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TWO-PHASE FLOW, BOILING, AND CONDENSATION IN CONVENTIONAL AND MINIATURE SYSTEMS

Providing a comprehensive introduction to the fundamentals and applications of flow and heat transfer in conventional and miniature systems, this fully enhanced and updated edition covers all the topics essential for graduate courses on two-phase flow, boiling, and condensation.

Beginning with a concise review of single-phase flow fundamentals and interfacial phenomena, detailed and clear discussion is provided on a range of topics including two-phase hydrodynamics and flow regimes, mathematical modeling of gas–liquid two-phase flows, pool and flow boiling, flow and boiling in mini- and microchannels, external- and internal-flow condensation with and without noncondensables, condensation in small flow passages, and two-phase choked flow.

Numerous solved examples and end-of-chapter problems that include many common design problems likely to be encountered by students make this an essential text for graduate students. With up-to-date detail on the most recent research trends and practical applications, it is also an ideal reference for professionals and researchers in mechanical, nuclear, and chemical engineering.

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Two-Phase Flow, Boiling, and Condensation

IN CONVENTIONAL AND MINIATURE SYSTEMS

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To my wife Pari Fatemeh Shafiei,
and my son Saam

Contents

Preface to the Second Edition

Since the publication of the first edition of this book significant advances have been made in the art and science of gas–liquid two-phase flow and phase-change phenomena, in particular with respect to flow and heat transfer in miniature and micro-systems. Furthermore, more emphasis is now placed on flow of pure and mixed refrigerants and cryogens owing to their expanding applications in industry. This edition is meant to reflect these changes, as well as address numerous helpful comments and suggestions that I have received from the users of the first edition.

The objectives, methods of presentation, and overall structure of this edition are the same as those for the first edition. The chapters and their general topics of discussion have thus remained unchanged. However, all chapters have been revised, although to different extents. Two-phase flow, boiling, and condensation in binary fluid mixtures; and flow and heat transfer in helically coiled flow passages, are among the new topics that have been added and discussed in some detail in several chapters due to their growing significance. Chapters 8, 10, and 14 have been revised most extensively in response to the rapidly evolving arena of flow and heat transfer in mini- and microchannels. A large number of new solved examples and end-of-chapter problems have also been added, most of which deal with refrigerants and cryogens.

I am indebted to numerous colleagues and former students for the completion of this book. Most recently, in fall of 2014, I had the pleasure of teaching Transport Phenomena in Multiphase Flow, a graduate-level course out of which this book actually originated. This was the most enjoyable two-phase flow and boiling class I had ever taught. Many of the newly added end-of-chapter problems have been solved and in some cases modified/corrected by the students of that class. I thank them all!

Preface to the First Edition

This book is the outcome of more than fifteen years of teaching graduate courses on nuclear reactor thermal-hydraulics and two-phase flow, boiling, and condensation to mechanical and nuclear engineering students. It is targeted to be the basis of a semester-level graduate course for nuclear, mechanical, and possibly chemical engineering students. It will also be a useful reference for practicing engineers.

The art and science of multiphase flow are indeed vast, and it is virtually impossible to provide a comprehensive coverage of all of their major disciplines in a graduate textbook, even at an introductory level. This textbook is therefore focused on gas–liquid two-phase flow, with and without phase change. Even there, the arena is too vast for comprehensive and in-depth coverage of all major topics, and compromise is needed to limit the number of topics as well as their depth and breadth of coverage. The topics that have been covered in this textbook are meant to familiarize the reader with a reasonably wide range of subjects, including well-established theory and technique, as well as some rapidly developing areas of current interest.

Gas–liquid two-phase flow and flows involving change-of-phase heat transfer apparently did not receive much attention from researchers until around the middle of the twentieth century, and predictive models and correlations prior to that time were primarily empirical. The advent of nuclear reactors around the middle of the twentieth century, and the recognition of the importance of two-phase flow and boiling in relation to the safety of water-cooled reactors, attracted serious attention to the field and led to much innovation, including the practice of first-principle modeling, in which two-phase conservation equations are derived based on first principles and are numerically solved. Today, the area of multiphase flow is undergoing accelerating expansion in a multitude of areas, including direct numerical simulation, flow and transport phenomena at mini- and microscales, and flow and transport phenomena in reacting and biological systems, to name a few. Despite the rapid advances in theory and computation, however, the area of gas–liquid two-phase flow remains highly empirical owing to the extreme complexity of the processes involved.

