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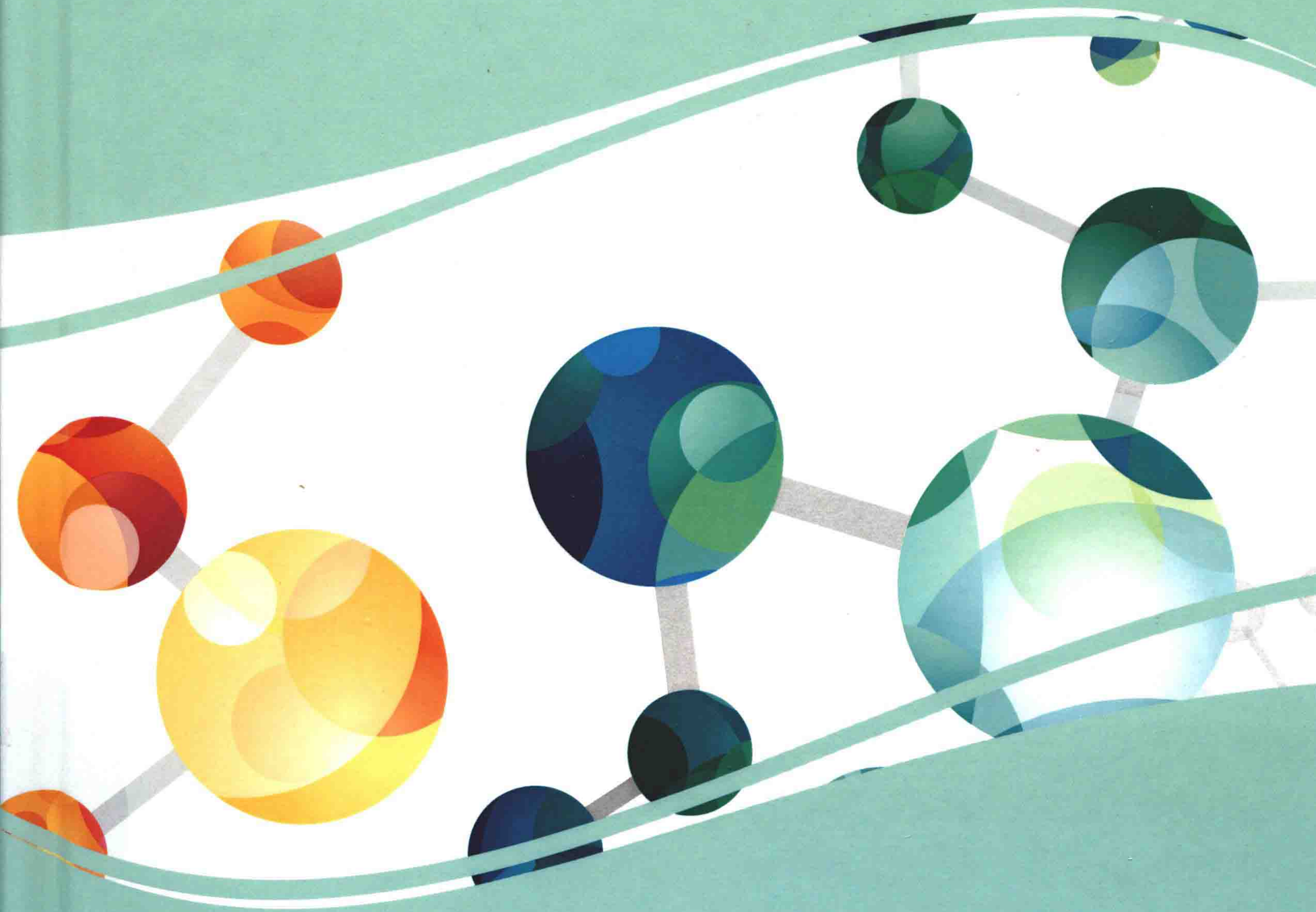
Advanced Applications of Supercritical Fluids in Energy Systems



