LIQUID–VAPOR PHASE-CHANGE PHENOMENA

An Introduction to the Thermophysics of Vaporization and Condensation Processes in Heat Transfer Equipment

Van P. Carey

Series in Chemical and Mechanical Engineering

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TAYLOR & FRANCIS

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LIQUID–VAPOR PHASE-CHANGE PHENOMENA

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G. F. Hewitt and C. L. Tien, *Editors*

Carey, Liquid–Vapor Phase-Change Phenomena: An Introduction to the Thermophysics of Vaporization and Condensation Processes in Heat Transfer Equipment

FORTHCOMING TITLES

Banerjee, Chemical Plant Safety
Kemp, Pinch Technology and Process Integration

To my daughter, Elizabeth Megan, and my son, Sean Wesley, whose curiosity is a constant reminder that eagerness to explore and the desire to understand are essential elements of the human spirit.

PREFACE

This text was inspired by the need for instructional material for a graduate-level course on heat transfer with phase change taught on a yearly basis in mechanical engineering at the University of California at Berkeley. Several books published over the last 20 years have summarized the state-of-the-art in boiling and/or condensation phenomena. However, these texts invariably were less than ideal for instructional purposes because they focused almost entirely on the heat transfer and fluid mechanics aspects of boiling and condensation. They generally provided little, if any, treatment of the nonequilibrium thermodynamics and interfacial phenomena that frequently play central roles in such processes. In assembling this text, the goal was to provide a coherent presentation of the nonequilibrium thermodynamics and interfacial phenomena associated with vaporization and condensation processes, as well as the heat transfer and fluid flow mechanisms.

This book focuses on basic elements of condensation and vaporization processes. Those who work in the field know that the number of technical reports, papers, and books dealing with boiling and condensation processes is enormous. Coverage of all the work in these areas is clearly impossible within the limited space in a basic text. In the interest of conciseness, the tone of the presentation in this book is therefore illustrative rather than exhaustive. In most cases, the basic physical mechanisms associated with a particular phase-change phenomenon are described in detail, followed by a representative sample of the best models applicable to the circumstances of interest. Throughout the text, the importance of the basic phenomena to a wide variety of applications is discussed. However, space limitations precluded extensive discussion of special features that arise in some applications.

The sequence of material in this book was chosen to facilitate instruction at the advanced undergraduate or graduate level in mechanical or chemical engineering. The chapters in Part 1 of the book deal entirely with nonequilibrium thermodynamics and interfacial phenomena. If covered first, this material provides a useful foundation on which the later discussions of boiling and condensation phenomena can build. Part 2 covers boiling and condensation processes on the external surfaces of a body exposed to an extensive ambient. The material on internal flow boiling and condensation in Part 3 follows that in Part 2 because many of the concepts that apply to external condensation and boiling apply in a modified form to convective boiling or condensation in tubes.

Part 4 is a chapter that covers some additional special topics and applications. This material can be presented most efficiently after an understanding of the basic physics is attained from study of preceding chapters. A special effort has been made to incorporate material on the enhancement of boiling and condensation heat transfer, because engineers involved with such processes most often want to enhance the transport. The progressive flow of ideas provided by the book's structure should also make it useful to practicing engineers who wish to gain a further understanding of the thermophysics of vaporization and condensation processes through individual study.

As noted at the outset, this text evolved from material used to teach a graduate-level class in phase-change heat transfer at Berkeley. The author is indebted to the numerous students in that class who questioned and criticized the class notes that preceded this text. The author is also grateful to Professor John H. Lienhard, Professor Dennis O'Neal, and Professor Ralph Seban for their insightful comments on the early manuscript version of this text. An expression of appreciation is also due to the many investigators who have contributed to this area over the past 50 years. It is only through their combined efforts that a clear overview of this area is possible. Finally, the author wishes to express his thanks for the understanding and patience of his family during the many hours of work required to assemble the material in this text.

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Berkeley, California

NOMENCLATURE

A	surface or cross-sectional area
A_f	fin area
A_o	tube open area
A_p	prime surface area
b	fin height
Bo	Bond number $[=g(\rho_l - \rho v)L_B^2/\sigma$ (where the length scale L_B depends on the circumstances of interest)]
	boiling number $(=q''/Gh_{lv})$
c_{pl}	liquid specific heat
c_{pv}	vapor specific heat
Co	convection number $\{=[(1 - x)/x]^{0.8}[\rho_v/\rho_l]^{0.5}\}$
d_d	bubble departure diameter
d_t	tube diameter
d_h	hydraulic diameter based on wetted perimeter
d_{hp}	hydraulic diameter based on heated perimeter
$(dP/dz)_{fr}$	frictional component of two-phase pressure gradient
$(dP/dz)_l$	pressure gradient for liquid flow alone through tube
$(dP/dz)_{lo}$	pressure gradient for entire flow as liquid through tube
$(dP/dz)_v$	pressure gradient for vapor flow alone through tube
D	tube diameter
D_C^*	binary diffusion coefficient for more volatile component
D_{AB}	binary diffusion coefficient for species A and B
E	mass fraction of liquid phase entrained in the core during annular flow
E''	rate of entrainment in mass of droplets per unit time per unit of wall area
E_{kin}	system kinetic energy
E_{pot}	system potential energy
f	bubble frequency
	friction factor

