1999

Cavitation in valves

Kevin Simon Boddéus
University of Wollongong

1999

Cavitation in valves

Kevin Simon Boddéus
University of Wollongong

CAVITATION IN VALVES

A thesis submitted in fulfilment of the
requirements for the award of the degree

DOCTOR OF PHILOSOPHY
IN ENGINEERING

from the

UNIVERSITY OF WOLLONGONG

by

Kevin Simon Boddéus BE(Hons), ME(Hons)

Volume 1

DEPARTMENT OF MECHANICAL ENGINEERING

1999

DECLARATION

This is to certify that the work presented in this thesis was carried out by the author in the Department of Mechanical Engineering at the University of Wollongong and has not been submitted for a degree to any other university or institution.

Kevin Simon Boddeus

Acknowledgements

I am deeply indebted to my thesis supervisor Associate Professor Wee King Soh for his guidance throughout the period of this study. His insight, persistence and patience has been an invaluable aid to this work. Through nine years of effort he has never erred in his role as supervisor.

I also owe a debt of thanks to the staff and students within the Department of Mechanical Engineering who provided assistance along the way, in particular to Mr. R. Young, Mr. T. Rodwell and Mr. P. Cowey.

Financial assistance was received with gratitude from BHP, the original sponsors of this work as well as from the Australian Government for a HECs exemption covering the duration. BMCH and Fluor Daniel have also contributed by allowing me time and resources to complete this study.

Finally, I would like to dedicate a special acknowledgement to my family for their support and understanding throughout the years. To my wife Diané, my children Sye, Olivia and Kody who put up with my study and occasional absence. To my parents Jacobus and Tina Boddeus for their encouragement and their insistence upon the great value of education.

Abstract

Cavitation is a phenomenon that is manifest in a wide variety of liquid flow situations. Of particular relevance to this thesis is its appearance in industrial pumps and valves. Much of the early work proceeded in the form of fundamental research. The mathematical formulae coupled with and shaped by the experimental work done in cavitation laboratories established the foundations of this subject. In the early twentieth century, the relevance of this fundamental research to industrial problem areas such as short-lived valves and pumps was realised. Driven by the commercial advantage of providing cavitation resistant products, various companies established, within their existing research and development departments, sections which examined the impacts of and solutions to cavitation. Using the fundamental research as a springboard for their own, these industrial engineers undertook extensive laboratory and field test work. From this they developed products and the formulae and rules of thumb that enabled them to scale-up (or scale-down) these products to suit various industrial applications. Much of the knowledge produced by these companies remains private.

The situation at present shows a marked divergence in these two areas of research. However, this thesis contends that the current climate in academia and industry, where co-operative research projects in other fields of interest set a precedent, is well suited to the establishment of a combined effort in the area of cavitation. The establishment of such co-operative research is complex and varied when considered against the background of the many institutions, companies, products and test equipment involved. The approach adopted by the author has been to examine the history and current state of the two avenues of research (fundamental and industrial) with a view to establishing the broader bases for the seeding of links between them. This has been done by examining some examples in industry that display the nature of the problem that cavitation poses together with some of the solutions, which are often only means of mitigating the effects of cavitation. Some general test work with both venturis and multiple orifice plate test rigs is presented where the problems associated with cavitation are discussed.

The terms of this examination have included a study of the products of industry as well as the basic experimental research tools adopted within institutions (orifice plate and venturi test rigs). It has been shown that there are grounds for work with such test rigs to develop industrial products whilst simultaneously leading to the furthering of our understanding of cavitation. Some phenomena (such as out of sequence, interstage cavitation) were discovered during testing that would lead to a re-examination of the mathematics currently being applied.

Within this thesis the author has developed a technique for examining the cavitation signatures of test items. This has been done by using a unique combination of tools such as high speed photography, image analysis and signal analysis software. This work is supplemented by a detailed study of multiple plate orifice arrays. The author presents means of overcoming the subjective nature of determining the points of incipient and desinent cavitation that have plagued researchers in the past. Finally, more detailed work, arising out of the practical need to protect valves and pumps from cavitation in severe service duties, has led to a method for designing multiple orifice plate arrays.

In addition to this, the author presents the concept for a device that performs high pressure liquid letdown (as used in large power stations) without suffering cavitation.

The over-riding conclusion of this thesis is that whilst there is significant ground for the establishment of common efforts in cavitation research, there is both much merit in and momentum for continuing the current divergent streams. The development of the common ground, however, acts to enrich both the public knowledge domain and accelerate the development of solutions to industrial cavitation.

