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Aerating Butterfly Valves to Suppress Cavitation

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AERATING BUTTERFLY VALVES
TO SUPPRESS CAVITATION

by

R. Ted Davis

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

UTAH STATE UNIVERSITY

Logan Utah

1986

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In closing, I would like to thank my wife, Linda, who has patiently supported me in my education and helped everything come together.

R. Ted Davis

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ABSTRACT

Aerating Butterfly Valves
To Suppress Cavitation

by

R. Ted Davis, Master of Science

Utah State University, 1986

Major Professor: Dr. J. Paul Tullis
Department: Civil Engineering

Proper aeration of cavitating hydraulic equipment can greatly reduce cavitation intensity, noise, and damage. This thesis quantifies the benefit, in terms of damage and noise, from aerating a six inch butterfly valve. The incipient damage level of cavitation was obtained for both aerated and non-aerated conditions. The level is defined as one pit per square inch of a soft aluminum test specimen per one minute of operation. A description of the cavitation pits that occurred plus where they appeared is presented. A graph showing the aerated and non-aerated limits of incipient damage is given along with a table showing the percent reduction of damage from aeration. A graph and table are also given depicting the reduction in noise. The proper location of aeration ports to allow natural aeration is outlined.

(61 pages)

CHAPTER I

INTRODUCTION

Since their inception, butterfly valves have lended themselves to many applications in hydraulics. The butterfly valve is not only convenient in such systems due to its narrow design, but also because the valve is inexpensive in price relative to many other types of valves. However, one potential problem with the butterfly valve, as well as many other valve types, is the destructive cavitation caused by the sudden pressure drop across the valve. The term cavitation is used to describe the process of water vapor bubbles forming in very low pressure points of the flow and then violently collapsing in higher pressure regions. This cavitation can erode away the valve seat and downstream piping plus cause unacceptably high noise levels.

There are four basic ways to handle this cavitation which include letting the equipment cavitate and replace it when its severely eroded, lining the cavitation zones with a more damage resistant material such as stainless steel, using a special cavitation controlling valve or using air to suppress the cavitation damage. The first two options do nothing in lowering the noise level and can also become very costly. The third option can be considerably more expensive due to the cost of a more specialized and complicated valve. The fourth option greatly reduces both damage and noise and if properly used can be quite inexpensive.

This study examined the effect of the fourth option by using aspirated air to suppress both cavitation damage and noise. In order to measure the benefits of the air, it was necessary to obtain cavitation data for non-aerated cavitation. The main objective for this study was then to obtain this data for the non-aerated condition and then to quantify the benefit, in terms of noise and damage, of using air to suppress the cavitation. Guidelines are also given on the proper placement of air ports in the system.

CHAPTER II

CAVITATION BACKGROUND

Cavitation Mechanism

One of the fundamental properties inherent with a liquid is it's pressure of vaporization or vapor pressure. When the pressure of a liquid equals this vapor pressure, vapor cavities or bubbles begin to form within the liquid. When heat is involved in this process, the describing term is "boiling". This is when the liquid's vapor pressure is raised to that of the surrounding atmosphere by addition of heat. If, instead of raising the vapor pressure through heat, the pressure of the surroundings are lowered to the vapor pressure of the liquid, a term called "cavitation" results.

Researchers have identified two types of cavitation known as gaseous cavitation and vaporous cavitation. Gaseous cavitation results from a bubble that has considerable amounts of free air in it obtained either from suspended air in the liquid or degassing of the liquid. The collapse of these bubbles are relatively mild due to the cushion effect of the trapped air inside the cavities. In contrast to gaseous cavitation, cavities of vaporous cavitation are almost completely made up of liquid vapor. Growth and collapse rates are very rapid for these bubbles and the collapse can occur violently. This is the cavitation associated with damage to hydraulic structures whereas gaseous cavitation can be associated with suppressing vaporous cavitation (Tullis 1984).

From the preceding discussion, a low pressure or vapor pressure region is necessary for cavitation cavities to form. In a valve, such as the one used in this study, low pressures occur in both the separation region of the flow and in the cores of vortices that are present downstream of the valve. Figure 1 shows the separation region and the position where the vortices are likely to form. Streamline theory predicts how the flow will look through the valve.

Since cavitation is in essence a rupture of the liquid, another necessary component of cavitation is weak spots, bubbles, or voids in the liquid where rupture can occur. These voids are the underlying reasons that natural water does not support tensile forces. The voids are called nuclei and are the actual places which cavitation initiates.

One of the contributors to cavitation is the free air content. From totally independent tests performed by Numachi, Crump, Williams, McNulty, and Ziegler on venturi type nozzles, it was generally found that the pressure at cavitation inception fell with reduced air content (Knapp et al. 1970). The part of the air contributing to cavitation is the undissolved gasses that are present in the interstices of the containing boundaries plus the interstices of sediment within the water. Harvey proposed

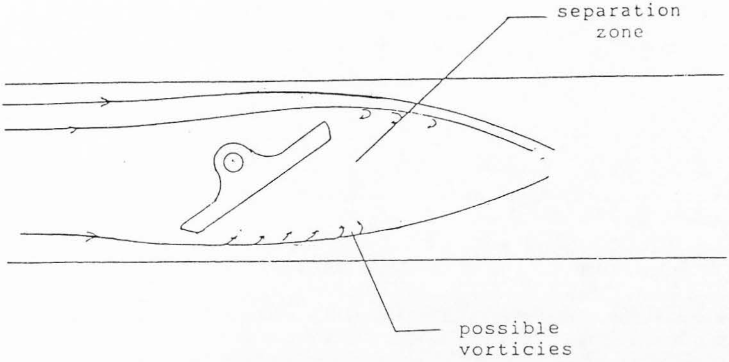


FIGURE 1. Streamline paths and resulting low pressure region of a butterfly valve.

that a cavitation nucleus consists of a pocket of undissolved gas trapped in the crevice of a hydrophobic solid. The walls of the crevice are un-wetted, and therefore the gas pressure is less than the water pressure by the effect of surface tension. This inhibits the water from dissolving the gas and this gas pocket or nucleus becomes an active center for the formation of a cavitation bubble (Harvey et al. 1947).

Even small dust particles have a potential for harboring nuclei and therefore all natural waters are assumed to be subject to possible cavitation. Only under careful laboratory conditions can water be purified enough to allow it to support tensile forces and thus reduce the pressure at which cavitation occurs.

The actual cavitation damage to a system is not due to the small bubble itself, but rather due to the life cycle of the bubble. As the bubble enters a low pressure zone, it begins to grow and expand. Once a critical diameter is reached, its growth can occur almost instantaneously. As this bubble then enters a high pressure zone, it is relatively large and unstable. The high pressure causes the bubble to immediately collapse in a violent manner. This collapse is what is associated with cavitation damage.

Two of the most widely accepted sources for the damage are pressure shock waves and micro jets. The shock wave theory explains that some damage is due to impacts from pressure shock waves that radiate from the collapse center of a small bubble. These shock waves have been estimated to cause pressures as large as 1×10^6 psi (Knapp et al. 1970). These pressures occur very close to the bubble center, and therefore only bubbles adjacent to a boundary will cause direct damage under this mechanism. The vibrations and loud noise associated with cavitating flow however, can be attributed to such collapses throughout the flow field.

A second cause of cavitation damage is the result of micro jets. Actual photographs of cavitating flow show that the bubbles collapsing near the boundary collapse unsymmetrically. This is due to the pressure gradients within the fluid. The side of the bubble that is subjected to the higher pressure collapses at a much faster rate than the side in the lower pressure area. This collapse continues right on through the bubble and causes a microscopic jet to shoot through the other side. Jet velocities of several hundred to several thousand feet per second are predicted (Knapp et al. 1970). As with the pressure of collapse theory, these micro jets need to occur very close to a boundary to cause direct damage. If the jets occur farther into the flowing stream, they will be quickly dissipated in the fluid.

