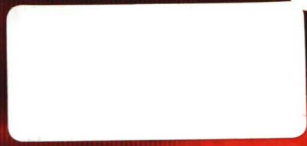


Emerging Topics in



Heat Transfer

**Enhancement and
Heat Exchangers**

EDITORS

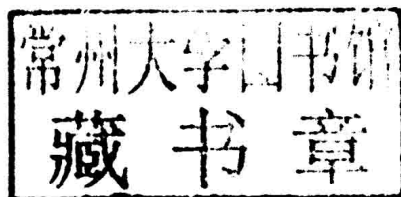
**Qiuwang Wang,
Yitung Chen &
Bengt Sundén**



WIT PRESS

Emerging Topics in Heat Transfer

Enhancement and Heat Exchangers



WITPRESS

WIT Press publishes leading books in Science and Technology.

Visit our website for the current list of titles.

www.witpress.com

WIT*eLibrary*

Home of the Transactions of the Wessex Institute, the WIT electronic-library provides the international scientific community with immediate and permanent

access to individual papers presented at WIT conferences.

Visit the WIT eLibrary at <http://library.witpress.com>

Editors:

Qiuwang Wang
Xi'an Jiatong University, China

Yitung Chen
University of Nevada, USA

Bengt Sundén
Lund University, Sweden

Published by

WIT Press

Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK
Tel: 44 (0) 238 029 3223; Fax: 44 (0) 238 029 2853
E-Mail: witpress@witpress.com
<http://www.witpress.com>

For USA, Canada and Mexico

WIT Press

25 Bridge Street, Billerica, MA 01821, USA
Tel: 978 667 5841; Fax: 978 667 7582
E-Mail: infousa@witpress.com
<http://www.witpress.com>

British Library Cataloguing-in-Publication Data

A Catalogue record for this book is available
from the British Library

ISBN: 978-1-84564-818-3

eISBN: 978-1-84564-819-0

Library of Congress Catalog Card Number: 2013935720

No responsibility is assumed by the Publisher, the Editors and Authors for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein. The Publisher does not necessarily endorse the ideas held, or views expressed by the Editors or Authors of the material contained in its publications.

© WIT Press 2014

Printed by Lightning Source, UK.

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 written permission of the Publisher.

International Series on Developments in Heat Transfer

Objectives

The Developments in Heat Transfer book Series publishes state-of-the-art books and provides valuable contributions to the literature in the field of heat transfer, thermal and energy engineering. The overall aim of the Series is to bring to the attention of the international community recent advances in thermal sciences by authors in academic research and the engineering industry.

Research and development in heat transfer is of significant importance to many branches of technology, not least in energy technology. Developments include new, efficient heat exchangers, novel heat transfer equipment as well as the introduction of systems of heat exchangers in industrial processes. Application areas include heat recovery in the chemical and process industries, and buildings and dwelling houses where heat transfer plays a major role. Heat exchange combined with heat storage is also a methodology for improving the energy efficiency in industry, while cooling in gas turbine systems and combustion engines is another important area of heat transfer research. Emerging technologies like fuel cells and batteries also involve significant heat transfer issues.

To progress developments within the field both basic and applied research is needed. Advances in numerical solution methods of partial differential equations, turbulence modelling, high-speed, efficient and cheap computers, advanced experimental methods using LDV (laser-doppler-velocimetry), PIV (particle-image-velocimetry) and image processing of thermal pictures of liquid crystals, have all led to dramatic advances during recent years in the solution and investigation of complex problems within the field.

The aims of the Series are achieved by contributions to the volumes from invited authors only. This is backed by an internationally recognised Editorial Board for the Series who represent much of the active research worldwide. Volumes planned for the series include the following topics: Compact Heat Exchangers, Engineering Heat Transfer Phenomena, Fins and Fin Systems, Condensation, Materials Processing, Gas Turbine Cooling, Electronics Cooling, Combustion-Related Heat Transfer, Heat Transfer in Gas-Solid Flows, Thermal Radiation, the Boundary Element Method in Heat Transfer, Phase Change Problems, Heat Transfer in Micro-Devices, Plate-and-Frame Heat Exchangers, Turbulent Convective Heat Transfer in Ducts, Enhancement of Heat Transfer, Transport Phenomena in Fires, Fuel Cells and Batteries as well as Thermal Issues in Future Vehicles and other selected topics.

