

Oxford University Press, Walton Street, Oxford OX2 6DP

OXFORD LONDON GLASGOW NEW YORK
TORONTO MELBOURNE WELLINGTON CAPE TOWN
NAIROBI DAR ES SALAAM ADDIS ABABA
KUALA LUMPUR SINGAPORE JAKARTA HONG KONG TOKYO
DELHI BOMBAY CALCUTTA MADRAS KARACHI

© Oxford University Press 1977

ISBN 0 19 851718 1

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior permission of Oxford University Press

First published 1977

Reprinted (with corrections) 1978
First reprinted in Paperback 1979

British Library Cataloguing in Publication Data

Two phase flow and heat transfer.
— (Harwell series).

1. Heat—Convection
2. Two-phase flow

I. Butterworth, D II. Hewitt, Geoffrey
Frederick III. Series
536'.25 QC327

ISBN 0-19-851718-1

~~PAUD-236~~
18654

Printed in Great Britain
by Thomson Litho Ltd.,
East Kilbride

Contents

LIST OF SYMBOLS		xii
1.	INTRODUCTION: G.L. SHIRES	1
1.0.	Chapter objectives	1
1.1.	Two-phase flow	1
1.2.	Nomenclature	4
1.3.	The need to study two-phase flow	7
1.4.	The information required	9
1.5.	Guide to the chapters	10
1.5.1.	Two-phase flow	11
1.5.2.	Two-phase heat transfer	13
1.5.3.	Hydrodynamic instability	16
1.5.4.	Condensation	17
1.5.5.	Loss-of-coolant accidents	17
2.	FLOW PATTERNS: G.F. HEWITT	18
2.0.	Chapter objectives	18
2.1.	The definition of flow regimes	18
2.2.	Delineation of flow patterns	22
2.3.	Flow-pattern maps	24
2.4.	Mechanistic approach to flow pattern delineation	27
2.5.	Phase change and phase equilibrium	35
2.6.	Flow and heat-transfer regimes in evaporating and condensing systems	36
3.	ONE-DIMENSIONAL FLOW: D. BUTTERWORTH	40
3.0.	Chapter objectives	40
3.1.	Introduction	40
3.2.	Continuity relationship	41
3.3.	Single phase momentum and energy balances	44
3.4.	Two-phase energy and momentum balances	46
3.4.1.	Momentum equation	46
3.4.2.	Energy equation	48
3.4.3.	Homogeneous equation	49
3.4.4.	Relationship between the momentum and energy equations	49
3.5.	Introduction to critical flow	51
3.6.	Integrated form of the momentum equation	54

4.	EMPIRICAL METHODS FOR PRESSURE DROP: D. EUTTERWORTH	58
4.0.	Chapter objectives	58
4.1.	Introduction	58
4.2.	Correlating parameters	61
4.3.	Homogeneous flow	66
4.4.	Separated flow	68
4.4.1.	Separate cylinders model	68
4.4.2.	Lockhart - Martinelli correlation	70
4.5.	Mixed-flow models	72
4.5.1.	Baroczy correlation	72
4.5.2.	Chisholm and Sutherland correlation	75
4.6.	Void-fraction correlations	79
4.7.	Relationship between void fraction and frictional pressure gradient	82
4.8.	Integrated forms of the momentum equation	83
4.9.	Pressure drop in fittings	86
4.9.1.	Abrupt enlargement in flow area	86
4.9.2.	Abrupt reduction in flow area	88
4.9.3.	Bends	89
5.	VERTICAL BUBBLE AND SLUG FLOW: G.F. HEWITT	91
5.0.	Chapter objectives	91
5.1.	One-dimensional two-phase flow	91
5.2.	Unsteady one-dimensional flow	96
5.3.	The Bankoff variable-density model	97
5.4.	Generalized model for slip: Zuber and Findlay analysis	99
5.5.	Techniques for local void measurement in bubble flow	101
5.6.	Vertical slug flow	103
6.	VERTICAL ANNULAR FLOW: G.F. HEWITT	107
6.0.	Chapter objectives	107
6.1.	Parameters in annular flow	107
6.2.	The 'triangular relationship'	108
6.3.	Interfacial waves in annular flow	113
6.4.	Measurement of liquid-entrained fraction	119
6.5.	Droplet mass transfer	122
6.6.	Liquid entrainment	125
6.7.	Application of the closed-form solution for annular flow	126
7.	POOL BOILING: D.B.R. KENNING	128
7.0.	Chapter objectives	128
7.1.	Introduction and definitions	128
7.2.	The boiling curve	130
7.3.	Effect of surface conditions	133

