

0361.3

B658

8763393

Heat and Mass Transfer in MHD Flows

E. Blūms
Yu. A. Mikhailov
R. Ozols



E8763393



World Scientific

Authors

E. Blūms, Yu. Mikhailov and R. Ozols

Latvian SSR Academy of Sciences, Institute of Physics
229021 Riga, Salaspils, USSR

Series Editor-in-Chief

R. K. T. Hsieh

Department of Mechanics, Royal Institute of Technology
S-10044 Stockholm, Sweden

Published by

World Scientific Publishing Co. Pte. Ltd.
P. O. Box 128, Farrer Road, Singapore 9128

Distributed by

Taylor & Francis Inc. (in USA)
John Wiley & Sons Ltd. (in Europe)
D A Book Pty Ltd. (in Australia)
Allied Publishers Pvt Ltd. (in India)

Library of Congress Cataloging-in-Publication Data

Blūms, Elmārs

Heat and mass transfer in MHD flows.

Includes index.

1. Heat—Transmission. 2. Mass transfer.
3. Magnetohydrodynamics. 4. Electromagnetic fields.
- I. Mikhailov, Yu. A. (Yuriy Anan'evich) II. Ozols, R. (Roberts).
- III. Title.

QC320.B517 1986 538'.6 86-15752

ISSN 0218-0235

ISBN 9971-50-112-0

Copyright © 1987 by World Scientific Publishing Co Pte Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

Printed in Singapore by Utopia Press.

3

SERIES IN THEORETICAL AND APPLIED MECHANICS

Edited by R.K.T. Hsieh



SERIES IN THEORETICAL AND APPLIED MECHANICS

Editor: R. K. T. Hsieh

Volume 1 Nonlinear Electromechanical Effects and Applications
by G. A. Maugin

Volume 2 Lattice Dynamical Foundations of Continuum Theories
by A. Askar

Volume 3 Heat and Mass Transfer in MHD Flows
by E. Blüms, Yu. Mikhailov, R. Ozols

Volume 4 Mechanics of Continuous Media (in 2 volumes)
by L. I. Sedov

Preface to the English Edition



During the past few decades scientists of the international communities have been focusing attention on the study of diverse aspects of how a magnetic field acts upon heat and mass transfer processes. Magnetohydrodynamic machines, technical devices using magnetic fluids and various problems of magnetobiology may serve as typical examples of the magnetic field application in controlling the hydrodynamics and thermophysical processes. It should be, however, noted that the literature devoted to magnetohydrodynamics does not treat systematically heat and mass transfer problems. Our book "Heat and Mass Transfer in a Magnetic Field" (Riga, "Zinātne" Publishers, 1980) was an attempt to fill a gap. The book sold well, and our colleagues encouraged us to submit an English version. We are indebted to the World Scientific Publishing Co. Pte. Ltd. for having undertaken the publication of this work.

In writing the present book we used the Russian edition of 1980, and this is the reason why the references to the most recent works are missing, except for some sections. The latest results published are introduced in Chapter 5.

We very much hope that readers will find useful information here and this would also stimulate the generation of new ideas. We are of course fully aware that our book is not devoid of drawbacks. Constructive criticisms and comments would, therefore be greatly appreciated.

We wish to thank Professor R. Viskanta (USA), Professor P.S. Lykoudis (USA), Professor R.K.T. Hsieh (Sweden), Professor R. Moreau (France), Dr. V.M. Soundalgekar (India) and others for valuable contributions and help in publishing the book. We are also grateful to our colleagues who participated in getting the manuscript ready - U. Ābeltiņš for the translation, M. Mikhailova, M. Oginte and S. Viļuma - for the lay out of figures and preparation of the text of the manuscript.

E. Blūms
Yu. Mikhailov
R. Ozols

Riga, December 1985

PREFACE

Interest in the effects of applied magnetic field upon thermo-physical processes dates back to over twenty years ago. Research development was stimulated by two major problems confronting the engineering sciences, protection of bodies in outer space from aerodynamic overheating or destruction in passing through dense layers of atmosphere and ensurance of working capacity of the structural elements of high-temperature MHD-generator installations for direct conversion of thermal energy into electrical. In the former case magnetohydrodynamic interaction with ionized gases appeared to offer a convenient means for controlling the hydrodynamics and the heat and mass processes, but in the latter this interaction was directly linked with the principle underlying the work of the converter, hence its presence was indispensable. Solving problems like these was accompanied by an upsurge in the growth in the numbers of analytical and thereupon also of experimental studies on heat transfer in MHD-boundary layers in pipe and channel flows. By and by these investigations came to be linked with new applied problems. Thus the successes in creating MHD devices for liquid metals attracted the attention of people engaged in metallurgy. Magnetic field turned out to be capable of contributing a lot to perfecting a great many technological processes. Development of atomic energetics, including huge reactors-breeders based on fast neutrons, as well as creation of the blanketing systems of the future thermo-nuclear reactors are unthinkable without extensive use of MHD devices. It is

