: Calculation using UseCAD 7.0
The software also provides a graphical output of the cavitation curve (figure 34).

Figure 34: Cavitation curve from UseCAD 7.0

Considering a temperature of the water $T = 20^\circ C$ I have evaluated the values of the “service” cavitation indices $(\sigma_2, \sigma, K)$ for the various opening degree with the formulas presented previously. The results are listed in table 4.

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>H1 (mWC)</th>
<th>H2(mWC)</th>
<th>$\sigma_2$</th>
<th>K</th>
<th>$\sigma$</th>
<th>$\sigma_{pipe}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>19,87</td>
<td>10,13</td>
<td>1,02</td>
<td>0,50</td>
<td>2,02</td>
<td>2,08</td>
</tr>
<tr>
<td>20</td>
<td>19,61</td>
<td>10,39</td>
<td>1,10</td>
<td>0,48</td>
<td>2,10</td>
<td>2,21</td>
</tr>
<tr>
<td>30</td>
<td>19,00</td>
<td>11,00</td>
<td>1,35</td>
<td>0,43</td>
<td>2,35</td>
<td>2,58</td>
</tr>
<tr>
<td>40</td>
<td>18,06</td>
<td>11,94</td>
<td>1,91</td>
<td>0,34</td>
<td>2,91</td>
<td>3,40</td>
</tr>
<tr>
<td>50</td>
<td>17,13</td>
<td>12,87</td>
<td>2,97</td>
<td>0,25</td>
<td>3,97</td>
<td>4,79</td>
</tr>
<tr>
<td>60</td>
<td>16,47</td>
<td>13,53</td>
<td>4,52</td>
<td>0,18</td>
<td>5,52</td>
<td>6,56</td>
</tr>
<tr>
<td>70</td>
<td>16,12</td>
<td>13,88</td>
<td>6,09</td>
<td>0,14</td>
<td>7,09</td>
<td>8,11</td>
</tr>
<tr>
<td>80</td>
<td>15,87</td>
<td>14,13</td>
<td>7,98</td>
<td>0,11</td>
<td>8,98</td>
<td>9,68</td>
</tr>
<tr>
<td>90</td>
<td>15,70</td>
<td>14,30</td>
<td>10,04</td>
<td>0,09</td>
<td>11,04</td>
<td>11,08</td>
</tr>
<tr>
<td>100</td>
<td>15,63</td>
<td>14,37</td>
<td>11,22</td>
<td>0,08</td>
<td>12,22</td>
<td>11,81</td>
</tr>
</tbody>
</table>

Table 4: Service cavitation indices

In the last column of table 4 there are the values of $\sigma$ that come from the UseCAD 7.0 program.
2.5.2  CASE 2: RIKO plunger valve

The project scheme is the same seen for case 1.

Input data:

Pipes: \( H_1: \) 20 mWC  
\( H_2: \) 10 mWC  
\( \text{DN}_1: \) 200 mm  
\( \text{DN}_2: \) 200 mm  
\( \zeta_1: \) 5,374  
\( \zeta_2: \) 5,374  

Valve: RIKO CONTROL VALVE  
Pressure rate PN: 10  
Nominal DN: 200 mm  

The calculations that the software UseCAD 7.0 provides for this case are listed in the following table 5.

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>( \zeta ) Valve</th>
<th>( \zeta ) Valve</th>
<th>( v(m/s) )</th>
<th>( Q(m^3/s) )</th>
<th>( Q(m^3/h) )</th>
<th>( H_1 ) (mWC)</th>
<th>( H_2 ) (mWC)</th>
<th>( \Delta P(mWC) )</th>
<th>( \sigma ) pipe</th>
<th>( \sigma ) full Cav.</th>
<th>( \sigma ) beg. Cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10253</td>
<td>29,02</td>
<td>10264</td>
<td>0,138</td>
<td>0,00434</td>
<td>15,64</td>
<td>19,99</td>
<td>10,01</td>
<td>9,99</td>
<td>2,02</td>
<td>0,250</td>
</tr>
<tr>
<td>20</td>
<td>683,1</td>
<td>60,60</td>
<td>693,9</td>
<td>0,531</td>
<td>0,0167</td>
<td>60,10</td>
<td>19,92</td>
<td>10,08</td>
<td>9,85</td>
<td>2,05</td>
<td>0,550</td>
</tr>
<tr>
<td>30</td>
<td>124,4</td>
<td>142,0</td>
<td>135,2</td>
<td>1,20</td>
<td>0,0377</td>
<td>135,7</td>
<td>19,61</td>
<td>10,39</td>
<td>9,21</td>
<td>2,21</td>
<td>0,855</td>
</tr>
<tr>
<td>40</td>
<td>33,73</td>
<td>272,7</td>
<td>44,47</td>
<td>2,08</td>
<td>0,0653</td>
<td>234,9</td>
<td>18,82</td>
<td>11,18</td>
<td>7,64</td>
<td>2,71</td>
<td>1,05</td>
</tr>
<tr>
<td>50</td>
<td>13,56</td>
<td>430,2</td>
<td>24,30</td>
<td>2,78</td>
<td>0,0875</td>
<td>314,9</td>
<td>17,88</td>
<td>12,12</td>
<td>5,75</td>
<td>3,62</td>
<td>1,25</td>
</tr>
<tr>
<td>60</td>
<td>6,92</td>
<td>602,3</td>
<td>17,66</td>
<td>3,24</td>
<td>0,102</td>
<td>366,8</td>
<td>17,12</td>
<td>12,88</td>
<td>4,24</td>
<td>4,81</td>
<td>1,35</td>
</tr>
<tr>
<td>70</td>
<td>4,16</td>
<td>776,2</td>
<td>14,90</td>
<td>3,51</td>
<td>0,110</td>
<td>397,2</td>
<td>16,62</td>
<td>13,38</td>
<td>3,25</td>
<td>6,07</td>
<td>1,43</td>
</tr>
<tr>
<td>80</td>
<td>2,85</td>
<td>937,5</td>
<td>13,59</td>
<td>3,67</td>
<td>0,115</td>
<td>414,7</td>
<td>16,32</td>
<td>13,68</td>
<td>2,64</td>
<td>7,16</td>
<td>1,46</td>
</tr>
<tr>
<td>90</td>
<td>2,19</td>
<td>1070</td>
<td>12,93</td>
<td>3,75</td>
<td>0,118</td>
<td>424,5</td>
<td>16,14</td>
<td>13,86</td>
<td>2,29</td>
<td>7,98</td>
<td>1,49</td>
</tr>
<tr>
<td>100</td>
<td>1,86</td>
<td>1161</td>
<td>12,60</td>
<td>3,80</td>
<td>0,119</td>
<td>429,5</td>
<td>16,05</td>
<td>13,95</td>
<td>2,10</td>
<td>8,48</td>
<td>1,50</td>
</tr>
</tbody>
</table>

Table 5: Calculation using UseCAD 7.0

If a RIKO plunger valve is included in the system, the cavitation curve assumes the following form (figure 35).
Considering a temperature of the water $T = 20^\circ C$ I made the same calculations explained in the case 1 and the results are listed in table 6:

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>H1 (mWC)</th>
<th>H2 (mWC)</th>
<th>$\sigma_2$</th>
<th>$K$</th>
<th>$\sigma$</th>
<th>$\sigma_{pipe}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>19,99</td>
<td>10,01</td>
<td>0,98</td>
<td>0,51</td>
<td>1,98</td>
<td>2,02</td>
</tr>
<tr>
<td>20</td>
<td>19,92</td>
<td>10,08</td>
<td>1,00</td>
<td>0,50</td>
<td>2,00</td>
<td>2,05</td>
</tr>
<tr>
<td>30</td>
<td>19,61</td>
<td>10,39</td>
<td>1,10</td>
<td>0,48</td>
<td>2,10</td>
<td>2,21</td>
</tr>
<tr>
<td>40</td>
<td>18,82</td>
<td>11,18</td>
<td>1,43</td>
<td>0,41</td>
<td>2,43</td>
<td>2,71</td>
</tr>
<tr>
<td>50</td>
<td>17,88</td>
<td>12,12</td>
<td>2,06</td>
<td>0,33</td>
<td>3,06</td>
<td>3,62</td>
</tr>
<tr>
<td>60</td>
<td>17,12</td>
<td>12,88</td>
<td>2,98</td>
<td>0,25</td>
<td>3,98</td>
<td>4,81</td>
</tr>
<tr>
<td>70</td>
<td>16,62</td>
<td>13,38</td>
<td>4,06</td>
<td>0,20</td>
<td>5,06</td>
<td>6,07</td>
</tr>
<tr>
<td>80</td>
<td>16,32</td>
<td>13,68</td>
<td>5,09</td>
<td>0,16</td>
<td>6,09</td>
<td>7,16</td>
</tr>
<tr>
<td>90</td>
<td>16,14</td>
<td>13,86</td>
<td>5,97</td>
<td>0,14</td>
<td>6,97</td>
<td>7,98</td>
</tr>
<tr>
<td>100</td>
<td>16,05</td>
<td>13,95</td>
<td>6,53</td>
<td>0,13</td>
<td>7,53</td>
<td>8,48</td>
</tr>
</tbody>
</table>

*Table 6: Service cavitation indices*
2.5.3 CASE 3: CEREX 300 Wafer Butterfly Valve

The project scheme is the same.

Input data:

Pipes: 

<table>
<thead>
<tr>
<th>H₁</th>
<th>20 mWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>10 mWC</td>
</tr>
</tbody>
</table>

Valve: 

<table>
<thead>
<tr>
<th>CEREX 300 Wafer Butterfly Valve</th>
</tr>
</thead>
</table>

DN₁: 200 mm 

ζ₁: 5,374

DN₂: 200 mm 

ζ₂: 5,374

The calculation that the software UseCAD 7.0 provides in this case are listed in the following table 7.

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>ζ Valve</th>
<th>Kv Valve</th>
<th>ζ All</th>
<th>v(m/s)</th>
<th>Q(m3/s)</th>
<th>Q(m3/h)</th>
<th>H₁ (mWC)</th>
<th>H₂ (mWC)</th>
<th>ΔP(mWC)</th>
<th>σ pipe</th>
<th>σ full Cav.</th>
<th>σ beg. Cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>200,0</td>
<td>112,0</td>
<td>210,7</td>
<td>0,963</td>
<td>0,0302</td>
<td>108,9</td>
<td>19,75</td>
<td>10,25</td>
<td>9,49</td>
<td>2,14</td>
<td>0,800</td>
<td>1,80</td>
</tr>
<tr>
<td>20</td>
<td>65,31</td>
<td>196,0</td>
<td>76,05</td>
<td>1,60</td>
<td>0,0501</td>
<td>180,5</td>
<td>19,30</td>
<td>10,70</td>
<td>8,61</td>
<td>2,38</td>
<td>1,50</td>
<td>2,40</td>
</tr>
<tr>
<td>30</td>
<td>26,45</td>
<td>308,0</td>
<td>37,19</td>
<td>2,27</td>
<td>0,0712</td>
<td>256,4</td>
<td>18,59</td>
<td>11,41</td>
<td>7,19</td>
<td>2,89</td>
<td>1,80</td>
<td>2,75</td>
</tr>
<tr>
<td>40</td>
<td>11,07</td>
<td>476,0</td>
<td>21,81</td>
<td>2,93</td>
<td>0,0921</td>
<td>331,7</td>
<td>17,65</td>
<td>12,35</td>
<td>5,29</td>
<td>3,92</td>
<td>1,98</td>
<td>3,00</td>
</tr>
<tr>
<td>50</td>
<td>5,12</td>
<td>700,0</td>
<td>15,86</td>
<td>3,41</td>
<td>0,107</td>
<td>385,8</td>
<td>16,81</td>
<td>13,19</td>
<td>3,63</td>
<td>5,52</td>
<td>2,10</td>
<td>3,25</td>
</tr>
<tr>
<td>60</td>
<td>2,61</td>
<td>980,0</td>
<td>13,35</td>
<td>3,70</td>
<td>0,116</td>
<td>418,2</td>
<td>16,26</td>
<td>13,74</td>
<td>2,52</td>
<td>7,43</td>
<td>2,15</td>
<td>3,40</td>
</tr>
<tr>
<td>70</td>
<td>1,42</td>
<td>1330</td>
<td>12,16</td>
<td>3,86</td>
<td>0,121</td>
<td>436,7</td>
<td>15,92</td>
<td>14,08</td>
<td>1,84</td>
<td>9,32</td>
<td>2,10</td>
<td>3,60</td>
</tr>
<tr>
<td>80</td>
<td>0,806</td>
<td>1764</td>
<td>11,55</td>
<td>3,95</td>
<td>0,124</td>
<td>447,2</td>
<td>15,72</td>
<td>14,28</td>
<td>1,44</td>
<td>10,91</td>
<td>2,00</td>
<td>3,75</td>
</tr>
<tr>
<td>90</td>
<td>0,488</td>
<td>2268</td>
<td>11,23</td>
<td>4,01</td>
<td>0,126</td>
<td>453,0</td>
<td>15,61</td>
<td>14,39</td>
<td>1,22</td>
<td>12,05</td>
<td>1,90</td>
<td>3,90</td>
</tr>
<tr>
<td>100</td>
<td>0,320</td>
<td>2800</td>
<td>11,06</td>
<td>4,03</td>
<td>0,127</td>
<td>456,2</td>
<td>15,55</td>
<td>14,45</td>
<td>1,09</td>
<td>12,78</td>
<td>1,80</td>
<td>4,15</td>
</tr>
</tbody>
</table>

Table 7: Calculation using UseCAD 7.0

If a CEREX 300 wafer butterfly valve is included in the system, the cavitation curve assumes the following form (figure 36).
Considering a temperature of the water $T = 20^\circ C$ I made the same calculations explained in case 1 and the results are reassumed in the following table 8:

![Cavitation curve from UseCAD 7.0](image)

**Figure 36: Cavitation curve from UseCAD 7.0**

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>H1 (mWC)</th>
<th>H2(mWC)</th>
<th>$\sigma_2$</th>
<th>K</th>
<th>$\sigma$</th>
<th>$\sigma$ pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>19,75</td>
<td>10,25</td>
<td>1,05</td>
<td>0,49</td>
<td>2,05</td>
<td>2,14</td>
</tr>
<tr>
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<td>19,30</td>
<td>10,70</td>
<td>1,22</td>
<td>0,45</td>
<td>2,22</td>
<td>2,38</td>
</tr>
<tr>
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<td>11,41</td>
<td>1,56</td>
<td>0,39</td>
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<td>2,89</td>
</tr>
<tr>
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<td>12,35</td>
<td>2,29</td>
<td>0,30</td>
<td>3,29</td>
<td>3,92</td>
</tr>
<tr>
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<td>16,81</td>
<td>13,19</td>
<td>3,58</td>
<td>0,22</td>
<td>4,58</td>
<td>5,52</td>
</tr>
<tr>
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<td>16,26</td>
<td>13,74</td>
<td>5,36</td>
<td>0,16</td>
<td>6,36</td>
<td>7,43</td>
</tr>
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<td>15,92</td>
<td>14,08</td>
<td>7,52</td>
<td>0,12</td>
<td>8,52</td>
<td>9,32</td>
</tr>
<tr>
<td>80</td>
<td>15,72</td>
<td>14,28</td>
<td>9,75</td>
<td>0,09</td>
<td>10,75</td>
<td>10,91</td>
</tr>
<tr>
<td>90</td>
<td>15,61</td>
<td>14,39</td>
<td>11,60</td>
<td>0,08</td>
<td>12,60</td>
<td>12,05</td>
</tr>
<tr>
<td>100</td>
<td>15,55</td>
<td>14,45</td>
<td>12,92</td>
<td>0,07</td>
<td>13,92</td>
<td>12,78</td>
</tr>
</tbody>
</table>

