INVESTIGATION OF INCIPIENT CAVITATION LIMITS FOR SQUARE-EDGED ORIFICE PLATE PRESSURE DISSIPATORS IN HIGH PRESSURE WATER RETICULATION SYSTEMS

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A DISSERTATION SUBMITTED TO THE FACULTY OF ENGINEERING,
UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG,
FOR THE DEGREE OF MASTER OF SCIENCE (ENGINEERING)

JOHANNESBURG, 1985

DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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15th day of JULY 1985

ABSTRACT

The problem, as presented, was to provide a simple device for dissipating pressure in mine underground high pressure water reticulation systems, a required feature of the device being operation without cavitation. An orifice place was selected and the object of the study was to evaluate various orifice diameter ratios (0,206 to 0,444), for a range of upstream pressures (2000 kPa to 7000 kPa), for their incipient cavitation points and flow/pressure drop data.

Selected literature was reviewed to establish factors affecting the phenomena of cavitation (eg. air content of water, pressure levels of occurrence, effect of suspended solids, etc.), and cavitation prediction methods that were available for use.

Experimental work was conducted in two parts, low pressure and high pressure; the low pressure part being carried out at the University of the Witwatersrand, and used to investigate the validity of an existing cavitation prediction equation, and to provide visual observations of cavitating flow. This also involved the formulation and application of a method to determine the incipient cavitation point. The gathered experimental results being inconsistant with predicted values. The high pressure part of the work was carried out at East Driefontein Gold Mine, the experiments again yielding data that was inconsistent with predicted values.

From analysis of the incipient cavitation results it is concluded that upstream pressure affected the pressure drop required for incipient cavitation, for the same orifice size; and that the orifice ratio affected the pressure drop required for incipient cavitation, for the same upstream pressure. These effects are explained by reference to flow turbulence. The flowrate/pressure drop relationships for the orifices were also found to be inconsistent with theory; however, this is explained by reference to the error analysis and to possible external factors that could not be controlled during the experiments.

For the gathered incipient cavitation data a prediction equation was derived, its range of use being 2000 kPa to 7000 kPa, for orifice diameter ratios of 0,206 to 0,444; this is also presented in graphical form.

ACKNOWLEDGEMENT

This investigation was carried out as part of the research programme conducted by the Environmental Engineering Laboratory of the Chamber of Mines of South Africa Research Laboratories.

During the course of the investigation I was assisted by various people at the Chamber of Mines (Johannesburg) and East Driefontein Gold Mine (Carletonville); I take this opportunity of formerly acknowledging the valuable assistance and help given by them, as well as the interest shown, during the investigation.

Also, I would like to thank Professor E A Bunt of the University of the Witwatersrand (Johannesburg) and Dr J M Stewart of the Chamber of Mines Research Laboratories (Johannesburg), for their role as supervisors.

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NOMENCLATURE

A	Area	m^2
C	Velocity of Sound	m/s
C_c	Contraction coefficient	-
C_d	Discharge coefficient	-
C_p	Specific heat	kJ/kg K
C_v	Velocity coefficient	-
d	Orifice diameter	m
D	Pipe diameter	m
de/dt	Rate of strain	1/s
dR/dt	Velocity	m/s
d^2R/dt^2	Acceleration	m/s^2
du/dt	Acceleration	m/s^2
du/dy	Boundary layer velocity gradient	(m/s)/m
e_{db}	Vapour pressure at dry bulb temperature	kPa
e_s	Vapour pressure at surface temperature	kPa
g	Gravitation constant, 9,81	m/s^2
h_c	Heat transfer coefficient	W/m^2 K
ΔH	Pressure loss (H_2O)	m (H_2O)
K	Pressure loss coefficient	-
Le	Lewis Number	-
m	Area ratio $(D/d)^2$	-
m	Mass	kg
M_e	Evaporation rate	kg/s
P	Pressure	kPa
ΔP	Pressure loss	kPa
Q	Flow	m^3/s
r	Correlation coefficient	-
Re	Reynolds Number	-
R	Radius	m
R	Resistance to flow	s/m^2
R_*	Gas constant	J/kg K

S	Surface tension	N/m
t	Time	s
T	Temperature	°C
T_{db}	Dry bulb temperature	°C
T_s	Surface temperature	°C
T_{wb}	Wet bulb temperature	°C
T_{sat}	Saturation temperature	°C
U	Velocity (orifice jet)	m/s
V	Volume	m^3
V	Velocity (Pipe)	m/s
w	Work	J/s
y	Distance	m
z	Height	m

