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# ON FLOW PATTERNS IN CONTROL VALVES AND DAMAGE INDUCED BY CAVITATION

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## ABSTRACT

There are industry based cavitation problems that do not readily lend themselves to mathematical solution techniques. The example studied here deals with the need to find an alternative to the cavitation prone leak-off valve used at a number of electric power stations. Following a fluids approach, an examination of the operating characteristics and design features is conducted with a view to linking these to the cavitation damage observed. Far from abandoning the available mathematical weaponry in the face of the complexities involved, the illation promulgated here emphasises the value of persuing the problem as far as practicable with such techniques. It becomes apparent, however, that the final solution to this problem is not determinable without conducting an empirical study. The foundations for such a study come in the form of flow visualisation methods, damage quantification techniques, video-image digitisation and surface roughness image analysis. In combination, these provide for a rich heuristics approach to the solution of this costly problem.

## INTRODUCTION

The damage sustained by valves as a result of cavitation appears as a significant operational expense in the accounts of a wide range of industries. The direct costs involved would include the maintenance expenses, both material and labour. The indirect costs are more varied and sometimes less obvious. Often, however, these indirect costs are far more significant. This is usually so when the damaged valve leads to plant downtime. In some cases a damaged valve may not necessitate an immediate plant shutdown but it will incur reduced yields or other plant inefficiencies. When a damaged valve is still serviceable the plant engineer is faced with the problem of determining the best time to initiate a shutdown in order to effect a repair. Of assistance here is information provided by a number of cavitation erosion rate studies. This is also of importance to the power generation industry where such information plays a part in determining the service life of the plant (for older plants the service life is typically 100,000 hours). Prolonging the service life typically costs only 15 to 20% of the costs of a new plant. In order to take advantage of this one must have a good understanding of the ageing processes taking place during operation.

For those plants that are well within their original design life, the reliable production of power can only continue if there are adequate preventative maintenance programmes in place to minimise the occurrence of unplanned shutdowns for repairs. Cavitation damage is generally easy to detect by suitable monitoring equipment and routine inspections. It is difficult, however, to determine when to effect a repair once cavitation has been identified. Giles et al {1} report on the merits of a probabilistic approach to cavitation repairs. Having gathered suitable historic data for an operating plant they outline a method for determining the likelihood that a certain piece of equipment is either fully operational, slightly worn or severely worn. These transitional probabilities are combined to quantify operating benefits and costs for the equipment in question. This provides the basic information for a decision analysis of the various maintenance alternatives and their expected costs. Such costs are not insignificant. The Tennessee Valley Authority reports that repairs for cavitation damage to their hydroturbines require outages of 2 to 9 weeks, direct costs being $15,000 to $20,000 per week {1}. Such repairs are required every 1 to 6 years. More significant than this though is the costs incurred by accidents in nuclear power plants as a result of cavitation. The Chernobyl disaster is one case in point. Recent investigations have revealed that as a result of tests on the cooling water system, four of the eight pumps were shut down. The remaining pumps began cavitating and the resultant loss of flow caused the reactor power to rapidly rise to 160 times the normal.

## THE PROBLEM AT PACIFIC POWER

The power generation industry faces some of the most difficult cavitation problems, primarily due to the requirement to pipe very hot water and subject it to substantial pressure drops. At Pacific Power's Munmorah Station the most obdurate cavitation problem centers on their leak-off valves.

Leak off valves are used when the load on the plant falls below a given level. Under such circumstances the water flowrate to the boiler is reduced. The feedpumps supplying the water, however, must pump above a specific flowrate in order to prevent pump and motor damage. The water temperature is approximately 160°C, pressure 23 MPa. This pressure must be reduced to 0.7 MPa before the deaerator, with constant flow. Naturally, the bulk of the pressure drop occurs across this valve. Various valve trims have been used such as hush trim, cascade trim, and stacked disc. These specially constructed trims are expensive (typically $10,000 per valve), difficult to install and require long lead times. For all their expense, though, they have met with little success, their service life typically being six months. The complete solution to this industrial problem requires several related studies centering on the nature of cavitation and the flow patterns in the existing valve designs and in other possible valves designs not currently used.

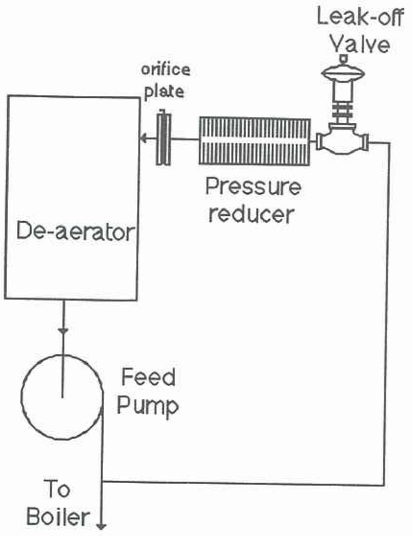

Figure 1
Piping circuit at Munmorah
containing the Leak-off valve.