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Advanced Applications of Supercritical Fluids in Energy Systems

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Foreword

This book treats fundamentals and applications of supercritical fluids. To my understanding, the clear explanation of supercritical states and the critical processes are very new and challenging. However, applications of supercritical fluids have already been proposed more than half a century ago. There are a lot many publications of supercritical fluids in chemical extraction using their unique thermal and chemical properties. However, the wide applications of such fluids in energy related fields are truly new and important. My personal research experience is mainly focused on the basics of fluid phase and thermodynamics. I'm very glad to see the publication of this book as it covers from the fundamentals to practical designs and applications, which should be welcomed by both scientists and engineers who are working related topics.

We have recognized rather recently that the thermodynamic states of supercritical fluids can be changed almost instantaneously by a heat input through a boundary. These changes are adiabatic in the bulk (at constant entropy per unit mass), while heat exchange between the solid and the fluid produces thermal diffusion layers. These layers are very thin (~10^{-3} cm, typically) as compared to a macroscopic cell size (~1 cm), but they can play the role of an efficient thermal-mechanical "piston" upon their thermal expansion or shrinkage. Particularly near the gas-liquid critical point, where the isobaric thermal expansion is largely enhanced, this effect gives rise to rapid heat transport through the cell in the form of sounds. In the literature of physics and hydrodynamics, however, not enough attention has yet been paid to the underlying fast acoustic processes taking place on a timescale of $L=c$, where L is the cell length and c is the sound velocity. These dynamical processes are in fact ubiquitous in confined compressible fluids and are thus crucial in heat-exchange applications, as discussed in this book. We stress that they are even fundamental in understanding traditional thermodynamics, where adiabatic and isothermal changes of thermodynamic states are just assumed without analysis of the actual physical processes. I noticed that several chapters of this book are doing such topics and the mechanisms of the very critical process will be helpful for the understanding of practical system performances.

Recently, a number of simulations have been performed on convection motions in supercritical fluids in two and three dimensions, not only in small scale models but also in large scale energy conversion cycles, which have been revealing unique features of supercritical hydrodynamics. First of all, in such fluids, convective fluid motions can easily be induced even by small thermal disturbances owing to the enhanced thermal expansion and a relatively small shear viscosity with and without earth gravity. For example, jet-like fluid ow has been observed around a heated boundary even in gravity-free conditions. As another unique effect, overall temperature changes in the cell take place due to the piston effect, for example, upon arrivals of thermal plumes at the boundary walls, which is unfamiliar in the usual

Rayleigh-Benard convection. Namely, local and global dynamical processes are inseparably coupled in supercritical fluids, leading to unique hydrodynamics different from that of incompressible fluids.

Supercritical fluids can be used in various technological applications because of their high ability of heat transport. In one phase states, the piston effect yields energy transport in the form of sounds. In two-phase states, latent heat is adsorbed or released at the gas-liquid interfaces upon evaporation and condensation, which is indeed the well-known mechanism of heat pipes used in refrigerators. Hydrodynamics of highly compressible fluids in the supercritical and two-phase regions is not easy to understand, but it should be new and crucial in science and technology. Also, the large density gradients may lead to a preferable potential for natural circulation flow systems, such as solar and mechanical heating/cooling systems. Then the focus of this book is on energy conversion, which includes the heat transfer and flow dynamics details, natural convection systems, power generation, solar process, nuclear thermo-hydraulic problems, various energy cycles, as well as related thermodynamic topics, fluid dynamics, multi-scale experiments and analysis.

I believe that this book provides timely and adequate accounts of the above-mentioned aspects of supercritical fluids and very new and important energy conversion applications. Many of the contributors are my friends and in this book they summarized the very best research works in fluid system and energy conversion fields. I would like to thank Dr. Lin Chen for inviting me to be the first reader of the raw chapters and write a foreword. Sincerely I recommend this book to readers who have interest in this field. I'm sure this book will be one useful reference for researchers, engineers and even graduate students who have interest in flow dynamics studies and energy topics.