**Table 8: Service cavitation indices**
2.5.4 COMPARISON OF THE RESULTS

Table 9 reports the following values of the cavitation index $\sigma$ obtained for the three types of valve considered with the UseCAD 7.0 program and with the equation from the literature:

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>UseCAD 7.0</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EKN</td>
<td>RIKO</td>
</tr>
<tr>
<td>10</td>
<td>2.08</td>
<td>2.02</td>
</tr>
<tr>
<td>20</td>
<td>2.21</td>
<td>2.05</td>
</tr>
<tr>
<td>30</td>
<td>2.58</td>
<td>2.21</td>
</tr>
<tr>
<td>40</td>
<td>3.4</td>
<td>2.71</td>
</tr>
<tr>
<td>50</td>
<td>4.79</td>
<td>3.62</td>
</tr>
<tr>
<td>60</td>
<td>6.56</td>
<td>4.81</td>
</tr>
<tr>
<td>70</td>
<td>8.11</td>
<td>6.07</td>
</tr>
<tr>
<td>80</td>
<td>9.68</td>
<td>7.16</td>
</tr>
<tr>
<td>90</td>
<td>11.08</td>
<td>7.98</td>
</tr>
<tr>
<td>100</td>
<td>11.81</td>
<td>8.48</td>
</tr>
</tbody>
</table>

Table 9: Comparison of $\sigma$ from the software UseCAD 7.0 and calculated for the different types of valve considered at different opening angle.

To better clarify the situation the following figure 37 presents the graphical comparison of the cavitation index provided by the software UseCAD 7.0 for the three different valves considered with respect of the opening angle.

![Figure 37: Comparison of the cavitation index provided by UseCAD 7.0 for the type of valves considered](image-url)
In figure 38, the comparison is between the calculate cavitation index $\sigma$ for the three valves considered with respect to the opening angle.

![Diagram showing calculated cavitation index $\sigma$ vs opening degree for different valve types]

**Figure 38: Comparison of the cavitation index calculated for the type of valves considered**

The following figures, from 39 to 41 show the comparison of the cavitation index provided by UseCAD 7.0 and calculated for each type of valve considered, with respect to the opening degree.
Figure 39: Comparison between the cavitation index provided by UseCAD 7.0 and calculated for an EKN butterfly valve

Figure 40: Comparison between the cavitation index provided by UseCAD 7.0 and calculated for a RIKO plunger valve
Figure 41: Comparison between the cavitation index provided by UseCAD 7.0 and calculated for a CEREX 300 wafer butterfly valve.
2.6 VALVE SCALE EFFECTS

Cavitation data for the valve are obtained experimentally and usually with a reduced size model operated at reduced pressure.

The cavitation behavior and cavitation coefficients are not independent or constant with either different pressure or valve size. The change in the value of a cavitation coefficient associated with change in pressure is known as the “pressure scale effect” \((PSE)\). Likewise, the change in the value of a cavitation coefficient associated with valve size is known as the “side scale effect” \((SSE)\) [4].

Calling the reference coefficient obtained with the model \(\sigma_R\), we can obtain \(\sigma_V\) with the following relationship:

\[
\sigma_V = (\sigma_R \times SSE - 1) \times PSE + 1
\]

The coefficient \(\sigma_V\) is the cavitation parameter for the particular valve considered in the system. The value of \(\sigma_R\) usually is chosen from the cavitation limits that are discussed in the next chapter. After \(\sigma_V\) has been calculated, it is compared to the value of the index \(\sigma\) obtained with the formula showed above. To be more clear this index can be called “\(\sigma\) service”.

If the value of the service coefficient \((\sigma)\) is greater than \(\sigma_V\), the valve will operate at a level of cavitation that is lower with respect to the one chosen as reference.

**Pressure scale effects \((PSE)\):**

The intensity and level of cavitation increase with increasing the value of \((P_1 - P_V)\). The pressure scale effect or scaling correction \(PSE\) can be calculated from the following equation:

\[
PSE = \left[ \frac{(P_1 - P_V)}{(P_1 - P_V)_R} \right]^\alpha
\]

Or in alternative:

\[
PSE = \left[ \frac{(P_2 - P_V)}{(P_2 - P_V)_R} \right]^\alpha
\]

The subscript \(R\) at denominator refers to reference test pressures.
The exponent $a$ of the equation is obtained by measuring the slope of the log-log plot of $\sigma_n$, the subscript $n$ is for the cavitation limit selected (for example for critical cavitation, $n = c$); versus $P_1 - P_V$ or $P_2 - P_V$.

In figure 42, the graph presented, shows the variation of $\sigma_c$ with pressure, for a 12-in. (305 mm) butterfly valve tested at several openings.

Figure 42: Pressure scale effect for a butterfly valve [2]

The lines are practically parallel and with a slope, that corresponds to the value of the exponent $a$, equal to 0.24. This means that in applications, for this type of valve, considering the critical cavitation as limit, in the formula of $PSE$ we have to introduce $a = 0.24$.

Several similar experiments have been made and the table 10 shows a list of typical values of the coefficient $a$ for different valve types and for different levels of cavitation.
Table 10: Pressure scale effect exponent [4]

Where the value is 0 it means that there is no pressure scale effect. It is easy to observe that for choking there is no scale effects of any type of valve considered.

**Size scale effects (SSE):**

Intensity and level of cavitation also increase with valve size. The size scale effect correction $SSE$ can be calculated with the equation:

$$SSE = \left(\frac{d}{d_R}\right)^b$$

Where $d$ is the valve diameter, $d_R$ is the reference valve diameter and the exponent $b$ is evaluated by:

$$b = 0,068 \left(\frac{C_V}{d^2}\right)^{1/4}$$

$C_V$ is the valve flow coefficient.
The exponent $b$ was derived from limited testing for scale effect for the cavitation levels of incipient, constant and incipient damage. Note that there is no size effect for cavitation level of choking. Therefore, the coefficient $b$ has a value of zero for the level of choking cavitation. [4]

It also must be noted that the equation for scaling cavitation coefficients is rigorously valid only when the valves are geometrically similar. Most valves usually are not geometrically similar for different sizes. However, limited testing has suggested that these equations may be used whenever two valves are of the same style, flow is in the same direction, and:

$$\frac{C_V}{d^2} = \frac{C_{VR}}{d_R^2}$$

As usual the subscript $R$ is for reference values. [4]

