## CONTENTS

Preface \hspace{1cm} xv
Preface to the First Edition \hspace{1cm} xvii
Symbols \hspace{1cm} xix
Unit Conversions \hspace{1cm} xxix

1 INTRODUCTION

1.1 Regimes of boiling \hspace{1cm} 1
1.2 Two-Phase Flow \hspace{1cm} 3
1.3 Flow Boiling Crisis \hspace{1cm} 4
1.4 Flow Instability \hspace{1cm} 4

2 POOL BOILING

2.1 Introduction \hspace{1cm} 7
2.2 Nucleation and Dynamics of Single Bubbles \hspace{1cm} 7
\hspace{1cm} 2.2.1 Nucleation \hspace{1cm} 8
\hspace{1cm} \hspace{1cm} 2.2.1.1 Nucleation in a Pure Liquid \hspace{1cm} 8
\hspace{1cm} \hspace{1cm} 2.2.1.2 Nucleation at Surfaces \hspace{1cm} 10
\hspace{1cm} 2.2.2 Waiting Period \hspace{1cm} 19
\hspace{1cm} 2.2.3 Isothermal Bubble Dynamics \hspace{1cm} 23
\hspace{1cm} 2.2.4 Isobaric Bubble Dynamics \hspace{1cm} 26
\hspace{1cm} 2.2.5 Bubble Departure from a Heated Surface \hspace{1cm} 37
2.2.5.1 Bubble Size at Departure 37
2.2.5.2 Departure Frequency 40
2.2.5.3 Boiling Sound 44
2.2.5.4 Latent Heat Transport and Microconvection by Departing Bubbles 45
2.2.5.5 Evaporation-of-Microlayer Theory 45
2.3 Hydrodynamics of Pool Boiling Process 50
  2.3.1 The Helmholtz Instability 50
  2.3.2 The Taylor Instability 52
2.4 Pool Boiling Heat Transfer 54
  2.4.1 Dimensional Analysis 55
    2.4.1.1 Commonly Used Nondimensional Groups 55
    2.4.1.2 Boiling Models 58
  2.4.2 Correlation of Nucleate Boiling Data 60
    2.4.2.1 Nucleate Pool Boiling of Ordinary Liquids 60
    2.4.2.2 Nucleate Pool Boiling with Liquid Metals 71
  2.4.3 Pool Boiling Crisis 80
    2.4.3.1 Pool Boiling Crisis in Ordinary Liquids 81
    2.4.3.2 Boiling Crisis with Liquid Metals 97
  2.4.4 Film Boiling in a Pool 102
    2.4.4.1 Film Boiling in Ordinary Liquids 103
    2.4.4.2 Film Boiling in Liquid Metals 109
2.5 Additional References for Further Study 116

3 HYDRODYNAMICS OF TWO-PHASE FLOW 119

3.1 Introduction 119
3.2 Flow Patterns in Adiabatic and Diabatic Flows 120
  3.2.1 Flow Patterns in Adiabatic Flow 120
  3.2.2 Flow Pattern Transitions in Adiabatic Flow 128
    3.2.2.1 Pattern Transition in Horizontal Adiabatic Flow 130
    3.2.2.2 Pattern Transition in Vertical Adiabatic Flow 133
    3.2.2.3 Adiabatic Flow in Rod Bundles 136
    3.2.2.4 Liquid Metal–Gas Two-Phase Systems 140
  3.2.3 Flow Patterns in Diabatic Flow 140
3.3 Void Fraction and Slip Ratio in Diabatic Flow 147
  3.3.1 Void Fraction in Subcooled Boiling Flow 152
  3.3.2 Void Fraction in Saturated Boiling Flow 155
  3.3.3 Diabatic Liquid Metal–Gas Two-Phase Flow 159
  3.3.4 Instrumentation 161
    3.3.4.1 Void Distribution Measurement 161
    3.3.4.2 Interfacial Area Measurement 163
    3.3.4.3 Measurement of the Velocity of a Large Particle 164
    3.3.4.4 Measurement of Liquid Film Thickness 166
4 FLOW BOILING