Damage Rate

The rate at which cavitation damages material is not a constant rate but rather a time dependent relationship.

This relationship can be divided into four zones known as the incubation zone, the accumulation zone, the attenuation zone, and the steady state zone.

The incubation zone has little or no measurable weight loss. The accumulation zone represents the time during which the rate of weight loss increases either due to increasing energy absorbtion rate or due to a reduction in mechanical properties of the metal caused by cold working.

The attenuation zone is characterized by the weight loss rate reaching a peak value and then decreasing with time due to the attenuation of the energy absorbtion rate. Isolated deep craters begin to form on the surface of the test material in this zone. The roughness caused by these craters starts to introduce hydrodynamic factors which could possibly reduce the energy transfer of the collapsing bubble and result in a decrease in the damage rate. The steady state zone follows the attenuation zone and is characterized by the weight loss settling to an equilibrium value (Waring et al. 1965).

Resistance of materials

Many studies have been performed on the resistance of material to cavitation attack. This resistance has been difficult to quantify do to factors such as physical and chemical erosion plus the long times involved for cavitation damage to become significant. One underlying conclusion remains however, which is that all known materials practical for liquid conveyance can be damaged by cavitation.

Aeration Effects

Studies have been made that show the substantial benefit of using air to suppress cavitation damage on hydraulic structures. One such test was reported by Peterka in which he subjected concrete specimens to a venturi type cavitation apparatus with and without air injection. The test period was two hours and the velocity through the throat of the venture section was over 30 m/s. The weight loss of the specimens was plotted against the percent (by volume) of air entrained in the flow. The plot is show in figure 2. For 7.4 percent of entrained air, there was no measurable weight loss, and the losses were greatly reduced for air concentrations higher than two percent (Peterka 1955).

Previous test results appear to point to three possible mechanisms by which the air reduces cavitation. One such idea states that air absorbed around the vapor cavity cushions the collapse, reducing its intensity. If the gas content of the vaporous cavity could be increased enough to transform the cavitation from vaporous to gaseous cavitation, damage would greatly decrease (Hall 1960).

Another result of introducing air to the system might be found in the separation zone or cavity as a whole. Daily reported on tests which revealed that for low

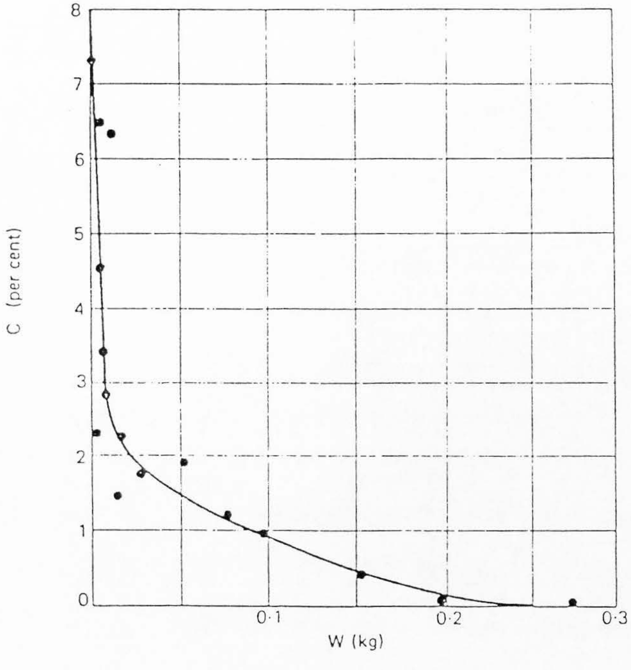


FIGURE 2. Air concentration versus cavitation weight loss of concrete specimens (according to Peterka 1955)

cavitation numbers, cavities formed by the same body have been found either as a smooth transparent walled void or a turbulent fluctuating region. Both regions apparently enclose a vapor or gas filled volume. The smooth transparent cavities are practically steady state in that the cavity wall is nearly stationary and smooth resulting in essentially free streamline flow. On the other hand, the turbulent region appears very rough and unstable. The difference in the cavities has not been completely understood, but it is thought that the smooth transparent cavities are associated with the presence of large amounts of non-condensible gas. It is thought that bleeding air into the turbulent cavity might cause a transition from the turbulent to the steady state cavity resulting in suppression of vibration, noise, and cavitation intensity (Daily 1965).

A third possible mechanism to reduce cavitation is to eliminate the low pressure zones which are necessary for the nuclei to grow into vapor cavities. Results from Tullis and Skinner indicate that bypassing water from upstream of the valve and injecting into the pipe downstream of the valve did not reduce the cavitation intensity, but injecting air into the separation zone caused a significant reduction (Tullis and Skinner 1968). This indicates that relieving the low pressure zone alone might not totally account for the cavitation reduction otherwise the water bypass would be effective, but it could possibly be a contributing factor.

Results from various valve types point out important information as to air injection location and amount. Tullis and Skinner found that pressurized air at 140 psi through the sides of the pipe behind a butterfly valve did not reduce cavitation as well as aspirated air through the valve stem did. This points out that the most critical factor in reducing cavitation with air is the location of the air injection ports and not the pressures at which it was injected. It was also found that this air admitted through the valve stem caused the critical cavitation index to be reduced by one fourth of it's normal value (Tullis and Skinner 1968).

Mumford performed tests on a solid plug cone valve and found that injecting one percent air (by volume) can reduce the incipient damage cavitation index from eight percent at 70 degrees open to 60 percent at 20 degrees open. Injecting more than one percent of air did not further reduce cavitation in his tests. He attributes this fact to the possibility that the greater amounts of air just washed downstream in the high velocity flow and no more than one percent seems to be able to reach the cavitation zone. In addition, The valve structure itself prevents aeration of certain possible key areas of the valve (Mumford 1985).

Scale Effects

As with non-aerated cavitation, scale effects are also found with aerated cavitation. Research from Clyde and Tullis performed on a variety of orifices indicates that the percent air required to suppress cavitation increases as the size of the model decreases or as the velocity increases. They recommend that the largest model possible be used in studies and that these models be tested at prototype velocities to avoid aeration effects (Clyde and Tullis 1983).

CHAPTER III

PARAMETERS USED IN STUDY

Cavitation and Discharge Parameters

In order to discuss cavitation, its intensity, and conditions of the system that cause it, a quantitative measure or parameter needs to be defined. From the variables of velocity, pressure, vapor pressure, density, surface tension, diameter and viscosity, four dimensionless parameters can be derived. These parameters are the Reynolds Number, the Euler Number, the Weber Number and the Cavitation Parameter.

The Reynolds Number is the ratio of inertial forces to viscous forces. There are scale effects associated with the Reynolds Number and need to be taken into effect as described later in the chapter. The Euler number is the ratio of the pressure forces to inertial forces and is a basis for valve discharge coefficients. The Weber Number is the ratio of inertial forces to surface tension, and its effect on cavitation is assumed small in the case of water. It is therefore neglected. Of the four parameters, the Cavitation Parameter is the one that best describes the cavitation that occurs. Knapp shows the derivation of the cavitation parameter which has been widely adopted for comparison of cavitating events (Knapp et al. 1970). This parameter is defined as

$$\sigma_2 = \frac{2(Pu-Pvg)}{\rho v^2} \qquad (1)$$

Pu = pressure just upstream of valve
Pvg = gage vapor pressure
ρ = mass density of fluid
v = mean velocity of flow

This dimensionless similarity parameter is the ratio of the forces suppressing cavitation to the forces causing cavitation. The smaller the cavitation parameter, the more intense is the cavitation. A form of the equation that is often used for valves and will be used in this study is (Tullis 1984)

$$\sigma = \frac{Pd-Pvg}{\Delta P} \qquad (2)$$

Pd = pressure measured about 10 diameters downstream of the device and projected back by adding the friction loss
ΔP = the net pressure drop across the device