## FLOW AND CAVITATION IN THE EXISTING VALVE

A component of the complete solution to this problem is to determine in greater detail the aspects of the current process and valve trim design features that lead to cavitation. Laser Doppler Anemometry (LDA) is one method of examining the flow in an appropriate model of the valve. LDA has a major advantage over physical probes placed in the flow field in that it does not interfere with the flow. In addition, by using several laser beams it is possible to measure all three components of the velocity vector giving the required turbulence information. One of the disadvantages is that it can only measure velocity at one point at a time and so the velocity profile within a valve would be time consuming to develop. Naturally, since the measurements can not be made simultaneously, any stochastic elements of the flow would be lost or otherwise misrepresented. Such stochastic elements can play a very significant role, especially at incipient cavitation. Also worthy of mention is the laser-speckle-velocimeter. This device measures the complete velocity profile in a plane.

Another method available is flow visualisation. For the work at hand it would require the construction of a transparent model of the valve (or at least sufficient windows in the body of the valve). Obviously, it would be difficult to exactly replicate the cavitation conditions in the Munmorah valve. However, the use of cavitation scaling equations enables one to design a practical working model suited to the reduced temperatures, pressures and flowrates obtainable in the laboratory. Details of the flow patterns are made possible by constructing a suitably enlarged model and placing particles or dyes in the flow stream. Dye injection permits the visualisation of vortices. Fluorescent dyes are most appropriate for the observation of wakes and other flow separations. The use of particles (typically of polystyrene construction) permit the use of video image processing techniques to reproduce velocity fields. The implicit assumption behind these particle methods is that no rotational or shear flows are present. The dye methods are used to verify the validity of these assumptions. In most cases of turbulent flow these assumptions are invalid. In order to overcome this the video is operated at exceptionally high rates (5 - 10,000 frames/sec) and the grid size being examined is kept small. Although the work has not yet been carried out, the type of equipment that would be used to perform such studies has been identified. An existing NAC Model E-10 high speed camera 'films' the flow and this is captured and digitised via a video-grabber. The digitised images are processed by customised software (IPLab). Final analysis reproduces the three-dimensional velocity profile.

As stated above, the leak-off valve does not easily avail itself of such flow visualisation techniques. Much is required by way of locating appropriate cavitation data and correctly applying relevant scaling formulae to design a suitable glass or perspex valve (or part thereof) in order to carry out such an examination. While it will lack some detail, a more practical solution method is computational fluid dynamics (CFD). CFD packages are generally readily available and it is relatively easy to set up the appropriate data in order to obtain a good estimate of the major features of the flow within the valve.

## EXAMINATION OF THE ALTERNATIVES

It has been stated that a complete solution to this problem calls for an examination of the existing valves and trims in order to ascertain what features of the flow and valve design are combining to generate the poor cavitation performance. From a practical viewpoint, however, it is not necessary to carry out such a study on the existing valves. It would be enough to find a suitable alternative where the cavitation is greatly reduced or even absent. However, the understanding of the current problem promised by conducting a detailed flow study of the cavitating valve should enable one to greatly reduce the list of possible candidates to those which have a high degree of promise with regards to the solution of the problem.

One of the more basic and well used means of handling cavitation problems in valves is to harden the valve internals in those areas where cavitation is most severe. This, however, is limited to relatively low pressure drops and offers no assistance where noise and vibration are also of concern.

The most common solution is to employ multistep trims. These breakup the total pressure drop into a number of manageable drops. The aim here is to ensure that at no stage will the pressure fall below the vapour pressure. There are two common forms of multistage trim; expanding and constant area. The expanding area trims attempt to concentrate around 50% of the total pressure drop across the first stage thereby opening up the possibility of velocity induced erosion if placed in continuous service. The constant area trims aim for equal pressure drops across all stages but suffer their greatest potential for cavitation at the last stage. A compromise solution is generally best where an initial series of equal stages is used with a final series of expanding stages designed to reduce the last trim's cavitation potential.

Multistage trims generally provide either a radial or axial flow method of pressure letdown although some designs do supply a combination of both. Multistep restrictions, packed in discrete layers, form the basis for radial flow designs. Layers are exposed or hidden by an axial stroke of the plug within the cage. This design type has a major drawback. At that part of the plug where throttling is taking place the area available for flow between the plug and cage is much less than the available area in the radial flow path. This results in the bulk of the drop occurring at the leading edge of the plug (see Figure 2). The cavitation that occurs as a result of this leads to material removal, loss of flow control rangeability, reduced guiding between plug and cage and damage to seating surfaces.