f_l	friction factor for liquid flowing alone in tube
f_v	friction factor for vapor flowing alone in tube
F	Helmholtz function $(= U - TS)$
	force
	Chen correlation parameter
F_{TD}	Taitel-Dukler flow regime parameter
Fr_{le}	Froude number $[= G^2/(\rho_l^2 gD)]$
g	gravitational acceleration
	specific Gibbs function
G	Gibbs function $(= H - TS)$
	mass flux through tube or channel
h	local heat transfer coefficient
$\bar{h}$	mean heat transfer coefficient
$\hat{h}$	specific enthalpy on per unit mass basis
h^*	mass transfer coefficient
h_l	heat transfer coefficient for the liquid phase flowing alone in the tube
h_{le}	heat transfer coefficient for entire flow as liquid
h_{lo}	heat transfer coefficient for entire flow as liquid
h_{lv}	latent heat of vaporization per unit mass
H_f	fin height
j_l	volume flux of liquid $[= G(1 - x)/\rho_l]$
j_v	volume flux of vapor $[Gx/\rho_v]$
J	flux of droplet or bubble embryos through size space
J^*	dimensionless droplet flux in size space
Ja	Jakob number [$= c_p\, \Delta T/h_{lv}$ (where the choices of c_p and ΔT depend on the circumstances of interest)]
k_B	Boltzmann constant $(= 1.3805 \times 10^{-23}$ J/K)
k_d	deposition coefficient in model of entrainment and deposition for annular flow
k_l	thermal conductivity of liquid
k_v	thermal conductivity of vapor
K_{TD}	Taitel-Dukler flow regime parameter
L	tube length
L_b	bubble or capillary length scale $\{= [\sigma/g(\rho_l - \rho_v)]^{1/2}\}$
L_f	fin length
m	mass of one molecule
$\dot{m}'$	mass flow rate of condensate in liquid film per unit width of surface
m''	mass flux
M	mass
$\bar{M}$	molecular weight
N_A	Avogadro's number $(= 6.02 \times 10^{26}$ molecules/kg mol)
N_l	number of liquid molecules per unit volume
N_n	number of embryos of n molecules at equilibrium per unit volume
P	pressure
P_c	critical pressure
P_l	ambient liquid pressure
$P_{pi}(T)$	saturation pressure of pure component i in mixture at temperature T

P_v	ambient vapor pressure
Pr_l	liquid Prandtl number
Pr_t	turbulent Prandtl number $(=\epsilon_M/\epsilon_H)$
Pr_v	vapor Prandtl number
q''	heat flux
q''_{cr}	critical heat flux
$q''_{\min}$	minimum heat flux on pool boiling curve
q''_{mkc}	maximum heat flux limit dictated by kinetic theory for condensation
q''_{mkv}	maximum heat flux limit dictated by kinetic theory for vaporization
$\dot{q}$	total heat transfer rate
Q^*	dimensionless heat flux $\{=[4q''L/d_h(G/\rho_{\mathrm{in}})h_{lv}][(\rho_l - \rho_v)/\rho_v\rho_l]\}$
R	ideal gas constant on a per unit mass basis
	liquid jet radius
$\bar{R}$	universal gas constant (= 8.3144 kJ/(kg mol K))
Re	Reynolds number
Re_F	film Reynolds number
Re_l	Reynolds number for liquid phase flowing alone $[=G(1 - x)d_h/\mu_l]$
Re_{le}	Reynolds number for entire flow as liquid $(=Gd_h/\mu_l)$
Re_{lo}	Reynolds number for entire flow as liquid $(=Gd_h/\mu_l)$
Re_L	film Reynolds number $(=4\dot{m}'/\mu_l)$
Re_v	Reynolds number for vapor phase flowing alone $(=Gxd_h/\mu_v)$
s	specific entropy
	distance between fins in an offset fin matrix
S	entropy
	supersaturation ratio $[=(P_v)_{\mathrm{SSL}}/P_{\mathrm{sat}}(T_v)]$
	suppression factor in Chen correlation
	slip ratio $(=u_v/u_l)$
Sc	Schmidt number $(=\nu/D_{AB})$
$\mathrm{Sp}l_s$	spreading coefficient $[=-(\partial F/\partial A_s l)]$
St	Stanton number $(=h/Gc_p)$
Su	subcooling number $\{=[c_{pl}(T_{\mathrm{sat}} - T_{\mathrm{in}})/h_{lv}][(\rho_l - \rho_v)/\rho_v]\}$
T	temperature
T_c	critical temperature
T_i	interface temperature
T_{in}	fluid temperature at tube inlet
T_{sat}	saturation temperature
T_{TD}	Taitel-Dukler flow regime parameter
T_w	wall temperature
u	specific internal energy
	velocity component in the x direction
u_l	liquid mean downstream velocity in two-phase flow $[=G(1 - x)/\rho_l(1 - \alpha)]$
u_v	vapor mean downstream velocity in two-phase flow $(=Gx/\rho_v\alpha)$
U	internal energy
UA	overall conductance of a heat transfer device (= $\dot{q}$ divided by the driving temperature difference)
v	specific volume

