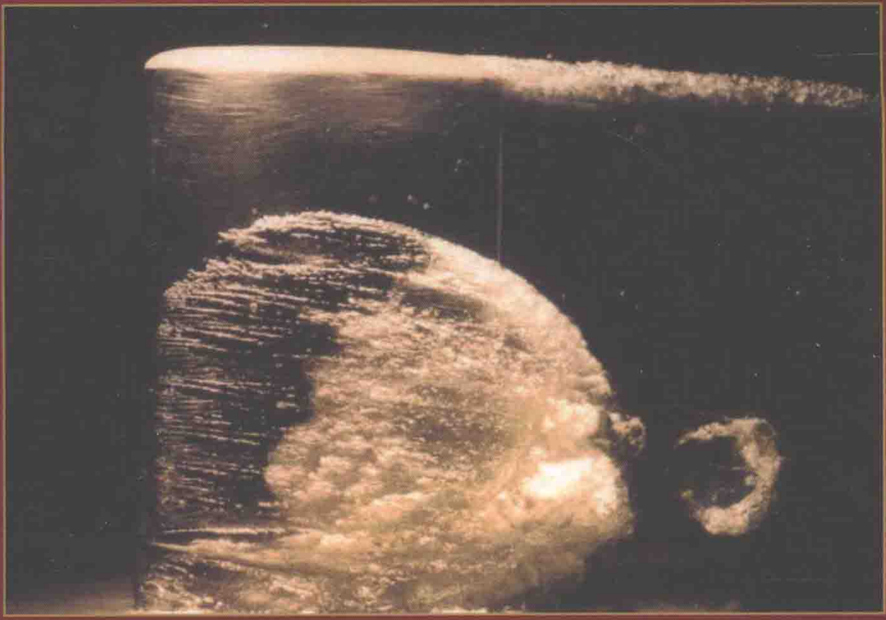
CHRISTOPHER EARLS BRENNEN



CAVITATION AND BUBBLE DYNAMICS

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CAVITATION AND BUBBLE DYNAMICS

Cavitation and Bubble Dynamics deals with the fundamental physical processes of bubble dynamics and the phenomenon of cavitation. It is ideal for graduate students and research engineers and scientists; a basic knowledge of fluid flow and heat transfer is assumed. The analytical methods presented are developed from basic principles.

The book begins with a chapter on nucleation and describes both the theory and observations in flowing and non-flowing systems. Three chapters provide a systematic treatment of the dynamics and growth, collapse, or oscillation of individual bubbles in otherwise quiescent fluids. The following chapters summarize the motion of bubbles in liquids; describe some of the phenomena that occur in homogeneous bubbly flows, with emphasis on cloud cavitation; and summarize some of the experimental observations of cavitating flows. The last chapter provides a review of free streamline methods used to treat separated cavity flows with large attached cavities.

Christopher Earls Brennen is the Richard and Dorothy M. Hayman Professor of Mechanical Engineering Emeritus in the Faculty of Engineering and Applied Science at the California Institute of Technology. He has published more than 200 refereed articles and is especially well known for his research on cavitation, turbomachinery, and multiphase flows. He is the author of three textbooks – *Fundamentals of Multiphase Flows*, *Hydrodynamics of Pumps*, and *Cavitation and Bubble Dynamics* – and has edited several others. Among his many honors and positions are UN Consultant to India (1980); NASA New Technology Award (1980); ASME Centennial Medallion (1980); Chair ASME Fluids Engineering Division (1984–1985); ASME R. T. Knapp Award for Best Paper (1978 and 1981); Caltech Student Award for teaching excellence (1982, 1995, 1996); Christensen Fellow, St. Catherine's College, Oxford (1992); Fellow of the Japan Society for Promotion of Science (1993); JSME Fluids Engineering Award (2002); and Vice-President of Student Affairs at Caltech.

"Where Alph, the sacred river, ran
Through caverns measureless to man ..."

Samuel Taylor Coleridge (1772–1834)

Preface

This book is intended as a combination of a reference book for those who work with cavitation or bubble dynamics and as a monograph for advanced students interested in some of the basic problems associated with this category of multiphase flows. A book like this has many roots. It began many years ago when, as a young postdoctoral Fellow at the California Institute of Technology, I was asked to prepare a series of lectures on cavitation for a graduate course cum seminar series. It was truly a baptism by fire, for the audience included three of the great names in cavitation research, Milton Plesset, Allan Acosta, and Theodore Wu, none of whom readily accepted superficial explanations. For that, I am immensely grateful. The course and I survived, and it evolved into one part of a graduate program in multiphase flows.

