Chapter 1
Introduction

1.1 General Overview

The rapid advances made during the past decade in the field of production and use of high power micro-devices led to widespread interest in the problems of micro-fluid mechanics and the need for both comprehensive and detailed treatment of the fundamental aspects of these phenomena.

Despite the fact that experimental and theoretical studies of flow in small pipes began already in the first part of the nineteenth century, systematic treatment of the vast class of problems associated with flow and heat transfer in micro-channels started only in the middle of the twentieth century. It was then that the true significance of such investigations was realized for different applications in micro-system technology, in particular, micro-scaled cooling systems of electronic devices which generate high power. Accordingly, experimental and theoretical investigations were aimed at detailed study of the flow of incompressible and compressible fluids in regular and irregular micro-channels under adiabatic conditions, conditions corresponding to intensive heat transfer with the environment, and phase change. At the same time specific problems associated with roughness, energy dissipation, heat losses, etc., were considered. As a result, important features of flow and heat transfer in micro-channels were revealed, simple models of the processes were developed, and empirical and semi-empirical correlations for drag and heat transfer coefficient were suggested. Comparison of systematic experimental data with predictions of the conventional theory based on the Navier–Stokes equation reveals the actual sources of disparity between them. The recent developments in micro-scale heat transfer and fluid flow have been discussed by e.g. Zhang et al. (2004), Celata (2004), Kakac et al.(2005), Kandlikar et al. (2005), Zhang (2007).

In spite of the progress described above, certain fundamental problems in flow and heat transfer are still unclear. This leads to difficulties in understanding the essence of micro-thermohydrodynamic phenomena.

L.P. Yarin, *Fluid Flow, Heat Transfer and Boiling in Micro-Channels*

1.2 Scope and Contents of Part I

The first part of this book deals with the characteristics of flow and heat transfer in the channels and comparison between conventional size and micro-channels, which are important to understanding micro-processes in cooling systems of electronic devices with high power density and many other applications in engineering and technology.

It contains six chapters related to the overall characteristics of the cooling systems: single-phase and gas–liquid flow, heat transfer and boiling in channels of different geometries.

Chapter 2 presents general schemes of these systems, as well as the characteristics of the micro-channels used.

In Chap. 3 the problems of single-phase flow are considered. Detailed data on flows of incompressible fluid and gas in smooth and rough micro-channels are presented. The chapter focuses on the transition from laminar to turbulent flow, and the thermal effects that cause oscillatory regimes.

Chapter 4 is devoted to single-phase heat transfer. Data on heat transfer in circular micro-tubes and in rectangular, trapezoidal and triangular ducts are presented. Attention is drawn to the effect of energy dissipation, axial conduction and wall roughness on the thermal characteristics of flow. Specific problems connected with electro-osmotic heat transfer in micro-channels, three-dimensional heat transfer in micro-channel heat sinks and optimization of micro-heat exchangers are also discussed.

The results of experimental and theoretical investigations related to study of drag and heat transfer in two-phase gas–liquid flow are presented in Chap. 5.

The concepts of boiling in micro-channels and comparison to conventional size channels are considered in Chap. 6. The mechanism of the onset of nucleate boiling is treated. Specific problems such as explosive boiling in parallel micro-channels, drag reduction and heat transfer in surfactant solutions are also considered.

Chapter 7 deals with the practical problems. It contains the results of the general hydrodynamical and thermal characteristics corresponding to laminar flows in micro-channels of different geometry. The overall correlations for drag and heat transfer coefficients in micro-channels at single- and two-phase flows, as well as data on physical properties of selected working fluids are presented. The correlation for boiling heat transfer is also considered.

1.3 Scope and Contents of Part II

The second part treats specific problems typical of capillary flow with a distinct interface. It contains four chapters in which steady and unsteady capillary flow are treated.

The quasi-one-dimensional model of two-phase flow in a heated capillary slot, driven by liquid vaporization from the interface, is described in Chap. 8. It takes into account the principal characteristics of the phenomenon, namely, the effect of inertia, pressure and friction forces and capillary pressure due to the curvature of the interface, as well as the thermal and dynamical interactions of the liquid and vapor phases.

Chapter 9 is devoted to regimes of capillary flow with a distinct interface. The effect of certain dimensionless parameters on the velocity, temperature and pressure within the liquid and vapor domains are considered. The parameters corresponding to the steady flow regimes, as well as the domains of flow instability are defined.

Chapter 10 deals with laminar flow in heated capillaries where the meniscus position and the liquid velocity at the inlet are unknown in advance. The approach to calculate the general parameters of such flow is considered in detail. A brief discussion of the effect of operating parameters on the rate of vaporization, the position of the meniscus, and the regimes of flow, is also presented.

