

# Heat and Mass Transfer

*Editorial Board*

D. Mewes

F. Mayinger

L.P. Yarin · A. Mosyak · G. Hetsroni

# Fluid Flow, Heat Transfer and Boiling in Micro-Channels

 Springer

L.P. Yarin  
Technion-Israel Institute of Technology  
Dept. Mechanical Engineering  
Technion City  
32000, Haifa, Israel  
meromro@techunix.technion.ac.il

G. Hetsroni  
Technion-Israel Institute of Technology  
Dept. Mechanical Engineering  
Technion City  
32000, Haifa, Israel  
hetsroni@tx.technion.ac.il

A. Mosyak  
Technion-Israel Institute of Technology  
Dept. Mechanical Engineering  
Technion City  
32000, Haifa, Israel

ISBN 978-3-540-78754-9

e-ISBN 978-3-540-78755-6

DOI 10.1007/978-3-540-78755-6

Heat and Mass Transfer ISSN 1860-4846

Library of Congress Control Number: 2008936040

© 2009 Springer-Verlag Berlin Heidelberg

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

*Cover design:* deblik, Berlin

*Production:* le-tex publishing services oHG, Leipzig

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

# Preface

The subject of the book is fluid dynamics and heat transfer in micro-channels. This problem is important for understanding the complex phenomena associated with single- and two-phase flows in heated micro-channels.

The challenge posed by high heat fluxes in electronic chips makes thermal management a key factor in the development of these systems. Cooling of micro-electronic components by new cooling technologies, as well as improvement of the existing ones, is becoming a necessity as the power dissipation levels of integrated circuits increases and their sizes decrease. Miniature heat sinks with liquid flows in silicon wafers could significantly improve the performance and reliability of semiconductor devices. The improvements are made by increasing the effective thermal conductivity, by reducing the temperature gradient across the wafer, by reducing the maximum wafer temperature, and also by reducing the number and intensity of localized hot spots.

A possible way to enhance heat transfer in systems with high power density is to change the phase in the micro-channels embedded in the device. This has motivated a number of theoretical and experimental investigations covering various aspects of heat transfer in micro-channel heat sinks with phase change.

The flow and heat transfer in heated micro-channels are accompanied by a number of thermohydrodynamic processes, such as liquid heating and vaporization, boiling, formation of two-phase mixtures with a very complicated inner structure, etc., which affect significantly the hydrodynamic and thermal characteristics of the cooling systems.

The multiplicity of phenomena characteristic of flow in heated micro-channels determined the content of the book. We consider a number of fundamental problems related to drag and heat transfer in flow of a pure liquid and a two-phase mixture in micro-channels, coolant boiling in restricted space, bubble dynamics, etc. Also considered are capillary flows with distinct interfaces developing under interaction of inertia, pressure, gravity, viscous and capillary forces.

In this book we use our own results on a number of problems related to flow and heat transfer in micro-channels, as well as those of numerous theoretical and experimental investigations published in current literature. The presented materials

are easily comprehensible for engineers and applied scientists with some graduate level familiarity with fluid mechanics and theory of heat transfer.

The book consists of two parts: hydrodynamics and heat transfer of single- and two-phase media in micro-channels (Chaps. 1–7), capillary flow with distinct interfaces (Chaps. 8–11).

The book is not meant to be an undergraduate text, but can be used in graduate level courses.

# Acknowledgements

While writing the book we felt support and encouragement from our wives Nelly Sakharov-Yarin, Lidia Kharchenko-Mosyak and Ruthie Hetsroni who gave us the inspiration to complete the book successfully. Unfortunately, Nelly and Lidia passed away and cannot see a printed version of the book. We dedicate it to their memory; it is also dedicated to Ruthie.

We would like to express our gratitude to our colleagues Professor J. Zakin, Dr. E. Pogrebnyak, Dr. R. Rozenblit, Dr. Z. Segal, Dr. I. Tiselj, Dr. G. Ziskind, as well as D. D. Klein (M.Sc.), Y. Mishan (M.Sc.) and R. Zimmerman (M.Sc.) for their participation in the investigations of a number of problems considered in this book.