Equation (2) can be easily converted to equation (1) by

$$\sigma = (\sigma_2/Kl)-1 \qquad (3)$$

Kl = loss coefficient analogous to fl/d in pipe flow

In this study Cd was used for the loss coefficient in place of Kl where

$$Kl = (1/Cd^2)-1 \qquad (4)$$

and

$$Cd = v/\sqrt{2g\Delta H+v^2} \qquad (5)$$

ΔH = total head or pressure drop (including any change in velocity head)
v = mean flow velocity
g = acceleration of gravity

Equation (2) can be used to describe the cavitation when the flow has not been choked, but needs to be modified slightly when the valve chokes. This choking condition, sometimes termed "choking cavitation", can occur when the pressure just downstream of the valve drops to vapor pressure and the valve is passing its maximum flow for a set valve opening and a set upstream pressure. For choking flow a term ΔPch is substituted in for Pu-Pd giving the following choking cavitation parameter.

$$\sigma ch = \frac{Pu-\Delta Pch-Pvg}{\Delta Pch} \qquad (6)$$

For this study, ΔPch was obtained by rearranging equation 5 to obtain

$$Pch(psi) = \frac{62.4{v_{ch}}^2(1/Cd^2-1)}{144*2g} \qquad (7)$$

Cd = non-choking discharge coefficient
v_{ch} = flow velocity for choked conditions

Minimum Pressure Coefficient

The minimum pressure coefficient is an important parameter in judging whether a valve is operating at a condition where it will naturally draw in air to its separation region. Tests were performed on the butterfly valve to obtain the minimum pressure coefficient from the following equation.

$$cpmin = \frac{Pu-Pdmin}{\rho v^2/2}*144 \qquad (8)$$

cpmin = minimum pressure coefficient
Pu = upstream pressure (psi)
Pdmin = pressure immediately downstream of valve (psi)
v = average velocity of flow
ρ = 1.94 slugs/ft^3

Air Quantity Calculations

When suppressing cavitation with air, it is important to know what quantities are needed and how much air is introduced to the system. In certain systems too much air can collect at high points possibly causing hydrodynamic problems, and in infiltration systems, the air can plug sand filters. The air flow rates and resulting air to water percentages by volume were calculated by using a simple Newton Method. This method was also employed by Mumford in his aeration study on a solid plug cone valve.

$$\%air = \frac{Q'air}{Q'air + Q'water} * 100 \qquad (9)$$

where

$$Q'air(cfs) = Qair\ SCFH/3600sec/hr*\rho o/\rho$$

and

$$\rho = \frac{1(144\ sqin/sqft)(Pb-Pdmin\ psi)}{(53.35)(T\ deg\ R)}$$

Q'air = air flow rate adjusted to separation zone pressure
ρo = density of air under standard conditions 0.0807223 lbm/cuft
ρ = density of air as it enters the separation region
Pb = barometric pressure
Pdmin = minimum sub-atmospheric pressure in the separation region
T = air temperature in degrees Rankine

Scale Effect Adjustment

Pressure scale effects are present with the incipient damage cavitation parameter used in this study. To adjust all of the data points to the same upstream pressure the following equation was used (Tullis 1984).

$$\sigma id = \sigma ido*PSE$$

where

$$PSE = \left[\frac{Pu-Pvg}{Pu\ \ -Pvg}\right]^{x} \qquad (10)$$

where $x = .18$ for butterfly valves and Puo and Pvgo are the experimental upstream and gage vapor pressures measured. Pu and Pvg are the upstream and gage vapor pressures at which σid is desired.

CHAPTER IV

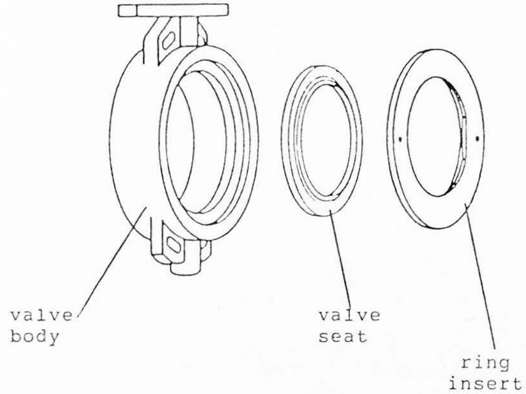
EXPERIMENTAL PROCEDURES

Laboratory Facility

This study was performed at the Utah Water Research Laboratory at Utah State University in Logan, Utah. Water is supplied by a small reservoir on the Logan River and conveyed a short distance through a 48-inch supply line. Horizontal test lines on the Laboratory floor are subject to approximately 26 feet of reservoir head with higher pressures being obtained from a variety of pumps. For this study, a vertical turbine pump rated at 4500 gpm at 70 feet of head was employed. Flow rates were measured with two 25,000 lb. capacity weigh tanks and a digital timer.

Test Valve

The test valve used was a six inch high performance Jamesbury butterfly valve with a worm gear type operator. The valve is shown in figure 3. Degree opening readings were taken from a protractor attached to the indicator on top of the operator. As shown in the figure, the valve has an internal ring that reduces the flow diameter from 6.125 inches to 5.563 inches. This ring is to be placed on the high pressure side for normal operation, however in this study it was placed on the low pressure side. This installation allowed the placing an aluminum test specimen as close to this ring as possible to detect any seat damage



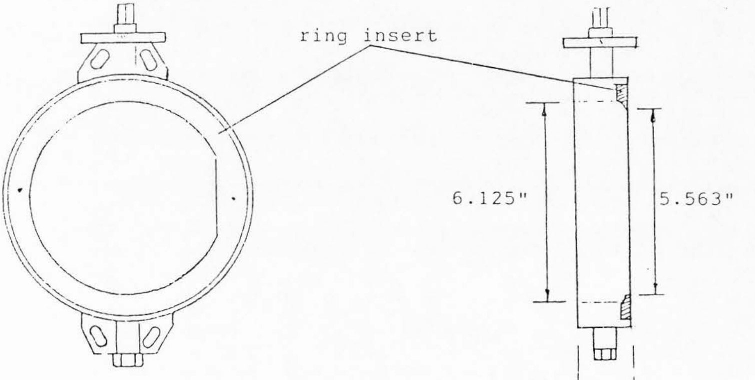


FIGURE 3. Diagram of test valve emphasizing the internal ring that reduces the flow.

that could occur from the ring and the disk. This installation also allowed better aeration of the valve seat.

Measurement Devices

The measurements required in the study were:

* Flow through the valve
* Pressures up and downstream of the valve
* Friction loss of the piping
* Barometric pressure
* Water temperature
* noise levels
* cavitation levels
* aspirated air flow

As mentioned previously, flow through the valve was obtained by two 25,000 lb. capacity weigh tanks in conjunction with a digital timer. The upstream and downstream pressures for the valve were obtained from a single Heise precision dial gage that read to the nearest 0.1 psi. In order to be free from errors involved with using two gages, only one was employed that had a control valve to allow for switching between upstream and downstream pressure measurements. This gage had previously been calibrated with a dead weight tester.

The friction loss of the piping was measured with a U-tube mercury manometer. Barometric pressures were obtained from a mercury barometer located at the laboratory, and water temperatures were obtained from a conventional mercury thermometer.

Noise level measurements were obtained from a hand held sound level meter with the meter being placed 48 inches downstream of the valve and 29 inches out perpendicular from the pipe. This standard was suggested by Hutchison (Hutchison 1976).

The cavitation level that this study focused upon was the incipient damage level. Knapp defines this level for laboratory purposes as being one cavitation produced pit per square inch in a soft aluminum test specimen per one minute of operation. To obtain the pit count and also see where the cavitation was occurring, a one foot long polished aluminum test sleeve was placed inside of a plastic pipe section immediately downstream of the valve.

The sleeve was built from standard aluminum conduit and milled to a six inch inside diameter. This diameter is the same as the upstream and downstream piping that was used in the test.

The sleeve was polished to a mirror finish using a cloth wheel and rubbing compound. This type of surface is necessary to pick out the pits, count them, and study their shapes.