	velocity component in the y direction
v_c	critical volume
V	volume
	velocity
w	velocity component in the z direction
$\bar{w}$	mean distance between fins
W	mass flow rate
x	coordinate (downstream coordinate for external flows)
	mass quality
x_a	actual ratio of vapor mass flow rate to total mass flow rate
x_{crit}	dryout quality
x_e	equilibrium quality
X	Martinelli parameter $\{=[(dP/dz)_l/(dP/dz)_v]^{1/2}\}$
X_l	mole fraction of more volatile component in liquid phase
X_{li}	mole fraction of component i in liquid phase
	mole fraction of more volatile component at the liquid–vapor interface
X_{tt}	Martinelli parameter for turbulent-turbulent flow
X_v	mole fraction of more volatile component in vapor phase
X_{vi}	mole fraction of more volatile component in vapor phase at the liquid–vapor interface
y	coordinate, surface normal coordinate for external flows
	twisted-tape insert ratio of length for 180° twist to tube inside diameter
y^+	dimensionless y coordinate $(=y\sqrt{\tau_0/\rho_l}/\nu_l)$
z	coordinate (downstream coordinate for tube flows)
α	wave number
	void fraction
α_c	critical wave number
α_T	thermal diffusivity $(=k/\rho c_p)$
α_{Tl}	thermal diffusivity of liquid
α_{Tv}	thermal diffusivity of vapor
β	frequency
β_f	volume fraction of liquid flowing in liquid film on tube wall
$\beta_{\max}$	frequency of most rapidly growing disturbance
γ	multiplier in Baroczy correlation
δ	film thickness
δ^+	dimensionless film thickness $(=\delta\sqrt{\tau_0/\rho_l}/\nu_l)$
δ_f	fin thickness
δ_t	thermal boundary-layer thickness
ΔT_{vl}	temperature difference across liquid–vapor interface
ϵ	emissivity
ϵ_H	eddy diffusivity of heat for turbulent flow
ϵ_M	eddy diffusivity of momentum for turbulent flow
η_f	fin efficiency
θ	liquid contact angle
	angular coordinate
λ_c	critical wavelength
λ_D	most dangerous wavelength

μ	absolute viscosity
	chemical potential
μ_l	liquid viscosity
	liquid chemical potential
μ_v	vapor viscosity
	vapor chemical potential
ν_l	liquid kinematic viscosity
ν_v	vapor kinematic viscosity
ρ_l	liquid density
ρ_v	vapor density
σ	interfacial tension
$\hat{\sigma}$	accommodation coefficient
σ_{SB}	Stefan-Boltzmann constant ($=5.67 \times 10^{-8}$ W/m^2 K^4)
τ	shear stress
τ_i	shear stress at interface
τ_0	shear stress at wall
τ_w	shear stress at wall
ϕ_l	two-phase multiplier $\{=[(dP/dz)_{fr}/(dP/dz)_l]^{1/2}\}$
ϕ_{lo}	two-phase multiplier $\{=[(dP/dz)_{fr}/(dP/dz)_v]^{1/2}\}$
ϕ_v	two-phase multiplier $\{=[(dP/dz)_{fr}/(dP/dz)_v]^{1/2}\}$
Ω	vorticity
	angle between tube axis and horizontal

Subscripts

a	actual value
b	bulk
bp	bubble point
c	properties evaluated at the critical point
dp	dew point
ex	exit conditions
f	film
	fin
i	interface
in	inlet conditions
l	liquid
	corresponding to the liquid phase flowing alone
le	corresponding to the entire flow as liquid
	corresponding to liquid flow in equivalent separate cylinder
lo	corresponding to the entire flow as liquid
sat	corresponding to saturation conditions
SSL	supersaturation limit
v	vapor
	corresponding to the vapor phase flowing alone
ve	corresponding to vapor flow in equivalent separate cylinder
w	wall value
∞	far ambient conditions
0	wall value

CONTENTS