Second Edition

Boiling Heat Transfer and Two-Phase Flow

L. S. Tong and Y. S. Tang

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L. S. Tong, Ph.D.

Y. S. Tang, Ph.D.

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In Memory of Our Parents

PREFACE

Since the original publication of *Boiling Heat Transfer and Two-Phase Flow* by L. S. Tong almost three decades ago, studies of boiling heat transfer and two-phase flow have gone from the stage of blooming literature to near maturity. Progress undoubtedly has been made in many aspects, such as the modeling of two-phase flow, the evaluation of and experimentation on the forced-convection boiling crisis as well as heat transfer beyond the critical heat flux conditions, and extended research in liquid-metal boiling. This book reexamines the accuracy of existing, generally available correlations by comparing them with updated data and thereby providing designers with more reliable information for predicting the thermal hydraulic behavior of boiling devices. The objectives of this edition are twofold:

1. To provide engineering students with up-to-date knowledge about boiling heat transfer and two-phase flow from which a consistent and thorough understanding may be formed.
2. To provide designers with formulas for predicting real or potential boiling heat transfer behavior, in both steady and transient states.

The chapter structure remains close to that of the first edition, although significant expansion in scope has been made, reflecting the extensive progress advanced during this period. At the end of each chapter (except Chapter 1), additional, recent references are given for researchers' outside study.

Emphasis is on applications, so some judgments based on our respective experiences have been applied in the treatment of these subjects. Various workers from international resources are contributing to the advancement of this complicated field. To them we would like to express our sincere congratulations for their valuable contributions. We are much indebted to Professors C. L. Tien and G. F. Hewitt for their review of the preliminary manuscript. Gratitude is also due to the

editor Lynne Lachenbach as well as Holly Seltzer, Carolyn Ormes, and Lisa Ehmer for their tireless editing.

L. S. Tong
Gaithersburg, Maryland

Y. S. Tang
Bethel Park, Pennsylvania

PREFACE TO THE FIRST EDITION

In recent years, boiling heat transfer and two-phase flow have achieved worldwide interest, primarily because of their application in nuclear reactors and rockets. Many papers have been published and many ideas have been introduced in this field, but some of them are inconsistent with others. This book assembles information concerning boiling by presenting the original opinions and then investigating their individual areas of agreement and also of disagreement, since disagreements generally provide future investigators with a basis for the verification of truth.

The objectives of this book are

1. To provide colleges and universities with a textbook that describes the present state of knowledge about boiling heat transfer and two-phase flow.
2. To provide research workers with a concise handbook that summarizes literature surveys in this field.
3. To provide designers with useful correlations by comparing such correlations with existing data and presenting correlation uncertainties whenever possible.

This is an engineering textbook, and it aims to improve the performance of boiling equipment. Hence, it emphasizes the boiling crisis and flow instability. The first five chapters, besides being important in their own right, serve as preparation for understanding boiling crisis and flow instability.

Portions of this text were taken from lecture notes of an evening graduate course conducted by me at the Carnegie Institute of Technology, Pittsburgh, during 1961–1964.

Of the many valuable papers and reports on boiling heat transfer and two-phase flow that have been published, these general references are recommended:

"Boiling of Liquid," by J. W. Westwater, in *Advances in Chemical Engineering* **1**

(1956) and **2** (1958), edited by T. B. Drew and J. W. Hoopes, Jr., Academic Press, New York.

"Heat Transfer with Boiling," by W. M. Rohsenow, in *Modern Development in Heat Transfer,* edited by W. Ibele, Academic Press (1963).

"Boiling," by G. Leppert and C. C. Pitts, and "Two-Phase Annular-Dispersed Flow," by Mario Silvestri, in *Advances in Heat Transfer* **1,** edited by T. F. Irvine, Jr., and J. H. Hartnett, Academic Press (1964).

"Two-Phase (Gas-Liquid) System: Heat Transfer and Hydraulics, An Annotated Bibliography," by R. R. Kepple and T. V. Tung, ANL-6734, USAEC Report (1963).