**Installation of valves in larger sized pipeline:**

There is an important effect on cavitation when a valve is installed in larger sized pipeline; the variation in cavitation level is due to the upstream pipe reducer and the downstream pipe expansion. For this reason after evaluating the cavitation coefficient for the valve $\sigma_V$, this must be introduced in the following equation:

$$\sigma_P = F_P^2 \left[ \sigma_V + (K_1 + K_{B1}) \frac{C_V^2}{d^4} \right]$$

Where $\sigma_P$ is the cavitation coefficient that take into account that the valve is introduced in a larger pipeline. The other quantities are:

$$F_P = \left[ 1 + (K_{B1} - K_{B2} + K_1 + K_2) \frac{C_V^2}{d^4} \right]^{-1/2}$$

$$K_{B1} = 1 - \frac{d^4}{D_1^4}$$

$$K_{B2} = 1 - \frac{d^4}{D_2^4}$$

$$K_1 = 0.5 \left( 1 - \frac{d^2}{D_1^2} \right)^2$$
\[ K_2 = 1.0 \left( 1 - \frac{d^2}{D_2^2} \right)^2 \]

They represent respectively: \( F_P \), the piping geometry factor that modifies the valve sizing for reducers or other devices attached to the valve body; \( K_{B1} \), the Bernoulli coefficient for upstream pipe reducer; \( K_{B2} \), the Bernoulli coefficient for downstream pipe expansion; \( K_1 \), the head loss coefficient for upstream pipe reducer; \( K_2 \), the head loss coefficient for downstream pipe increaser. Finally, \( D_1 \), is the internal diameter of the upstream pipe and \( D_2 \) is the internal diameter of downstream pipe.

The coefficient \( \sigma_P \) has to be compared with the \( \sigma \) “service” evaluated for the system and if \( \sigma \) is higher than \( \sigma_P \) means that the valve will operate at a level of cavitation lower than the one established as the limit.

Practically in the case of a valve installed in a larger sized pipeline the coefficient that has to be compared with the service coefficient (\( \sigma \)) is \( \sigma_P \) and no more \( \sigma_V \).
2.7 TESTING

The aim of this chapter is to present the practical methodology for testing the valve performance characteristics in a cavitating fluid service. In the figure 43 is shown the scheme of the flow test system used.

![Flow test system diagram]

Figure 43: Flow test system

It includes:

- Test specimen:
  valve for which test data are required.

- Test section:
  the test specimen upstream and downstream shall conform to the nominal size of the test specimen connection and to the following length requirements: the upstream pressure tap shall be 2 nominal pipe diameters from the test specimen connection, while the downstream pressure tap shall be 6 nominal pipe diameters from the test specimen connection. In addition there shall be at least 18 nominal pipe diameters of straight pipe upstream of the upstream pressure tap, and at least one pipe diameter of straight pipe downstream of the downstream pressure tap [4].
- **Throttling valves:**
  Throttling valves are introduced in the system in order to control the pressure differential across the test section pressure taps. The downstream throttling valve should be of sufficient capacity to ensure that the desired cavitation level (incipient, critical, etc.) can be achieved. Moreover it is important that noise or cavitation from these valves does not influence the test specimen result.

- **Accelerometer:**
  An accelerometer is rigidly mounted on the pipe wall downstream of the test specimen. The main sensitivity axis of the accelerometer shall be perpendicular to the pipe axis. The exact location of the downstream pipe should be determined by test (to obtain maximum vibration sensing); however, one nominal pipe diameter downstream of the test specimen connection is a good starting point [4]. The accelerometer is connected to the cavitation detection system that is schematized in the figure 4.4.

![Figure 4.4: Cavitation detection system](image)

The acceleration measurements shall be made with an error not exceeding ±5% (not so accurate). A vibration preamplifier should be used as recommended by the accelerometer manufacturer. For 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 [4].

In the system scheme shown in figure 43 several measurement devices are present. As regards for pressure and flow rate, measurements shall be to an error not exceeding ±2% and in the case of temperature the error shall not exceeding ±2°C (1°C C).

Measurement should be taken at travel positions of 20%, 40%, 60%, 80% and 100% rated travel, as minimum. For some valves, additional travel position, may be needed.

At each test point, cavitation index is calculated:

\[ \sigma = \frac{P_1 - P_V}{\Delta P} \]

A log/log plot of acceleration versus the cavitation index (\( \sigma \)) has to be made for each test made at a particular travel. From these plots the cavitation levels can be obtained where there are intersections of the straight line segments, as shown in the figure 2.

Note that some valves will not exhibit all inflection points in the test data which are always subjected to expert interpretation [4].
2.8 CONTROLLING CAVITATION

TYPE OF VALVE

The type of valve to introduce in a system is usually chosen considering not only the system requirements, but also the economical aspect, in particular, sometimes the cheapest one is chosen.

Care must be taken also on cavitation: by selecting a proper valve is possible to avoid cavitation in certain cases. For example if a butterfly valve is subjected to cavitation for the application considered, it could be that considering a globe valve for the same situation does not produce cavitation problems. In the following figure 45 is showed on the same graph the cavitation limits for three different type of valve:

- RIKO plunger valve;
- DURA globe valve;
- Butterfly valve: EKN, CEREX 300.

For these three types of valve produced by VAG-Armaturen GmbH, the software UseCAD 7.0 provides the values of cavitation limits with respect of the valve opening degree.
Note that, for each kind of valve, the dashed line is referred to beginning cavitation, while the continuous line is referred to full cavitation. In the case of the two different type of butterfly valves: EKN and CEREX 300, the limits assume the same values.

Looking at the figure 45, it is clear how for butterfly valves cavitation is more probable since the values of cavitation limits are higher with respect of the other two cases.

In order to better clarify the aspect about the choice of the type of valves the following example is proposed.

In figure 46 the scheme of the system is represented:

![System scheme](image)

**Figure 46: System scheme**

Input data:

<table>
<thead>
<tr>
<th>$H_1$</th>
<th>20 mWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$DN_1$</td>
<td>150 mm</td>
</tr>
<tr>
<td>$\zeta_1$</td>
<td>0,7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$H_2$</th>
<th>8 mWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$DN_2$</td>
<td>150 mm</td>
</tr>
<tr>
<td>$\zeta_2$</td>
<td>0,7</td>
</tr>
</tbody>
</table>

By using the software UseCAD 7.0, the cavitation values have been calculated for the different type of valves.

**RIKO plunger valve:**

First of all is considered a plunger valve with a nominal diameter $DN = 150 \text{ mm}$ and a pressure rate $PN = 10$.

The table 11 shows the output values obtained with UseCAD 7.0.
Table 11: Output values for a RIKO plunger valve

The cavitation parameter referred to the system (σ pipe) and to the valve (σ full cav. and σ beg. cav) are included in the following graph (figure 47).