GREEK SYMBOLS

α	Crack angle		-
β	Area ratio		-
δ	Boundary layer thickness		m
ϵ	Eddy viscosity		m^2/s
θ	Contact angle		-
μ	Absolute viscosity		kg/ms
ρ	Density		kg/m^3
σ_1	Cavitation index	$\left(\frac{P_D - P_V}{P_U - P_D}\right)$	-
σ_2	Cavitation index	$\left(\frac{P_D - P_V}{\rho V^2}\right)$	-
τ	Shear stress		N/m^2
ϕ	Relative humidity		-

SUBSCRIPTS

a	At time t
c	Choking
CR	Critical
D	Downstream
e	Equilibrium
g	Gas
I	Incipient
ID	Incipient damage
P	Pipe
R	Reference
U	Upstream
V	Vapour
VC	Vena contracta
W	Wall
1,2,3	Principal directions
∞	Free stream
ϵ	Vortex

INTRODUCTION

In the South African gold mining industry there exists a need for a relatively simple device to dissipate high pressure fluid heads (above 3000 kPa). It was suggested by the late Dr A Whillier of the Chamber of Mines Research Laboratories that a square-edged orifice plate would be an appropriate device; and to the best of the author's knowledge orifice places are not used on mines to dissipate high pressure heads.

Typically, such an orifice would be used to allow water to flow freely from a high pressure supply system into associated low pressure reticulation systems; also, such an orifice could be used in a turbine by-pass circuit when either the required flow is outside turbine operating limits, or when turbine maintenance work is being carried out.

However, the operating characteristics of an orifice with its associated high pressure drops do not appear to have been examined in any depth. In particular, such devices are [illegible] to generate considerable cavitation. The investigation [illegible]ribed here into the use of orifice plates was therefore to [illegible]

(i) The use of orifice plate pressure dissipators in high pressure water lines,

AND

(ii) The flow associated cavitation effects

The thesis is divided into eight chapters. The first outlines the Problem. The second chapter contains a review of selected literature on cavitation, the purpose of which is two-fold: one, to explain the phenomena of cavitation, and two, to highlight areas where insufficient literature is available to throw light on the problem posed in Chapter 1. This chapter is split up into five sections, each covering a specific area of cavitation literature. The first section deals with bubble growth : this outlines two mechanisms whereby cavitation bubbles are formed. The second section looks at factors affecting cavitation inception : this highlights various areas where generalised cavitation data or prediction equations may have certain inherent inaccuracies. A third section deals with bubble collapse : this looks at the prediction of the forces that bubbles exert on a solid boundary, and the life cycle of a cavitation bubble. The fourth section examines prediction methods, commenting on their usefulness when applied to a high pressure situation. The final section of this chapter then deals with various procedures that are available for determining useful cavitation data, and how suitable they are for application to high pressure conditions.

The third chapter examines the background to the use of an orifice plate as a flow measuring and pressure dissipating device, and describes flow through such a orifice.

A a check on the available cavitation prediction equations and on associated cavitation data, and to enable further cavitation data to be gathered, both a low pressure and a high pressure facility for cavitation tests were set up; these are described in the fourth chapter, the specific use and operation of each experimental facility being explained in detail.

In the fifth chapter, results from the low and the high pressure test facilities are discussed and analysed. A semi-empirical equation is advanced for predicting incipient cavitation, and to explain physically the phenomenon of orifice cavitation and any scale effects arising therefrom. The sixth chapter is specifically a discussion of the analysed results in the context of the mining problem referred to in the first chapter.

The seventh chapter presents conclusions arising from the results and their application, while the eighth chapter makes recommendations concerning cavitation in actual low and high pressure water systems.