I sincerely thank Dr. Poul S. Larsen and Messrs. Hunter B. Currin, James N. Kilpatrick, and Oliver A. Nelson and Miss Mary Vasilakis for their careful review of this manuscript and suggestions for many revisions; the late Prof. Charles P. Costello, my classmate, and Dr. Y. S. Tang, my brother, for their helpful criticisms, suggestions, and encouragement in the preparation of this manuscript. I am also grateful to Mrs. Eldona Busch for her help in typing the manuscript.

L. S. Tong

SYMBOLS*

A	constant in Eq. (2-10), or in Eq. (4-27)
A_c	cross-sectional area for flow, ft^2
A_h	heat transfer area, ft^2
A_{VC}	vena contracta area ratio
a	acceleration, ft/hr^2
a	gap between rods, ft
a	void volume per area, Eq. (3-40), ft
B	constant in Eq. (2-10)
B	dispersion coefficient
b	thickness of a layer, ft
C	slip constant ($= \alpha/\beta$)
C	constant, or accommodation coefficient
C	crossflow resistance coefficient
C	concentration, lb/ft^3
C, c_p	specific heat at constant pressure, Btu/lb °F
C_c	contraction coefficient
C_{fg}	friction factor
C_i	concentration of entrained droplets in gas core of subchannel i
c_o	empirical constant, Eq. (5-16)
D	diffusion constant
D	damping coefficient
D_b	bubble diameter, ft
D_e	equivalent diameter of flow channel, ft
D_h	equivalent diameter based on heated perimeter, ft
DNBR	predicted over observed power at DNB, Eq. (5-123)
d	wire or rod diameter, ft, or subchannel equivalent diameter, in

* Unless otherwise specified, British units are shown to indicate the dimension used in the book.

E	energy, ft-lb
E	free flow area fraction in rod bundles, used in Eq. (4-31)
E	(wall-drop) heat transfer effectiveness
E_{bow}	bowing effect on CHF
E_L	liquid holdup
e	emissivity of heating surface
e	$e = 2.718$
e	constant
F	force, such as surface tension force, F_S, and tangential inertia force, F_t
F	a parameter (forced convection factor) Eq. (4-15), F = $Re_{tp}/Re_L)^{0.8}$
F	free energy, ft-lb
F	friction factor based on D_e (Weisbach), or frictional pressure gradient
F	shape factor applied to non-uniform heat flux case, or empirical rod-bundle spaces factor
F'	activation energy, ft-lb
F_e	view factor including surface conditions
F_k	a fluid-dependent factor in Kandlikare's Eq. (4-25)
F	force vector
f	friction factor based on r_h (Fanning, $F = 4f$), as f_f, f_G, f_i are friction factors between the liquid and wall, the gas and the wall, and the gas–liquid interface, respectively
f	frequency, hr^{-1}
$f_m(z)$	a mixing factor in subchannel analysis, Eq. (5-132)
G	mass flux, lb/hr ft²
G	volumetric flow rate, ft³/hr
G_o	empirical parameter for gas partial pressure in cavity, ft-lb/°R
G', G^*	effective mixing mass flux in and out the bubble layer, lb/hr ft²
g	acceleration due to gravity, ft/hr²
g_c	conversion ratio, lb ft/lb hr²
g(mH)	difference in axial pressure gradient caused by the cross flow
H	enthalpy, Btu/lb
H_{fg}	latent heat of evaporation, Btu/lb
H_{in}	inlet enthalpy, Btu/lb
ΔH_{sub}	subcooling enthalpy ($H_{sat} - H_{local}$), Btu/lb
h	heat transfer coefficient, Btu/hr ft² °F
h	mixture specific enthalpy, Btu/lb
h	height of liquid level, ft
I	flow inertia ($\rho L/A$), lb/ft⁴
i_b	turbulent intensity at the bubble layer–core interface
J	volumetric flux, ft/hr
J	mechanical–thermal conversion ratio, J = 778 ft-lb/Btu