4.1 Introduction 245
4.2 Nucleate Boiling in Flow
   4.2.1 Subcooled Nucleate Flow Boiling 248
      4.2.1.1 Partial Nucleate Flow Boiling 248
      4.2.1.2 Fully Developed Nucleate Flow Boiling 257
   4.2.2 Saturated Nucleate Flow Boiling
      4.2.2.1 Saturated Nucleate Flow Boiling of Ordinary Liquids 258
      4.2.2.2 Saturated Nucleate Flow Boiling of Liquid Metals 265
4.3 Forced-Convection Vaporization
   4.3.1 Correlations for Forced-Convection Vaporization 266
   4.3.2 Effect of Fouling Boiling Surface 268
   4.3.3 Correlations for Liquid Metals 268
4.4 Film Boiling and Heat Transfer in Liquid-Deficient Regions 274
   4.4.1 Partial Film Boiling (Transition Boiling) 275
   4.4.2 Stable Film Boiling 276
      4.4.2.1 Film Boiling in Rod Bundles 277
   4.4.3 Mist Heat Transfer in Dispersed Flow
      4.4.3.1 Dispersed Flow Model 279
      4.4.3.2 Dryout Droplet Diameter Calculation 281
   4.4.4 Transient Cooling 283
      4.4.4.1 Blowdown Heat Transfer 283
      4.4.4.2 Heat Transfer in Emergency Core Cooling Systems 287
      4.4.4.3 Loss-of-Coolant Accident (LOCA) Analysis 288
   4.4.5 Liquid-Metal Channel Voiding and Expulsion Models 297
4.5 Additional References for Further Study 299

5 FLOW BOILING CRISIS

5.1 Introduction 303
5.2 Physical Mechanisms of Flow Boiling Crisis in Visual Observations 304
   5.2.1 Photographs of Flow Boiling Crisis 304
   5.2.2 Evidence of Surface Dryout in Annular Flow 309
   5.2.3 Summary of Observed Results 309
5.3 Microscopic Analysis of CHF Mechanisms 317
   5.3.1 Liquid Core Convection and Boundary-Layer Effects 318
      5.3.1.1 Liquid Core Temperature and Velocity Distribution Analysis 319
      5.3.1.2 Boundary-Layer Separation and Reynolds Flux 320
      5.3.1.3 Subcooled Core Liquid Exchange and Interface Condensation 323
   5.3.2 Bubble-Layer Thermal Shielding Analysis 328
      5.3.2.1 Critical Enthalpy in the Bubble Layer (Tong et al., 1996a) 329
5.3.2.2 Interface Mixing 336
5.3.2.3 Mass and Energy Balance in the Bubble Layer 342
5.3.3 Liquid Droplet Entrainment and Deposition in High-Quality Flow 343
5.3.4 CHF Scaling Criteria and Correlations for Various Fluids 351
5.3.4.1 Scaling Criteria 351
5.3.4.2 CHF Correlations for Organic Coolants and Refrigerants 357
5.3.4.3 CHF Correlations for Liquid Metals 360
5.4 Parameter Effects on CHF in Experiments 366
5.4.1 Pressure Effects 367
5.4.2 Mass Flux Effects 369
5.4.2.1 Inverse Mass Flux Effects 369
5.4.2.2 Downward Flow Effects 373
5.4.3 Local Enthalpy Effects 377
5.4.4 CHF Table of p-G-X Effects 378
5.4.5 Channel Size and Cold Wall Effects 378
5.4.5.1 Channel Size Effect 378
5.4.5.2 Effect of Unheated Wall in Proximity to the CHF Point 379
5.4.5.3 Effect of Dissolved Gas and Volatile Additives 382
5.4.6 Channel Length and Inlet Enthalpy Effects and Orientation Effects 383
5.4.6.1 Channel Length and Inlet Enthalpy Effects 383
5.4.6.2 Critical Heat Flux in Horizontal Tubes 387
5.4.7 Local Flow Obstruction and Surface Property Effects 391
5.4.7.1 Flow Obstruction Effects 391
5.4.7.2 Effect of Surface Roughness 391
5.4.7.3 Wall Thermal Capacitance Effects 392
5.4.7.4 Effects of Ribs or Spacers 393
5.4.7.5 Hot-Patch Length Effects 394
5.4.7.6 Effects of Rod Bowing 395
5.4.7.7 Effects of Rod Spacing 395
5.4.7.8 Coolant Property (D$_2$O and H$_2$O) Effects on CHF 396
5.4.7.9 Effects of Nuclear Heating 397
5.4.8 Flow Instability Effects 398
5.4.9 Reactor Transient Effects 399
5.5 Operating Parameter Correlations for CHF Predictions in Reactor Design 401
5.5.1 W-3 CHF Correlation and THINC-II Subchannel Codes 405
5.5.1.1 W-3 CHF Correlation 405
5.5.1.2 THINC II Code Verification 410
5.5.2 B & W-2 CHF Correlation (Gellerstedt et al., 1969) 415
5.5.2.1 Correlation for Uniform Heat Flux 415
5.5.2.2 Correlation for Nonuniform Heat Flux 416
5.5.3 CE-1 CHF Correlation (C-E Report, 1975, 1976) 416
5.5.4 WSC-2 CHF Correlation and HAMBO Code 417
5.5.4.1 Bowring CHF Correlation for Uniform Heat Flux (Bowring, 1972) 417
5.5.4.2 WSC-2 Correlation and HAMBO Code Verification (Bowring, 1979) 418
5.5.5 Columbia CHF Correlation and Verification 423
  5.5.5.1 CHF Correlation for Uniform Heat Flux 423
  5.5.5.2 COBRA IIIC Verification (Reddy and Fighetti, 1983) 425
  5.5.5.3 Russian Data Correlation of Ryzhov and Arkhipow (1985) 426
5.5.6 Cincinnati CHF Correlation and Modified Model 427
  5.5.6.1 Cincinnati CHF Correlation and COBRA IIIC Verification 427
  5.5.6.2 An Improved CHF Model for Low-Quality Flow 428
5.5.7 A.R.S. CHF Correlation 429
  5.5.7.1 CHF Correlation with Uniform Heating 429
  5.5.7.2 Extension A.R.S. CHF Correlation to Nonuniform Heating 431
  5.5.7.3 Comparison of A.R.S. Correlation with Experimental Data 432
5.5.8 Effects of Boiling Length: CISE-1 and CISE-3 CHF Correlations 433
  5.5.8.1 CISE-1 Correlation 433
  5.5.8.2 CISE-3 Correlation for Rod Bundles (Bertoletti et al., 1965) 439
5.5.9 GE Lower-Envelope CHF Correlation and CISE-GE Correlation 441
  5.5.9.1 GE Lower-Envelope CHF Correlation 441
  5.5.9.2 GE Approximate Dryout Correlation (GE Report, 1975) 443
5.5.10 Whalley Dryout Predictions in a Round Tube (Whalley et al., 1973) 447
5.5.11 Levy's Dryout Prediction with Entrainment Parameter 449
5.5.12 Recommendations on Evaluation of CHF Margin in Reactor Design 453
5.6 Additional References for Further Study 454