There are many people to whom I owe a debt of gratitude for the roles they played in making this book possible. It was my great good fortune to have known and studied with six outstanding scholars, Les Woods, George Gadd, Milton Plesset, Allan Acosta, Ted Wu, and Rolf Sabersky. I benefited immensely from their scholarship and their friendship. I also owe much to my many colleagues in the American Society of Mechanical Engineers whose insights fill many of the pages of this monograph. The support of my research program by the Office of Naval Research is also greatly appreciated. And, of course, I feel honored to have worked with an outstanding group of graduate students at Caltech, including Sheung-Lip Ng, Kiam Oey, David Braisted, Luca d'Agostino, Steven Ceccio, Sanjay Kumar, Douglas Hart, Yan Kuhn de Chizelle, Beth McKenney, Zhenhuan Liu, Yi-Chun Wang, Ronald J. Franz, Tricia A. Waniewski, Fabrizio d'Auria, Garrett E. Reisman, Mark E. Duttweiler, and Keita Ando, all of whom studied aspects of cavitating flows.

The original edition of this book was published by Oxford University Press in 1995. This corrected edition is published by Cambridge University Press and I wish to express my sincerest thanks to Peter Gordon of Cambridge for his expert help and encouragement on this and other projects.

This edition is dedicated with great love and deep gratitude to my wife and lifelong friend, Barbara.

Pasadena, Calif. C.E.B.
January 2013

Nomenclature

Roman Letters

a	Amplitude of wave-like disturbance
A	Cross-sectional area or cloud radius
b	Body half-width
B	Tunnel half-width
c	Concentration of dissolved gas in liquid, speed of sound, chord
c_k	Phase velocity for wavenumber k
c_P	Specific heat at constant pressure
C_D	Drag coefficient
C_{ij}	Lift/drag coefficient matrix
C_L	Lift coefficient
$\tilde{C}_{Lh}, \tilde{C}_{Lp}$	Unsteady lift coefficients
C_M	Moment coefficient
$\tilde{C}_{Mh}, \tilde{C}_{Mp}$	Unsteady moment coefficients
C_p	Coefficient of pressure
C_{pmin}	Minimum coefficient of pressure
d	Cavity half-width, blade thickness to spacing ratio
D	Mass diffusivity
f	Frequency in Hz
f	Complex velocity potential, $\phi + i\psi$
f_N	A thermodynamic property of the phase or component, N
Fr	Froude number
g	Acceleration due to gravity
g_N	A thermodynamic property of the phase or component N
g_x	Component of the gravitational acceleration in direction x
$\mathcal{G}(f)$	Spectral density function of sound
h	Specific enthalpy, wetted surface elevation, blade tip spacing
H	Henry's law constant
Hm	Haberman-Morton number, normally $g\mu^4/\rho S^3$
i,j,k	Indices

i	Square root of -1 in free streamline analysis
I	Acoustic impulse
I^*	Dimensionless acoustic impulse, $4\pi I\mathcal{R}/\rho_L U_\infty R_H^2$
I_{Ki}	Kelvin impulse vector
j	Square root of -1
k	Boltzmann's constant, polytropic constant or wavenumber
k_N	Thermal conductivity or thermodynamic property of N
K_G	Gas constant
K_{ij}	Added mass coefficient matrix, $M_{ij}/\frac{4}{3}\rho\pi R^3$
Kc	Keulegan-Carpenter number
Kn	Knudsen number, $\lambda/2R$
ℓ	Typical dimension in the flow, cavity half-length
L	Latent heat of vaporization
m	Mass
m_G	Mass of gas in bubble
m_p	Mass of particle
M_{ij}	Added mass matrix
n	Index used for harmonics or number of sites per unit area
$N(R)$	Number density distribution function of R
$\dot{N}_E$	Cavitation event rate
Nu	Nusselt number
p	Pressure
p_a	Radiated acoustic pressure
p_s	Root mean square sound pressure
p_S	A sound pressure level
p_G	Partial pressure of gas
P	Pseudo-pressure
Pe	Peclet number, usually WR/α_L
q	Magnitude of velocity vector
q_c	Free surface velocity
Q	Source strength
r	Radial coordinate
R	Bubble radius
R_B	Equivalent volumetric radius, $[3\tau/4\pi]^{\frac{1}{3}}$
R_H	Headform radius
R_M	Maximum bubble radius
R_N	Cavitation nucleus radius
R_P	Nucleation site radius
$\mathcal{R}$	Distance to measurement point
Re	Reynolds number, usually $2WR/\nu_L$
s	Coordinate measured along a streamline or surface
s	Specific entropy
S	Surface tension