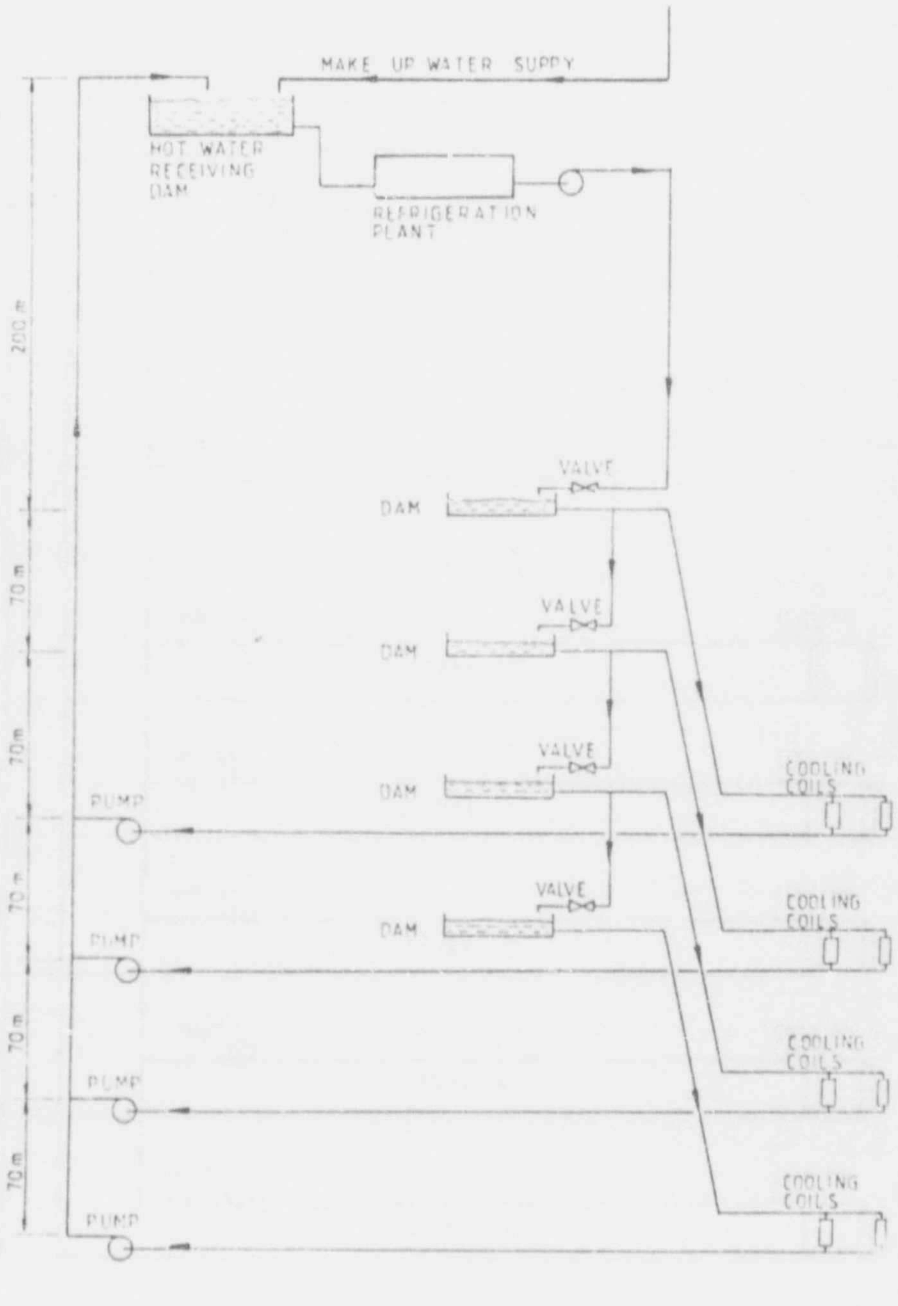
1. PROBLEM

Gold mine water reticulation systems can be classified as low pressure, or as high pressure in character. Both systems fulful the same function, that is, to supply water to mine workings, including equipment such as spray chambers and air-to-water heat exchangers.