J	mixture average superficial velocity, ft/hr
J_G	crossflow of gas per unit length of bundle, ft/hr ft
K	a gas constant, or scaling factors
K	inlet orifice pressure coefficient
K	grid loss coefficient
k	a parameter, Eq. (3-39), or mass transfer coefficient
k	thermal conductivity, Btu/hr ft^2
k	ratio of transverse and axial liquid flow rates per unit length in Eq. (5-51)
L	length of heated channel, ft
ℓ	length in different zones, as ℓ_s = length of liquid slug zone and ℓ_f = length of film zone
ℓ	Prandtl mixing length, ft
ln	logarithm to the base e
M	mass, lb
M	molecular weight
M_k	mass transfer per unit time and volume to phase k, lb/hr ft^3
m	constant exponent in Eq. (2-78)
m	mass per pipe volume, lb/ft^3
m	wave number ($= 2\pi/\lambda$)
N	number of nuclei or molecules
N_{AV}	Avogadro's constant
N_f	dimensionless inverse viscosity, Eq. (3-93)
n	number of nuclei
n	number of rods
n	bubble density or nucleus density, ft^{-2}
n	droplet flux, ft^{-2}
n	wave angular velocity, hr^{-1}
n	constant exponent, Eq. (2-78)
$\boldsymbol{n}_G$	normal vector in gas phase direction
P	power, Btu/hr
$\tilde{P}$	perimeter for gas or liquid phase
p	pressure, lb/ft^2 or psi
Δp	pressure drop. psi
Q	volumetric flow rate, ft^3/hr
Q_k	heat transferred per unit time and volume to phase k, Btu/hr ft^3
q	heat transfer rate, Btu/hr
q'	linear power, Btu/hr ft
q''	heat flux, Btu/hr ft^2
$\overline{q}''$	average heat flux, Btu/hr ft^2
q'''	power density, Btu/hr ft^3
$\boldsymbol{q}$	heat flux vector
R	resistance, hr °F/Btu

R	radius of bubble, ft
R	liquid holdup, or liquid fraction
R'	dimensionless heater radius, $R' = R[g_c\sigma/g(\rho_L - \rho_G)]^{-1/2}$
R_{eff}	effective radius, $[= R(1 + 0.02\theta/R')]$, ft
R_f	ratio of rough-pipe friction factor to smooth-pipe friction factor
R_g	gas constant
r	radius, ft
r_h	hydraulic radius, $D_e = 4r_h$, ft
S	slip ratio, or boiling suppression factor
S	periphery on which the stress acts, ft
s	width, or thickness, ft
s	entropy, Btu/lb °F
T	temperature, °F
T'	temperature deviations, °F
T_∞	temperature in superheated liquid layer, °F
ΔT_{FDB}	ΔT_{sat} at the beginning of fully developed boiling, °F
$\Delta T_{J\&L}$	Lens and Lottes temperature difference, °F
T_{LB}	bulk temperature of coolant at start of local boiling, °F
$[T]$	$n \times$ n matrix with elements $\partial P_j^c/\partial V_k^i$
ΔT_{sat}	$(T_{wall} - T_{sat})$, °F
ΔT_{sub}	subcooling $(T_{sat} - T_{local})$, °F
t	time, hr
t	average film thickness, in
U	internal energy
U_b	velocity of vapor blanket in the turbulent stream [Eq. (5-45)], ft/hr
U_{bl}	velocity of liquid at $y = \delta_m + (D_b/2)$ (Fig. 5.21), ft/hr
U_o	relative velocity (or rise velocity), ft/hr
U_s	velocity of sound in the vapor, ft/hr
$\underline{\underline{U}}$	metric tensor of the space
u	velocity in the axial direction, or radial liquid velocity, ft/hr
u'	local velocity deviation (in the axial direction)
u^*	friction velocity in Eq. (3-124)
u_{GJ}	drift velocity in Eq. (3-58), ft/hr
u_{GM}	gas velocity relative to the velocity of the center of mass, ft/hr
$\boldsymbol{u}$	velocity vector
$\overline{u'v'}$	Reynolds stress, time average of the product of the velocity deviations in the axial and radial direction
V	volume, ft^3
V	velocity, ft/hr
V_∞	terminal velocity, ft/hr
v	velocity in the normal direction, ft/hr
v	specific volume, ft^3/lb