We are especially grateful to Dr. M. Fichman and Dr. G. Ziskind for many valuable discussions and comments made after reading the manuscript.

Special thanks are directed to Mr. E. Goldberg for correction of the text, as well as to Dr. E. Pogrebnyak for her help in preparation of the manuscript.

During the work on the book some of us were recipients of grants from the Committee of the Council of Higher Education, the Israel Academy of Sciences and Humanities. L.P. Yarin and A. Mosyak were also partially supported by the Center of Absorption (State of Israel) and the Israel Council for Higher Education.

# Contents

<b>1</b>	<b>Introduction</b> .....	1
1.1	General Overview .....	1
1.2	Scope and Contents of Part I .....	2
1.3	Scope and Contents of Part II .....	2
 <b>Part I Flow and Heat Transfer</b>		
<b>2</b>	<b>Cooling Systems of Electronic Devices</b> .....	7
2.1	High-Heat Flux Management Schemes .....	7
2.2	Pressure and Temperature Measurements .....	25
2.3	Pressure Drop and Heat Transfer in a Single-Phase Flow .....	33
2.4	Steam–Fluid Flow .....	43
2.5	Surfactant Solutions .....	65
2.6	Design and Fabrication of Micro-Channel Heat Sinks .....	73
	Summary .....	88
	References .....	92
	Nomenclature .....	98
<b>3</b>	<b>Velocity Field and Pressure Drop in Single-Phase Flows</b> .....	103
3.1	Introduction .....	103
3.2	Characteristics of Experiments .....	104
3.3	Comparison Between Experimental and Theoretical Results .....	106
3.4	Flow of Incompressible Fluid .....	107
	3.4.1 Smooth Micro-Channels .....	107
	3.4.2 Micro-Channels with Rough Walls .....	113
	3.4.3 Surfactant Solutions .....	117
3.5	Gas Flows .....	120
3.6	Transition from Laminar to Turbulent Flow .....	121
3.7	Effect of Measurement Accuracy .....	127
3.8	Specific Features of Flow in Micro-Channels .....	127
	3.8.1 General Remarks .....	127

3.8.2	Thermal Effects .....	130
3.8.3	Oscillatory Regimes .....	132
3.8.4	Laminar Drag Reduction in Micro-Channels Using Ultrahydrophobic Surfaces .....	135
	Summary .....	138
	References .....	139
	Nomenclature .....	143
<b>4</b>	<b>Heat Transfer in Single-Phase Flows .....</b>	<b>145</b>
4.1	Introduction .....	145
4.2	Experimental Investigations .....	148
4.2.1	Heat Transfer in Circular Tubes .....	148
4.2.2	Heat Transfer in Rectangular, Trapezoidal and Triangular Ducts .....	152
4.2.3	Heat Transfer in Surfactant Solutions Flowing in a Micro-Channel .....	158
4.3	Effect of Viscous Energy Dissipation .....	161
4.4	Axial Conduction .....	168
4.4.1	Axial Conduction in the Fluid .....	168
4.4.2	Axial Conduction in the Wall .....	171
4.4.3	Combined Axial Conduction in the Fluid and in the Wall ..	171
4.5	Micro-Channel Heat Sinks .....	173
4.5.1	Three-Dimensional Heat Transfer in Micro-Channel Heat Sinks .....	173
4.5.2	Entrance Effects .....	178
4.5.3	Characteristic Parameters .....	178
4.5.4	Effect of Wall Roughness .....	179
4.5.5	Interfacial Effects .....	179
4.5.6	Effect of Measurement Accuracy .....	179
4.6	Compressibility Effects .....	180
4.7	Electro-Osmotic Heat Transfer in a Micro-Channel .....	182
4.8	Closing Remarks .....	185
	Summary .....	187
	References .....	188
	Nomenclature .....	192
<b>5</b>	<b>Gas-Liquid Flow .....</b>	<b>195</b>
5.1	Two-Phase Flow Characteristics .....	195
5.2	Flow Patterns in a Single Conventional Size Channel .....	198
5.2.1	Circular Channels .....	199
5.2.2	Triangular and Rectangular Channels .....	201
5.3	Flow Patterns in a Single Micro-Channel .....	205
5.3.1	Experimental Observations .....	205
5.3.2	Effect of Surface Wettability and Dryout .....	207
5.3.3	Probability of Appearance of Different Flow Patterns .....	209