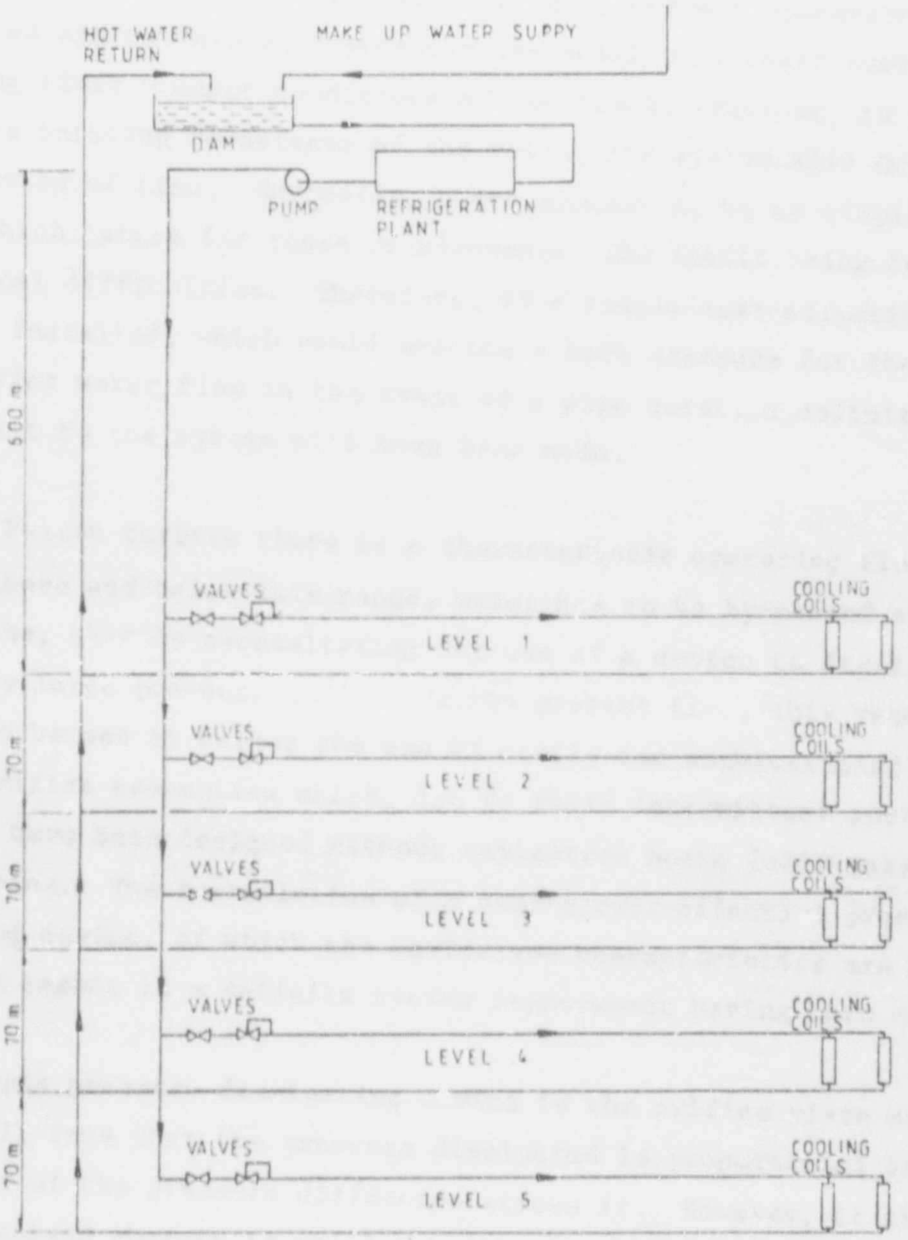
Typically, the low pressure systems operate at pressures below 3000 kPa and the pipework configuration in the shafts and on the mining levels is such that the pressure head created by the vertical distances between levels is broken at regular intervals. One such system is shown in Figure 1.1, where pressure reducing valves and dams are used to break the accumulating pressure head.

With high pressure systems, the shaft pipework configuration is essentially that of a long unrestricted pipe, and the pressure at the base of the pipe is that due to the total height of the water column (typically 7000 kPa to 15 000 kPa or 700 to 1500 m H_2O). Water is drawn from the shaft column and passes through pressure reducing valves before entering low pressure pipework systems on the various levels. An example of such a system is shown in Figure 1.2.

Due to the South African gold mines having become progressively deeper, the use of Pelton turbine energy recovery systems has become an accepted practice during recent years. These systems consist primarily of a turbine coupled to a pump, or to a generator. The pump is used to pump water out of the mine, and the generator is used to produce electricity which is fed back into the mine electrical system. Generally, the turbines are situated close to the shaft, so that high pressure water from the shaft water column can be fed directly to the turbines. Pressures at the turbine inlet typically range from 7000 kPa to 15 000 kPa (700 to 1500 m H_2O), which obviously depends on the mine and the level at which the turbine is to be situated. A secondary function of the turbine is that it also acts as a pressure reducing valve, water entering at a high pressure and leaving at a lower pressure.



<u>FIGURE 1.1</u> <u>MINE LOW PRESSURE WATER RETICULATION SYSTEM</u>



<u>FIGURE 1.2</u> <u>MINE HIGH PRESSURE WATER RETICULATION SYSTEM</u>

A feature of the above-mentioned sytems (low pressure, high pressure, and turbines) is that valves of one form or another are required to enable the system to operate correctly. There are, however, certain inadequacies associated with these systems. With both the low and the high pressure reticulation systems, the pressure reducing valves have a characteristic operating range and for their correct operation they require an appropriate back pressure (especially at their lower operating limit - under conditions of low flow). Further, in the event of a pipe bursting downstream of the valve, the system will empty in a short period of time. Currently, there appears to be no simple device in use which caters for these requirements, the result being certain operational difficulties. Therefore, if a simple cost-effective device could be installed, which would provide a back pressure for the valve, and restrict water flow in the event of a pipe burst, a definite design improvement to the system will have been made.

