

TABLE OF CONTENTS

Foreword by Dr. Hiroharu KATO	XIII
Preface	XV
Symbols	XIX
1. Introduction – The main features of cavitating flows	1
1.1. The physical phenomenon.....	1
1.1.1. Definition	1
1.1.2. Vapor pressure	2
1.1.3. The main forms of vapor cavities	4
1.2. Cavitation in real liquid flows.....	5
1.2.1. Cavitation regimes.....	5
1.2.2. Typical situations favorable to cavitation.....	5
1.2.3. The main effects of cavitation in hydraulics	6
1.3. Specific features of cavitating flow	7
1.3.1. Pressure and pressure gradient.....	7
1.3.2. Liquid-vapor interfaces.....	8
1.3.3. Thermal effects	10
1.3.4. Some typical orders of magnitude	10
1.4. Non-dimensional parameters	10
1.4.1. Cavitation number σ_v	10
1.4.2. Cavitation number at inception, σ_{vi}	11
1.4.3. Relative underpressure of a cavity, σ_c	12
1.5. Some historical aspects	13
References	14
2. Nuclei and cavitation	15
2.1. Introduction.....	15
2.1.1. Liquid tension	15
2.1.2. Cavitation nuclei.....	15
2.2. Equilibrium of a nucleus	17
2.2.1. Equilibrium condition [BLAKE 1949]	17
2.2.2. Stability and critical pressure of a nucleus	18
2.2.3. Nucleus evolution in a low pressure region.....	20
2.3. Heat and mass diffusion	21
2.3.1. The thermal behavior of the gas content.....	21
2.3.2. Gas diffusion and nucleus stability	23

2.4.	Nucleus population	27
2.4.1.	Measurement methods.....	27
2.4.2.	Conditions for inception of bubble cavitation	30
	References	32
3.	The dynamics of spherical bubbles	35
3.1.	Basic equations	35
3.1.1.	Introduction.....	35
3.1.2.	Assumptions.....	35
3.1.3.	Boundary and initial conditions	36
3.1.4.	RAYLEIGH-PLESSET equation	36
3.1.5.	Interpretation of the RAYLEIGH-PLESSET equation in terms of energy balance	37
3.2.	The collapse of a vapor bubble	38
3.2.1.	Assumptions.....	38
3.2.2.	The interface velocity	38
3.2.3.	The pressure field	40
3.2.4.	Remark on the effect of surface tension	41
3.3.	The explosion of a nucleus.....	42
3.3.1.	The interface velocity	42
3.3.2.	The equilibrium case ($p_\infty = p_{\infty 0}$).....	43
3.3.3.	The case of nucleus growth ($p_\infty < p_{\infty 0}$)	43
3.3.4.	Dynamic criterion	44
3.3.5.	Remark on two particular cases	45
3.4.	The effect of viscosity	46
3.4.1.	Linear oscillations of a bubble	46
3.4.2.	Effect of viscosity on explosion or collapse of bubbles.....	46
3.5.	Non-linear oscillations of a bubble	47
3.6.	Scaling considerations	48
3.6.1.	Non-dimensional form of the RAYLEIGH-PLESSET equation	48
3.6.2.	Characteristic time scales of the RAYLEIGH-PLESSET equation	49
3.6.3.	Qualitative discussion of the RAYLEIGH-PLESSET equation	50
3.6.4.	Case of a transient bubble near a foil.....	51
3.7.	Stability of the spherical interface	53
	References	55
4.	Bubbles in a non-symmetrical environment	57
4.1.	Introduction.....	57
4.2.	Motion of a spherical bubble in a liquid at rest	57
4.2.1.	Translation of a solid sphere in a liquid at rest.....	57
4.2.2.	Translation with simultaneous volume variations.....	58
4.2.3.	Application to bubbles.....	59
4.3.	Non-spherical bubble evolution	60