5.4	Flow Patterns in Parallel Channels . . . . .	211
5.5	Flow Regime Maps . . . . .	214
5.5.1	Circular Channels . . . . .	215
5.5.2	Triangular and Rectangular Channels . . . . .	216
5.6	Flow Regime Maps in Micro-Channels . . . . .	219
5.7	Void Fraction . . . . .	222
5.7.1	Void Fraction Definition and Correlations . . . . .	222
5.7.2	Experiments in Conventional Size Channels . . . . .	224
5.7.3	Experiments in Micro-Channels . . . . .	225
5.8	Pressure Drop . . . . .	227
5.8.1	Frictional Pressure Drop Correlations . . . . .	227
5.8.2	Experiments in Conventional Size Channels . . . . .	229
5.8.3	Experiments in Micro-Channels . . . . .	230
5.9	Heat Transfer . . . . .	234
5.9.1	Effect of Superficial Liquid Velocity . . . . .	234
5.9.2	Effect of Superficial Gas Velocity . . . . .	241
5.9.3	Heat Transfer in Micro-Channels and Dryout . . . . .	247
5.10	Comparison of Gas–Liquid Two-Phase Flow Characteristics Between Conventional Size Channels and Micro-Channels . . . . .	250
	Summary . . . . .	251
	References . . . . .	252
	Nomenclature . . . . .	255
<b>6</b>	<b>Boiling in Micro-Channels . . . . .</b>	<b>259</b>
6.1	Onset of Nucleate Boiling in Conventional Size Channels . . . . .	259
6.1.1	Models for Prediction of Incipient Boiling Heat Flux and Wall Superheat . . . . .	260
6.1.2	Comparison Between Models and Experiments . . . . .	261
6.1.3	Effect of Inlet Velocity on Wall Superheat . . . . .	271
6.1.4	Effect of Inlet Parameters on Incipient Boiling Heat Flux . . . . .	277
6.1.5	Incipience of Boiling in Surfactant Solutions . . . . .	277
6.2	Onset of Nucleate Boiling in Parallel Micro-Channels . . . . .	281
6.2.1	Physical Model of the Explosive Boiling . . . . .	281
6.2.2	Effect of Dissolved Gases on ONB During Flow Boiling of Water and Surfactant Solutions in Micro-Channels . . . . .	283
6.2.3	Effect of Roughness . . . . .	286
6.3	Dynamics of Vapor Bubble . . . . .	286
6.3.1	The State of the Art of the Problem . . . . .	286
6.3.2	Dimensional Analysis . . . . .	288
6.3.3	Experimental Data . . . . .	289
6.4	Pressure Drop and Heat Transfer . . . . .	294
6.4.1	Pressure Drop in Two-Phase Flow Boiling . . . . .	294
6.4.2	Heat Transfer in Two-Phase Flow Boiling . . . . .	301
6.4.3	Critical Heat Flux of Flow Boiling . . . . .	305