Choking cavitation was also of interest in this study. It is defined as the point where the pressure just downstream of the valve reaches vapor pressure, and the valve is passing its maximum flow for a constant upstream pressure. This means that lowering the downstream pressure further will not allow any increase in flow.

Aspirated air flow rates were also needed to be able to calculate the optimum flow rate to best suppress cavitation and also determine the percent of air (by volume) that will be entrained in the piping. These flow rates were measured by two Dwyer tapered tube flow meters that have a combined capacity of 800 SCFH.

Test Setup

A general view of the test setup is shown in figure 4. For upstream isolation and filling, a cone valve was used with 21 feet of piping between it and the test valve. During the tests, the upstream valve was always fully open and this, in conjunction with the 21 feet of piping, insured that no undesirable flow conditions were present at the test valve. The desired upstream pressures were obtained by adjusting a globe type bypass valve at the pump and a ball type valve at the end of the piping section.

Figure 5 shows a closer view of the valve, aluminum test section, and aeration ports. Note that the air ports were drilled into a 1/2 inch thick aluminum ring just behind the valve. in the field, it would be possible to drill them through the flange on the downstream pipe.

Test Procedure

The purpose of this study was to obtain non-aerated limits for incipient damage level of cavitation, aerated limits for that same condition, cavitation limits when the valve chokes, and sound level measurements of the cavitating conditions.

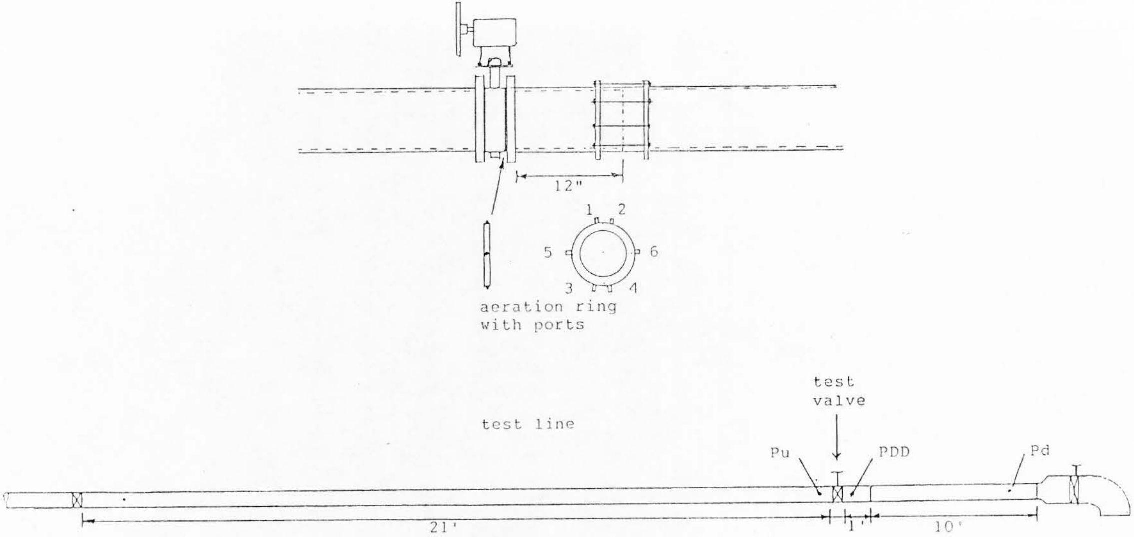
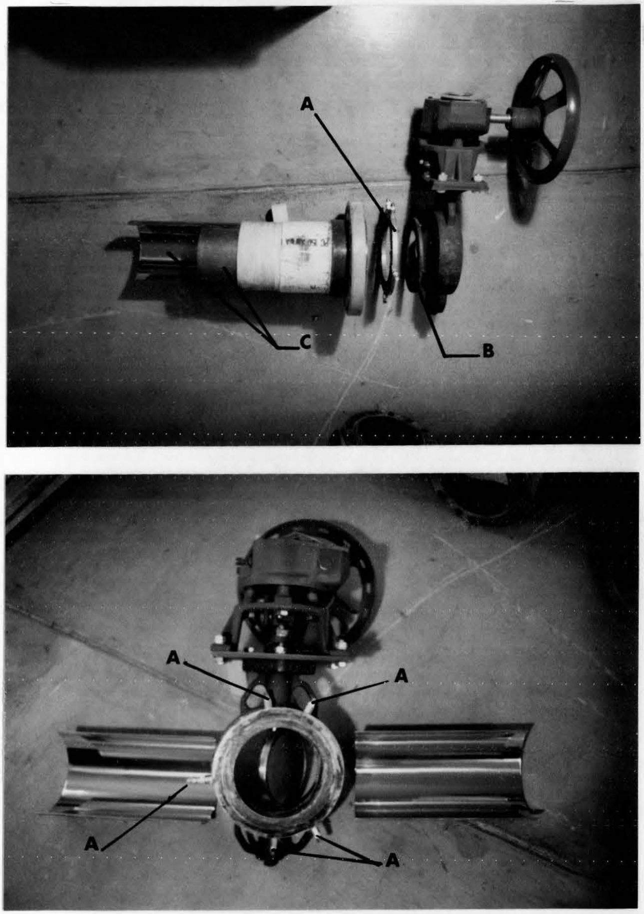


FIGURE 4. General view of test line with close view of test valve and sleeve.



A. Aeration ring with ports
B. Internal ring
C. Aluminum inserts

FIGURE 5. Photographs of test valve, aeration ring, test sleeves, and aluminum inserts

As stated previously, incipient damage level of cavitation was measured using the aluminum test sleeve. Each test run was initiated by inserting the sleeve and starting flow through the system. The desired valve opening was then set, and the operator was clamped so as not to move during all the runs of interest for that particular opening. Upstream and downstream pressures for the test valve were set with the pump bypass valve and the downstream control valve respectively. When all conditions were set, the system was shut down, and the sleeve removed and polished to eliminate all surface imperfections. The sleeve was then again inserted and the flow was pumped through the system for five minutes at the previously set conditions. The recorded pressures and flow rates were taken on this test run.

Once again the sleeve was removed and inspected for the place of maximum pit density. One square inch of this area was marked off and the number of pits counted. A 4X magnifying glass was used to aid in the identification and counting of the pits. The sleeve was then polished again and the process was repeated for four or five different levels of cavitation.

A semi-log plot was made with the calculated cavitation parameter on the rectangular axis and the pits/in^2/min of operation on the log axis. A best eye fit of a straight line was drawn between the points, and where this line crossed the 1.0 pits/in^2/min line, was the incipient damage level. The cavitation parameter corresponding to this point is actually referred to as the incipient damage limit.

Obtaining the incipient damage limit only necessitated varying the cavitation intensity by varying the pressure drop across the valve. When air was introduced, the effect of varying amounts of air was also needed. To obtain this, the valve was allowed to draw all the air it could through the taper tube meter while operating slightly above the incipient damage level (approximately 3-5 pits/in^2/min). Separate tests were run with a constant pressure drop but with varying amounts of air. The optimum air flow rate was chosen as the rate that would correspond to the least damage on the sleeve. This optimum air flowrate was then held constant, and tests were run at varying pressure drops to obtain the aerated incipient damage level of cavitation.

To obtain the choking level, the upstream pressure was held constant and the downstream pressure successively lowered until no increase in flow was detected. The proper cavitation parameter was then calculated for this condition using equation 6.

Sound level measurements were obtained from a hand held meter with readings in decibels. The placement of the meter was discussed previously in this report. The noise test was performed by establishing a flowing system with the test valve fully open. Sound level readings were then taken for both aerated and non-aerated conditions as the valve was closed in 10 degree increments. The results of all these tests mentioned appears in chapter V .

CHAPTER V

RESULTS AND DISCUSSION

The object of the study was to first identify where the cavitation damage took place and to get an idea of the type of damage that resulted. After identification and quantification of the damage, aeration ports were placed in the system to examine the benefits of aspirated air. As a final note, sound level measurements were taken for both aerated and non-aerated conditions to quantify the possible noise reduction. Results of the above topic will be discussed separately.