established that magnetic field can directly affect a variety of processes in chemical engineering. Control of the crystallization processes in metallurgy and the influence exerted by the magnetic field on particular chemical systems have now led to magnetohydrodynamics and thermophysics addressing themselves to problems which used to be the province of others at times far from being related disciplines (for example, physicochemical kinetics and biophysics).

Additional stimulus for tracing further interrelationships was provided by the research developing along the lines of probing the interaction of the field with magnetizable homo- and heterogeneous systems. In altering the kinetic processes, the magnetic properties of the components come largely into play. Inasmuch as ferrohydrodynamic processes are manifested mainly in the presence of temperature or concentration non-uniformities in the system, investigation into the physical phenomena in magnetizable media would pertain to the competency of thermophysics rather than to that of hydrodynamics. Growth of ferrohydrodynamics has substantially extended the range of practical applications of MHD-processes, impinging not only on energetics and chemical engineering but also on electrical and radio engineering, automation systems and so forth. And finally, the analogies traced in the influence of magnetic field upon mechanical and biological suspensions have brought about a situation with real possibilities of applying the results of thermophysical investigations in the magnetic field to a series of magnetobiological phenomena.

It should be pointed out that, notwithstanding the importance of the contributions to research on thermophysical processes subject to external magnetic influence, there are to date practically no generalizing works in this field. It is for a partial bridging of this gap that the authors of the present book have set themselves the aim of summing up the results of thermophysical investigations into incompressible conducting and magnetizable media. In writing the book the authors have drawn mainly on material based on research carried out in the Thermophysics Laboratory at the Physics Institute of the Academy of Sciences of the Latvian SSR. In addition, for a more comprehensive

view of the problem as a whole the results of other works have also been largely used. In selecting their material, however, the authors were guided by the desire to throw light on the vastness of the research done and that is why certain specific questions concerning the methods of analytic or numerical solution of problems have remained outside the scope of the book. Striving to pay attention mainly to the physical aspects of the problems dealt with, we have tried to make maximum use of various approximation methods in analysis. On the basis of integral solution methods a degree of exactness is attained, which suffices in engineering calculations, and a rather obvious pattern of the major governing laws and applicability limits of diverse approximations is arrived at.

It stands to reason that not all the problems touched upon in the book have been investigated to equal degree. Thus, for example, the problems of heat transfer in MHD pipe flows turned out to have been more fully covered, whereas mass transfer problems in scientific literature have received little attention. Notwithstanding the comparatively large amount of work, experimental among it, research on turbulent heat and mass transfer in a magnetic field cannot be considered completed by far.

In dealing with thermophysical processes in magnetizable fluids we confined ourselves deliberately to analysis of the equilibrium quasi-stationary approximation considering questions linked with the relaxation of hydrodynamic and electromagnetic processes to be subject to special investigation.

With a view of attracting the attention of those engaged in thermophysics to new topical problems, we considered it to the point to include a chapter concerned with certain aspects of magnetobiology. To this end, questions were chosen, proving the feasibility of direct application of the investigation approaches and the results obtained in mechanical systems to biological media.

Fully aware of the present work not being free of short-comings, we are grateful in advance for possible matter-of-fact critical comments, which we shall regard as very useful in further work. We ask to forward

your considerations to the address: Latvian SSR, Riga region, 229021, Salaspils, Physics Institute at the Acad. Sci. of Latvian SSR.

Chapter 1 was written by R. Ozols and Yu.A. Mikhailov, Chapter 7 by Yu.A. Mikhailov, E. Blūms and R. Ozols, Chapters 2 to 6 and Chapter 8 were contributed by E. Blūms.