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>Open (degrees)</th>
<th>H1 (mWC)</th>
<th>H2 (mWC)</th>
<th>ΔH (mWC)</th>
<th>σ pipe</th>
<th>σ full cav.</th>
<th>σ beg. cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9</td>
<td>20,00</td>
<td>8,00</td>
<td>12,00</td>
<td>1,51</td>
<td>0,25</td>
<td>0,33</td>
</tr>
<tr>
<td>20</td>
<td>18</td>
<td>19,99</td>
<td>8,01</td>
<td>11,97</td>
<td>1,51</td>
<td>0,55</td>
<td>0,73</td>
</tr>
<tr>
<td>30</td>
<td>27</td>
<td>19,93</td>
<td>8,07</td>
<td>11,86</td>
<td>1,52</td>
<td>0,86</td>
<td>1,14</td>
</tr>
<tr>
<td>40</td>
<td>36</td>
<td>19,75</td>
<td>8,25</td>
<td>11,50</td>
<td>1,55</td>
<td>1,05</td>
<td>1,40</td>
</tr>
<tr>
<td>50</td>
<td>45</td>
<td>19,44</td>
<td>8,56</td>
<td>10,88</td>
<td>1,60</td>
<td>1,25</td>
<td>1,66</td>
</tr>
<tr>
<td>60</td>
<td>54</td>
<td>19,05</td>
<td>8,95</td>
<td>10,09</td>
<td>1,67</td>
<td>1,35</td>
<td>1,80</td>
</tr>
<tr>
<td>70</td>
<td>63</td>
<td>18,66</td>
<td>9,34</td>
<td>9,32</td>
<td>1,73</td>
<td>1,43</td>
<td>1,90</td>
</tr>
<tr>
<td>80</td>
<td>72</td>
<td>18,34</td>
<td>9,66</td>
<td>8,67</td>
<td>1,79</td>
<td>1,46</td>
<td>1,96</td>
</tr>
<tr>
<td>90</td>
<td>81</td>
<td>18,10</td>
<td>9,90</td>
<td>8,21</td>
<td>1,83</td>
<td>1,49</td>
<td>1,99</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
<td>17,96</td>
<td>10,04</td>
<td>7,93</td>
<td>1,86</td>
<td>1,50</td>
<td>2,00</td>
</tr>
</tbody>
</table>

Figure 47: Cavitation values for a RIKO plunger valve

The graph shows that using a RIKO plunger valve in this system a state of beginning cavitation will start when the valve is open a little bit more than 40 degrees.

DURA globe valve:

The same passages have been made considering a DURA globe valve in the system with a nominal diameter $DN = 150 \, mm$ and a pressure rate $PN = 10$ (anti cavitating cylinder: 100).

The table 12 contains the values obtained using the software UseCAD 7.0.
Table 12: Output values for a DURA globe valve

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>Open (degrees)</th>
<th>H1 (mWC)</th>
<th>H2 (mWC)</th>
<th>ΔH (mWC)</th>
<th>σ pipe</th>
<th>σ full cav.</th>
<th>σ beg. cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9</td>
<td>19.99</td>
<td>8.01</td>
<td>11.98</td>
<td>1.51</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>20</td>
<td>18</td>
<td>19.96</td>
<td>8.04</td>
<td>11.91</td>
<td>1.52</td>
<td>0.27</td>
<td>0.34</td>
</tr>
<tr>
<td>30</td>
<td>27</td>
<td>19.90</td>
<td>8.10</td>
<td>11.81</td>
<td>1.58</td>
<td>0.41</td>
<td>0.54</td>
</tr>
<tr>
<td>40</td>
<td>36</td>
<td>19.83</td>
<td>8.17</td>
<td>11.67</td>
<td>1.54</td>
<td>0.55</td>
<td>0.69</td>
</tr>
<tr>
<td>50</td>
<td>45</td>
<td>19.75</td>
<td>8.25</td>
<td>11.49</td>
<td>1.52</td>
<td>0.69</td>
<td>0.88</td>
</tr>
<tr>
<td>60</td>
<td>54</td>
<td>19.65</td>
<td>8.35</td>
<td>11.29</td>
<td>1.57</td>
<td>0.78</td>
<td>1.02</td>
</tr>
<tr>
<td>70</td>
<td>63</td>
<td>19.54</td>
<td>8.46</td>
<td>11.07</td>
<td>1.58</td>
<td>0.95</td>
<td>1.19</td>
</tr>
<tr>
<td>80</td>
<td>72</td>
<td>19.42</td>
<td>8.58</td>
<td>10.83</td>
<td>1.60</td>
<td>1.05</td>
<td>1.31</td>
</tr>
<tr>
<td>90</td>
<td>81</td>
<td>19.29</td>
<td>8.71</td>
<td>10.58</td>
<td>1.62</td>
<td>1.15</td>
<td>1.44</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
<td>19.17</td>
<td>8.83</td>
<td>10.33</td>
<td>1.65</td>
<td>1.20</td>
<td>1.50</td>
</tr>
</tbody>
</table>

The graph in figure 48 is obtained with the cavitation parameters (σ pipe, σ full cav., σ beg. cav.) provided by the program and listed in the table 12.

The figure 48 shows that there are no cavitation problems if a DURA globe valve is introduced in the system.

**EKN butterfly valve:**

Now is considered the situation in which the valve chosen for the system is a EKN butterfly valve with a nominal diameter $DN = 150 \, mm$ and a pressure rate $PN = 10$. 
The output values provided by the software UseCAD 7.0 are included in the table 13.

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>Open (degrees)</th>
<th>H1 (mWC)</th>
<th>H2 (mWC)</th>
<th>ΔH (mWC)</th>
<th>σ pipe</th>
<th>σ full cav.</th>
<th>σ beg. cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9</td>
<td>19,98</td>
<td>8,02</td>
<td>11,96</td>
<td>1,51</td>
<td>0,80</td>
<td>1,80</td>
</tr>
<tr>
<td>20</td>
<td>18</td>
<td>19,93</td>
<td>8,07</td>
<td>11,87</td>
<td>1,52</td>
<td>1,50</td>
<td>2,40</td>
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<tr>
<td>30</td>
<td>27</td>
<td>19,81</td>
<td>8,19</td>
<td>11,62</td>
<td>1,54</td>
<td>1,80</td>
<td>2,75</td>
</tr>
<tr>
<td>40</td>
<td>36</td>
<td>19,54</td>
<td>8,46</td>
<td>11,09</td>
<td>1,58</td>
<td>1,98</td>
<td>3,00</td>
</tr>
<tr>
<td>50</td>
<td>45</td>
<td>19,11</td>
<td>8,89</td>
<td>10,21</td>
<td>1,66</td>
<td>2,10</td>
<td>3,25</td>
</tr>
<tr>
<td>60</td>
<td>54</td>
<td>18,58</td>
<td>9,42</td>
<td>9,16</td>
<td>1,75</td>
<td>2,15</td>
<td>3,40</td>
</tr>
<tr>
<td>70</td>
<td>63</td>
<td>18,16</td>
<td>9,84</td>
<td>8,31</td>
<td>1,82</td>
<td>2,10</td>
<td>3,60</td>
</tr>
<tr>
<td>80</td>
<td>72</td>
<td>17,74</td>
<td>10,26</td>
<td>7,48</td>
<td>1,90</td>
<td>2,00</td>
<td>3,75</td>
</tr>
<tr>
<td>90</td>
<td>81</td>
<td>17,38</td>
<td>10,62</td>
<td>6,76</td>
<td>1,98</td>
<td>1,90</td>
<td>3,90</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
<td>17,20</td>
<td>10,80</td>
<td>6,40</td>
<td>2,01</td>
<td>1,80</td>
<td>4,15</td>
</tr>
</tbody>
</table>

Table 13: Output values for an EKN butterfly valve

In this case there is a σ pipe that is lower than σ full cav. from 27 to 72 opening degrees of the valve (this interval is highlighted in yellow in the table 13). This means that in the interval from 27 to 72 opening degrees there is the negative situation of high cavitation.

The figure 49 reports the graph with the cavitation parameters listed in table above.

![Figure 49: Cavitation parameters for an EKN butterfly valve](image)

The figure 49 shows the interval in which there is heavy cavitation that corresponds to the part where the black line (σ pipe) is below the continuous blue line (σ full cav.).
This example demonstrates how the choice of the type strongly affects the possibility to have cavitation, in particular, for this case, is a big mistake to introduce in the system an EKN butterfly valve since the consequences of cavitation will be very important. On the other hand DURA globe valve is a good choice.

**CEREX 300 butterfly valve:**

Finally it is considered the situation in which the valve chosen for the system is a CEREX 300 butterfly valve with a nominal diameter $D_N = 150 \ mm$ and a pressure rate $P_N = 16$.