7.4.	Effect of geometry	134
7.5.	Effect of pressure	134
7.6.	Effect of time-varying surface temperature	137
7.7.	Effect of non-uniform surface temperature	137
7.8.	Effect of dissolved gas	137
7.9.	Low-liquid regimes	137
7.10.	Stable film boiling	139
7.11.	Critical heat flux	141
7.12.	Nucleate boiling	143
7.12.1.	Bubble nucleation	143
7.12.2.	Bubble growth	148
7.12.3.	Heat-transfer models	150
7.13.	Conclusion	152
8.	NUCLEATE BOILING IN FORCED CONVECTION: D.B.R. KENNING	153
8.0.	Chapter objectives	153
8.1.	Introduction	153
8.2.	Bubble nucleation	155
8.3.	Heat-transfer correlations	158
8.4.	Void fraction in subcooled boiling	161
8.5.	Pressure drop in subcooled boiling	167
8.6.	Conclusion	169
9.	CONVECTIVE HEAT TRANSFER IN ANNULAR FLOW: R.A.W. SHOCK	170
9.0.	Chapter objectives	170
9.1.	Introduction to annular-flow heat transfer	170
9.2.	Laminar-flow solutions	172
9.2.1.	The energy equation	172
9.2.2.	Case 1.	174
9.2.3.	Case 2.	176
9.2.4.	Case 3.	176
9.2.5.	Case 4.	178
9.3.	Turbulent-flow solutions	178
9.4.	Heat transfer in two-component systems	189
10.	ESTIMATION METHODS FOR FORCED-CONVECTIVE BOILING: R.A.W. SHOCK	200
10.0.	Chapter objectives	200
10.1.	Convective correlations and relation to theories	200
10.2.	Superposition of nucleate boiling in saturated and subcooled boiling	204
10.2.1.	Introduction	204
10.2.2.	Partial subcooled boiling	205
10.2.3.	Saturated convective boiling	213

11. BOILING AND FLOW IN HORIZONTAL TUBES: D. BUTTERWORTH and J.M. ROBERTSON	223
11.0. Chapter objectives	223
11.1. Flow-pattern map for horizontal flow	223
11.2. Stratified flow	226
11.2.1. Useful geometric relationships	226
11.2.2. Laminar flow in both phases	227
11.2.3. Laminar liquid - turbulent gas	229
11.2.4. Turbulent flow of both phases	232
11.3. Stratified to slug transition	232
11.4. Slug flow	234
11.5. Bubble flow	234
11.6. Annular flow	235
11.6.1. Illustration of horizontal annular flow	235
11.6.2. Suggested mechanisms for transporting liquid to the top of the tube	236
11.7. Heat-transfer coefficients	242
11.8. Burnout in horizontal tubes	243
11.8.1. Occurrence of burnout and its effect in practice	243
11.8.2. Observations of burnout in horizontal tubes	244
11.8.3. Tentative interpretations of burnout data	249
12. INTRODUCTION TO BURNOUT: G.L. SHIRES	252
12.0. Chapter objectives	252
12.1. A description of burnout	252
12.2. History	255
12.3. Factors influencing burnout	255
12.4. Evaluation of burnout	258
12.5. Basic burnout measurements in vertical straight tubes	260
12.5.1. Uniform heat flux	260
12.5.2. Straight tube, non-uniform heat flux	262
12.6. Modelling of burnout using Freon	264
12.7. Burnout in complex geometries	267
12.7.1. Burnout evaluation of reactor fuel	268
12.7.2. Burnout evaluation of boiler tubes	273
12.8. Summary	278
13. MECHANISMS OF BURNOUT: G.F. HEWITT	279
13.0. Chapter objectives	279
13.1. Definition of burnout	279
13.2. Evaluation of the burnout mechanism	280
13.3. The entrainment diagram and its applications	284
13.4. Calculation of onset of burnout in annular flow	291