St	Strouhal number, $2fR/W$
t	Time
t_R	Relaxation time for relative motion
t_*	Dimensionless time, t/t_R
T	Temperature
u, v, w	Velocity components in Cartesian coordinates
u_i	Velocity vector
u_r, u_θ	Velocity components in polar coordinates
u'	Perturbation velocity in x direction, $u - U_\infty$
U, U_i	Fluid velocity and velocity vector in absence of particle
U_∞	Velocity of upstream uniform flow
V, V_i	Absolute velocity and velocity vector of particle
w	Complex conjugate velocity, $u - iv$
w	Dimensionless relative velocity, W/W_∞
W	Relative velocity of particle
W_∞	Terminal velocity of particle
We	Weber number, $2\rho W^2 R/S$
z	Complex position vector, $x + iy$

Greek Letters

α	Thermal diffusivity, volume fraction, angle of incidence
β	Cascade stagger angle, other local variables
γ	Ratio of specific heats of gas
Γ	Circulation, other local parameters
δ	Boundary layer thickness or increment of frequency
δ_D	Dissipation coefficient
δ_T	Thermal boundary layer thickness
ϵ	Fractional volume
ζ	Complex variable, $\xi + i\eta$
η	Bubble population per unit liquid volume
η	Coordinate in ζ-plane
θ	Angular coordinate or direction of velocity vector
κ	Bulk modulus of compressibility
λ	Mean free path of molecules or particles
Λ	Accommodation coefficient
μ	Dynamic viscosity
ν	Kinematic viscosity
ξ	Coordinate in ζ-plane
ϖ	Logarithmic hodograph variable, $\chi + i\theta$
ρ	Density
σ	Cavitation number
σ_c	Choked cavitation number

σ_{ij}	Stress tensor
Σ	Thermal parameter in bubble growth
τ	Volume of particle or bubble
ϕ	Velocity potential
ϕ'	Acceleration potential
φ	Fractional perturbation in bubble radius
Φ	Potential energy
χ	$log(q_c/\lvert w\rvert)$
ψ	Stream function
ω	Radian frequency
ω^*	Reduced frequency, $\omega c/U_\infty$

Subscripts

On any variable, Q:

Q_o	Initial value, upstream value, or reservoir value
Q_1, Q_2, Q_3	Components of Q in three Cartesian directions
Q_1, Q_2	Values upstream and downstream of a shock
Q_∞	Value far from the bubble or in the upstream flow
Q_B	Value in the bubble
Q_C	Critical values and values at the critical point
Q_E	Equilibrium value or value on the saturated liquid/vapor line
Q_G	Value for the gas
Q_i	Components of vector Q
Q_{ij}	Components of tensor Q
Q_L	Saturated liquid value
Q_n	Harmonic of order n
Q_P	Peak value
Q_S	Value on the interface or at constant entropy
Q_V	Saturated vapor value
Q_*	Value at the throat

Superscripts and Other Qualifiers

On any variable, Q:

$\bar{Q}$	Mean value of Q or complex conjugate of Q
$\tilde{Q}$	Complex amplitude of oscillating Q
$\dot{Q}$	Time derivative of Q
$\ddot{Q}$	Second time derivative of Q
$\hat{Q}(s)$	Laplace transform of $Q(t)$
$\breve{Q}$	Coordinate with origin at image point
Q^+, Q^-	Values of Q on either side of a cut in a complex plane

δQ	Small change in Q
$Re\{Q\}$	Real part of Q
$Im\{Q\}$	Imaginary part of Q

Units

In most of this book, the emphasis is placed on the nondimensional parameters that govern the phenomenon being discussed. However, there are also circumstances in which we shall utilize dimensional thermodynamic and transport properties. In such cases the International System of Units is employed using the basic units of mass (kg), length (m), time (s), and absolute temperature (K); where it is particularly convenient units such as a joule (kg m^2/s^2) are occasionally used.