Contents

Declaration			i
Acknowledgements			ii
Abstract			iii
Table Of Contents			v
Nomenclature			viii
Chapter 1		**Introduction**	1-1
	1.1	Aims and Overview	1-1
Chapter 2		**Literature Search**	2-1
	2.1	Motivation For Continuing Cavitation Research	2-1
	2.2	The History of Cavitation	2-2
	2.3	The Physics of Cavitation	2-5
	2.3.1	Metastable Phases of Liquids	2-6
	2.3.2	Cavitation Nuclei	2-8
	2.3.2.1	Harvey Gas-Vapour Bubble Stabilisation Mechanism	2-10
	2.3.2.2	Fox-Herzfeld Organic Skin Stabilisation Mechanism	2-14
	2.3.2.3	Summary of Mote and Skin Models	2-17
	2.3.2.4	Further Considerations	2-17
	2.3.2.5	Summary	2-20
	2.4	Some General Equations of Bubble Dynamics	2-21
	2.4.1	Dynamics of Collapsing Spherical Bubbles	2-24
	2.4.1.1	Empty Bubbles	2-24
	2.4.1.3	Gas-Filled Bubbles	2-27
	2.4.2	An Overview of the Work on Bubble Dynamics	2-29
	2.5	The Literature in General	2-31
	2.6	Major Texts	2-32
	2.7	Minor Texts	2-35
	2.8	Journals, Conference Papers, Databases and the Internet	2-36
	2.9	Specific Topic Areas	2-37
	2.9.1	Bubble Nucleation and Growth	2-37
	2.9.2	Bubble Collapse and Damage Mechanisms	2-45
Chapter 3		**The Costs and Research Methodologies Associated With Cavitation**	3-1
	3.1	Introduction	3-1
	3.2	Costs Associated with Cavitation	3-3
	3.3	Research Methodologies	3-9
	3.3.1	Current Research Trends and Facilities	3-9
	3.3.1.1	Research Facilities	3-14
	3.3.1.2	The Working Section	3-17
	3.3.1.3	The Resorber	3-20
	3.3.2	The Missing Link Between University Based Research and Industrial Activity	3-23

	3.4	Summary	3-28
Chapter 4		**Valves and Valve Trim Design Considerations**	4-1
	4.1	Introduction	4-1
	4.2	Valve Design Considerations	4-2
	4.3	Control Valve Design Characteristics	4-9
	4.4	Maintenance	4-14
	4.5	Computer Assisted Valve Design	4-17
	4.6	Cavitation Characteristics of Different Valve Types	4-26
	4.7	The ISA Recommended Practice on Cavitation in Control Valves	4-30
	4.8	The Quantification of Damage in Test Work	4-33
	4.9	Conclusion	4-34
Chapter 5		**Industrial Case Studies and Aspects of Cavitation**	5-1
	5.1	Introduction	5-1
	5.2	Case Studies	5-5
	5.2.1	Flow Into an Open Tank	5-6
	5.2.2	High Pressure Cooling Water Onto Steel Strip	5-8
	5.2.3	High Pressure Liquid Letdown Valve on Pump Recirculation Line (the Long Orifice)	5-9
	5.2.3.1	Harland Engineering Solution	5-9
	5.3	Alternative Solutions - the Multi-holed Orifice Plate	5-11
	5.4	Summary	5-15
Chapter 6		**A Practical Solution to Valve and Pump Cavitation**	6-1
	6.1	Introduction	6-1
	6.2	Step Outline for the Three Tank System (Figure 6.3)	6-4
	6.3	Step Outline for the Two Tank System (Figure 6.4)	6-7
	6.4	Further Designs	6-10
Chapter 7		**The Orifice Plate Test Rig - Instrumentation and Design Considerations**	7-1
	7.1	Introduction	7-1
	7.2	The Experimental Apparatus	7-5
	7.3	Examining the Repeatability of the Test Rig	7-5
	7.4	Results	7-12
	7.4.1	Use of the Strobe Light	7-12
	7.4.2	Results of the Repeatability of the Test Rig	7-14
	7.4.3	Additional Experimental Work and Qualitative Observations	7-15
	7.5	Non-Cavitating Multiple Orifice Plate Arrangements	7-24
	7.6	Conclusion	7-24

Chapter 8		**Experimental Design of the Venturi Test Circuit and Preliminary Analysis of the Test Data**	8-1
	8.1	Aims and Overview	8-1
	8.2	Test Rig and Experiment Design	8-2
	8.3	Results, Preliminary Data Analysis and a Critique of Experimental Method	8-4
	8.4	Some Final Comments	8-17
Chapter 9		**Theoretical Analysis**	9-1
	9.1	Introduction	9-1
	9.2	Fourier Analysis of Voidage Fraction Fluctuations	9-3
Chapter 10		**Analysis of Multiple Orifice Plate Data**	10-1
	10.1	Introduction	10-1
	10.2	Theoretical Considerations	10-3
	10.2.1	Plates Spaced Equal to or Greater Than Two Pipe Diameters	10-3
	10.2.2	Plates Spaced Less Than Two Pipe Diameters	10-8
	10.3	Analysis of Multiple Orifice Plate Results - Two Pipe Diameters Spacing	10-11
	10.4	Analysis of Multiple Orifice Plate Results - 5 mm Spacing	10-16
	10.5	A Design Methodology for Multiple Orifice Plate Arrays	10-18
Chapter 11		**Conclusion and Recommendations**	11-1
	11.1	Introduction	11-2
	11.2	Fundamental Research and Industry	11-6
	11.3	Development of a Viable High Pressure Liquid Letdown Device	11-11
	11.4	Recommendations	11-12
	11.4.1	Orifice Plates	11-13
	11.4.2	Ultrasonic Instrumentation	11-15
	11.4.3	Venturis and Modern Technology	11-16
	11.5	Summary	11-18
Appendix A		Experimental Test Results of the Multiple Orifice Plate Test Rig	A-1
Appendix B		Summary of Analysis of Results Calculations for Chapter 10	AB-1
Appendix C		Summary of Data used for Graphs 8.3.25 and 8.3.26.	C-1
Bibliography			B-1