E. Blūms, Yu. Mikhailov, R. Ozols

Heat and Mass Transfer in MHD Flows

8763393

CONTENTS

Preface to the English Edition	v
Preface	vii
Chapter 1: THERMODYNAMIC ANALYSIS OF TRANSFER PHENOMENA IN ELECTRIC AND MAGNETIC FIELDS	1
1.1 General Principles of Non-Equilibrium Thermo- dynamics	1
<i>Linear non-equilibrium thermodynamics</i>	2
<i>Substance, momentum and internal energy conservation</i>	5
<i>Dissipative function</i>	9
<i>Linear phenomenological laws</i>	13
<i>Motive force of mass transfer</i>	21
<i>Equation for temperature</i>	24
<i>Effects of the magnetic field on heat and mass transfer</i>	26
1.2 Equation for Heat and Mass Transfer in Conducting Media	30
<i>Single-component conducting medium</i>	30
<i>Mass exchange in conducting media</i>	34
<i>Anisotropy of heat and mass transfer in a magnetic field</i>	41
<i>Similarity criteria and preliminary estimates</i>	45
<i>Electrochemical systems</i>	55
1.3 Equations for Heat and Mass Transfer in Non-Conducting Media	57
<i>Cross effects of mutual diffusion</i>	57

<i>Mutual diffusion coefficients</i>	63
<i>Magneto- and dielectrophoresis</i>	67
<i>Dimensionless equations</i>	70
 Chapter 2: HEAT TRANSFER IN A LAMINAR MHD-FLOW	 75
2.1 Features of Laminar MHD-Flow in a Channel and in a Boundary Layer	75
<i>A stationary Hartmann flow in a flat channel</i>	76
<i>Couvette plane flow in a magnetic field</i>	79
<i>Some features of two-dimensional flows in a magnetic field</i>	80
<i>The Karman-Pohlhausen method for approximate calculations of an MHD-boundary layer</i>	84
2.2 Heat Transfer at One-Dimensional MHD-Flow	88
<i>A fully stabilized temperature field</i>	89
<i>Convective heat transfer in the case of a developed temperature field $\partial T/\partial x \neq 0$</i>	99
<i>Heat transfer in the entrance region of a flat channel</i>	110
<i>Influence of Joule and viscous heat</i>	126
<i>Influence of longitudinal heat conduction</i>	131
2.3 Heat Transfer in Two-Dimensional Flows	135
<i>Heat transfer in an MHD-boundary layer on a semi-infinite plate in a transverse field</i>	136
<i>Heat transfer at the stagnation point</i>	141
<i>Heat transfer in the entrance region of a plane channel</i>	149
<i>Some problems of heat transfer in longitudinal magnetic field</i>	154
 Chapter 3: FREE MHD CONVECTION	 165
3.1 One-Dimensional Free Convective Flows	165
<i>A vertical closed channel</i>	166
<i>Simultaneous action of free and forced convection</i>	169
3.2 Free Convection in Boundary Layer	172
<i>Integral equations for boundary layer and method of local similarity</i>	174
<i>Semi-infinite plate and vertical cone</i>	183
<i>Horizontal circular cylinder and spatial stagnation point</i>	188
<i>Free convection in magnetic boundary layer</i>	193

3.3	Some Features of Non-Stationary Convection	196
	<i>One-dimensional flow</i>	196
	<i>Boundary layer development on semi-infinite plate</i>	199
Chapter 4:	CONVECTIVE MASS TRANSFER IN MAGNETIC FIELD	205
4.1	Special Features of Mass Transfer in Electrically-Conducting Media	205
	<i>Boundary conditions in mass transfer problems</i>	205
	<i>Control of boundary conditions in electro-chemical systems</i>	207
	<i>Effect of migratory currents</i>	210
	<i>Special features of mass transfer in electrochemical systems in the presence of a magnetic field</i>	215
4.2	Experimental Investigations into Mass Transfer in Electrolytes	221
	<i>Analogy between mass transfer and non-dissipative heat transfer</i>	221
	<i>Convective mass transfer in Hartmann flow</i>	223
	<i>Mass transfer in transverse flow round a cylinder</i>	223
	<i>Mass transfer in isothermal free convection</i>	228
	<i>Some measurements of non-stationary mass transfer</i>	230
4.3	Mass Transfer Under Combined Diffusion and Chemistry Kinetics of Reactions on the Boundaries	233
	<i>Mass transfer in Hartmann flow for slow first-order reactions</i>	233
	<i>Mass transfer specifics at change of order of reaction</i>	235
	<i>Mass transfer in MHD-flow round a plate</i>	239
	<i>Magnetic field effect on the chemical reaction kinetics</i>	241
4.4	Heat and Mass Transfer in an MHD-Boundary Layer on a Permeable Surface	244
	<i>Calculation of the boundary layer on a porous plate by the Karman-Pohlhausen method</i>	244
	<i>Special features of boundary layer development in magnetic field</i>	248
	<i>Heat and mass transfer in a boundary layer</i>	252
	<i>Boundary layer on a porous plate in longitudinal field</i>	256