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Akira Onuki *obtained his B.S (1971) and PhD (1976) from the University of Tokyo. Then he worked as a research associate in Kyushu University (1977), associate professor (1983) and full professor in Kyoto University (1991-2012). Now he is a Professor Emeritus of Kyoto University. His research is focused on soft matters and physical understanding of phase transitions, equilibriums, as well as thermodynamics and some applications in real systems. In recent years, he has published many highly cited scientific papers on those topics in PRL, PRB, PRE, JCP, EPL, etc. He has authored many professional books/chapters, including the most famous one "Phase Transition Dynamics" (Cambridge, 2004).*

Preface

Supercritical fluids are now increasingly utilized in various energy related systems. The applications of supercritical fluids contribute to both the improvement of energy efficiency as well as reducing greenhouse gas emissions. Applications of supercritical fluids in recent years could be found in solar heater, geothermal process, extraction, refrigeration, cooling of the turbine blades and electronic components, heat pumps, power generations, nuclear systems and many other occasions.

A supercritical fluid is one fluid state that at a temperature and pressure above the critical point, where no distinct liquid or gas phases exist. This fluid status is specially controlled or maintained to take advantage of the preferable thermal and transport properties. Near to the critical point, small changes in pressure or temperature will result in large changes in thermos-dynamic properties. It is only for those thirty-years or so that scientists and engineers began to treat the in-depth exploration and utilization of such fluids. As it is well known that supercritical fluids are suitable as a substitute solvent, energy conversion working fluid, more and more attentions have been attracted in this topic in recent decades.

Flow dynamics and fundamental heat transfer of supercritical fluids are of critical importance in both practical supercritical devices design and fluid sciences. For example, the most often studied/used supercritical fluid CO_2, as a natural working fluid, is a nonflammable, nontoxic alternative that could be safely used as substitute of traditional CFCs, HCFCs and hydrocarbons, ammonia, etc. Such fluid has potential for future energy systems and transportation mechanisms. CO_2 is also proved to be environmentally benign due to the fact that it's ODP (Ozone Depletion Potential) = 0 and GWP (Global Warming Potential) = 1. Now both in the laboratory and industrial fields, supercritical CO_2 is widely employed. Supercritical water is also widely used for high temperature applications (mainly power cycles) for its suitable critical temperature and pressure operation ranges. The critical point data is shown in Table 1 for some representative fluids, which can also be easily referenced in engineering handbooks. Such utilization of supercritical fluids indeed has provided new choices of future green working fluids with both high efficiency and benign environmental impacts.

The basic flow and thermal physical behaviors of supercritical fluids have been discussed by many researchers since early 20s century. The basic property changes and heat transfer characteristics, in a unique range of temperature and pressure for specific applications, of supercritical working fluids have shown new challenges to scientists and engineers of that time. The main question is: what is the nature of supercritical states and how to improve heat transfer? It is only in recent years that such mechanisms are revealed to the scientific community. System behavior and optimal design of supercritical flow have also been widely investigated after 1980s. And later one very important Space Mission of Europe (D-1 mission in 1984), quick and homogeneous heating up of critical fluids are experimentally identified under microgravity. This opens a new world of critical phenomena and it attracted scientist to explore in detail what is happening when a fluid goes approaching/across the critical point.