Contents

1 Phase Change, Nucleation, and Cavitation

1.1 Introduction

This first chapter will focus on the mechanisms of formation of two-phase mixtures of vapor and liquid. Particular attention will be given to the process of the creation of vapor bubbles in a liquid. In doing so we will attempt to meld together several overlapping areas of research activity. First, there are the studies of the fundamental physics of nucleation as epitomized by the books of Frenkel (1955) and Skripov (1974). These deal largely with very pure liquids and clean environments in order to isolate the behavior of pure liquids. On the other hand, most engineering systems are impure or contaminated in ways that have important effects on the process of nucleation. The later part of the chapter will deal with the physics of nucleation in such engineering environments. This engineering knowledge tends to be divided into two somewhat separate fields of interest, cavitation and boiling. A rough but useful way of distinguishing these two processes is to define cavitation as the process of nucleation in a liquid when the pressure falls below the vapor pressure, while boiling is the process of nucleation that ocurs when the temperature is raised above the saturated vapor/liquid temperature. Of course, from a basic physical point of view, there is little difference between the two processes, and we shall attempt to review the two processes of nucleation simultaneously. The differences in the two processes occur because of the different complicating factors that occur in a cavitating flow on the one hand and in the temperature gradients and wall effects that occur in boiling on the other hand. The last sections of this first chapter will dwell on some of these complicating factors.

1.2 The Liquid State

Any discussion of the process of phase change from liquid to gas or vice versa must necessarily be preceded by a discussion of the liquid state. Though simple kinetic theory understanding of the gaseous state is sufficient for our purposes, it is necessary to dwell somewhat longer on the nature of the liquid state. In doing so we shall follow Frenkel (1955), though it should also be noted that modern studies are usually couched in terms of statistical mechanics (for example, Carey 1992).

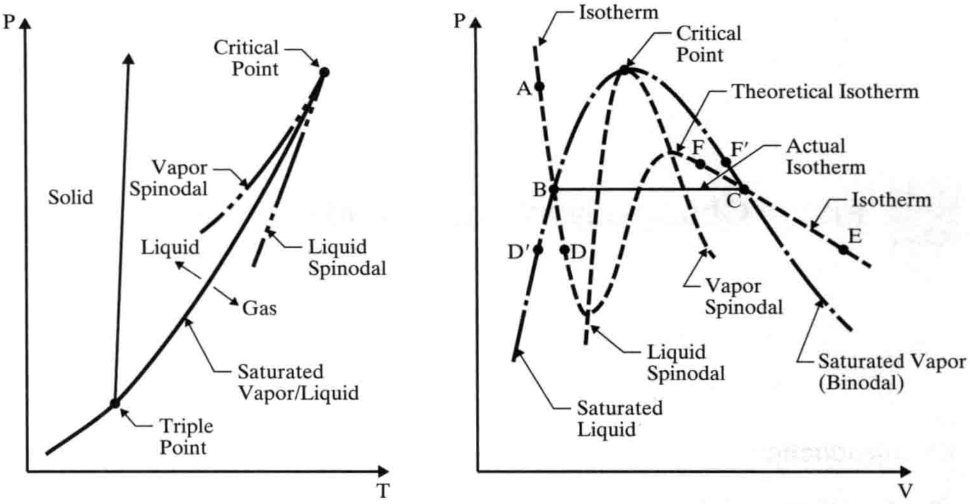

Figure 1.1 Typical phase diagrams.

Our discussion will begin with typical phase diagrams, which, though idealized, are relevant to many practical substances. Figure 1.1 shows typical graphs of pressure, p, temperature, T, and specific volume, V, in which the state of the substance is indicated. The triple point is that point in the phase diagram at which the solid, liquid, and vapor states coexist; that is to say the substance has three alternative stable states. The saturated liquid/vapor line (or binodal) extends from this point to the critical point. Thermodynamically it is defined by the fact that the chemical potentials of the two coexisting phases must be equal. On this line the vapor and liquid states represent two limiting forms of a single "amorphous" state, one of which can be obtained from the other by isothermal volumetric changes, leading through intermediate but unstable states. To quote Frenkel (1955), "Owing to this instability, the actual transition from the liquid state to the gaseous one and vice versa takes place *not* along a *theoretical* isotherm (dashed line, right, Figure 1.1), but along a horizontal isotherm (solid line), corresponding to the splitting up of the original homogeneous substance into two different coexisting phases..." The critical point is that point at which the maxima and minima in the theoretical isotherm vanish and the discontinuity disappears.

The line joining the maxima in the theoretical isotherms is called the vapor spinodal line; the line joining the minima is called the liquid spinodal line Clearly both spinodals end at the critical point. The two regions between the spinodal lines and the saturated (or binodal) lines are of particular interest because the conditions represented by the theoretical isotherm within these regions can be realized in practice under certain special conditions. If, for example, a pure liquid at the state A (Figure 1.1) is depressurized at constant temperature, then several things may happen when the pressure is reduced below that of point B (the saturated vapor pressure). If sufficient numbers of nucleation sites of sufficient size are present (and this needs further discussion later) the liquid will become vapor as the state moves