Series Editor

B. Sundén

Lund University

PO Box 118

SE-22100 Lund

Sweden

Associate Editors

R. Amano

University of Wisconsin, USA

C.A. Brebbia

Wessex Institute of Technology, UK

G. Comini

University of Udine, Italy

R.M. Cotta

COPPE/UFRJ, Brazil

S.K. Das

India Institute of Technology, Madras,

India

L. De Biase

University of Milan, Italy

G. De Mey

University of Ghent, Belgium

S. del Giudice

University of Udine, Italy

M. Faghri

University of Rhode Island, USA

C. Herman

John Hopkins University, USA

Y. Jaluria

Rutgers University, USA

S. Kabelac

Helmut Schmidt University, Hamburg,
Germany

D.B. Murray

Trinity College Dublin, Ireland

P.H. Oosthuizen

Queen's University Kingston, Canada

P. Poskas

Lithuanian Energy Institute, Lithuania

B. Sarler

Nova Gorica Polytechnic, Slovenia

A.C.M. Sousa

University of New Brunswick, Canada

D.B. Spalding

CHAM, UK

J. Szymd

University of Mining and Metallurgy,
Poland

D. Tafti

Viginia Tech., USA

Q. Wang

Xi'an Jiatong University, China

S. Yanniotis

Agricultural University of Athens, Greece

Emerging Topics in Heat Transfer

Enhancement and Heat Exchangers

Editors

Qiuwang Wang

Xi'an Jiatong University, China

Yitung Chen

University of Nevada, USA

Bengt Sundén

Lund University, Sweden

WITPRESS Southampton, Boston



Preface

Advances in high temperature equipment continue to be important because involved heat transfer and related phenomena are commonly of a complex nature and different mechanisms like heat conduction, convection, turbulence, thermal radiation and phase change as well as chemical reactions may occur simultaneously. In addition operating problems like fouling, corrosion and mechanical loading might be severe. Typically, applications are found in heat exchangers, gas turbine cooling, turbulent combustion and fires and combustion engines. Heat transfer might be regarded as an established and mature scientific discipline, but it is playing a major role in new emerging areas such as sustainable development and reduction of greenhouse gases as well as for micro- and nano-scale structures and advanced gas turbines and heat exchangers. In engineering design and development, reliable and accurate computational methods are requested to replace or complement expensive and time consuming experimental trial and error work. Tremendous advancements in knowledge and competence have been achieved during recent years due to improved computational solution methods for non-linear partial differential equations, turbulence modeling advancement and developments of computers and computing algorithms to achieve efficient and rapid simulations. Nevertheless, to enable further progress in computational methods for complex problems of engineering significance, developments in theoretical and predictive procedures – both basic and innovative – are needed. In addition, accurate experimental investigations are needed to provide reliable data and to validate the computational methods.

This book contains ten edited chapters encompassing important emerging topics in heat transfer equipment, particularly heat exchangers. The chapters have been selected by invitation only. All the chapters have been reproduced directly from material submitted by the authors but an attempt has been made to use a unified outline and methods of presentation for each chapter.

The editors would like to acknowledge the National Science Foundation China for providing financial support for the international cooperation

between Xi'an Jiaotong University, Lund University and University of Nevada (Grant No. 51120165002). The excellent administrative work and the efficient co-operation and encouragement by the staff at WIT Press contributed significantly in producing this book.

Qiuwang Wang, Yitung Chen and Bengt Sundén
Xi'an, Las Vegas and Lund

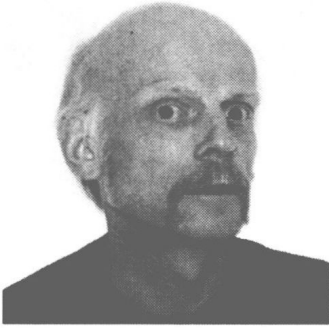
About the Editors



Dr. Qiuwang Wang received a B.Sc. in Fluid Machinery from Xi'an Jiaotong University, China, in 1991 and a Ph.D. degree in Engineering Thermophysics from the same university in 1996. He then joined the faculty of the university. He is now a full professor at the School of Energy and Power Engineering, Xi'an Jiaotong University where is actively involved in both teaching and research in heat transfer. He is a member of several committees, editorial boards and various professional societies. He has given many invited talks worldwide. He has supervised more than 60 PhD or master students. He has also been author or co-author of 4 books and more than 150 journal papers, about half of which are in international journals. He has obtained 15 China invent patents and one US patent.