The output values provided by the software UseCAD 7.0 are included in the table 14.

<table>
<thead>
<tr>
<th>Open(%)</th>
<th>Open (degrees)</th>
<th>$H_1$ (mWC)</th>
<th>$H_2$ (mWC)</th>
<th>$\Delta H$ (mWC)</th>
<th>$\sigma_{pipe}$</th>
<th>$\sigma_{full \ cav.}$</th>
<th>$\sigma_{beg. \ cav.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9</td>
<td>19,87</td>
<td>8,13</td>
<td>11,74</td>
<td>1,55</td>
<td>0,80</td>
<td>1,80</td>
</tr>
<tr>
<td>20</td>
<td>18</td>
<td>19,62</td>
<td>8,38</td>
<td>11,25</td>
<td>1,62</td>
<td>1,50</td>
<td>2,40</td>
</tr>
<tr>
<td>30</td>
<td>27</td>
<td>19,17</td>
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<td>10,33</td>
<td>1,77</td>
<td>1,80</td>
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</tr>
<tr>
<td>40</td>
<td>36</td>
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<td>8,78</td>
<td>2,08</td>
<td>1,98</td>
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</tr>
<tr>
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<td>10,52</td>
<td>6,96</td>
<td>2,55</td>
<td>2,10</td>
<td>3,25</td>
</tr>
<tr>
<td>60</td>
<td>54</td>
<td>16,70</td>
<td>11,30</td>
<td>5,39</td>
<td>3,11</td>
<td>2,15</td>
<td>3,40</td>
</tr>
<tr>
<td>70</td>
<td>63</td>
<td>16,12</td>
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<td>3,67</td>
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<tr>
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<td>15,74</td>
<td>12,26</td>
<td>3,48</td>
<td>4,14</td>
<td>2,00</td>
<td>3,75</td>
</tr>
<tr>
<td>90</td>
<td>81</td>
<td>15,51</td>
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<td>3,02</td>
<td>4,48</td>
<td>1,90</td>
<td>3,90</td>
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<tr>
<td>100</td>
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<td>15,38</td>
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<td>2,76</td>
<td>4,70</td>
<td>1,80</td>
<td>4,15</td>
</tr>
</tbody>
</table>

*Table 14: Output values for an CEREX 300 butterfly valve*

As is possible to see from the table above, the value of $\sigma_{pipe}$ is lower than $\sigma_{full \ cav.}$ when the opening degree of the valve opening corresponds to 27 degrees.

The figure 50 shows the graph with the cavitation parameters listed in table 14.
VALVES IN SERIES

It is possible to suppress cavitation by placing valves in series in order to reduce the pressure drop across each valve. In this way there is no more the large pressure drop that is present in the case of the single valve, and so vapor pressure will not be reached. The following figure 51 shows the difference in the trend of the pressure in the two cases.

Figure 51: Pressure trends with a single valve and with valves in series
\( P_1 \) and \( P_2 \) are respectively the upstream and the downstream pressure, \( P_V \) is the vapor pressure and \( P_{VC} \) is the pressure at the vena contracta for the case of a single valve.

The figure 51 shows a case in which by substituting the single valve with a series of valves, the pressure doesn’t go below the vapor pressure, and so cavitation is avoided.

Proper spacing of valves placed in series is important. The spacing between valves depends on the type of the valve. For butterfly valves, 5-8 pipe diameters are required between valves to prevent flutter of the leaf of the downstream valve and obtain the normal pressure drop across each valve.

For globe, cone, and other types of valves, it is possible to bolt them flange to flange and have satisfactory operation based on head loss [2].

The disadvantage of this solution is the cost in terms of additional valves, but it could be less expensive than to produce a single specially engineered valve.

A problem that can occur regards the first valve that for a very short time take the entire pressure drop until the flow reaches the following valve. This could cause cavitation damage at the first valve and so, for these particular cases, other preventive solution for avoid cavitation, for example installing an anti-cavitation trim (presented in the following chapters) in the first valve, must be considered.

**CAVITATION RESISTANT MATERIALS**

Cavitation easily attacks softer materials, which have a lower tensile strength than harder materials [1]. A common method to avoid the cavitation damages is to build the valve with hard or hardened materials, or to cover parts of the valve and downstream piping with this type of material.

The methods used to measure the resistance of the materials to the erosion due to cavitation are presented in the chapter 1.6: Laboratory testing method of cavitation erosion.

The advantage of this method is that a single valve made with hard materials, entirely or in some parts, can control the flow.

The disadvantage is the cost, since the materials involved are more expensive.

**AERATION**

Injection of air into the system to suppress cavitation is another way to face the problem. At first this may appear to worsen a bad solution as the addition of air will provide additional nuclei that can play host to vapor bubbles and increase the damage. However, cavitation studies have shown
that at a certain point, additional air content to the process stream disrupts the explosive force of the imploding bubbles and can reduce the overall damage [1].

In the case of valve it is difficult to individuate all the zones in which cavitation occurs and supply air to these areas.

One of the most common mistakes when attempting to reduce cavitation by injection air is placing the air inlet port in the wrong location so the air does not get to the cavitation zone [2]. For example, in a butterfly valve, if the air is introduced in correspondence of the high-velocity jets springing, it is washed downstream. This happens because the air injected is not able to penetrate through the jets and reach the separation zone in the shadow of the disk.

By using this method, cavitation damages may be not entirely eliminate.

**DOWNSTREAM BACK-PRESSURE DEVICE**

The downstream back-pressure device is an element used to lower the pressure drop across the valve increasing the resistance of the downstream and the downstream pressure. It is installed between the valve and the and the downstream pipe.

Because back-pressure devices may limit the flow capacity of the valve, a larger valve or different trim reduction may be required. The device must be examined periodically to ensure that is not wearing out through erosion or minimal cavitation. A worn back-pressure device will ultimately decrease the downstream pressure, increase the pressure drop, and create cavitation. [1]

The function of these devices is not only to increase the downstream pressure, but in special cases they allow cavitation to occur in the small tubes where cavitation intensity is lower and can be adsorbed by the tubes themselves. In this way, the control of the existing cavitation, is done.

In figure 52 a downstream back-pressure devices used with globe valves is shown.

![Figure 52: Downstream back-pressure device used with globe valves [1]](image-url)
CAVITATION-ELIMINATION DEVICES

Even if these solutions are usually expensive, in some applications anti-cavitation design features are the only choice. Globe-style valves can be designed with special retainers or cages, which use either (or a combination of) a tortuous path, pressure-drop staging, and/or expanded flow areas to decrease the pressure drop through the valve and prevent cavitation [1]. The following figure 53 shows the position of the cage in the globe valves.

![Figure 53: Valve cage](image)

In figure 53, the valve cage is the red part.

The “tortuous path device” consist in a series of channel through which the flow passes. This causes a series of losses energy and so there is no more a large pressure drop that can make the water to reach the vapor pressure.

A typical tortuous path trim is showed in the figure 54:
Another method used in order to reduce the pressure drop across the valve is the so called “stage pressure reduction”. In this case the cage is designed with several restrictions in which the flow passes through. During his course, the flow has a small pressure drop as it reaches a restriction and so the result is a series of small pressure drops instead of a single larger pressure drop.

Related to “staged pressure drop” concept is the “expanded flow area” concept, in which the flow continues through several restrictions in the trim, the flow area is increased at each stage [1].

The figure 55 presents a section of the cage that is designed to exploit the expanded flow area concept.
These concepts (tortuous path, pressure-drop staging, and expanded flow areas) are also used in combination in the multiple pressure reduction mechanism showed in the figure 56.