With the Pelton turbine there is a characteristic operating flow range. Above and below this range, water has to be by-passed around the turbine, thereby necessitating the use of a device to dissipate relatively large pressure heads. At the present time, this requirement appears to be met by either the use of costly and sophisticated valves, or long orifice assemblies which, due to their intermittent operation, appear to have been designed without cavitation being fully taken into consideration. The installation of a simple cost-effective pressure dissipating device, of which the cavitation characteristics are known, will again result in a definite system improvement having been made.

Such a simple pressure dissipating device is the orifice plate and it is generally true that the pressure dissipated is proportional to the square root of the pressure difference across it. However, it should also be realised that it is still possible for cavitation to occur, but to the best of the author's knowledge, minimal information is available on cavitation limits for orifice plates operating in high pressure head situations.

Information is, however, available for low pressure head situations from the work of Tullis J.P. and Ball J.W. (1974), Sweeney C.E. (1974) and Ball J.W. et al (1975) - all at the Colorado State University - and is given in Section 2.4.

Therefore, considering the potential applications for the orifice (though stopping short of saying that it can or should replace all valves), the purpose of this investigation was to examine the use of orifice plates in high pressue head situations, and in particular, to provide information on the behaviour of an orifice when it is called upon to dissipate large pressure heads under cavitation conditions.

2. CAVITATION

The aim of this chapter is to provide some general information relating to the phenomena of cavitation, and to highlight some of the factors that affect cavitation - thus indicating variables for consideration when attempting to predict its occurrence.

Whilst conducting the literature survey for this chapter it was found that much of the extant literature related to erosion of solid boundaries rather than to prediction of the occurrence of cavitation; and since erosion is recognised as being a major problem area, it is this aspect which has been best documented. The aspects of prediction and the factors affecting the occurrence of cavitation appear to be much less well documented, yet they are of equal importance as they lead up to the occurrence of erosion, and a knowledge of them would allow a fuller understanding of cavitation phenomena. This chapter is, therefore, directed towards providing that knowledge by means of reference to selected literature.

In all cases, whether fluid flow occurs in a closed or in an open system, cavitation is characterised by a two-phase flow (gas/vapour and liquid), the cavitation bubbles forming in high velocity, low pressure areas, and collapsing in low velocity high pressure areas : the formation of bubbles generally being associated with surface irregularities or flow restrictions.

Cavitation research - as with other fields of research - has experienced fashionable periods where both money and intensive effort have been focussed on solving particular problems. The first investigation into cavitation appears to have been carried out in the latter half of the nineteenth century. At that time screw propellor propulsion was in its infancy and problems were being encountered with the erosion of propellors. During the sea trials of HMS Daring in 1893 (Pearsall I.S. 1972) it was noted that the maximum speed attained was far less than expected; this was finally attributed to vapour bubbles forming on the propellor blades. Similar problems were also experienced in later years with the Turbinia (Parsons C.A. 1911). These problems appear to have stayed with the ship building industry for a number of years, since Parsons C.A. and Cook S.S. (1919) mention that deep pitting occurred on the propellors of both the Mauritania and the Lusitania, while the destroyer Swift had had 24 propellors made for it.

At a later date water became extensively used as a major energy source for the production of electricity in hydroelectric power schemes, the method of energy conversion being for the water to drive turbines coupled to generator sets. Here problems were experienced with the erosion of turbines, valves and water conduits under conditions of high velocity and low pressure. This led to the use and development of geometrically similar models to establish working designs, thus reducing the need for later re-design or repair on an ad hoc basis.

An example of such a model was the design of a sudden enlargement pressure dissipator for the Mica Dam (Russell S.O. and Bail J.W. 1967); the purpose of the study was to design a special pressure dissipator to reduce pressure on the outlet control gates of the water conduits. The most recent application of cavitation research has been in the use of liquid metals, cryogenic and organic liquids as heat transfer media and as working fluids in thermodynamic cycles in space and nuclear applications - where a failure in any particular application could possibly lead to a major disaster.

For flow systems, four levels of cavitation have been defined by Tullis J.P. and Govindarajan R. (1973). These are - incipient, critical, incipient damage and choking, and are described as follows :-

Incipient cavitation	This represents the onset of cavitation, the noise produced is light and intermittent, and vibration is negligible.