Dr. Yitung Chen received his Ph.D. degree in mechanical engineering at University of Utah, Salt Lake City, Utah in 1991 after obtaining his M.S. in 1988 from the same school. His B.S. received in 1983 is in chemical engineering from Feng Chia University, Taichung, Taiwan. Since 1994 he has been affiliated with the Department of Mechanical Engineering, University of Nevada, Las Vegas where he was promoted to full professor in 2009. His academic and industrial experiences in numerical and experimental fluid mechanics and thermal-fluid sciences cover multidisciplinary areas of mechanical, biomedical, environmental, chemical, and nuclear engineering. Dr. Chen is an expert in computational and experimental aspects of momentum, heat, and mass transfer. He is a fellow of ASME. Dr. Chen has over the last six years published more than 50 journal papers and more than 100 conference papers in a wide variety of topics. In addition, he has co-authored a monograph, book chapters and technical reports.



Bengt Sundén received his M.S. in 1973, Ph.D. in thermodynamics and fluid mechanics in 1979, and docent in applied thermodynamics and fluid mechanics in 1980, all from Chalmers Universities of Technology, Goteborg, Sweden. He became Professor of Heat Transfer in 1992 at Lund University. Since 1995 he serves as the head of the Department of Energy Sciences, Lund University, Sweden. His research topics are enhancement of heat transfer in compact heat exchangers, computational methods of

convective flow and heat transfer in complex narrow geometries, combustion-related heat transfer including thermal radiation, gas turbine heat transfer (impinging jets, film cooling, ribbed ducts), evaporation and condensation in plate heat exchangers, thermal imaging techniques, PIV, and multiscale and multiphysics transport phenomena in fuel cells. He has published more than 500 journal papers, books, and proceedings. He has also delivered many keynote and invited lectures. He has been editor of 25 books published by international publishing houses and author of two textbooks (one in Swedish, one in English). He is involved in referee tasks for more than 40 international journals and has been active in several international and organizing committees and boards. He is also editor-in-chief for a book series, *Developments in Heat Transfer* (also published by WIT Press). In addition, he is active editor for four journals. He is a fellow of the ASME and a 2011 recipient of the ASME Heat Transfer Memorial Award.

Contents

CHAPTER 1

Gas-Side Fouling of Fin Surfaces in Exhaust Gas Recirculators 1

D.K. Tafti, N. Krishnamurthy & A.K. Viswanathan

1	Introduction.....	1
2	Dry Soot Deposition in Fin Passages	7
2.1	Mathematical model.....	7
2.2	Geometry and computational grid.....	9
2.3	Simulation conditions and postprocessing	11
2.4	Relative magnitude of particle forces at EGR conditions	12
2.5	Results.....	15
2.6	Expressions for the correlations	21
3	Reduced-order modeling of fouling in EGR.....	21
3.1	Dry soot fouling layer characterization	22
3.2	Wet soot fouling layer characterization.....	22
3.3	Fouling layer removal	24
3.4	Conditions	27
3.5	Results and discussion.....	28
4	Summary and Conclusions.....	33
	Acknowledgments.....	34
	References	34

CHAPTER 2

Heat Transfer Enhancement by Turbulent Impinging Jets

and Ribbed Channel Flows.....39

R.S. Amano

1	Introduction.....	39
1.1	Impinging jet.....	39
1.2	Turbulence models.....	40
2	Experimental Study.....	42
3	Mathematical and Physical Model	44
3.1	Governing equations	44
3.2	Near-wall turbulence models for high Reynolds.....	46
3.3	The $k-\epsilon$ turbulence model	46