![Figure 56: Anti cavitation trim with multiple pressure reduction mechanism [1]](image)

The flow passes through a series of cylinders at each passage determining a staged pressure reduction that allow the pressure to remain above the vapor pressure. As is possible to see in the figure 56, the cylindrical channels become progressively deeper at each stage providing expanded flow areas.
3 NUMERICAL METHOD TO PROVIDE CAVITATION INDEX FOR CONTROL VALVE

Cavitation tests on valve are expensive and present several difficulties especially in the case of large sized valve. Moreover, since valve’s geometry changes with the dimension, scaled models are difficult to use, even considering the pressures scale effect (PSE) and the side scale effect (SSE) presented in the chapter 2.6: valve scale effects. Using these two parameters to scale, the cavitation index, can lead to results affected by important errors. It must be considered, in addition, that the flow test system for big valve are very cumbersome and difficult to realize. For these reasons predict cavitation by using a numerical simulation analysis is very helpful.

The purpose is to obtain through a CFD analysis the onset of cavitation in terms of incipient cavitation index that is considered in several technical standards. CFD is the “Computational Fluid Dynamics” i.e. the technique used for the studies of the fluid dynamics with the computer.

As discussed in the previous chapter, the incipient cavitation index is evaluated with experimental test that measure the vibration with an accelerometer and noise measured with sound level meter.

It has been shown (Malavasi and Messa [9]) that in a single hole orifice, the presence of cavitation can be predicted by means of an extended pressure criterion that simply state that the system is subjected to cavitation when \( p_{\text{min}} < p_v \), conversely the system is not subjected to cavitation if \( p_{\text{min}} > p_v \); where \( p_{\text{min}} \) is the minimum pressure and \( p_v \) is the vapor pressure.

The problem is that for the case of the single hole orifice it is easy to detect the position of the vena contracta and so where there is the section with the lowest level of pressure in which cavitation begins, but for a more complex system like a valve this is not so immediate. In fact for valve is difficult to identify the position in which there is the bubble formations.

The research will focus on a specific type of control valves, named Cage Ball Valves, that are an evolution of the common ball valve where a changeable internal cage is inserted and divides the pressure drop in several stages [8].

The following figure 57 presents an example of this kind of valve.
In particular two different dimension of these valves will be used: 77 mm and 203 mm of nominal diameter [8].

The interest of this work is not to accurately describe the physics of the “real” cavitation inception, i.e. the formation of the very first vapor bubble, but to provide a reliable prediction of its detectable effects by means of a technical parameter, which is the incipient cavitation index [8].

First of all it must be chosen the dimension of the elements in order to have an accurate prediction of the pressure field.

Since there is a geometry symmetry, in order to reduce the computational cost and the simulation run, it can be considered only half-pipe system as shown in the figure 58 that represents the whole domain considered.
The arrow present in the figure above indicates the flow direction from the inlet section.

To evaluate the stability of the system, the parameter used, is the flow coefficient that is described by the following formula:

\[ C_v = \frac{Q}{N \left( \frac{\Delta p}{\gamma_f} \right)^{1/2}} \]

Where \( Q \) is the flow rate expressed in \([m^3/h]\), \( \Delta p \) the difference of pressure expressed in \([bar]\) (the upstream pressure is recorded at a distance of two diameters from the valve and the downstream pressure at six diameters from the valve), \( \gamma_f \) is the ratio between the specific gravity of the fluid under test conditions and the specific gravity of water at the temperature of 15°C and \( N \) is a conversion factor \([m^3/h/gpm \times (psi/bar)^{0.5}]\).

Starting with a low grid, the number of volume cells is increased until the flow coefficient is constant. At this point the minimum grid which provided a stable result was chosen [8].

The minimum pressure criteria consists in the evaluation in the whole domain of the \( p_{min} \) and then use it to find the incipient cavitation index \( \sigma \).

The value of \( p_{min} \) is obtained as a mean value of a certain volume that is composed by several computational volume units. This calculation could be affected by numerical errors depending on the CFD code and the mesh type used.

In order to eliminate these errors is introduced a cut of values based on the difference of the pressure associated to neighboring cells. This procedure eliminate a cell if his value differs from the values associated to the other neighboring cells more than the threshold established.

Obviously the lower the threshold the more are the cells that will be cut.

The figure 59 shows an example of cells considered in this procedure to remove numerical errors.
In the case considered in the figure above the generic cell, with associated a pressure value $P_c$, is kept if at least one of the per cent difference between $P_c$ and $P_x$ is less than the threshold value, otherwise it is cut. $P_x$ is the pressure value relative to the other cells, in this case $x$ goes from 1 to 6.

Anyway is important to choose a cut value that allow to avoid the numerical errors without remove significant cells.

Once the numerical errors are excluded, it has to be evaluated the sufficient number of cells of which must be composed the grid to solve the pressure field. Moreover, the so called “cavitation volume” has to be introduced. This consists in the purposeful volume which is associated to the minimum pressure that gives the best match between the predicted and the experimental $\sigma$ [8].

The steps performed in order to obtain these quantities are not discussed in detail in this work, an interested reader may consult the studies done by Malavasi, Rossi, Ferrese and Messa [8].

At this point the minimum pressure can be evaluated.

Obtained the minimum pressure, all the pressure field is translated in order to reproduce the incipient cavitation conditions. In this configuration it is calculated a new upstream pressure that corresponds to the value of the upstream pressure $P_{up}$ which cavitation will arise with, for the flow rate imposed. Finally, using this new upstream value, the numerical incipient cavitation index can be evaluated and compared with the experimental data [8].

With this procedure the minimum pressure criteria is exploited, in fact his purpose is to obtain the minimum pressure $P_{min}$, considering a characteristic volume that identifies the cavitation condition (cavitation volume) and then the upstream pressure $P_{up}$ providing a good cavitation
index prediction. In fact the predicted cavitation index can be now evaluated by introducing the value of the upstream pressure, obtained as discussed above, in the common formula of $\sigma$:

$$\sigma = \frac{P_{up} - P_{vap}}{P_{up} - P_{down}} = \frac{P_{up} - P_{vap}}{\Delta P}$$

Note that the pressure drop in the denominator does not undergo any variation with the translation of the pressure field.

Finally the results obtained through the numerical method are compared with the results obtained experimentally in order to understand if it is a good prediction of cavitation index.

As discussed in the previous chapters, by using the experimental way, the onset of cavitation is defined in the point where there is an abrupt increase of the acceleration. The problem is that sometimes there is not a specific value of $\sigma$ in which there is the abrupt increase and this mainly depends on the difficulty of the data acquisition during the experimental test.

The following figures from 60 to 63 show the comparison of the results obtained with the two methods for the valves considered and at different degrees of opening. In the graphs, the continuous vertical red line, is referred to the experimental $\sigma$; while the dashed blue line, to the $\sigma$ predicted numerically.

![Graph showing comparison of numerical and experimental results for a cage ball valve with nominal diameter of 77 mm and opening angle of 60°](image)

Figure 60: Comparison of numerical and experimental results for a cage ball valve with nominal diameter of 77 mm and opening angle of 60° [8]
Figure 61: Comparison of numerical and experimental results for a cage ball valve with nominal diameter of 77 mm and opening angle of 40° [8]

Figure 62: Comparison of numerical and experimental results for a cage ball valve with nominal diameter of 203 mm and opening angle of 90° [8]
The table 15 below reassumes the values of the cavitation index obtained with the numerical prediction and experimentally in the various cases considered.

