Preface

This book treats near-critical and supercritical fluid, one of functional fluids, as a representative of new "green" fluids, which can be widely utilized in energy systems/applications, chemical extraction and synthesis, micro-manufacturing, heat transfer apparatus, etc. Supercritical fluids are now increasingly utilized in such fields, as substitutive working fluids, which contribute to both the energy efficiency aspect and the combat in reducing the greenhouse gas emissions.

Recently, the near-critical property evolution and diverges are found critical for both hydrodynamic and heat transfer applications. Systematic investigations into the near-critical fluid convective flow and heat transfer inside microscales are presented in this book, which covers from the fundamentals of near-critical fluids to their practical development in real applications.

The key topic of this book is the near-critical fluid status, which is specially controlled or maintained at specific parameter ranges in the near-critical region to take advantages of the preferable thermal and transport properties. This book will cover the "abnormal" properties and new thermodynamic mechanisms of near-critical fluid, which starting from the thermophysical basics, the basic flow dynamics, and heat transfer, to a deep discussion of recent new findings and their indications in real applications. The behaviors in possible microscale chemical engineering process, microscale phenomena, and transient convection in fast and critical environment are analyzed and compared. After that, most recent and challenging problems and outlook for the applications and innovations of supercritical fluids are discussed in this book.

In the background and introduction section, the recent developments of near-critical theories, fluid dynamics, and heat transfer studies in the past 30 years are summarized. Though the utilization of supercritical fluids has a relative long history, it was only in those recent years that the supercritical fluid research went close to the near-critical region. After the original finding of "abnormal" near-critical thermodynamics in 1980s, the transitions from sub- to supercritical states and its interesting critical effects under gravity/microgravity conditions have become major challenging topics in related critical fluid field. The basic topics, breakthroughs, and new trends are summarized in this section. And it is found that there exist urgent needs in the study of microscale near-critical flow dynamics and heat transfer.

In this book, precise interferometry visualization experimental systems are first established to test the near-critical fluid flow and heat transfer phenomena in microscales. The system is consisted of a modified Mach–Zehnder interferometer design, near-critical fluid flow and control system, data monitor, calibration system, and visualization parts for microchannel designs. It is found that inside the vertically set thin long microchannel (60 mm × 3 mm × 0.3 mm), near-critical fluid flows are successfully visualized by interferometer system in a wide range of initial and boundary conditions. New findings for near-critical fluids are found for the near-critical through-flows: the interference pattern will become widened and more flatten for higher pressure and the boundary blurs are less seen, which means that higher pressure show less critical changes; also the interference patterns show that critical diverges and unstable flow will happen for critical-transition region, at which time new peaks and valley sets in the interference pattern; in the flow rate tests, it is found that the basic boundary pattern follows classical predictions of text book. Such critical-transition and the flow pattern expansion and disturbance are very new and important for near-critical fluids.

Computational fluid dynamics study of near-critical flows is also designed as a useful method to test and compare with the experimental results. Careful numerical procedures and theoretical verifications are carried out by modified Navier–Stokes equations, energy and near-critical CO_2 fluid state equations. The numerical method has been refined and the characteristics of such near-critical fluid configuration in microscales are systematically explored with sudden application of boundary heat fluxes. Good agreement is found for the comparison of critical flow pressure curve with classical Churchill correlation. And it is interestingly found strong near-critical vortex flows can be achieved in a relatively wide range of initial and controlling conditions in microchannels. It is seen that soon after the wall heat flux is applied, the vortex mixing flow originates from the hot boundaries in microchannels with height D = 100–200 μm, while natural convection (thermal plume) will gradually become dominant for microchannels with D = 300–500 μm. Basic temperature "collapse" and unstable thin hot boundary layer (HBL) thermal–mechanical (T–M) effects are identified. For relative larger channels, multi-factors including T–M, microscale effects and gravity will have complicated coeffects for the current system.

This book also goes deeper into the real process in near-critical boundary evolutions. The new features of near-critical heat transfer flow also give rise to new phenomena: critical speeding up and critical cooling are found for heating channels of microscale. In accordance with the "thermal/temperature collapse," local heat transfer enhancement is found. In very short timescales (before vortex flow), heat transfer coefficient and Nusselt number will decrease with time, due to the very low thermal diffusivity of near-critical fluids; however, in the critical region, thermal perturbation and fast boundary break-up happens and it leads to sudden high heat transfer rate process. Well-correlated characteristic numbers are identified for the effective near-critical microchannel mixing cases. Further discussion on the dynamic feature of near-critical flows show that such flows can sustain very high micromixing with only a small energy dissipation rate. Also it is found that near-critical fluids with follow exponential mixing characteristic parameter laws, instead of classical linear evolution pattern.

Transitions from vortex mixing flow to buoyancy convections are found during the microchannel spatial scaling. Theoretical analysis shows that the basic Kelvin–Helmholtz instability applies to the current microchannel instability evolution. The specific boundary thermal-mechanical perturbation process (with hot boundary stratification and expansion) serves as the origin of current instability phenomena (both under terrestrial and microgravity conditions). The near-critical fluctuations and multi-timescale analysis show that different from traditional acoustic Piston Effect in closed systems or classical K-H instability; thermal-mechanical effects dominate the convective structures for the current open channel configurations and serves as the key perturbation source instead of gravity waves in classical theory. Further, the current study developed a set of controlling factor analysis for the current near-critical evolutions. Analytical solutions to the near-critical boundary conduction for the early thermal evolution stages are also found by Green's function process, and it gives basic theoretical route for understanding the pre-vortex thin hot boundary process.

The current near-critical boundary perturbation and mixing flow process happens both in very small time and spatial scales. Such microscale fasts thermal relaxation and vortex mixing have the potential of related system control and microheat transfer applications. The current results are hoped to contribute to the understanding of related near-critical phenomena and the design of novel heat transfer systems.

After this thesis was recommended for publication as a book by a joint committee from Peking University and Springer in June 2016, I tried to read again the paragraphs and figures in the manuscript to develop it as a true professional book that worthy of reading. The main chapters and text have been reworded and revised to make it suitable for a professional book. Several new figures have been added to the book in order to include recent developments. Also the discussion and comparisons of the result have been revised to make the contents more suitable for a relative wide range of readership.

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