In this book I have attempted to come up with a balanced coverage of fundamentals, well-established as well as recent empirical methods, and rapidly developing topics. Wherever possible and appropriate, derivations have been presented at least at a heuristic level.

The book is divided into seventeen chapters. The first chapter gives a concise review of the fundamentals of single-phase flow and heat and mass transfer. Chapter 2 discusses two-phase interfacial phenomena. The hydrodynamics and mathematical modeling aspects of gas–liquid two-phase flow are then discussed in

Chapters 3 through 9. Chapter 10 rounds out Part One of the book and is devoted to the hydrodynamic aspects of two-phase flow in mini- and microchannels.

Part Two focuses on boiling and condensation. Chapters 11 through 14 are devoted to boiling. The fundamentals of boiling and pool boiling predictive methods are discussed in Chapter 11, followed by the discussion of flow boiling and critical and postcritical heat flux in Chapters 12 and 13, respectively. Chapter 14 is devoted to the discussion of boiling in mini- and microchannels. External and flow condensation, with and without noncondensables, and condensation in small flow passages are then discussed in Chapters 15 and 16. The last chapter is devoted to two-phase choked flow. Various property tables are provided in several appendices.

Frequently Used Notation

A	Flow area (m^2); atomic number
A_C	Flow area in the vena-contracta location (m^2)
A_d	Frontal area of a dispersed phase particle (m^2)
a	Speed of sound (m/s)
a''_I	Interfacial surface area concentration (surface area per unit mixture volume; m^{-1})
Bd	Bond number $= l^2/\left(\frac{\sigma}{g\Delta\rho}\right)$
B_h	Mass-flux-based heat transfer driving force
$\tilde{B}_h$	Molar-flux-based heat transfer driving force
B_m	Mass-flux-based mass transfer driving force
$\tilde{B}_m$	Molar-flux-based mass transfer driving force
Bi	Biot number $= hl/k$
Bo	Boiling number $= q''_w/(Gh_{fg})$
C	Concentration (kmol/m^3)
C	Constant in Wallis's flooding correlation; various constants
c	Wave propagation velocity (m/s)
Ca	Capillary number $= \mu_L U/\sigma$
Cr	Crispation number $= \frac{\mu}{\sigma l}\left(\frac{k}{\rho C_P}\right)$
C_2	Constant in Tien–Kutateladze flooding correlation
C_C	Contraction ratio
C_D	Drag coefficient
C_{He}	Henry's coefficient (Pa; bar)
Co	Convection number $= (\rho_g/\rho_f)^{0.5}[(1-x)/x]^{0.8}$
C_P	Constant-pressure specific heat (J/kg·K)
$\tilde{C}_P$	Molar-based constant-pressure specific heat (J/kmol·K)
C_{sf}	Constant in the nucleate pool boiling correlation of Rohsenow
C_v	Constant-volume specific heat (J/kmol·K)
$\tilde{C}_v$	Molar-based constant-volume specific heat (J/kg·K)
C_0	Two-phase distribution coefficient in the drift flux model
D	Tube or jet diameter (m)
D_H	Hydraulic diameter (m)
Dn	Dean number $\left[= \text{Re}_{D_H}(R_i/R_{cl})^{1/2}\right]$
Dn_{eq}	Equivalent Dean number
$\boldsymbol{D}$	Mass diffusivity (m^2/s)
D_{ij}	Binary mass diffusivity for species *i* and *j* (m^2/s)
$\boldsymbol{D}_{iG}, \boldsymbol{D}_{iL}$	Mass diffusivity of species *i* in gas and liquid phases (m^2/s)