<table>
<thead>
<tr>
<th>Valve diameter [mm]</th>
<th>Opening [°]</th>
<th>Numerical σ</th>
<th>Experimental σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>60</td>
<td>2,76</td>
<td>2,8</td>
</tr>
<tr>
<td>77</td>
<td>40</td>
<td>2,61</td>
<td>2,3</td>
</tr>
<tr>
<td>203</td>
<td>90</td>
<td>6,21</td>
<td>5,3</td>
</tr>
<tr>
<td>203</td>
<td>60</td>
<td>4,96</td>
<td>4,4</td>
</tr>
</tbody>
</table>

Table 15: Comparison of numerical and experimental results for the two types of valve at different opening angle [8]

Looking at the values obtained it is easy to notice that there is a good correspondence between the results obtained with the two different methods. In particular for the case of 77 mm valve with an opening angle of 60° the two cavitation indices are almost the same and in the other cases the numerical σ overestimates a little the experimental one, but anyway this is in favor of security.

With these considerations is possible to affirm that the numerical prediction presented is a good way to obtain the onset of cavitation and it provides a reliable cavitation index.
CONCLUSION

Cavitation in valves is a serious problem that engineers have to face in several applications. The parameter used to quantify his level is very popular and comes directly from the first studies on the subject at the beginning of the twentieth century (1923-1925) thanks to Thoma and Leroux. This is the cavitation parameter that compare in literature under different forms linked together and that is still used nowadays unchanged.

More complicated is to establish the cavitation limit that the valve in the particular system has to respect. First of all the difficulties come from the fact that the level of cavitation that can be sustained by a specific pipe system where is located the valve depends on a large variety of factors that are not only correlated to the capacity to overcome cavitation by the valve, but also on environmental aspects like the level of noise that can be reached in the area where the system take place. Different limits are defined by literature as the ones listed in the present work: incipient cavitation, constant or critical cavitation, incipient damage and chocking cavitation. Anyway it is common for the valves manufacturer companies to provide to customers an index called manufacturer’s recommended limit that take into account not only the results coming from the laboratory tests, but also the accumulated knowledge coming from the past experiences in practical applications.

Different types of valve have been compared for what concern their cavitation characteristics in order to understand which one behave better.

This analysis in included in the chapter 2.8 (Controlling cavitation) where the possibility to avoid cavitation by selecting a particular type of valve is considered. The comparison is made on reliance on the values from the software UseCAD 7.0 provided by VAG-Armaturen GmbH. By considering the same pipe system, four different types of valves produced by VAG are included in the analysis:

- RIKO plunger valve
- DURA globe valve
- EKN butterfly valve
- CEREX 300 butterfly valve

The results obtained are listed in the following table 16:
Looking at the table it can be seen that installing a DURA globe valve in the system is the best choice since σ pipe is higher than σ full cav. and σ beg. cav. for the whole stroke of the valves. This implies that the valve is never subjected to cavitation.

If a RIKO plunger valve is installed, a state of beginning cavitation will be established when the valve is open from 45 to 90 degree (part surrounded in yellow in the table).

The worst situation is when a butterfly valve is chosen. In this case full cavitation appears in the system, in fact, as is possible to see in the table, σ pipe is lower than σ full cav. for certain values of opening degree of the valves. Even if the cavitation limits are the same for the two types of butterfly valve, the situation in which an EKN valve is chosen, it is worse than if a CEREX 300 is chosen. This is because the latter implies lower pressure drop at the same valve opening, and this means higher σ pipe.

It must noticed that in this analysis is considered a RIKO plunger valve with the simple outlet type “E”. As discussed in the chapter 2.4.2, the cavitation limits of this type of valve can be reduced by installing a different kind of outlet type. In particular installing an outlet type “LH” with orifice cylinder provides the lowest cavitation limits for the RIKO valve, as well as low level of noise produced.

In the chapter 2.6 are presented two scale effects: pressure scale effect (PSE) and size scale effect (SSE), that are used when the cavitation index is obtained with a reduced scale model. Once the reference index (incipient, incipient damage, etc.) is obtained experimentally with the model, by using this two parameter in the formula presented in the chapter 2.6, it is possible to evaluate directly the index related to the real valve that has to be included in the system. Even though this method is very simple and allow to obtain the cavitation parameter without doing test on too big valves, which would mean to deal with a cumbersome facility difficult to set up, it can lead to

<table>
<thead>
<tr>
<th>Open (deg)</th>
<th>RIKO plunger valve</th>
<th>DURA globe valve</th>
<th>EKN butterfly valve</th>
<th>CEREX 300 butterfly valve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ pipe</td>
<td>σ full cav.</td>
<td>σ beg. cav.</td>
<td>σ pipe</td>
</tr>
<tr>
<td>5</td>
<td>1.51</td>
<td>0.25</td>
<td>0.33</td>
<td>1.51</td>
</tr>
<tr>
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<td>1.51</td>
<td>0.55</td>
<td>0.73</td>
<td>1.52</td>
</tr>
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<td>1.52</td>
<td>0.86</td>
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<td>1.53</td>
</tr>
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<td>1.55</td>
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<td>1.40</td>
<td>1.54</td>
</tr>
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<td>1.60</td>
<td>1.25</td>
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<td>1.55</td>
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<td>1.67</td>
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<tr>
<td>90</td>
<td>1.86</td>
<td>1.50</td>
<td>2.00</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Table 16: Comparison of the cavitation values for the types of valve considered
rather significant errors. Just think about the fact that the geometry of the valve change with respect of the size.

New perspectives are being introduced for what concern the prediction of the cavitation index with numerical methods. This is a very interesting innovation in the field of valve cavitation since it allows to provide the parameters without doing the classical experimental procedures that in some cases are not so simple to perform. The results presented in the chapter 3 relating the studies done by Malavasi, Ferrese and Messa with a numerical modeling shown a very good agreement with the incipient cavitation index obtained experimentally.

An important advantage of the numerical method is that allows to take no more into account the scale coefficients (PSE, SSE) since the size of valve included in the modeling corresponds to the size of the valve that has to be installed in the real pipe system.

For these reasons the numerical method to provide the cavitation indices is a very interesting perspective that has to be developed by valves manufacturer companies, in order to predict the cavitation characteristics of a large variety of valves with a good approximation.
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ACKNOWLEDGEMENTS

Prima di tutto desidero ringraziare la mia famiglia, senza la quale non sarei mai riuscito a raggiungere questo traguardo. Ringrazio i miei genitori che mi hanno dato la possibilità di seguire questo percorso e che insieme a mio fratello Francesco mi hanno sempre sostenuto ed incoraggiato durante questi anni.

Ringrazio tutti i miei amici, che non sto a nominare uno per uno, ma che sanno già che mi riferisco a loro. La loro presenza mi ha premesso di vivere molti momenti felici ed ha alleggerito i momenti più critici. Grazie anche a Mariaelena che mi è stata vicina per parte di questo percorso.

Ringrazio tutte le persone che ho conosciuto durante gli anni universitari, le quali oltre ad essere dei compagni di studio, si sono dimostrate dei veri amici.

Ringrazio il Professor Bianchi per avermi concesso la possibilità di svolgere questo lavoro e per la disponibilità che ha dimostrato durante la stesura dello stesso. Ringrazio l’azienda VAG-Armaturen GmbH che ha ispirato questa tesi, in particolare modo l’Ing. Veronese e l’Ing. Reinmüller per l’interesse e la vicinanza mostrati. Ringrazio inoltre il Professor Malavasi il quale è stato molto gentile nel fornirmi consigli molto utili durante lo svolgimento del lavoro.