Flow Coefficients

To get a comparison of cavitation parameters with different valve openings. Discharge coefficients (Cd) were used and were calculated from equation 5. These dimensionless coefficients measure the energy dissipation ability of the valve and allow performance comparison between different valves. A plot of these values versus valve opening are shown in figure 6.

Characteristics of Damage

The heaviest damage generally showed up in three different places on the aluminum test sleeve shown in figure 7. The center of the first area (A1) is about one to two inches downstream of the valve and about one half inch in from the side (measured around the curve of the

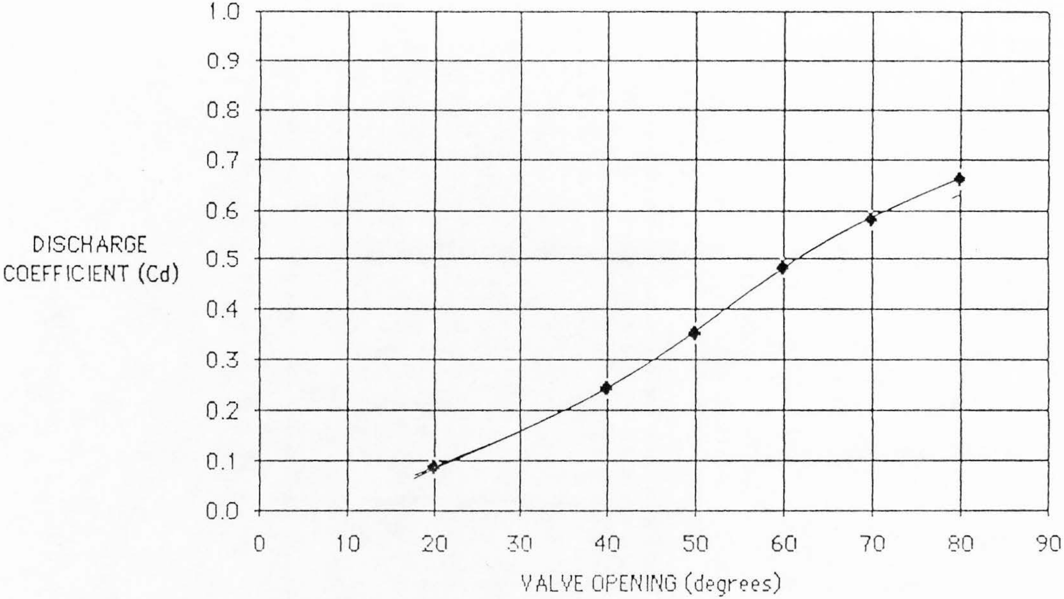


FIGURE 6. Discharge loss coefficients for the test butterfly valve.

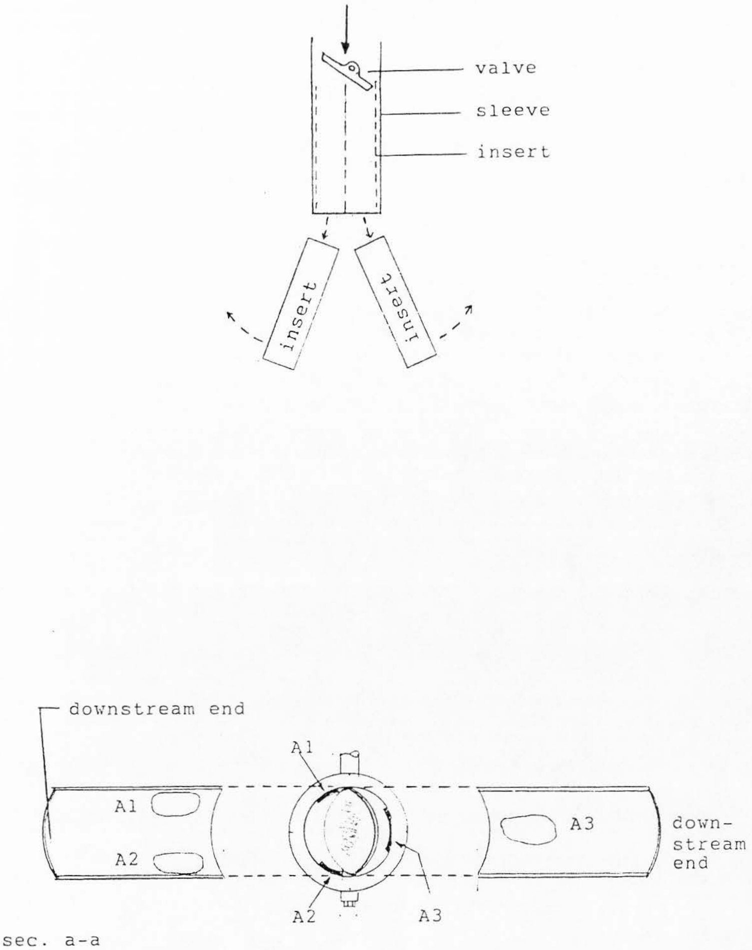


FIGURE 7. Diagram of the test valve and inserts showing the areas of cavitation damage.

sleeve). Area two (A2) appears at approximately the same place only on bottom of the sleeve. The damage that occurs in these places will be termed "crown damage". The third major area of damage intensity (A3) appears about four to six inches downstream from the valve and in the center of the opposite sleeve. In the rest of this report, damage in this area will be termed "zone 3 damage". It should be mentioned that these are approximate areas of maximum cavitation damage intensity, and the positions do shift downstream with larger valve opening and increased pressure drop. The areas of cavitation damage can also grow in length as the pressure drop increases and also with the addition of air. During the aerated tests, areas 1 and 2 sometimes extended nearly the length of the sleeve.

Another point which is characteristic of the cavitation pits is their size. The diameters of the pits in this study were found to range from smaller than 0.12mm to as large as 0.4 to 0.5mm in diameter. Figures 8,9,10 show the sizes of the pits. For reference purposes, figure 8 was taken at approximately 12.5X magnification whereas figures 9 and 10 were at approximately 37.5X. Like numbers in the photographs represent the same pits but at different magnification. Pit #2 is the smallest of the four and measures 0.12mm, whereas pit #4 measures 0.24mm. As previously mentioned, some pits were as large as 0.5mm, but they do not appear in these photographs. The size of the pits become important when analyzing the data and in

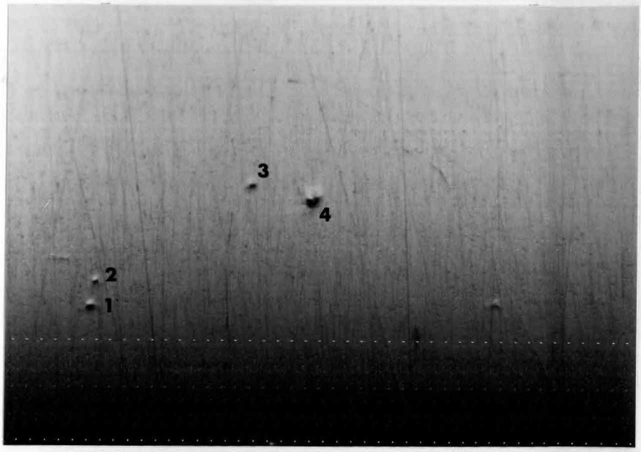


FIGURE 8. Photograph showing various sizes of cavitation pits. (approx. 12.5X)

FIGURE 9. Enlarged view of the two larger pits of figure 8. (approx. 37.5X)

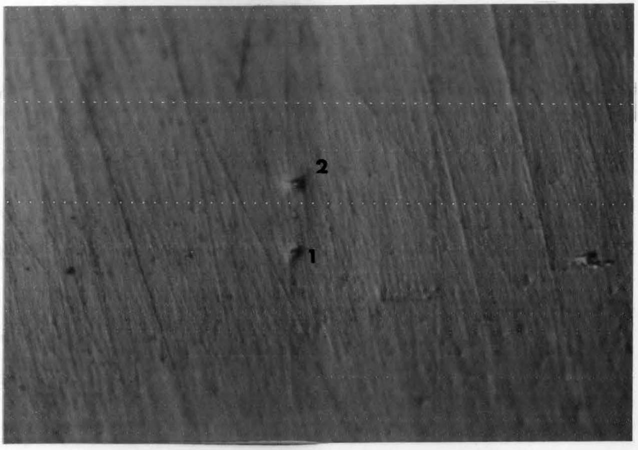


FIGURE 10. Enlarged view of the two smaller pits of figure 8. (approx 37.5X)

understanding the results of the cavitation limit plot discussed in the next section.

