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Lin Chen

Microchannel Flow Dynamics and Heat Transfer of Near-Critical Fluid

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Microchannel Flow Dynamics and Heat Transfer of Near-Critical Fluid

Doctoral Thesis accepted by
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Supervisor's Foreword 1

I was very pleased to know that Dr. Lin Chen's Ph.D. thesis has been recommended to publish as a Springer book. It is an exceptional honor for young researchers in the scientific community who have achieved good results in their Ph.D. studies.

I have known Dr. Chen for a long time since I visited China and had a short stay in Peking University. At that time, he was fresh in research and with every curiosity in science and engineering. Then I invited him to visit my laboratory in 2011–2012. It was within that period that we began to discuss the "abnormalities" for critical fluids in microchannels. And now he is working as a JSPS (Japan Society for the Promotion of Science) fellow in Tohoku University to continue his microscale flow and heat transfer research in energy fields.

It is only for those recent 30 that scientists and engineers began to conduct in-depth exploration and utilization of supercritical/near-critical fluids. The topic of near-critical is very challenging, especially when microscale transportation is considered. Dr. Chen's book is the first one that focuses on the measurement and simulation of the supercritical fluid behaviors in microscale flows. As discussed in this book, there are a number of new behaviors and structures in convection and heat transfer phenomena. The multiple timescale and spatial-scale analyses in this study may become one of the important points for analyzing such problems.

The discussions in new heat transfer mechanisms in this book are also very interesting and suggestive. The research field of supercritical fluid dynamics and engineering is still young. Several important problems are proposed in this book, which are keys to looking into this new field. For example, the paradox of "critical heating up" and "critical cooling down", or the "critical speeding up" and "critical slowing down" in near-critical systems give new findings and new visions in the consideration of heat transfer and energy conversions.

There are many other interesting findings for critical fluids in this book. Discussion of possible applications in thermal engineering, chemical engineering, and others make it also useful for practical developments. I hope this book will become a useful reference for graduate students and researchers in many aspects of critical fluids.

Sendai, Japan
August 2016

Prof. Shigenao Maruyama

Supervisor's Foreword 2

I entered the supercritical fluid field around 15 years ago when I was a research scientist in Japan. At that time, the concept of supercritical fluid and its applications in engineering heating and cooling systems was just very new to the public. However, now the supercritical technologies have already been often proposed and used in the industry and many aspects of commercial lives. The advantages of supercritical fluid with its "abnormal" thermal and physical properties have made it a very promising substitute for future working fluids.

In recent years, my lab is focussing on supercritical energy conversion systems. Dr. Lin Chen joined my lab since 2006 and he has achieved many by his own hardworking and continuous curiosity in supercritical field. It is of no doubt that he has opened new possibilities in critical fluids by his own effort in recent years. We often talked about the supercritical enhancement of deterioration in heat transfer from an engineering viewpoint, but Dr. Lin Chen tried to go deep with the thermodynamic evolutions of the near-critical process, which is indeed helpful for the explanation of critical phenomena.

In my opinion, this thesis is valuable because it not only provides new knowledge in near-critical dynamics but it also put forward many interesting questions and challenges for future studies. The supercritical fluid field is still young as it is stated "only in the recent twenty or thirty years." However, there are many novel thoughts and exciting points that may trigger new innovations in real development. The micromixing technologies could be added by supercritical fluids, which may be introduced to chemical engineering, microsynthesis process, etc.

The impact of this book may also include: (a) specifically oriented to energy conversion and harvestation, which is related broad and of much interests nowadays; (b) recent progress in near-critical fields covered from fundamental theoretical, numerical, experimental studies, as well as recent application tests/findings; and (c) open possibilities and wide applications.

As Dr. Lin Chen put in this book, the extension "from supercritical to near-critical," and "from Kelvin-Helmholtz instability to Rayleigh-Taylor instability" is very challenging, which show us how our research will contribute to the real world from such basic understandings in a fluid evolution. I would like to recommend this book, where the most recent findings and challenges are presented one by one for readers of interest. I'm sure that this book would be useful for the researchers in this field and open new possibilities in the study of near-critical fluids.

Beijing, P.R. China
August 2016

Prof. Xin-Rong Zhang

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.

Sincerely, I would like to thank many of my friends who have helped me with this thesis book, though I cannot list all their names here. The encouragement and kind help from Prof. S. Maruyama, Prof. X.R. Zhang, Prof. A. Komiya, Prof. J. Okajima made me more confident in finishing this task. The editorial assistant from J. Huang from Peking University and Wayne Hu from Springer China, and many other friends who read and commented on the manuscript should all be acknowledged.