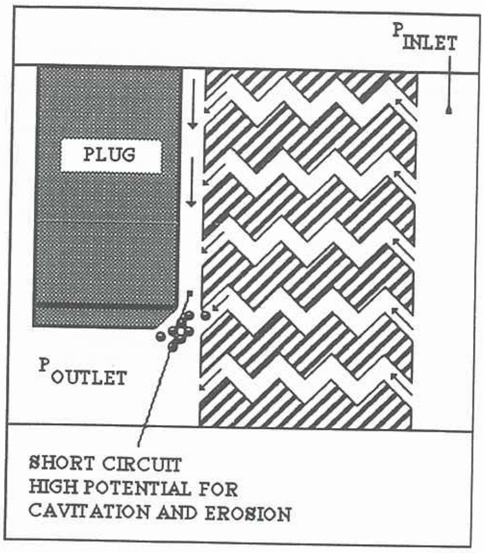

Figure 2
Multistep Radial Flow
Trim showing potential for cavitation erosion.

By contrast, axial flow trims space the pressure drop along the entire length of the plug. No one part is exposed to the full pressure differential. Consequently, seating surfaces are protected and trim life is extended. There are two types of axial trim, based upon the number of pressure reduction stages, namely fixed or variable. In fixed number trims all stages throttle in unison. Variable trim bypasses stages as the valve is stroked open.

Trims embody three of the five basic design strategies promulgated by Tullis {2}. The three strategies:

- ensure bubble collapse away from solid boundaries
- use hardened surfaces
- perform the pressure drop across a number of stages,

are the ones most easily applied to established sites, where more severe design restrictions apply. In new installations (greenfield sites) the remaining two strategies are more open to utilisation:

- designing the process operations such that the energy content of cavitation collapse is minimised (e.g. reduce the upstream pressure).
- supersaturate the system with air (or other suitable gas) to cushion the collapse of the bubbles

are more open to consideration, albeit each of these has its own skein of problems. Altering the process to reduce the energy inherent in cavitation will translate, thermodynamically, into poor energy efficiencies. When injecting air (or an inert gas such as nitrogen) into the pipeline to protect a valve care must be taken to ensure that injection ports are correctly located. It is also difficult to determine how much air is required as aeration scale effects are difficult to estimate correctly but it is generally experienced that the required air intake is approximately 2 - 6% of the total liquid volumetric flowrate.

## COMPUTER ASSISTED VALVE DESIGN

If a new basic valve design is chosen as a possible replacement to the existing leak-off valve, its detailed dimensions can be optimised via a combination of numerical optimisation routines and an expert system. Such a technique has been used to design heat fins (Kulkarni et al {3}), composite mechanical structures (Zumsteg et al {4}) and mechanical components (Chieng, et al {5}). Basing their system upon such concepts, Ellsworth et al {6} have developed a system to design a valve anti-cavitation device. On the basis that the design rule base can be made manageable using numerical optimisation to identify the best design, an expert system can be employed to define the optimisation problem and interpret the solution. In addition, it could apply the actual heuristics to the solution. Upon supplying the right valve trim archetypes to the system it locates the best set of design values for each trim type and then specifies the best one for a given duty. The problem of locating the right archetypes and forming suitable design rules and specifications is left for the design engineer. It is here, however, where greater creativity and flexibility is required as there is a need to propose solutions that are removed from the concept of valve trim types. The problem of finding the best pressure reduction and flow control device for Munmorah is not so readily solved by even this technique, although it does enable one to sort out the more reasonable designs proposed. For this reason, such an approach has great merit and is well worth further investigating.

## QUANTIFICATION OF DAMAGE

Essential in the evaluation of alternative high pressure liquid letdown valves for their resistance to cavitation is a methodology to quantify damage. As materials which suffer cavitation may undergo prohibitively long incubation periods before substantial mass loss is effected, it is desirable that the methodology enlisted is one which is sensitive. Damage quantification methods exist which can detect surface changes in the incubation period up to 2000 times earlier than the beginning of mass loss.