A few things can be observed by inspection of the pits that confirms reports of others (Knapp et al. 1970). First the pits in the aluminum appear to be indentations with no material removal. This can be seen in figure 9 by looking at the un-broken buff marks that go through the craters. Figure 9 also shows that the pits are not totally symmetrical or circular indicating that the micro jet trajectory is not always perpendicular to the pipe wall. The micro jet trajectory depends of the location of the bubble with respect to the pressure gradients and the flow of the fluid. The figures also indicate that the craters are caused by single events because of their clean and definite appearance.

Non-aerated Cavitation Limits

These limits consist of the incipient damage cavitation parameter and the choking parameter. The incipient damage parameter was obtained through the aluminum pit sleeve count as discussed earlier. The incipient damage level obtained from the tests is plotted against Cd if figure 11. All values for the cavitation parameters have been adjusted to an upstream pressure of 35 psi before being plotted.

One important note needs to be discussed about this incipient damage curve. As stated previously, a variation in pit sizes were observed throughout the testing. For

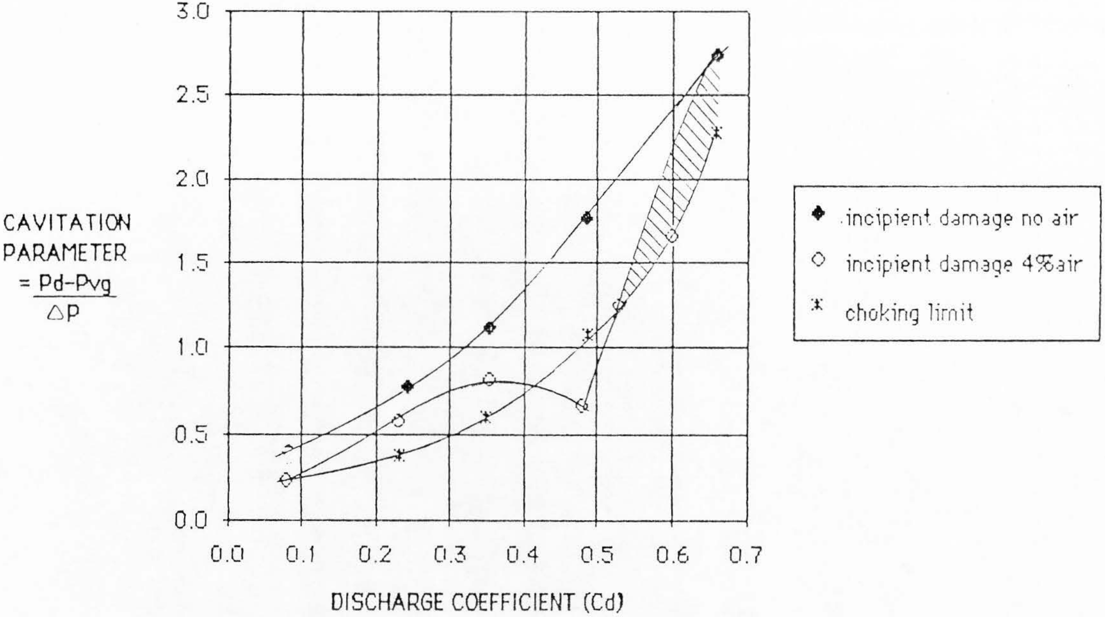


FIGURE 11. Plot of the incipient damage and choking cavitation parameter versus discharge coefficient

valve openings up to 50 degrees (Cd=.34), the pits were of the smaller size around 0.1mm in diameter. The maximum pit density for these openings occurred in the crown areas of the disk (A1 and A2) as shown in figure 7.

For valve opening above 50 degrees, the area of maximum cavitation damage completely changed to the zone 3 area. The pits that appeared in this area were much larger than those that occurred from the crown of the valve. These larger pits, which were up to five times larger than the crown pits, are assumed to be the result of the cavitation bubble being exposed to the low pressure zone for a longer period of time. This longer residence time allowed the pits to grow larger in size before they violently collapsed.

The choking limit for the valve was obtained to see how close this limit was to the incipient damage limit. The values of the choking limit versus the discharge coefficients (Cd)
are shown in figure 11. Note that no scale effect adjustments are necessary for the choking condition.

Aerated Cavitation Limit

The aerated limits were obtained for approximately the same valve openings as the non-aerated limits. Only naturally drawn air was used for this study to attempt to find a good cavitation suppression technique that was both inexpensive and simple to implement. The chapter on the laboratory procedures explains the aeration technique, and the results appear in Table 1 and figure 11. Table 1 shows that the cavitation limit curve drops anywhere from about 25 percent to 60 percent depending on the valve opening. The variation in this percentage depends a great deal on the cavitation potential of the valve at this opening and on the hydrodynamic conditions set up that allows the valve to draw the air in. Quantities of drawn air from 100 SCFH to 550 SCFH appear in table 1. This corresponds to an average of about 4 percent air by volume being introduced into the separation zone of the valve. These air quantities reported are the ones that seem to best suppress the cavitation.

Figure 11 shows that the aerated incipient damage limit not only drops to the choking limit curve, but also goes below it for Cd values from 0.4 to 0.55. This occurs because even though the valve was choking and the bulk of the bubble collapse was occurring many pipe diameters downstream of the valve, there was still noticeable cavitation at the valve. This cavitation at the valve was detected by the pit count and also audibly during the test run. In other words, it is possible for the valve to have cavitation damage directly downstream even though it is choking.

If the actual pit size is examined for the aerated cavitation limit, aeration appears to be even more beneficial than the curve in figure 11 indicates. The large pits that occurred with valve openings greater than

TABLE 1. Tabulated values showing the reduction of the incipient damage cavitation limit when air is introduced into the system.

1	2	3	4	5	6
% DROP IN SIGMA					
VALVE OPEN (degrees)	SIGMA * NO AIR	SIMGA * AERATED	% DROP IN SIGMA	AIR FLOW SCFH	APPROXIMATE AIR PERCENT
20	0.394	0.225	-43	100	3.3
40	0.77	0.57	-26	160	4.3
50	1.12	0.816	-27	450	3.4
60	1.77	0.664	-62	670	5
80	2.73	***	***	550	6

* cavitation parameter adjusted to an upstream pressure of 35 psi.

50 degrees for non-aerated conditions were completely eliminated when air was introduced to the system. The pit count was then taken using the smaller pits as with the smaller valve openings. If the large pits were the only ones being considered for the larger valve openings, the aeration could be assumed to totally eliminate the damage. It stands to reason that the events that cause the larger pits will erode the system away much faster than the cavitation that causes the smaller pits. In fact, some of the smaller pits were not much larger than erosion scratches from the sediment in the water, indicating that maybe these events might not be eroding the piping material anymore than the sediment would. These conclusions show that more research needs to be done that relates field damage to pit size in aluminum specimens.

The cross-hatched area in figure 11 is an area where the valve would not draw enough air to get below 2 pits/in^2/min on the aluminum sleeve. This gives a negative appearance to aeration at valve openings higher than 70 degrees, however it must be remembered that this count was based on the small pits whose damage potential was assumed to be much less than the larger pits. The valve did draw enough air at these openings to kill the large pits that were present in the non-aerated tests.