6 INSTABILITY OF TWO-PHASE FLOW 457
6.1 Introduction 457
  6.1.1 Classification of Flow Instabilities 458
6.2 Physical Mechanisms and Observations of Flow Instabilities 458
  6.2.1 Static Instabilities 460
    6.2.1.1 Simple Static Instability 460
    6.2.1.2 Simple (Fundamental) Relaxation Instability 461
    6.2.1.3 Compound Relaxation Instability 462
6.2.2 Dynamic Instabilities 463
  6.2.2.1 Simple Dynamic Instability 463
  6.2.2.2 Compound Dynamic Instability 465
  6.2.2.3 Compound Dynamic Instabilities as Secondary Phenomena 466

6.3 Observed Parametric Effects on Flow Instability 468
  6.3.1 Effect of Pressure on Flow Instability 469
  6.3.2 Effect of Inlet and Exit Restrictions on Flow Instability 470
  6.3.3 Effect of Inlet Subcooling on Flow Instability 470
  6.3.4 Effect of Channel Length on Flow Instability 471
  6.3.5 Effects of Bypass Ratio of Parallel Channels 471
  6.3.6 Effects of Mass Flux and Power 471
  6.3.7 Effect of Nonuniform Heat Flux 471

6.4 Theoretical Analysis 473
  6.4.1 Analysis of Static Instabilities 473
    6.4.1.1 Analysis of Simple (Fundamental) Static Instabilities 473
    6.4.1.2 Analysis of Simple Relaxation Instabilities 473
    6.4.1.3 Analysis of Compound Relaxation Instabilities 473
  6.4.2 Analysis of Dynamic Instabilities 474
    6.4.2.1 Analysis of Simple Dynamic Instabilities 476
    6.4.2.2 Analysis of Compound Dynamic Instabilities 478
    6.4.2.3 Analysis of Compound Dynamic Instabilities as Secondary Phenomena (Pressure Drop Oscillations) 478

6.5 Flow Instability Predictions and Additional References for Further Study 479
  6.5.1 Recommended Steps for Instability Predictions 479
  6.5.2 Additional References for Further Study 480

APPENDIX Subchannel Analysis (Tong and Weisman, 1979) 481
  A.1 Mathematical Representation 481
  A.2 Computer Solutions 484

REFERENCES 491
INDEX 533