d	Bubble or droplet diameter (m)
d_{cr}	Critical diameter for spherical bubbles (m)
d_{Sm}	Sauter mean diameter of bubbles or droplets (m)
E	Eddy diffusivity (m^2/s)
$\mathbf{E}_1$, $\mathbf{E}$	One-dimensional and three-dimensional turbulence energy spectrum functions based on wave number (m^3/s^2)
$\mathbf{E}_1^*$, $\mathbf{E}^*$	One-dimensional and three-dimensional turbulence energy spectrum functions based on frequency (m^2/s)
$\mathbf{E}_B$	Bulk modulus of elasticity (N/m^2)
E_H	Eddy diffusivity for heat transfer (m^2/s)
Eo	Eötvös number $= g\Delta\rho l^2/\sigma$
e	Total specific convected energy (J/kg)
$\mathbf{e}$	Unit vector
F	Degrees of freedom; force (N); Helmholtz free energy (J); correction factor
F^I	Interfacial Helmholtz free energy (J)
F_i	Interfacial force, per unit mixture volume (N/m^3)
Fo	Fourier number $= \left(\frac{k}{\rho C_P}\right)\frac{t}{l^2}$
Fr	Froude number $= U^2/(gD)$
F_{vm}	Virtual mass force, per unit mixture volume (N/m^3)
F_w	Wall force, per unit mixture volume (N/m^3)
F_{wG}, F_{wL}	Wall force, per unit mixture volume, exerted on the liquid and gas phases (N/m^3)
F_σ	Surface tension force (N)
f	Fanning friction factor; frequency (Hz); distribution function (m^{-1} or m^{-3}); specific Helmholtz free energy (J/kg)
f'	Darcy friction factor
f^I	Specific interfacial Helmholtz free energy (J/m^2)
$\hat{f}$	Fugacity (Pa)
f_{cond}	Condensation efficiency
G	Mass flux ($kg/m^2{\cdot}s$); Gibbs free energy (J)
G^I	Interfacial Gibbs free energy (J)
Ga	Galileo number $= \frac{\rho_L \Delta\rho g l^3}{\mu_L^2}$
Gr	Grashof number $= \left(\frac{gl^3}{\nu_L^2}\right)\left(\frac{\rho_L-\rho_g}{\rho_L}\right)$
Gz	Graetz number $= \frac{4Ul^2}{z}\left(\frac{\rho C_P}{k}\right)$
$\vec{g}$	Gravitational acceleration vector (m/s^2)
g	Specific Gibbs free energy (J/kg); gravitational constant (= 9.807 m/s^2 at sea level); breakup frequency (s^{-1})
g^I	Specific interfacial Gibbs free energy (J/m^2)
H	Heat transfer coefficient ($W/m^2{\cdot}K$); height (m); enthalpy (J)
Hn	Helical coil number $\left[= \mathrm{Re}_{D_H}(R_i/R_c)^{1/2}\right]$
H_r	Radiative heat transfer coefficient ($W\,m^2{\cdot}K$)
He	Henry number
h	Specific enthalpy (J/kg); mixed-cup specific enthalpy (J/kg); collision frequency function ($m^3{\cdot}s$)