Placement of Aeration Ports

Reports from previous tests on valve aeration point to the fact that placement of the air is the most important single factor in suppressing the cavitation (Tullis and Skinner 1968, Mumford 1985). This study also points to the same conclusion. By examining the valve in figure 3, it is seen that an internal insert cuts the flow diameter from 6.125 inches to 5.563 inches. This in effect makes a separation region all the way around the insert. I was possible therefore, to place ports anywhere around the valve just behind the insert and still have the ports draw air. This enabled a full examination of the best location for the ports.

As described earlier in the report, an aluminum ring with ports drilled into it was place just behind the valve. The placement of the ports is shown in figures 4 and 5. It was found throughout the tests that the most important ports were numbers 1,2,3, and 4 (see figure 4). Ports 5 and 6 had negligible effect on the cavitation intensity. This is thought to be caused by ports 1,2,3 and 4 feeding the large separation zone in the shadow of the disk where the most destructive cavitation was initiating plus supplying good aeration to the seat. The other two ports would not feed this zone because the air would be immediately washed downstream when it hit the flow next to the pipe wall. This agrees with work done by Tullis and Skinner mentioned just previously. The aeration points should be as close as practical to the high intensity shear regions between the jet and the separation zone.

Minimum Pressure Coefficients

A final note on aeration is that the valve has to be operating in such a manner that it will draw in air or else compressed air has to be injected. The minimum pressure coefficient can give an estimate on whether the valve will draw air or not.

The minimum pressure coefficient was obtained from the laboratory data and equation 8. The coefficient was recorded at various valve openings to obtain a curve of it versus discharge coefficient (Cd). The resulting curve appears in figure 12. By knowing the valve opening, flow rate, and upstream pressure in the field, equation 8 can be used to solve for the minimum downstream pressure. If this pressure is below the atmospheric pressure, the valve should naturally draw air.

Sound Level Measurements

The results of the sound level test are shown in table 2 and figure 13. In general, introducing air into the separation region of the valve lowered the noise approximately 10 decibels. It has to be remembered that the decibel measurement is a log scale and 10 decibels constitutes quite a large noise reduction. The noise reduction was very evident in running the tests.

In general terms, the type and intensity of the noise depends on the size of the valve. Cavitation in a small valve usually is heard as a small crackling or popping

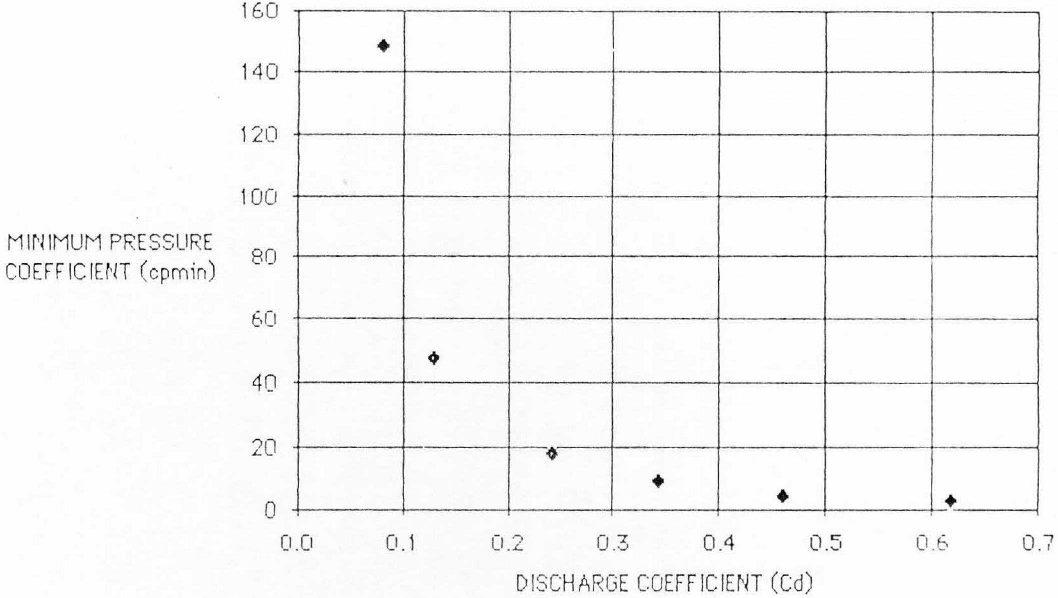


FIGURE 12. Plot of minimum pressure coefficient versus discharge coefficient

TABLE 2. Table of sound level measurements for aerated and non-aerated flows

1	2	3	4	5	6
NIOSE LEVEL	TESTS				
VALVE OPEN (degrees)	PU (psi)	PD (psi)	SIGMA	AIR FLOW SCFH	NOISE decibels
90	14.2	4.9	2.11	0	88
				100	86
				300	81
				450	80
80	15.9	4.9	1.74	0	89
				100	84
				300	81
				500	81
70	17.2	5	1.55	0	91
				100	87
				300	82
				550	80
60	23.2	5	1.01	0	91
				100	87
				300	82
				550	80
50	30.2	5	0.71	0	92
				100	88
				300	84
				550	83
40	38.2	5	0.529	0	93
				100	89
				300	86
				450	84
30	43.3	5	0.453	0	92
				100	87
				300	84
				450	83
20	55.6	5	0.34	0	90
				100	83
				200	82

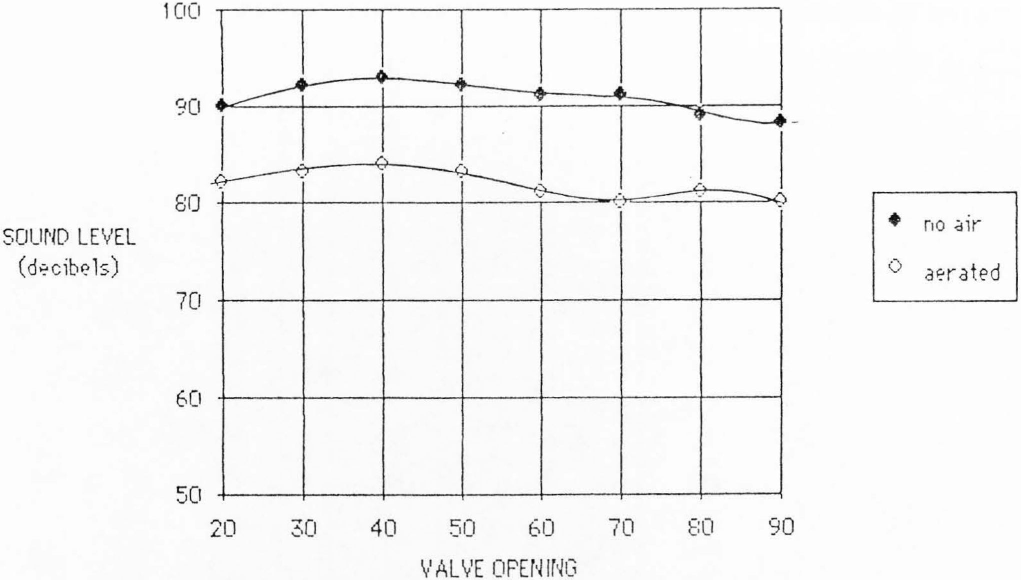


FIGURE 13. Plot of sound levels for aerated and non-aerated cavitating flows

noise like small pebbles hitting the pipe. In larger systems the noise is more like rocks traveling through the pipe and even as loud as small dynamite explosions (Tullis 1984). For systems larger than the six inch test valve, the noise level reductions with air could be even more significant than what appeared in these tests.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The purpose of this study was to examine the effects of air, which is drawn in naturally by a high performance butterfly valve, on the cavitation intensity, damage, and noise. The benefits were based on the incipient damage cavitation level, which was obtained by pit counts in soft aluminum. Noise levels were also measured in decibels for both the aerated and non-aerated conditions.