4.3.1. Principle of PLESSET-CHAPMAN numerical modeling.....	60
4.3.2. Some general results.....	61
4.3.3. BLAKE's analytical approach.....	64
4.4. The path of a spherical bubble	67
References	71
Appendix to section 4.3.3	72
5. Further insights into bubble physics.....	77
5.1. The effect of compressibility.....	77
5.1.1. TAIT's equation of state.....	77
5.1.2. Basic equations	78
5.1.3. The quasi acoustic solution [HERRING 1941 & TRILLING 1952]	79
5.1.4. The GILMORE approach (1952)	80
5.2. Bubble noise.....	83
5.2.1. Basic equations	83
5.2.2. Weak bubble oscillations.....	84
5.2.3. Noise of a collapsing bubble	85
5.3. Some thermal aspects	86
5.3.1. The idea of thermal delay.....	86
5.3.2. BRENNEN's analysis (1973)	89
5.4. A typical numerical solution	92
References	95
Appendix to section 5.1.3	96
6. Supercavitation.....	97
6.1. Physical aspects of supercavities	98
6.1.1. Cavity pressure	98
6.1.2. Cavity detachment	98
6.1.3. Cavity closure	101
6.1.4. Cavity length.....	102
6.2. Supercavity flow modeling using steady potential flow theory.....	105
6.2.1. The main parameters	105
6.2.2. Equations and boundary conditions	106
6.2.3. Cavity closure models	107
6.2.4. Overview of calculation techniques.....	108
6.3. Typical results	110
6.3.1. Infinite cavity behind a flat plate in an infinite flow field	110
6.3.2. Finite cavity behind a symmetrical body in an infinite flow field	111
6.3.3. Finite cavity behind a circular arc in an infinite flow field.....	112
6.3.4. Variation of lift and drag coefficients with cavity underpressure.....	113
6.3.5. Effect of submersion depth on the slope of the curve $C_L(\alpha)$	114
6.4. Axisymmetric cavities	115
6.4.1. The GARABEDIAN asymptotic solution for steady supercavities.....	115

6.4.2. Momentum balance and drag	116
6.4.3. Approximate, analytic solution for steady supercavities	117
6.4.4. Unsteady axisymmetric supercavities.....	121
6.5. Specific problems	124
6.5.1. Unsteady 2D supercavities	124
6.5.2. Compressible effects in supercavitating flows	125
References	126
Appendix: singular behavior at detachment.....	129
7. Partial cavities.....	131
7.1. Partial cavities on two-dimensional foils.....	131
7.1.1. Main patterns	131
7.1.2. Cavity closure	133
7.1.3. Cavity length.....	134
7.1.4. Three-dimensional effects due to an inclination of the closure line	135
7.1.5. Multiple shedding on 2D hydrofoils.....	137
7.2. Partial cavities in internal flows.....	138
7.3. The cloud cavitation instability.....	140
7.3.1. Conditions for the onset of the cloud cavitation instability	140
7.3.2. Global behavior	141
7.3.3. Pulsation frequency	143
7.3.4. Jet thickness	144
7.4. Wakes of partial cavities	145
7.4.1. Mean pressure distribution.....	145
7.4.2. Production of vapor bubbles	146
7.4.3. Pressure fluctuations.....	147
7.4.4. Wall pressure pulses at cavity closure	148
7.4.5. Scaling of pulse spectra.....	150
7.4.6. Main features of the noise emitted by partial cavities.....	152
7.5. Thermal effects in partial cavitation	153
7.5.1. The STEPANOFF B-factor.....	153
7.5.2. The entrainment method.....	154
7.6. System instability	159
7.7. Partial cavity flow modeling	161
References	162
Appendix: sonic velocity in a liquid/vapor mixture with phase change	165
8. Bubbles and cavities on two-dimensional foils.....	169
8.1. Attached cavitation	169
8.1.1. Cavitation inception on a circular cylinder.....	169
8.1.2. Cavity patterns on a two-dimensional foil.....	172
8.1.3. Boundary layer features on a slender foil	174
8.1.4. The connection between laminar separation and detachment	176