Chapter 5: HEAT AND MASS TRANSFER IN MAGNETIZABLE FLUIDS	259
5.1 Hydrostatics in Presence of a Magnetizable Field	259
<i>Interphase forces</i>	259
<i>The drop shape in a magnetic field</i>	261
<i>Surface instability of magnetic fluid</i>	271
<i>Levitation of permanent magnet in ferrofluids</i>	272
<i>Buoyance of bodies in magnetic field</i>	276
5.2 Thermomagnetic Convection	280
<i>Conditions for the appearance of convection</i>	280
<i>Analogy between magnetic and gravitational convection</i>	284
<i>Thermomagnetic convection in boundary layer</i>	287
<i>Some special features of spatial convection</i>	301
<i>Volume convection in the presence of a heat source</i>	304
<i>Relaxation processes in magnetic colloids and convection</i>	306
<i>Energy dissipation and microconvective heat transfer in colloids</i>	308
5.3 Diffusion in Magnetizable Fluids	312
<i>Non-stationary diffusion in binary paramagnetic solutions</i>	312
<i>Magnetophoresis in suspensions</i>	315
<i>Magneto-diffusion convection</i>	329
<i>Thermomagnetophoresis in uniform field</i>	337
Chapter 6: TURBULENT HEAT AND MASS TRANSFER IN MAGNETIC FIELD	348
6.1 Special Features of the Hydrodynamics of MHD-Flows	348
<i>The principal laws of semi-empiric description</i>	348
<i>The hydrodynamics of turbulent MHD-flows in channels</i>	354
<i>"Two-dimensional" MHD turbulence</i>	359
6.2 Heat and Mass Transfer Intensity	361
<i>Semi-empiric calculation</i>	361
<i>Results of experimental studies on heat transfer in liquid metals</i>	366
<i>Heat and mass transfer in electrolytes</i>	369
<i>Interpolation dependences for heat transfer in the transitional region</i>	373

6.3	Local Characteristics of Heat and Mass Transfer	375
	<i>On the turbulent Prandtl number in the magnetic field</i>	375
	<i>Spectral characteristics of turbulent temperature and concentration pulsations in electrolytes</i>	377
	<i>Temperature pulsations under heat transfer in liquid metals</i>	381
	Chapter 7: MAIN TRENDS IN APPLICATIONS	388
7.1	Heat and Mass Transfer in Conducting Media	388
	<i>Space research and energetics</i>	388
	<i>Chemical engineering and metallurgy</i>	389
7.2	Some Applications of Magnetic Fluids	392
	<i>Discrete bodies in magnetic fluid and finite volume of ferrofluid in external field</i>	394
	<i>Devices based on thermomagnetic convection</i>	397
	<i>Magnetic filters</i>	400
7.3	Magnetic Field in Biology and Medicine	402
	<i>Magnetic occlusion of arterial aneurysms</i>	403
	<i>Magnetophoresis in biological suspensions</i>	406
	Chapter 8: PROBLEMS OF METHODOLOGY FOR EXPERIMENTAL STUDIES ON HEAT AND MASS TRANSFER	417
8.1	Specifics of Heat Measurements in Magnetic Field	417
	<i>Special features of heat transfer in various conducting media</i>	417
	<i>Thermoanemometry in the magnetic field</i>	420
8.2	The Electrochemical Method in Mass Transfer Studies	425
	<i>The essence of the electrochemical method</i>	425
	<i>Choice of electrochemical system</i>	428
	<i>Electrochemical microelectrode in the role of the transducer in an anemometer</i>	432
	<i>A typical loop for measuring mass transfer</i>	434
8.3	The Interferometric Method of Investigating Heat and Mass Transfer	436
	<i>Diffraction shadow interferometer</i>	436
	<i>Measurement of temperatures, concentrations and heat and mass transfer coefficients</i>	440