The onset of flow instability in a heated capillary with vaporizing meniscus is considered in Chap 11. The behavior of a vapor/liquid system undergoing small perturbations is analyzed by linear approximation, in the frame work of a one-dimensional model of capillary flow with a distinct interface. The effect of the physical properties of both phases, the wall heat flux and the capillary sizes on the flow stability is studied. A scenario of a possible process at small and moderate Peclet number is considered. The boundaries of stability separating the domains of stable and unstable flow are outlined and the values of the geometrical and operating parameters corresponding to the transition are estimated.

Authors

Dr. Yarin is a Visiting Professor at the Faculty of Mechanical Engineering at the Technion–Israel Institute of Technology. He received his M.S. degree from the Polytechnic Institute of Kharkov in 1952, his Candidate of Technical Sciences (Ph.D.) degree from the Institute of Energetics, Acad. of Kazakhstan, in 1962, and his Doctor of Technical Sciences degree from the Institute of High Temperatures, Acad. Sci. USSR, in 1970. He is the author of about 200 research works (including five monographs) in the fields of combustion theory, heat and mass transfer, two-phase flows, turbulent flows, energetics, aircraft and rocket engines, experimental methods in gas dynamics and heat transfer, thermoanemometry, high temperature combustion reactors and micro-fluid mechanics. His research activities focus on detailed analysis of aerodynamics and thermal regimes of combustion in gas torches; gas, liquid fuels and coal combustion, combustion wave propagation in porous and bubbly media; aerodynamics of furnaces and combustion chambers of jet and rocket engines; gasodynamics of jet flows; hydrodynamics of stratified flows, magnetohydrodynamics; turbulent two-phase flows; the theory of chemical reactors; micro-fluid mechanics, in particular heat and mass transfer in micro-channels. He headed the Chair of Engineering Thermal Physics at the Ukta Industrial Institute, teaching undergraduate and graduate courses in hydrodynamics, heat and mass transfer and thermodynamics. He presents an undergraduate, and graduate course on "Principles of Combustion of Two-Phase Media" at the Technion–Israel Institute of Technology.

Dr. Mosyak is a Research Fellow, Senior A of the Faculty of Mechanical Engineering, Technion, Haifa, Israel. He received his M.S. degree from Polytechnic Institute of Odessa in 1960, his Candidate of Technical Sciences (Ph.D.) degree from Polytechnic Institute of Odessa in 1972. He is the author of about 100 research works in the fields of turbulent flows, two-phase flows, heat and mass transfer, microfluid mechanics and thermodynamics. He was Associate Professor of Energy Engineering, Kishinev Polytechnic Institute, USSR where he taught undergraduate and graduate courses in hydrodynamics, heat and mass transfer, and thermodynamics.

Dr. Hetsroni is an Emeritus Danciger Professor of Engineering, Faculty of Mechanical Engineering at the Technion–Israel Institute of Technology (IIT). He received his B.Sc. Cum Laude, Technion–IIT in 1957, and received his Ph.D. from Michigan State University in 1963. He was with the Atomic Power Division of Westinghouse for a few years before joining the Faculty at the Technion in 1965; since 1974 he has been the Danciger Professor of Engineering. In the USA he held positions also with the Electric Power Research Institute. At the Technion he has served as Dean of Mechanical Engineering, and as the Head of the Neaman Institute for Advanced Studies in Science and Technology. Dr. Hetsroni was also the Head of the National Council for Research and Development of Israel. He has also been a Visiting Professor at Carnegie Mellon University, Stanford University, the University of California-Santa Barbara, the University of Minnesota and the University of New South Wales. He was the Vice President for Region XIII of the ASME International and was a Governor of the ASME. He is the Founding Editor of the International Journal of Multiphase Flow. He is the author of about 250 research works (including five monographs) in the fields of multiphase flow and heat transfer, experimental and computational fluid mechanics and heat transfer, turbulent flows, thermal-hydraulic design of nuclear reactors, turbulent boundary layers, boiling and steam generators. The research activities of Professor Hetsroni have focused on detailed analysis of aerodynamics of two-phase turbulent jets, particle turbulent interactions, heat transfer in two-phase turbulent boundary layer, coherent structure of turbulent flows, direct numerical simulations of turbulent flows, boiling of surfactant solution, heat and mass transfer in micro-channels, as well as particle image velocimetry (PIV) and hot-foil infrared imaging (HFIRI) measurements in a flume. At present he is the Head of the Multiphase Flow Laboratory of Technion.