8.2. Traveling bubble cavitation.....	179
8.2.1. The effect of water quality and nuclei seeding.....	179
8.2.2. Scaling law for developed bubble cavitation.....	182
8.2.3. Saturation	184
8.3. Interaction between bubbles and cavities	186
8.3.1. Effect of exploding bubbles on a cavity	186
8.3.2. Critical nuclei concentration for transition between attached cavitation and traveling bubble cavitation.....	187
8.3.3. The prediction of cavitation patterns	188
8.4. Roughness and cavitation inception.....	189
References	191
9. Ventilated supercavities	193
9.1. Two-dimensional ventilated cavities	193
9.1.1. Ventilated hydrofoils.....	193
9.1.2. The main parameters	194
9.1.3. Cavity length.....	196
9.1.4. Air flowrate and cavity pressure	199
9.1.5. Pulsation regimes.....	202
9.1.6. Pulsation frequency	205
9.1.7. Concerning the pulsation mechanism.....	206
9.2. Axisymmetric ventilated supercavities.....	209
9.2.1. Different regimes of ventilated cavities.....	209
9.2.2. Gas evacuation by toroidal vortices.....	210
9.2.3. Deformation of the cavity axis by gravity	210
9.2.4. Gas evacuation by two hollow tube vortices	211
9.3. Analysis of pulsating ventilated cavities	214
9.3.1. Basic equations	214
9.3.2. Analysis of the pressure fluctuation equation.....	217
9.3.3. Comparison with experiments.....	218
References	220
10. Vortex cavitation	223
10.1. Theoretical results.....	223
10.1.1. Basic vorticity theorems.....	223
10.1.2. The main effects of cavitation on rotational flows.....	224
10.1.3. Axisymmetric cavitating vortex.....	226
10.1.4. Toroidal cavitating vortex	227
10.2. The non-cavitating tip vortex	231
10.2.1. Tip vortex formation.....	231
10.2.2. Vortex models in viscous fluids.....	232
10.2.3. Tip vortex structure	234
10.3. Cavitation in a tip vortex	239
10.3.1. Scaling laws for cavitation inception.....	239

10.3.2. Correlation of cavitation data with the lift coefficient	240
10.3.3. Effect of nuclei content	242
10.3.4. Effect of confinement.....	244
References	245
11. Shear cavitation	247
11.1. Jet cavitation	248
11.1.1. Some experimental results	248
11.1.2. Some elements of analysis of jet cavitation.....	251
11.2. Wake cavitation	252
11.2.1. Cavitation inception in the wake of circular discs	252
11.2.2. Modeling of wake cavitation inception	253
11.2.3. Cavitation in the wake of a two-dimensional wedge	256
References	262
12. Cavitation erosion	265
12.1. Empirical methods.....	266
12.2. Some global results.....	267
12.2.1. Influence of flow velocity	267
12.2.2. Time evolution of mass loss rate.....	267
12.2.3. Miscellaneous comments	268
12.3. Basic hydrodynamic mechanisms of energy concentration.....	269
12.3.1. Collapse and rebound of a spherical bubble	269
12.3.2. Microjet.....	269
12.3.3. Collective collapse.....	270
12.3.4. Cavitating vortices.....	270
12.4. Aggressiveness of a cavitating flow	271
12.4.1. Aggressiveness of a collapsing bubble	271
12.4.2. Pitting tests.....	273
12.4.3. Force measurements	275
12.4.4. Scaling laws for flow aggressiveness	278
12.4.5. Asymptotic behavior of pitting rate at high velocities	280
12.5. Insight into the material response	282
12.5.1. Interaction between the liquid flow and a solid wall	282
12.5.2. Cavitation erosion and strain rate.....	283
12.5.3. Correlation of volume loss with impact energy	284
12.5.4. Phenomenological model for mass loss prediction	285
References	289
Index	293