Table 1. Critical parameters of some fluids

Fluid	Critical T_c (K)	Critical p_c (MPa)	Critical ρ_c (kg/m^3)
H_2O	647.1	22.06	322.2
CO_2	304.13	7.378	467.8
N_2	126.24	3.398	313.9
O_2	154.58	5.043	436.2
Xe	289.74	5.840	1113
H_2	32.976	3.761	31.43
^3He	3.317	1.2928	41.45
SF_6	318.717	3.7545	742
R13	302.0	3.879	582.88
R23	299.29	4.832	526.5
R134a	374.21	4.0593	511.9
R410a (50%R32+50%R125)	344.49	4.9012	459.03

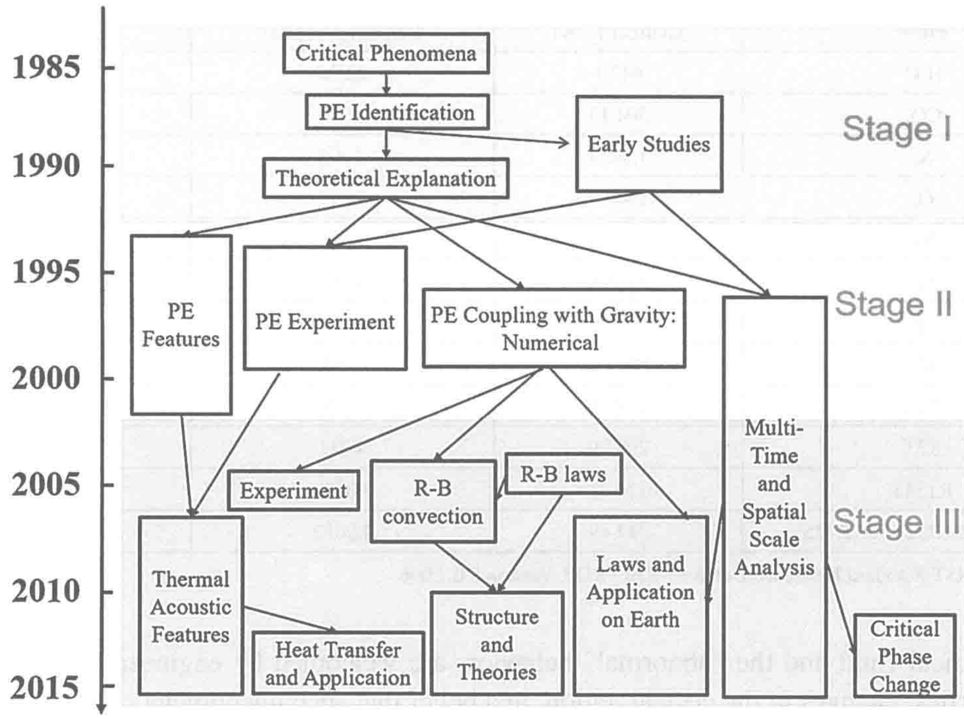
Data from: NIST Standard Reference Database-REFPROP, Version 8.0, 2006.

Supercritical fluid and the "abnormal" behaviors are welcomed by engineers so as to utilize the large properties' changes in the critical region, in a belief that such phenomena can be understood and controlled. For such large and drastic changes of properties, especially the density variations, viscosity fluctuations, thermal conductivity changes, and thermal capacity peaks are all dependent on how the status is close to the critical point, namely the critical distance, which can be defined by a reduced temperature parameter by the critical temperature. Figure 1 shows the schematic picture of the developments in near-critical phenomena, which is of critical importance for the understanding of the choices in supercritical application systems. Some detailed explanations of such basics as well as the heat mass transfer characteristics will be covered by chapters of Section 1 in this book.

Among the many applications, natural circulation flow and heat transfer attracted a lot of attention. In the absence of pumps and their associated mechanical devices, a natural circulation system can work well and thus it has advantage over a forced circulation system in terms of cost, system reliability and maintenance. Natural circulation systems using supercritical fluids give good performances with the large density changes inside a loop system when it is near the critical region. Such system yields both high thermal efficiency and good fluid mobility. However, as for near critical fluid the physical properties and transport coefficients would experience dramatic changes, leading to chaotic behaviors and instabilities. These instabilities are harmful in most application systems. Nevertheless, the mechanisms of these behaviors, especially system instabilities are due to the complexities of both system geometries and various boundary conditions. Section 2 of this book deals with such topics and the applications in solar and nuclear systems is also covered. The factors that might affect system stability are also identified through experiments and numerical simulations on this kind of fluid model.