Sendai, Japan Dr. Lin Chen
August 2016

Acknowledgments

The current topic on near-critical dynamic flow and heat transfer is based on the understanding in supercritical and transcritical development in recent years. In the Ph.D. years, I conducted several project studies related to supercritical CO_2 problems: the natural convection flow, transcritical power cycle, supercritical experimental system development, supercritical CO_2 solar conversion, supercritical heating and cooling, etc. Those experiences helped in accumulating the basic data and knowledge in critical fluids. Many of the topics related to "abnormal" heat transfer or fluid stability problems. For example, the high efficiency heat exchange in supercritical solar conversion systems, or the natural circulation flow systems, is all interesting and promising aspects of critical fluids. Nevertheless, it is difficult to explain why and how the fluid changes from sub-critical, near-critical to supercritical and then defines the system nature. At that time, many researches were focused on the microscale channel flows with supercritical fluid and the transcritical regions are usually recommended for energy systems. However, how will the near-critical and transcritical procedure contribute to the overall system performance and how will the critical diverges affect the convective flow and heat transfer are still yet to be clarified. Then I tried to find original sources of the critical phenomena and the basic thermal-acoustic descriptions in critical transitions. A new world of near-critical field was opened to me when I found this very young field, where the findings of "abnormal" have just emerges in recent 30 years.

This research has been continuously supported by the Natural Science Foundation of China (No. 50706001, No. 50976001, No. 51276001, No. 51476001), and under the help of Prof. Xin-Rong Zhang in Peking University. The idea came from the long years of supercritical fluid research in Peking University since I become a sophomore student and joined the research group of Prof. Xin-Rong Zhang. Prof. Xin-Rong Zhang, as a supervisor, has helped me in this thesis book in every aspect he could: discussion of the thesis workflow, fund support, group discussion, summary of problems, and proof readings.

A part of the numerical simulation work was conducted in the Institute of Fluid Science, Tohoku University (Japan), under the supervision of Prof. Shigenao Maruyama during the visiting research period in his laboratory. The Global COE program, World Center of Education and Research for Trans-Disciplinary Flow Dynamics supported the visit. Prof. Maruyama is renowned for his research in heat transfer and related energy conversion studies. The large-scale simulation and part of the fundamental analysis was originated in Maruyama laboratory. In the second year, Prof. Maruyama invited me to visit again in Tohoku University. Then the first design of near-critical microchannel was discussed. Though the first design failed in next step development, the major problems are identified for the critical experiment. In Maruyama laboratory, I met Prof. Atsuki Komiya, Prof. Junnosuke Okajima and many other members. They helped the research in weekly discussions. It should be noted that there was a professor who graduated from the Prandtl laboratory nearly 100 years ago in Germany, and then he helped the starting-up of this Institute of Fluid Science.

The help from Prof. Hiroshi Yamaguchi and his student, now Prof. Yuhiro Iwamoto should also be specially noted here, as we got to know each nearly 10 years ago. Prof. Yamaguchi is a professional in supercritical fluids. The discussion and debate on critical fluids contributed a lot to the current book. Also, the cross-disciplinary discussion with Prof. Hiroshi Mukai from Kyushu Institute of Technology expanded from academic to philosophy. The communications with Prof. Benard Zappoli from CNES also pushed me to seek deeper into near-critical fluids. Prof. Akira Onuki from Kyoto University stressed the importance of phase transition and possible microbubble dynamics in the two-phase critical region to me. Now and then, when I recall those experience and valuable friendship with my respected professors, I would feel very thankful.

In the development of the thesis book, I met Prof. Wenquan Tao from Xi'an Jiaotong University, Prof. Daqiang Cang and Prof. Hao Bai from University of Science and Technology Beijing, Prof. Bo Yu from China University of Petroleum and many others. Their valuable comments and suggestions helped me a lot. In the experimental system development, I visited and discussed with Prof. Peixue Jiang and Prof. Ruina Xu in Tsinghua University with Prof. Xin-Rong Zhang. In May of 2015, Prof. Jiang and Prof. Xu also helped me in organizing an international younger researcher conference. The development of interferometer system was under the help of Prof. Xiaobin Luo from Huazhong University of Science and Technology and directly from Dr. Wei Lv (now in Wuhan University of Science and Technology) and Dr. Caobo Qi in Prof. Huaichun Zhou's laboratory.

Sincere thanks should also be addressed to my professors in College of Engineering, Peking University: Shiyi Chen, Dongxiao Zhang, Xidong Wang, Xiaolei Wu, Dingguo Xia, Jianchun Mi, Yi Zheng, Zhangfu Yuan, Hao Wang, Zuotai Zhang, Ling Xu, and many others. Their lectures and seminars have equipped me with the fundamentals of engineering and scientific research. I should also thank Prof. Xingang Liang (Tsinghua University), Prof. Rong Zhu (University of Science and Technology Beijing), Jianjun Tao (Peking University) for their proof reading and insightful comments on the manuscript of the thesis.

I should recall my great friends and colleagues since my entry to the university around eight years ago. Dr. Yuhui Cao, Dr Xiaojuan Li, Dr. Zhenjun Xu, Dr. Yan Zhao, Dr. Bili Deng, Dr. Licong Jin, Ms. Jia Liu, Mr. Bin Jiang, Mr. Yimin Chen, Ms. Menghe Sun, Mr. Sicong Yu, Mr. Cao Wang and the secretary in Peking University lab, Mr. Dong Wang, Ms. Yijun Liu, and many others who have spent their valuable moments with me in helping me improve the thesis book and myself. I'm sure we have to remember the days together.

This dissertation is dedicated to my dear family.

Sendai, Japan Lin Chen
August 2016

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