6.5	Explosive Boiling of Water in Parallel Micro-Channels . . . . .	309
6.5.1	Quasi-Periodic Boiling in a Certain Single Micro-Channel of a Heat Sink . . . . .	310
6.5.2	The Initial Thickness of the Liquid Film . . . . .	311
6.5.3	System that Contains a Number of Parallel Micro-Channels . . . . .	312
6.5.4	Average Heat Transfer Coefficient . . . . .	315
	Summary . . . . .	317
	References . . . . .	319
	Nomenclature . . . . .	325
<b>7</b>	<b>Design Considerations . . . . .</b>	<b>329</b>
7.1	Single-Phase Flow . . . . .	329
7.2	Gas-Liquid Flow . . . . .	332
7.3	Boiling in Micro-Channels . . . . .	333
7.3.1	Boiling Incipience . . . . .	333
7.3.2	Flow Boiling: Pressure Drop Characteristics . . . . .	335
7.3.3	Flow Boiling: Heat Transfer . . . . .	336
7.3.4	Natural Convection Boiling . . . . .	339
7.3.5	Explosive Boiling . . . . .	339
7.4	Selected Properties of Liquids Used for Cooling Micro-Devices . . . . .	340
	References . . . . .	343
	Nomenclature . . . . .	344
 <b>Part II Special Topics</b>		
<b>8</b>	<b>Capillary Flow with a Distinct Interface . . . . .</b>	<b>349</b>
8.1	Preliminary Remarks . . . . .	349
8.2	The Physical Model . . . . .	351
8.3	Governing Equations . . . . .	352
8.4	Conditions at the Interface Surface . . . . .	353
8.5	Equation Transformation . . . . .	354
8.5.1	Equation for Pressure and Temperature at Interface Surface . . . . .	354
8.5.2	Transformation of the Mass, Momentum and Energy Equations . . . . .	355
8.6	Equations for the Average Parameters . . . . .	358
8.7	Quasi-One-Dimensional Approach . . . . .	359
8.8	Parameters Distribution in Characteristic Zones . . . . .	360
8.9	Parametrical Study . . . . .	364
8.9.1	Thermohydrodynamic Characteristics of Flow . . . . .	364
8.9.2	The Effect of Regulated Parameters . . . . .	366
	Summary . . . . .	374
	References . . . . .	376
	Nomenclature . . . . .	377

<b>9</b>	<b>Steady and Unsteady Flow in a Heated Capillary</b> .....	379
9.1	Introduction .....	379
9.2	The Physical Model .....	381
9.3	Parameters Distribution Along the Micro-Channel .....	385
9.4	Stationary Flow Regimes .....	388
9.5	Experimental Facility and Experimental Results .....	393
	Summary .....	398
	References .....	398
	Nomenclature .....	399
<b>10</b>	<b>Laminar Flow in a Heated Capillary with a Distinct Interface</b> .....	401
10.1	Introduction .....	401
10.2	Model of the Cooling System .....	403
10.3	Formulation of the Problem .....	404
	10.3.1 Conditions on the Interfacial Surface .....	404
	10.3.2 The Flow Outside of the Interfacial Surface .....	406
10.4	Non-Dimensional Variables .....	408
10.5	Parametrical Equation .....	410
10.6	Parametrical Analysis .....	413
10.7	Results and Discussion .....	418
10.8	Efficiency of the Cooling System .....	421
10.9	Equation Transformation .....	424
	10.9.1 The Dependence of the Saturation Pressure and Temperature .....	424
	10.9.2 Integral Relations .....	424
	10.9.3 Analysis of the Equations .....	427
10.10	Two-Dimensional Approach .....	428
	Summary .....	430
	References .....	433
	Nomenclature .....	434
<b>11</b>	<b>Onset of Flow Instability in a Heated Capillary</b> .....	437
11.1	Introduction .....	437
11.2	Capillary Flow Pattern .....	439
11.3	Equation Transformation .....	440
	11.3.1 Perturbed Equations .....	440
	11.3.2 Perturbed Energy Equation for Small Peclet Number .....	442
	11.3.3 Perturbed Energy Equation for Moderate Peclet Number .....	443
11.4	Flow with Small Peclet Numbers .....	445
	11.4.1 The Velocity, Pressure and Temperature Oscillations .....	445
	11.4.2 Dispersion Equation .....	447
	11.4.3 Solution of the Dispersion Equation .....	449
	11.4.4 Analysis of the Solution .....	450
11.5	Effect of Capillary Pressure and Heat Flux Oscillations .....	454
	11.5.1 Capillary Pressure Oscillations .....	454

11.5.2 Heat Flux Oscillations .....	457
11.6 Moderate Peclet Number .....	459
Summary .....	462
References .....	462
Nomenclature .....	464
<b>Author Index</b> .....	467
<b>Subject Index</b> .....	477