The detailed mechanisms of the abnormal behaviors of supercritical/trans-critical CO_2 thermal cycles are still less studied and systematic reports just can be found in very recent years. Some recent studies have focused on the heat and mass transport details in supercritical/trans-critical systems. In those supercritical energy conversion systems, typical generation feature was identified and unsteady cases are

Figure 1. Piston effect and thermal-mechanical effect related research history and major topic flow



more often seen than normal water cases due to the unique thermo-physical properties of near-critical fluid. The peculiar changes of properties, especially for conditions in the vicinity of critical point, are typical for supercritical fluid and it brings additional difficulties in related scaling and modeling process. Many recent studies have also set up transient multi-scale models and systematically analyzed the basic heat transfer, hydraulic behaviors and strategies for stability control. Such topics are covered in Section 3 of this book.

After the nuclear accident in Japan, though new generations of nuclear power plant are still under development, more and more people are becoming skeptical on the future of nuclear power. Now the major developments of new generation nuclear power plant focus on the working fluid and respective safety design. And the thermal and hydrodynamic behaviors of fluid are one of the core problems to be investigated, especially for non-linear fluids like supercritical water or supercritical CO_2, which are considered for utilization in new generation nuclear cooling cycles. Supercritical fluids have become one substitute for future nuclear power plant is partly due to their preferable loading performance with high heat capacity and high circulation rate even under pure natural convection condition. Chapters in Section 4 of this book mainly focus on the basic thermal and hydrodynamic behaviors of trans-critical/supercritical fluid in nuclear systems. Indeed the application of supercritical CO_2 should not be limited in nuclear engineering or related, in fact it has been proved to have equal or higher performance in heat pump or solar conversion system, and it has also been proposed and widely used in many other engineering systems.

ORGANIZATION OF THE BOOK

This book has gathered altogether 17 chapter contributions from representative groups of supercritical fluids research from Australia, China, Canada, Germany, France, India, Japan, Russia, Slovenia, United States, etc. Those chapters are organized into four major sections. The contents of the book chapters cover first the basic thermo-dynamic behaviors and 'abnormal' properties from a thermophysical aspect; then basic heat transfer and flow characteristics, recent findings in physical aspect, engineering, micro-/nano-scale phenomena, multi-scale analysis and transient behaviors in energy systems are discussed; after that, most recent and challenging problems and outlook for the applications and innovations of supercritical fluids in energy systems are discussed.

Section covers the fundamentals of supercritical fluids flow and heat transfer studies. Four chapters (Chapter 1-4) are included in this section. In those chapters, fundamentals of supercritical fluids and near-critical phenomena are reported and discussed, including the very basic thermophysics of critical transition under thermal and flow conditions. Thermal-mechanical effects of critical fluids and the related heat transfer and flow stability problems are discussed by major research groups in this field. Recent developments on the critical transition and a special liquid metal critical study are also included.

Chapter 1 is "Thermal Effects in Near-Critical Fluids: Piston Effect and Related Phenomena". This chapter deals with the very particular thermal behavior that supercritical fluids exhibit when nearing their critical point. In this region, supercritical fluids exhibit strong anomalies in their thermodynamic and transport properties. Pressure change associated to a temperature variation leads to a nearly isentropic thermalization of the fluid, the "piston effect", which leads to a paradoxical "critical speeding-up" and very interesting convection phenomena. These effects can deeply modify the supercritical fluids thermal behavior in space and energy activities, giving to these effects socio-economic relevance.