v_{fg}	specific volume change during evaporation, ft³/lb
v'	local velocity deviation, ft/hr
W	weight, lb
W	mass flux, lb/hr ft²
W_B	critical power over boiling length
w	flow rate, lb/hr
w	frequency
w'	flow exchange rate per unit length by mixing, lb/hr ft
X	quality, weight percent of steam
X_{tt}	Lockhart and Martinelli parameter, $X_{tt} = \left(\frac{1-X}{X}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_f}{\mu_G}\right)^{0.1}$
X	group of parameters, Eq. (3-7)
X'	static quality defined by Eq. (3-38)
x	length in x direction, ft
Y	axial heat flux profile parameter in Eq. (5-122)
Y	group of parameters in Eq. (3-8)
Y_r	a parameter for wall effects on vapor blanket circulation
Y'	subchannel imbalance factor in Eq. (5-122)
y	length in y direction, ft
y	a parameter [= ln (p)]
z	axial length, ft
z_b	distance from the inlet to the bulk boiling, ft
z_d	distance from the inlet to the void detachment, ft
z_{LB}	distance from the inlet to the start of local boiling, ft
z^*	distance from the inlet to the merging point of the Bowring void curve and the Martinelli-Nelson void curve, ft
α	thermal diffusivity (= $k/\rho c$) ft²/hr
α	absorptivity of liquid
α	void fraction
α'	dimensionless thermal diffusion coefficient (= ε/Vb)
$\langle\alpha\rangle$	average void fraction
α_0	steady-state sonic velocity, ft/hr
β	vapor volumetric rate ratio, or an entrainment parameter
β	volumetric compressibility of two-phase flow
β	bubble contact angle between liquid and solid surfaces
β_1, β_2	Parameters in wall-drop effectiveness calculation, Eq. (3-95)
Γ	volumetric interfacial area, Eq. (3-56)
Γ	volumetric flow per unit width of parallel-plate channel
γ	constant, or angle
γ'	isentropic exponent for vapor compression (c_p/c_v)
δ	boundary-layer or thermal-layer thickness, ft

δ_c	wave crest amplitude
ε	eddy viscosity, ft²/hr
ε	parameter for void fraction correlation
ε	ratio of liquid convective heat transfer to bubble latent heat transport
ε_H	eddy thermal conductivity, ft²/hr
ζ	constant
η	amplitude of a wave, ft
η	a function related to the critical distance, Eq. (2-112)
θ	angle, deg
θ	time, hr
θ	temperature difference, °F
κ	a constant
λ	wavelength, ft, or a scalar quantity
λ	ratio of superficial velocities, Eq. (3-104)
μ	viscosity, lb/ft hr
ν	kinematic viscosity, ft²/hr
ν_s	slug frequency
ξ	constant, a measure of inert gas in cavity at start of boiling, Eq. (2-20)
π	$\pi = 3.1416$
ρ	density, lb/ft³
σ	surface tension, lb/ft
σ	area ratio (A_1/A_2)
$\sigma_{\text{S-B}}$	Stefan-Boltzmann constant (= 17.3×10^{-10} Btu/hr ft² °R⁴
τ	nondimensional time, τ_D, drag relaxation time; τ_t, thermal relaxaton time
τ	shear force, lb/ft²
$\bar{\bar{\tau}}$	stress tensor
ϕ	a function, or heat flux, Btu/hr ft²
ϕ	contact angle, or angle from the vertical line
ϕ	average chemical function
ϕ_i	mass flux across the interface
ϕ_{LO}	$(\Delta p_{\text{TPF}}/\Delta p_{\text{LO}})^{1/2}$
ψ	a function
ψ	apex angle (Fig. 2.3)
ω	angular velocity, hr⁻¹
ω	frequency of oscillation, hr⁻¹

Superscripts

+	refers to nondimensional parameter
−	refers to time average or mean value

*	refers to critical value, or nondimensional parameter
i, *o*	refers to inlet and outlet values, respectively, Eq. (A-11)