14. PREDICTION OF BURNOUT: D.H. LEE	295
14.0. Chapter objectives	295
14.1. Trend of parameters	295
14.1.1. Inlet subcooling	296
14.1.2. Mass velocity	297
14.1.3. Pressure	298
14.1.4. Geometry	300
14.1.5. Local quality	301
14.2. Accuracy of burnout correlation	305
14.3. Correlating parameters	305
14.4. Burnout in tubes	306
14.5. Burnout in tubes at high pressure	309
14.6. Burnout in rectangular channels	309
14.7. Burnout in annular channels	311
14.8. Burnout in rod clusters	313
14.8.1. Whole channel model for correlating rod- cluster burnout	313
14.8.2. Subchannel models for correlating rod- cluster burnout	316
14.9. Secondary effects influencing prediction of burnout	319
14.9.1. Heat-flux profile	319
14.9.2. Direction of flow	320
14.10. Prediction of burnout margin	321
15. FOULING IN BOILING-WATER SYSTEMS: R.V. MACBETH	323
15.0. Chapter objectives	323
15.1. Introduction	323
15.2. Problems of experimenting with crud	324
15.3. The nature of crud deposits	326
15.4. The nature of boiling on a crudded surface	329
15.5. Model of wick boiling in a magnetite crud deposit	332
15.6. Effect of crud deposits on surface temperature	335
15.7. Effect of crud deposits on burnout	337
15.8. The effect of crud deposits on frictional pressure drop	339
16. INTRODUCTION TO HYDRODYNAMIC INSTABILITY: N.A. BAILEY	343
16.0. Chapter objectives	343
16.1. Introduction	343
16.2. The 'Ledinegg' instability	344
16.3. Oscillations due to compressible volumes	348
16.4. Flow oscillations due to the growth of voids	349
16.5. Acoustic effects	351
16.6. Parallel-channel and natural-circulation-loop instability	352

16.7. Situations where instabilities arise	353
16.8. The designer's requirements	354
16.9. Experimental methods to determine the onset of parallel-channel or natural-circulation-loop instability	356
16.10. A review of some experimental investigations into the onset of hydrodynamic instability	359
16.10.1. Natural-circulation-loop instability	361
16.10.2. Parallel-channel instability	364
16.11. Problems arising in the application of models and tests to designs	371
16.12. The application of models and experimental tests to plant problems	372
17. OSCILLATORY INSTABILITY: R. POTTER	374
17.0. Chapter objectives	374
17.1. Introduction	374
17.2. General background to instabilities and noise amplification	375
17.3. Outline of feedback analysis	376
17.4. Example of an instability mode in boiling-water reactors	380
17.5. Hydrodynamic instability	382
17.6. Illustrative example	385
17.7. Circuit geometry	389
17.8. Other methods of analysis	391
17.9. Concluding remarks	393
18. INTRODUCTION TO CONDENSATION: D. BUTTERWORTH	394
18.0. Chapter objectives	394
18.1. Modes of condensation	394
18.2. Resistances to heat transfer during condensation	396
18.3. Homogeneous condensation	399
18.3.1. Droplet equilibrium	399
18.3.2. Nucleation	400
18.4. Dropwise condensation	403
18.5. Direct-contact condensation	405
18.5.1. Spray condensers	405
18.5.2. Pool condensers	409
18.6. Interfacial resistance	409
18.7. Gas-phase heat and mass transfer	413
18.7.1. Mass transfer	413
18.7.2. Effect of mass transfer on heat transfer	415
18.7.3. Condensing curves	418
18.7.4. Single vapour in the presence of incondensable gas	420
18.7.5. Multicomponent condensation	423
18.8. Effect of condensation on interfacial shear stress	425

19. FILMWISE CONDENSATION: D. BUTTERWORTH	426
19.0. Chapter objectives	426
19.1. Condensation on a vertical surface	426
19.1.1. Laminar film condensation - Nusselt solution	426
19.1.2. Extension of the Nusselt analysis to include subcooling and non-linear temperature profile	433
19.1.3. Inclusion of inertial effects	438
19.1.4. Effect of vapour superheat	440
19.1.5. Effect of waves	441
19.1.6. Effect of turbulence	443
19.2. Condensation on a horizontal tube	447
19.2.1. Outside a single tube	447
19.2.2. Condensation outside a bundle of tubes	448
19.2.3. Inside a horizontal tube	451
19.3. Condensation with high vapour shear	453
19.3.1. Different tube orientations and vapour flow directions	453
19.3.2. Horizontal tube with perpendicular vapour flow	454
19.3.3. Flow in a tube	455
19.4. Special surfaces for enhancing film condensation	459
20. LOSS-OF-COOLANT ACCIDENTS: I. BRITAIN	463
20.0. Chapter objectives	463
20.1. Introduction	463
20.2. Fuel-pin behaviour	465
20.3. The loss-of-coolant accident	466
20.3.1. Blow-down phase	468
20.3.2. Core heat-up phase	468
20.3.3. Reflood phase	468
20.4. Critical-flow model	469
20.5. Hydrodynamics and heat transfer during blow-down	471
20.5.1. Fuel-pin heat transfer	471
20.5.2. Burnout correlations	472
20.5.3. Pump models	473
20.5.4. Steam drum behaviour	473
20.6. The stagnation problem	474
20.7. Emergency core-cooling systems	476
20.8. Summary	477
REFERENCES	479
INDEX	511