Chapter 2 is "Numerical Modelling of Hydrodynamic Instabilities in Supercritical Fluids". The case of a supercritical fluid heated from below (Rayleigh-Bénard) in a rectangular cavity is first presented. The stability of the two boundary layers (hot and cold) is analyzed by numerically solving the Navier-Stokes equations with a van der Waals gas and stability diagrams are derived. The very large compressibility and the very low heat diffusivity of near critical pure fluids induce very large density gradients which lead to a Rayleigh–Taylor-like gravitational instability of the heat diffusion layer. Depending on the relative direction of the interface or the boundary layer with respect to vibration, vibrational forces can destabilize a thermal boundary layer.

Chapter 3 is "Thermal-Mechanical Effects and Near-Critical Fluid Dynamic Behaviors in Micro-Scale". The chapter deals with near-critical CO_2 micro-scale thermal convective flow and the effects of thermal-mechanical process. When the scale becomes smaller, new and detailed figures of near-critical thermal effects emerges. To explore this new area, theoretical developments and numerical investigations discussed and explained in this chapter. The thermal-mechanical nature of near-critical fluid would play a leading role in small time and spatial scales. That effect dominants the thermal dynamic responses and convective structures in micro-scale. The scaling effects, boundary process, instability evolutions, mixing flows and characteristics, and applications are also discussed in this chapter.

Chapter 4 is "X-Ray Scattering Studies of Expanded Fluid Metals". Fluid metals exhibit significant properties of thermodynamic-state dependence, since the inter-particle interaction among the constituents (electrons and ions) considerably changes depending on their thermodynamic conditions. X-ray scattering experiments of fluid metals in the expanded state gives the microscopic understanding of the structural and electronic properties of fluid metals. The purpose of this chapter is to provide intriguing aspects of fluid metals originated from the existence of conduction electrons, which distinguishes fluid metals from non-conducting fluids, through the results of fluid rubidium and mercury.

Section 2 deals with the convection flow and heat transfer characteristics of supercritical fluids. Four chapters (Chapter 5-8) are included in this section. Chapters in this section are selected to discuss the convective behaviors and circulation flow heat transfer characteristics. Supercritical loop systems are very basic concept for various applications of effective energy conversion and thermal utilization processes. This section is then focused on the basic principles, mechanisms and applications in this aspect. The results and proposals in this section may contribute to related natural circulation system designs of supercritical fluids.

Chapter 5 is "Principles, Experiments, and Numerical Studies of Supercritical Fluid Natural Circulation System". The chapter presents the principals of supercritical natural circulation loop system and its application challenges. In this chapter, a specially designed experimental prototype system is introduced and compared with numerical findings. The system can be operated in wide range of high pressure in the critical region. Very high Reynolds number natural convection flow can be achieved only by simple heating and cooling. Thermal performance analysis and parameter effects are carried out along with the experimental development. The heat transfer dependency on operation and its mechanisms are also explained and summarized.

Chapter 6 is "Supercritical Natural Circulation Loop: A Technology for Future Reactors". Supercritical natural circulation loop is a compelling technology for cooling of modern nuclear reactors, which promises enhanced thermalhydraulic performance in a simple design. This chapter summarizes the observation till date, starting from the very fundamentals. Different methods of analyses, including analytical, simple 1-D numerical and multi-dimensional codes, as well as experimental are elucidated. A comprehensive discussion is made on various geometric and operating parameters from both thermalhydraulic and stability point of view.

Chapter 7 is "Application of Supercritical Carbon Dioxide for Solar Water Heater". The large variation of thermophysical properties of supercritical fluids allows a strong natural convection flow with absorbing as well as transporting a large amount of heat energy. Taking the low critical temperature, this study proposed a solar water heater using supercritical carbon dioxide. The new solar water heater has a great potential to more effectively supply heat energy from solar energy, comparing with the conventional solar water heaters of water-in-glass tube type. The measured collector and heat recovery efficiencies are over 60%. In this chapter, the overview of the new solar water heater using supercritical carbon dioxide is also included.