3.4	The Reynolds stress turbulence model.....	47
3.5	Heat transfer model.....	50
4	Numerical Solution Procedure.....	50
5	Results and Discussion.....	51
5.1	Impinging jets.....	51
5.2	Ribbed-channel flows.....	56
5.3	Large eddy simulation.....	58
6	Conclusion.....	61
	References.....	62

CHAPTER 3

Heat Transfer Enhancement of a Gas Turbine Blade-Tip Wall67

G. Xie & B. Sunden

1	Introduction.....	67
2	Physical Models of Eight Kinds of Tip-Cooling Concepts.....	72
3	Computational Details.....	73
3.1	Selection of turbulence model.....	73
3.2	Grid dependence.....	74
3.3	Boundary conditions.....	75
4	Fluid Flow and Heat Transfer Characteristics.....	76
4.1	Definitions of friction factor and Nusselt number.....	76
4.2	Model validation.....	76
4.3	Flow and temperature fields.....	77
4.4	Pressure drop and heat transfer.....	78
5	Overall Comparisons of Tip-Cooling Concepts.....	82
6	Concluding Remarks.....	84
	Acknowledgments.....	85
	Nomenclature.....	85
	References.....	85

CHAPTER 4

Shell-and-Tube Heat Exchangers with Helical Baffles89

G. Chen, M. Zeng, Q. Chen, B. Peng & Q. Wang

1	Introduction.....	89
2	Flow and Heat Transfer Enhancement	
	Mechanism of Helixchangers.....	91
2.1	Flow characteristics of helixchangers.....	92
2.2	Heat transfer enhancement mechanism of helixchangers.....	93
3	STHXs with Discontinuous Helical Baffles.....	95
3.1	Structure of the discontinuous helical baffles.....	95
3.2	Flow and heat transfer performance.....	96
3.3	Shell Side Design method for STHXs.....	99
4	Single Shell-Pass STHXs with Continuous Helical Baffles.....	108
4.1	Structure of the Continuous Helical Baffles.....	108
4.2	Flow and heat transfer performance of continuous	

helical baffled heat exchangers	109
4.3 Maximal velocity ratio design method	112
4.4 Effect of the inlet and outlet locations.....	113
4.5 Applications example.....	114
5 Single Shell-Pass STHXs with Combined Helical Baffles	117
5.1 Structure of the combined helical baffles.....	117
5.2 Flow streamlines	118
5.3 Flow and heat transfer performance.....	119
5.4 Maximal velocity ratio	121
6 Combined Multiple Shell-Pass STHXs with Helical Baffles.....	122
6.1 Structure of the combined multiple shell-pass SHTXs with helical baffles.....	122
6.2 Flow and heat transfer performance.....	123
7 Concluding Remarks.....	125
Acknowledgments.....	125
References	126

CHAPTER 5

Compact Metallic High-Temperature Heat Exchangers 131

T. Ma, L. Du, H. Liang, D. Zhang, Y. Ji, M. Zeng, L. Luo & Q. Wang

1 Introduction.....	131
2 Primary Surface Recuperator	134
2.1 Numerical investigation of heat transfer and pressure drop performances of CW primary surface recuperator	134
2.2 Stress and creep analysis of CW primary surface recuperator	145
2.3 Experimental investigation of heat transfer and pressure drop performances of primary surface recuperator	152
3 Bayonet Tube Heat Exchanger with Inner and Outer Fins.....	159
3.1 Design of Bayonet tube heat exchanger with inner and outer fins...	159
3.2 Numerical investigation of heat transfer and pressure drop performances of bayonet tube HTHE	161
3.3 Stress analysis of bayonet tube HTHE	168
3.4 Experimental study of pressure drop and heat transfer performances of bayonet tube HTHE	173
4 Concluding Remarks.....	178
Acknowledgments.....	179

CHAPTER 6

Turbulent Heat Transfer Performance of Internally

Longitudinally Finned Tubes 185

M. Lin & Q.W. Wang

1 Introduction.....	185
2 Physical Model.....	186
3 Experimental Apparatus.....	187
4 Data Reduction in Experiment	189

5	Numerical Model for Turbulence Flow	190
5.1	Turbulence Model.....	190
6	Results and Discussion.....	192
6.1	Validation of numerical model and grid independence.....	192
6.2	Optimal ratio of blocked core-tube outer diameter to - outer-tube inner diameter (d_o/D_i)	193
6.3	Effect of lateral fin profiles.....	195
6.4	Effect of different longitudinal fins.....	199
6.5	Correlations of periodic wavy channel of internally finned tube....	202
7	Conclusion	204
	Acknowledgments	205
	Nomenclature	205
	Greek symbols.....	206
	Subscripts	206
	References	207