h_L	Liquid level height in stratified flow regime (m); specific enthalpy of liquid (J/kg)
$h_\mathrm{fg}, h_\mathrm{sf}, h_\mathrm{sg}$	Latent heats of vaporization, fusion, and sublimation (J/kg)
$\tilde{h}_\mathrm{fg}, \tilde{h}_\mathrm{sf}, \tilde{h}_\mathrm{sg}$	Molar-based latent heats of vaporization, fusion, and sublimation (J/kmol)
I_m	Modified Bessels function of the first kind and mth order
J	Diffusive molar flux (kmol/m^2·s)
Ja	Jakob number $= (\rho C_\mathrm{P})_\mathrm{L} \Delta T / \rho_\mathrm{g} h_\mathrm{fg}$ or $C_\mathrm{PL} \Delta T / h_\mathrm{fg}$
J^{**}	Flux of a transported property in the generic conservation equations (Chapters 1 and 5)
J^*	Dimensionless superficial velocity in Wallis's flooding correlation
Ja*	Modified Jacob number $= \sqrt{\frac{\rho_\mathrm{L}}{\rho_\mathrm{G}}} \frac{C_\mathrm{PL} \Delta T}{h_\mathrm{fg}}$
j	Diffusive mass flux (kg/m^2·s); molecular flux (m^{-2}·s^{-1}); superficial velocity (m/s)
k	Thermal conductivity (W/m·K); wave number (m^{-1})
K	Loss coefficient; Armand's flow parameter; mass transfer coefficient (kg/m^2·s)
K	Parameter in Katto's DNB correlation (Chapter 13)
$\tilde{K}$	Molar-based mass transfer coefficient (kmol/m^2·s)
K*	Kutateladze number; dimensionless superficial velocity in Tien–Kutateladze flooding correlation
Ka	Kapitza number $= \upsilon_\mathrm{L}^4 \rho_\mathrm{L}^3 g / \sigma^3$
K_hor	Correction factor for critical heat flux in horizontal channels
Le	Lewis number $= \boldsymbol{\alpha} / \boldsymbol{D}$
L_B	Boiling length (m); bubble (vapor clot) length (m)
L_heat	Heated length (m)
L_slug	Liquid slug length (m)
l	Length (m); characteristic length (m)
l_D	Kolmogorov's microscale (m)
l_E	Churn flow entrance length before slug flow is established (m)
l_F	Length scale applied to liquid films (m)
M	Molar mass (kg/kmol); component of the generalized drag force (per unit mixture volume) (N/m^3)
Ma	Marangoni number $= \left(\frac{\partial \sigma}{\partial T}\right) \nabla T \frac{l^2}{\mu} \left(\frac{\rho C_\mathrm{P}}{\mathrm{k}}\right)$
Mo	Morton number $= g \mu_\mathrm{L}^4 \Delta \rho / \left(\rho_\mathrm{L}^2 \sigma^3\right)$
$\vec{M}_\mathrm{IK}$	Generalized interfacial drag force (N/m^3) exerted on phase k
$\vec{M}_\mathrm{ID}$	Interfacial drag force term (N/m^3)
$\vec{M}_\mathrm{IV}$	Virtual mass force term (N/m^3)
M_K	Signal associated with phase k
M_2	Constant in Tien–Kutateladze flooding correlation
m	Mass fraction; mass of a single molecule (kg); dimensionless constant
m	Mass (kg)
m''	Mass flux (kg/m^2·s)
N''	Molar flux (kmol/m^2·s)
$\vec{N}$	Unit normal vector
N_Av	Avogadro's number ($= 6.022 \times 10^{26}$ molecules/kmol)
N_con	Confinement number $= \sqrt{\sigma / g \Delta \rho} / l$
Nu	Nusselt number Hl/k

N_μ	Viscosity number $= \mu_L/[\rho_L\sigma\sqrt{\sigma/(g\Delta\rho)}]^{1/2}$
n	Number density (m^{-3}); number of chemical species in a mixture; dimensionless constant; polytropic exponent
p	Perimeter (m)
P	Pressure (N/m^2); Legendre polynomial
ΔP_P	Pump (supply) pressure drop (N/m^2)
ΔP_C	Channel (demand) pressure drop (N/m^2)
Pe	Péclet number $= Ul(\rho C_P/k)$
Pr	Prandtl number $= \mu C_P/k$
P_r	Reduced pressure $= P/P_{cr}$
Pr_{turb}	Turbulent Prandtl number
p_f	Wetted perimeter (m)
p_{heat}	Heated perimeter (m)
Q	Volumetric flow rate (m^3/s); dimensionless wall heat flux
q'	Heat generation rate per unit length (W/m)
q''	Heat flux (W/m^2)
$\dot{q}_v$	Volumetric energy generation rate (W/m^3)
R	Radius (m); gas constant (N·m/kg·K)
R_c	Radius of curvature (m)
R_C	Wall cavity radius (m)
R_{cl}	Coil radius in helically coiled tube (m)
R_t	Radius of torsion (m)
Re	Reynolds number $(\rho Ul/\mu)$
Re_F	Liquid film Reynolds number $= 4\Gamma_F/\mu_L$
R_j	Equilibrium radius of a jet (m)
$\dot{R}_l$	Volumetric generation rate of species l ($kmol/m^3\cdot s$)
R_u	Universal gas constant (= 8314 N·m/kmol·K)
r	Distance between two molecules (Å) (Chapter 1); radial coordinate (m)
$\dot{r}_l$	Volumetric generation rate of species l ($kg/m^3\cdot s$)
S	Sheltering coefficient; entropy (J/K); source and sink terms in interfacial area transport equations ($s^{-1}\cdot m^{-6}$); distance defining intermittency (m)
Sc	Schmidt number $= \nu/\boldsymbol{D}$
Sh	Sherwood number $= Kl/\rho\boldsymbol{D}$ or $\tilde{K}l/\boldsymbol{C}D$
So	Soflata number $= [(3\sigma^3)/(\rho^3 g v^4)]^{1/5}$
Su	Suratman number $= \rho l\sigma/\mu^2$
S_r	Slip ratio
s	Specific entropy (J/kg·K)
$\vec{T}$	Unit tangent vector
T	Temperature (K)
T_r	Reduced temperature $= T/T_{cr}$
t	Time (s); thickness (m)
t_c	Characteristic time (s)
$t_{c,D}$	Kolmogorov's time scale (s)
t_{gr}	Growth period in bubble ebullition cycle (s)
t_{res}	Residence time (s)
t_{wt}	Waiting period in bubble ebullition cycle (s)