Subscripts

A,*B*	refers to phase A and phase B, respectively
a	refers to apparent property, such as ρ_a = apparent density, Eq. (3-42)
B	refers to boiling condition
b	refers to bubble property or bulk flow condition
c	refers to crud, or cavity
c	refers to core condition
c, *crit*	refers to critical condition
c_{ij}	refers to turbulent interchange of entrained drops between subchannels of types *i* and *j*
D	refers to drag
D, *d*	refers to droplet or deposition
d	refers to bubble departure condition or droplet condition
E, *e*	refers to liquid entrainment
e	refers to exit condition
e_1, e_2, e_3	refers to dry patch due to evaporation at respective stages
F, *f*	refers to liquid film condition, such as pressure, p_F, and temperature, T_f
f	refers to saturated liquid
fg	refers to phase change from liquid to vapor
f.c.	refers to forced convection
g, *G*	refers to gas, or vapor, condition
g	refers to grid spacer
i	refers to inner diameter
i	refers to interfacial value
i	refers to subchannel type *i*
j	refers to vapor jets
j	refers to number of subchannels
ℓ, L	refers to saturated liquid condition
ℓ'	refers to local subcooled liquid condition
m	refers to matrix channel equivalent
m	refers to mixture property
m	refers to bubble collapse time (maximum)
o	refers to initial condition or outer diameter
o	refers to quantities at center, such as α_o is void fraction at the center
r	refers to reduced properties, such as p_r, T_r
r	refers to size *r* of the nucleation site

r	refers to bubble resonance
S	refers to superficial value, such as superficial velocity, V_S
s	refers to suspension
s	refers to slug
t	refers to thermal
u	refers to slug unit in slug flow geometry
v	refers to saturated vapor condition
w	refers to wall condition
w	refers to waiting period
atn	refers to attenuation coefficient
bulk	refers to bulk flow condition
conv	refers to forced-convection component
crit	refers to critical condition
DFB	refers to departure from film boiling
DNB	refers to departure from nucleate boiling
do	refers to dryout condition
eff	refers to effective value
elev.	refers to elevation
FB	refers to film boiling
FDB	refers to fully developed nucleate boiling
fric	refers to friction
GPF	refers to the friction of a flow with gas mass velocity component
HT	refers to homogeneous, isothermal conditions
hor	refers to horizontal flow
IB	refers to incipient boiling
LB	refers to local boiling condition
LDF	refers to Leidenfrost state
LE	refers to entrained liquid
LO	refers to the friction of a liquid flow with total mass flux
LPF	refers to the friction of a flow with liquid mass flux
LS	refers to liquid slug
max	refers to maximum value
mom	refers to momentum
NB	refers to nucleate boiling
Ob	refers to obstructions
rel	refers to relative value
sat	refers to saturated condition
SM	refers to Sauter mean, as in d_{SM}, Sauter mean diameter
sub	refers to subcooled condition
sup	refers to superheated condition
TB	refers to transition boiling, or Taylor bubble
td	refers to crossflow due to droplet deposition
TH	refers to a group of thermodynamic similitude

te	refers to liquid crossflow due to reentrainment
tot	refers to total condition
TP	refers to two-phase
TPF	refers to two-phase friction
vert	refers to vertical flow
ups	refers to upstream
(W-3)	refers to W-3 CHF correlation, Eq. (5-113)

Nondimensional Groups

Bo	boiling number ($= q''/H_{fg}\rho_G V$)
Co	convection number $\{= [(1 - X)/X]^{0.8} (\rho_G/\rho_L)^{0.5}\}$
Fr	Froude number ($= V^2/gD_e$)
Gr	Grashof number ($= L^3\rho^2\beta g\, \Delta T/\mu^2$)
Ja	Jacob number $[= c_p\rho_L(T_w - T_b)/H_{fg}\rho_G]$
Nu	Nusselt number ($= D_b q''/\Delta T_w\, k_L$)
Pr	Prandtl number ($= c\mu/k$)
Re	Reynolds number ($= D_b G/\mu$)
We	Weber number ($= D_b\rho V^2/\sigma g_c$)