This study first obtained the non-aerated incipient damage cavitation limit. The damage that occurred from the non-aerated tests guided the placement of aeration ports on the downstream side of the valve. The aerated incipient damage limit was then obtained. Both these limits can be see in figure 11. In order to see how close the aerated incipient damage limit was to the choking condition, the choking condition was also evaluated and plotted in figure 11.

There are situations in which the valve is not usually operated under heavy cavitation but can often pass through this condition on opening or closing cycles. In these situations, noise can be more of a problem than damage. Therefore, this study briefly examined the noise level reduction with aeration. The results of all these tests appear in the conclusions that follow.

Conclusion 1

Allowing the butterfly valve to draw between three and six percent of air by volume allowed the pressure drop across the valve to be increased from 25 percent at 40 degrees open to 60 percent at 60 degrees open (see table 1 where pressure drop is directly related to sigma). The actual benefits could even be greater than this when the pit size is examined. One hundred percent of the large pits (0.3 to 0.5mm in diameter) were totally eliminated with the air for all valve openings where they occurred.

Conclusion 2

Location of the aeration ports is essential in proper cavitation suppression. The ports should be placed in the shadow of the disk to feed the low pressure separation zone and properly aerate the valve seat. Ports placed here also have the advantage of naturally drawing in air so that an expensive compressed air apparatus does not have to be implemented.

Conclusion 3

The noise level reduction due to aeration showed a substantial average drop of 10 decibels. The highest non-aerated noise level was 93 decibels (see table 2 and figure 13). Even if the valve were only occasionally operated in the cavitating condition and damage is of no concern, the reduction in noise alone would make aeration attractive in areas around people. The aeration can be quite inexpensive and simple to implement.

Conclusion 4

In conducting the choking cavitation tests, it was evident, through noise and damage, that destructive cavitation can occur just downstream of the valve while the valve is choking. This also shows up in figure 11 where the aerated incipient damage limit drops below the choking limit.

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APPENDIX

TABLE 3. Cavitation parameter for the incipient damage level without aeration.

1	2	3	4	5	6	7	8	9	10
CAVITATION INCIPIENT NO AIR	PARAMETER DAMAGE								
VALVE OPEN (degrees)	FRICTION (cm HG)	PU (psi)	PD (psi)	SIGMA	PITS/SQIN/MIN	DISCHARGE (cfs)	CD	BARO. PRES (psi)	Vapor press (psi)
40	7.65	35.05	6.7	0.68	27	3.241	0.247	12.33	0.14926
	7.35	35.1	8.05	0.763	1.2	3.286	0.255		
	7.4	35.2	7.75	7.42	4	3.27	0.253	12.20	0.14926
	7.3	35	8.5	0.796	0.6	3.241	0.255		
50	12.5	30	9.75	1.13	0.8	4.11	0.359	12.37	0.1211
	12.5	30.05	9.15	1.06	0.9	4.175	0.359		
	12.6	29.95	7.95	0.958	2.8	4.239	0.356		
	13	31	7.1	0.84	5.8	4.288	0.346		
60	18.1	22.9	7.2	1.32	9.4	5.118	0.481		
	17.4	22.9	8.05	1.45	3.6	5	0.483	12.22	0.12133
	15.3	22.8	9.3	1.68	1	4.75	0.488	12.43	0.1211
	16.7	23	8.9	1.59	1.8	4.95	0.491		
80	24.5	14.7	6.25	2.51	0.8	5.97	0.668	12.40	0.12114
	25.4	14.75	5.65	2.25	3.6	6.07	0.66	12.47	0.12114
	25.9	14.6	5.25	2.15	8.4	6.126	0.658		

TABLE 4. Cavitation parameter for the incipient damage level with aeration.

1	2	3	4	5	6	7	8	9	10
CAVITATION	PARAMETER								
INCIPIENT	DAMAGE								
AIR ADDED									
VALVE OPEN (degrees)	FRICTION (cm HG)	PU (psi)	PD (psi)	SIGMA	PITS/SQIN/MIN	DISCHARGE (cfs)	CD	AIR FLOW SCFH	BARO PRESS (psi)
20	1.6	56.1	0	0.223	2.6	1.437	0.0799	100	12.54
	1.5	56	0.5	0.234	1.6	1.426	0.0797	100	
	1.5	56	0	0.245	0.4	1.416	0.0795	100	
40	6.45	34.85	4.9	0.582	0.6	3.01	0.225	160	12.31
	6.9	34.95	4.3	0.55	3.4	3.14	0.231	160	12.33
	7.2	35.05	3.6	0.514	8	3.166	0.23	160	
50	14.2	29.6	4.4	0.687	2.4	4.46	0.353	450	12.28
	14.7	29.5	2.6	0.576	5	4.61	0.351	450	
	14	30.5	6.2	0.798	1.2	4.45	0.356	450	
60	20.1	22.7	0	0.592	3	5.34	0.429	670	12.54
	20	22.8	0.85	0.647	0.6	5.31	0.433	670	
	19.9	22.9	0.3	0.603	2			670	
70	26.2	24.5	5.3	0.9942	1.6	6.08	0.51	630	12.28
	25.8	25	7.4	1.213	1	6.06	0.525	630	
80	30.8	21.5	6.9	1.468	2	6.596	0.598	600	
	30.6	21.8	8.1	1.66	2	6.47	0.6	600	

TABLE 5. Incipient damage level cavitation adjusted to 35 psi upstream pressure.

1	2	3	4	5	6
ADJUSTED CAVITATION PARAMETER TO 35 psi Us					
NO AIR ADD					
VALVE OPEN (degree)	PU (psi)	SIGMA	**SCALING** COEFF. PSE	SIGMA 35	CD
20	35	0.394	1	0.394	0.084
40	35	0.77	1	0.77	0.242
50	30	1.1	1.023	1.12	0.355
60	23	1.68	1.0541	1.77	0.486
70	14.7	2.47	1.1063	2.73	0.662
80	14.7	2.47	1.1063	2.73	0.662
AERATED					
20	56	0.24	0.93596	0.225	0.082
40	35	0.57	1	0.57	0.23
50	30	0.8	1.02	0.816	0.353
60	23	0.63	1.054	0.664	0.48
80	22	***	1.0596	***	0.66

TABLE 6. Minimum pressure coefficient values.

1	2	3	4	5	6
MINIMUM PRESSURE COEFFICIENT					
VALVE OPEN (degrees)	PU (psi)	PDD (psi)	Q (cfs)	CD	CPmin
20	55	-2.6	1.439	0.0322	148
40	39	-4	3.498	0.244	17.32
50	31	-3.5	4.46	0.343	8.42
60	22.9	-5.8	5.318	0.481	4.06
80	14.5	-5.4	6.326	0.619	2

TABLE 7. Choking cavitation limit values.

1	2	3	4	5	6	7
CHOKING CAVITATION LIMIT						
VALVE OPEN (degrees)	FRICTION (cm HG)	PU (psi)	PDD (psi)	SIGMA CHOKING	Q (cfs)	CD
20	1.5	55	1.95		1.439	0.0822
	1.5	55	2.5		1.435	0.0825
	1.5	55	3.95		1.424	0.08184
	1.4	55.05	7.4	0.342	1.388	0.08371
	1.4	55.25	11.3		1.354	0.085
40	11.1	55.9	7		3.97	0.232
	11.3	55.9	4.9	0.358	4.05	0.232
					4.06	0.232
	11.5	55.8	0		4.05	0.221
					4.05	0.221
50	14.5	29.4	2.7		4.55	0.3476
	14	31	4.6		4.46	0.343
	12.6	32	9.8		4.29	0.358
	14.6	29	0.5		4.58	0.3396
				0.579	4.597	0.3407
	14.6	29	1		4.582	0.3424
60	25.2	30.4	9.1		5.93	0.479
	24.8	30.8	10.6		5.94	0.49
	29.9				6.08	
	29.9			1.067	6.07	
	29.9				6.07	
80	26.3	28.5	19.1		6.139	0.66
	26.5	25.2		2.257	7.12	
					7.12	
					7.11	