$\mathbf{U}$	Internal energy (J)
U	Velocity (m/s); overall heat transfer coefficient ($W/m^2 \cdot K$)
U_B	Bubble velocity (m/s)
$U_{B,\infty}$	Rise velocity of Taylor bubbles in stagnant liquid (m/s)
U_r	Slip velocity (m/s)
U_τ	Friction velocity (m/s)
$\mathbf{u}$	Specific internal energy (J/kg)
u	Velocity (m/s)
u_D	Kolmogorov's velocity scale (m/s)
V	Volume (m^3)
V_1	Volatility parameter (Section 12.16)
V_d	Volume of an average dispersed phase particle (m^3)
V_{gj}	Gas drift velocity (m/s)
V'_{gj}	Parameter defined as $V_{gj} + (C_0 - 1)\langle j \rangle$ (m/s)
v	Specific volume (m^3/kg)
We	Weber number $= \rho U^2 l/\sigma$
W	Width (m)
w	Interpolation length in some flooding correlations (m)
x	Quality
x_{eq}	Equilibrium quality
X	Mole fraction; liquid-side mole fraction (in gas–liquid two-phase systems); Martinelli's factor
Y	Gas-side mole fraction (in gas–liquid two-phase systems)
Z	Compressibility factor

Greek characters

α	Void fraction; wave growth parameter (s^{-1}); phase index
$\boldsymbol{\alpha}$	Thermal diffusivity (m^2/s)
α_k	In situ volume fraction occupied by phase k
β	Volumetric quality; phase index; parameter defined in Eq. (1.75); coefficient of volumetric thermal expansion (K^{-1}); dimensionless parameter
$\beta(V, V')$	Probability of breakup events of particles with volume V' that result in the generation of a particle with volume V (m^{-1})
β_{ma}	Rate factor for mass transfer
β_{th}	Dimensionless transpiration rate for heat transfer
Δ	Plate thickness (m)
δ	Kronecker delta; gap distance (m); thermal boundary layer thickness (m)
γ	Activity coefficient
δ_F	Film thickness (m)
δ_m	Thickness of the microlayer (m)
ε	Porosity; radiative emissivity; Bowring's pumping factor (Chapter 12); turbulent dissipation rate (W/kg); perturbation
ε_D	Surface roughness (m)
$\tilde{\varepsilon}$	Energy representing maximum attraction between two molecules (J)
Ψ	Parameter in Baker's flow regime map (Chapter 4)

ψ	Cavity side angle (rad or degrees); transported property (Chapters 1 and 5); stream function (m^2/s)
Φ^2	Two-phase multiplier for pressure drop
Φ	Two-phase multiplier for minor pressure drops; dissipation function (s^{-2})
φ	Velocity potential (m^2/s); pair potential energy (J)
φ	Transported property (Chapters 1 and 5); relative humidity
$\hat{\phi}$	Fugacity coefficient
χ	Correction factor in CHF correlations for binary mixtures
Γ	Volumetric phase change rate (per unit mixture volume) ($kg/m^3{\cdot}s$); correction factor for the kinetic model for liquid–vapor interfacial mass flux; dimensionless coefficient; surface concentration of surfactants ($kmol/m^2$)
Γ_F	Film mass flow rate per unit width ($kg/m{\cdot}s$)
γ	Specific heat ration (C_P/C_v); perforation ratio
η	Local pressure divided by stagnation pressure
η_c	Convective enhancement factor
η_{ch}	Choking point pressure divided by stagnation pressure
K	Curvature (m^{-1})
κ	von Kármán's constant
κ_B	Boltzmann's constant ($= 1.38 \times 10^{-23}$ J/K)
Π	Interfacial pressure (N/m)
λ	Molecular mean free path (m); wavelength (m); coalescence efficiency; parameter in Baker's flow regime map (Chapter 4)
λ_d	Fastest growing wavelength (m)
λ_H	Critical Rayleigh unstable wavelength (m)
λ_L	Laplace length scale (capillary length) $= \sqrt{\sigma/g\Delta\rho}$
μ	Viscosity ($kg/m{\cdot}s$); chemical potential (J/kg)
ν	Kinematic viscosity (m^2/s)
π	Number of phases in a mixture; 3.1416
θ	Azimuthal angle (rad); angle of inclination with respect to the horizontal plane (rad or degrees); contact angle (rad or degrees)
θ'	Angle of inclination with respect to vertical (rad or degrees)
$\theta_0, \theta_a, \theta_r$	Equilibrium (static), advancing, and receding contact angles (rad or degrees)
ρ	Density (kg/m^3)
ρ'	Momentum density (kg/m^3)
σ	Surface tension (N/m)
σ_A, σ'_A	Smaller-to-lager flow area ratios in a flow-area change
$\tilde{\sigma}$	Molecular collision diameter (Å)
σ_A	Molecular scattering cross section (m^2)
σ_c, σ_e	Condensation and evaporation coefficients
T	Torsion (m^{-1})
τ	Molecular mean free time (s); shear stress (N/m^2)
$\bar{\bar{\tau}}$	Viscous stress tensor (N/m^2)
Ω	Azimuthal angle for film flow over horizontal cylinders (rad)
Ω_k, Ω_D	Collision integrals for thermal conductivity and mass diffusivity