Nomenclature

symbol	description	units
a	average amplitude	m
a_f	amplitude of low frequency fluctuation component	m
A	Venturi cross sectional area	m^2
A_u	Venturi cross sectional area at throat exit	m^2
c	velocity of sound in liquid	$m.s^{-1}$
c_g	velocity of sound in gas	$m.s^{-1}$
C	. concentration of dissolved gases in the liquid	mol ratio
	. coefficient of discharge	-
C_R	overall coefficient of recovery of velocity pressure	
	measured from the cavitation zone to the resorber	-
C_S	saturation concentration of the dissolved gases in the liquid	mol ratio
d	diameter of orifice	m
d_b	bubble diameter	mm
D	upstream internal pipe diameter	m
f	frequency	Hz
f_b	bubble natural frequency	Hz
f_{cav}	cavitation cloud natural frequency	Hz
f_f	frequency of low frequency component	Hz
f_{liq}	natural frequency of liquid portion of venturi loop	Hz
h'	small pressure oscillation	Pa

symbol	description	units
H	cavitation cloud pressure in terms of hydraulic head	m
H	Henry's law coefficient	m^{-1}
$\overline{H}$	average cavitation cloud pressure in terms of hydraulic head	m
k	uniform equivalent roughness	m
k_L	liquid film coefficient	$m.s^{-1}$
L_{cav}	cavitation cloud length	m
L_n	nth pipe length	m
m	number of venturi loop pipes in series	-
p	pressure in the liquid	Pa
p_g	pressure of the gas in the bubble	Pa
p_g	gas partial pressure	Pa
p_t	threshold pressure for cavitation inception	Pa
p_v	vapour partial pressure	Pa
p_∞	pressure in the liquid	Pa
P	cavitation cloud pressure; pressure at the bubble wall	Pa
P_1	upstream pressure	Pa
P_2	downstream pressure	Pa
P_L	liquid pressure	Pa
P_r	downstream reference pressure	Pa
P_{sat}	saturation pressure	Pa
P_v	vapour pressure	Pa
$\acute{q}$	small flowrate oscillation	$m^3.s^{-1}$

symbol	description	units
q_m	mass rate of flow	$kg.s^{-1}$
q_v	volume rate of flow	$m^3.s^{-1}$
Q	volume flowrate	$m^3.s^{-1}$
$\overline{Q}$	average flowrate	$m^3.s^{-1}$
R	bubble radius	m
$\acute{R}$	critical radius for nucleation	m
R_1	radius of a bubble as it enters the resorber	m
R_c	radius of the ring of contact between the interface and the wall of the crevice	m
Re	Reynold's number	-
S_{cav}	wave propagation speed in cavitation cloud	$m.s^{-1}$
S_g	wave propagation speed in gas-liquid mixture	$m.s^{-1}$
$S_{liq\ n}$	wave propagation speed in liquid for *n*th pipe	$m.s^{-1}$
S_v	wave propagation speed in vapour-liquid mixture	$m.s^{-1}$
t	time variable	s
T	water temperature	°C
T_L	liquid temperature	°C
v	velocity in venturi throat	$m.s^{-1}$
V	velocity	$m.s^{-1}$
x	venturi longitudinal coordinate	m
x_d	coordinate value of cavitation cloud downstream interface	m
x_u	coordinate value of cavitation cloud upstream interface	m

symbol	description	units
α	gas concentration (volume)	-
β	. crevice half angle	radians
	. diameter ratio $\beta = \frac{d}{D}$	-
γ	. ratio of specific heats	-
	. specific density of water	-
Δp	differential pressure	Pa
$\Delta\varpi$	pressure loss	Pa
μ	dynamic viscosity of the fluid	Pa.s
ν	kinematic viscosity of the fluid	$m^2.s^{-1}$
ρ	density	$kg.m^{-3}$
ρ_{cav}	cavitation cloud density	$kg.m^{-3}$
ρ_{gl}	gas-liquid mixture density	$kg.m^{-3}$
σ	cavitation number; surface tension	-
σ_{inc}	cavitation number for inception point	-
σ_{res}	cavitation number for cavitation resonance	-