CHAPTER 7

Air-Side Heat Transfer and Friction Characteristics of Fin-and-Tube Heat Exchangers with Various Fin Types

L.B. Wang, M. Zeng, L. Tang & Q.W. Wang

1	Introduction.....	212
2	Heat Transfer Performances of the Fin Patterns for Circular Tube.....	213
3	Heat Transfer Performances of the Fin Patterns for Flat Tube.....	219
4	Conclusion	230
	Acknowledgments.....	230
	Nomenclature	230
	Greek symbols.....	231
	Subscripts	232
	References	232

CHAPTER 8

High-Temperature Heat Exchanger and Decomposer Design

Y. Chen & V. Ponyavin

1	Introduction.....	238
1.1	IHX requirements.....	239
1.2	Helium gas properties	242
1.3	FLiNaK properties	244
2	Numerical Modeling of the Baseline HTHX Designs.....	244
2.1	Design including manufacturing geometrical effects.....	247
2.2	Analytical calculations.....	249
2.3	Numerical simulation of the offset strip fin heat exchanger with no gap in flow direction ($P_x = 1$)	251
3	Shell and Plate HTHX and Decomposer Design and Operation Conditions	253
3.1	Fluid flow model validation.....	255

3.2	Heat transfer model validation	261
3.3	Chemical reaction model validation.....	263
3.4	Improved design with hexagonal channels	265
3.5	Calculation of heat transfer and flow features of heat exchanger and decomposer	267
4	Modeling of Flow with Chemical Reactions.....	277
4.1	Geometry and boundary conditions	277
4.2	Material properties	278
4.3	Calculation results of the baseline design	279
4.4	Parametric study of the baseline design	281
4.5	Calculation results of the alternative designs and comparison with baseline design results.....	288
4.6	Stress analysis	288
5	Conclusions.....	295
	References	299

CHAPTER 9

Design Optimization and Performance Prediction of Compact

Heat Exchangers..... 301

Q. Wang, G. Xie & Bengt Sundén

1	Introduction.....	301
2	Design Optimization of a Plate-Fin Heat Exchanger	303
2.1	Physical model.....	303
2.2	Brief description of GA and optimization process.....	304
2.3	Optimization results and discussion.....	305
3	Performance Prediction of Tube-Fin Heat Exchangers.....	309
3.1	Physical model and experimental database.....	309
3.2	Brief description of ANN.....	310
3.3	Prediction of turbulent flow and heat transfer.....	311
3.4	Prediction of laminar flow and heat transfer	313
4	Concluding Remarks.....	314
	References	315

CHAPTER 10

Flow Boiling in Small to Microdiameter Tubes 321

M.M. Mahmoud, T.G. Karayiannis, & D.B.R. Kenning

1	Introduction.....	321
2	Applications of Microchannels Heat Exchangers	323
2.1	Refrigeration and air conditioning	323
2.2	Electronics cooling.....	324
3	Micro scale flow boiling issues.....	328
4	Experimental Facility and Data Reduction	331
5	Effect of Diameter on Flow Patterns.....	336
6	Pressure Drop Characteristics	345
7	Heat Transfer Characteristics.....	348

7.1	Heat transfer mechanism(s)	348
7.2	Effect of system pressure	351
7.3	Effect of tube diameter	354
7.4	Effect of surface characteristics	360
7.5	Flow instability	363
7.6	Effect of heated length	365
8	Heat transfer prediction	365
8.1	Empirical correlations	366
8.2	Mechanistic models	373
9	Pressure Drop Prediction	374
9.1	Empirical correlations	374
9.2	Mechanistic models	377
10	Conclusions	380
	Acknowledgement	383
	Nomenclature	383
	Greek symbols	385
	Subscripts	385
	References	387