ω	Angular frequency (rad/s); humidity ratio; dimensionless parameter (Chapter 17)
ξ	Chemical potential (J/kg); noncondensable volume fraction
ζ	Interphase displacement from equilibrium (m)
$\Im$	Tangential coordinate on the liquid–gas interphase

Superscripts

r	Relative
+	In wall units
•	In the presence of mass transfer
–	Average
$-t$	Time averaged
$-tk$	Time averaged for phase k
=	Tensor
*	Dimensionless
~	Molar based; dimensionless

Subscripts

avg	Average
B	Bubble
Bd	Bubble departure
b	Boiling; bulk
bp	Boiling point
c	Continuous phase; curved flow passage
ch	Choked (critical) flow
cond	Condensation
cont	Contraction
cr	Critical
d	Dispersed phase
dp	Dew point
eq	Equilibrium
ev	Evaporation
ex	Expansion
exit	Exit
f	Saturated liquid
f0	All vapor–liquid mixture assumed to be saturated liquid
fr	Frictional
FC	Forced convection
F	Liquid or vapor film
G	Gas phase
g	Saturated vapor; gravitational
g0	All liquid–vapor mixture assumed to be saturated vapor
GI	At interphase on the gas side
G0	All mixture assumed to be gas
h	Homogeneous
heat	Heated

I	Gas–liquid interface; irreversible
ideal	Ideal
in	Inlet
inc	Inception of waviness
L	Liquid phase
L0	All mixture assumed to be liquid
LI	At interphase on the liquid side
m	Mixture, mixture-average
ma	Mass transfer
n	Sparingly soluble (noncondensable) inert species
out	Outlet
R	Reversible
rad	Radiation
ref	Reference
res	Associated with residence time
s	"s" surface (gas-side interphase); isentropic; solid at melting or sublimation temperature; straight flow passage
sat	Saturation
SB	Subcooled boiling
slug	Liquid or gas slug
spin	Spinodal
TB	Transition boiling
TP	Two-phase
th	Thermal
tot	Total
turb	Turbulent
UC	Unit cell
u	"u" surface (liquid-side interphase)
V	Virtual mass force
v	Vapor when it is not at saturation; vapor in a multicomponent mixture; volumetric
W	Water
w	Wall
wG	Wall–gas interface
wL	Wall–liquid interface
z	Local quantity corresponding to location z
0	Equilibrium state

Abbreviations

BWR	Boiling water reactor
CFD	Computational fluid dynamics
CHF	Critical heat flux
DC	Direct-contact
DFM	Drift flux model
DNB	Departure from nucleate boiling
DNBR	Departure from nucleate boiling ratio
HEM	Homogeneous-equilibrium mixture

HM	Homogeneous mixture
MFB	Minimum film boiling
LOCA	Loss of coolant accident
NVG	Net vapor generation
OFI	Onset of flow instability
ONB	Onset of nuclear boiling
OSV	Onset of significant void
PWR	Pressurized water reactor