Microscopy and gravimetry are two of the more well accepted and robust methods employed to quantify cavitation erosion. Microscopy allows the detection of damage in the earlier stages of incubation and into mass loss but it is generally impossible to conduct an in-situ examination and it is not feasible to quantify material loss. Gravimetry allows in-situ measurements that adequately quantify cavitation damage but it is of no use until mass loss occurs. Non-destructive methods are being developed, however, that carry the positive benefits of each of these methods while minimising the negative side aspects. The most promising of these are the range of surface topography methods with computer assisted roughness data collection and evaluation. One system developed by Louis et al {7} utilises surface replication in conjunction with optical and scanning electron microscopy (SEM). Crucial to the accuracy of these methods is the ability of the replicate material to mirror image the damaged surface and then hold that image upon removal from the substrate. High fidelity is obtained from methylmethacrylate and various silicones. The advantage of the methylmethacrylate is that it sets in 15 minutes as opposed to silicone's 24 hours. However, it is more brittle and greater caution is required upon removal. The replicas are cut to reveal desired cross sections which are analysed via SEM. Test conducted by Louis show that fidelity in the vertical (i.e. pit depth) is better than 1 µm. Examination of these replicas has revealed a close relationship between surface roughness rate and hydrodynamic factors (Hutton et al, {8}). Furthermore, these replicas assist in the determination of wear processes and the formulation of wear mechanisms. Such information is critical in the prediction of component service life.

There are other details in the wear patterns that are of interest. Using microscopy, image analysis and Fourier transforms of the cavitation damaged surface profiles one can categorise the roughness via the surface's fractal dimension. Work yet to be undertaken aims at determining such fractal dimensions and relating these observations to material type, cavitation intensity and lifetime of the surface subjected to cavitation. Also of interest is a study yet to be performed which aims to examine the parallels between damage done by water microjets to crystal structures and cavitation damage done to metal surfaces. The former shows that damage is a function of the microhardness of the crystals. By analogy one would expect that damage to metals undergoing cavitation would be a function of the grain strength and intergranular weaknesses.

An important aspect of such studies is an index that serves as an independent measure of the intensity of cavitation. There are a few common indices such as Thoma's cavitation parameter but none have the potential to serve the purpose here so well as the Instrument Society of America's (ISA) Intensity Index. At the time of writing the ISA had prepared a draft recommended practise, ISA - dRP75.23, "Considerations for Evaluating Control Valve Cavitation". The usefulness of the index to the current study stems from the ISA's original intent in its design. Often in real-life industrial applications, the desire to eliminate all cavitation damage is thwarted by situational limitations such as physical space, infrequent use , process variables or even cost. In 1988, the ISA constructed an index to quantify the cavitation damage intensity or the relative service life reduction of control valves operating under damaging conditions. Developing this index to the form of equation 1 gives a measure of that could be interpreted as the damage intensity or the life reduction factor. The index only applies when the cavitation level exceeds the incipient damage level. There are several parameters within the intensity index that must be separately calculated. However, once it is evaluated, damage, wear and the intensity of vibrations can be expected to be roughly proportional to the numerical value of the index.

$$I = F_U \cdot F_T \cdot F_{DC} \cdot (\sigma_{id} - 1)/(\sigma_{ss} - 1) \quad \text{---(1)}$$

where $F_U$, $F_T$, and $F_{DC}$ are intensity modifiers allowing for fluid velocity, temperature and duty cycle (duration of the control valve in the cavitating condition) respectively.

Now, $\sigma_{id}$ is the incipient damage cavitation index and $\sigma_{ss}$ is the pressure and size scaled Thoma's cavitation index. As it stands the index accounts for many of the factors behind valve damage. However, it is not complete in its ability to determine the service life reduction, since there is no accounting for particulate matter or chemicals in the water (or for fluids other than water, e.g. petroleum) and valve material (different materials erode at different rates). No account is made of the fluid viscosities or dissolved gases. All these factors could be combined, linking the valve material mechanical properties and the fluid properties to erosion rates. The proposed alternative would give the relation:

$$I = F_U \cdot F_T \cdot F_{DC} \cdot F_P \cdot (\sigma_{id} - 1)/(\sigma_{ss} - 1) \quad \text{---(2)}$$

where $F_P$ is the required property modifier.

## CONCLUSION

Cavitation in control valves is a complex subject that promises great rewards to industry. The costs of inaction in this field are exemplified by the Chernobyl disaster. Research on the flow patterns in simplified systems does not extrapolate to the maze-like geometries of high pressure liquid letdown valves found in the power industry. The task of finding a complete solution to the problems posed at Munmorah Power Station is a formidable path to follow but it may be circumvented via the examination of valve types used in other industries or other power stations. Related studies examining the characteristics of cavitation damage give hope of finding better materials, manufacturing techniques and valve designs. An index serving as a measure of valve life reduction potential has been proposed by the ISA but it is not complete in its current form. It is left for further study to develop such an index to account for fluid and valve material properties.

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