Chapter 8 is "Heat Transfer and Fluid Flow of Supercritical Fluids in Advanced Energy Systems". This chapter aims to clarify the supercritical fluids thermal hydraulics characteristics including heat transfer, pressure drops and flow instabilities for advanced energy systems. The convection heat transfer models considering the effect of nonlinear properties and buoyancy acceleration are discussed. Then, the hydraulic resistance models are suggested for different conditions. The published models for supercritical flow instabilities are also summarized and clarified. At last, two typical case studies have been provided to further intuitively elaborate the thermal hydraulics of supercritical fluids within the advanced energy systems.

Section 3 is the supercritical thermal conversion of different scales. Four chapters (Chapter 9-12) are included in this section. In those chapters, multi-scale analysis is discussed for supercritical and near-critical fluid systems: from simple channels to complex heat transfer system designs. The confinement and scaling effect of supercritical fluid heat transfer flow is focused in this section. The knowledge obtained by major researchers in this field will contribute to various applications of supercritical fluid based heating, cooling, microscale transportation, reaction, etc.

Chapter 9 is "Heat Transfer in Supercritical Fluids: Going to Microscale Times and Sizes". Results of experimental study of non-stationary heat transfer in supercritical fluids, which were obtained using the method of controlled pulse heating of low-inertia wire probe, are discussed. The aim of this study was to clarify the peculiarities of heat conduction mode at significant heat loads. A threshold decrease in the "instant" heat transfer coefficient, the more pronounced the closer the pressure value to critical pressure, has been found. Small time and spatial scale in the experiments (units of millisecond and units of micrometer) in combination with high-power heat release (up to 20 MW/m^2) makes it possible to associate the results with the behavior of boundary layer of heat transfer agent.

Chapter 10 is "Study on Cooling Heat Transfer of Supercritical Carbon Dioxide Applied to Trans-Critical Carbon Dioxide Heat Pump". This chapter addresses to recent experimental, theoretical and numerical studies on cooling heat transfer of supercritical CO_2 under the effect of lubricating oil. A systematic study on heat transfer coefficient and pressure drop of supercritical CO_2 was carried out at wide ranges of tube diameter, mass flux, heat flux, temperature and pressure. Effects of parameters such as mass flux, pressure, heat flux, and cooling-tube diameter on the heat transfer coefficient and pressure drop were experimentally analyzed. It was found that the varied flow pattern of two-phase fluid caused by the difference in miscibility of oil with supercritical CO_2 lead to different heat transfers.

Chapter 11 is "Supercritical CO_2 and Its Application to Rankine Cycle". Supercritical CO_2 has been given much attention to be a working fluid in a power cycle due to its unique properties. The supercritical CO_2 solar Rankine cycle system was designed and developed by using the benefit of supercritical state of CO_2 to generate electric power. Operating the power cycle in the supercritical region of CO_2 enhances the heat transfer in energy exchanging process and improves the cycle efficiency. In this chapter, the development of main components in the system are introduced and discussed particularly by focusing on the properties of CO_2 for higher performance.

Chapter 12 is "Supercritical Fluids and Their Applications in Heat Conversion". The chapter presents the importance of the selection of supercritical fluids for both high- and low-grade heat sources for power generation. Low-grade heat sources, typically defined as below 300 °C, are abundantly available as industrial waste heat, solar thermal, and geothermal, to name a few. This chapter investigates the potential of supercritical Rankine cycles in the conversion of low-grade heat to power, while the second part discusses supercritical fluids used in higher grade heat conversion system. This chapter discusses supercritical fluids fundamentals, selection of supercritical working fluids for different heat sources, and the current research, development, and commercial status of supercritical power generation systems.

Section 4 is supercritical power generation systems and green energy harvestation. Five chapters (Chapter 13-17) are included in this section. Chapters in this section are mainly focused on power generation systems assisted by supercritical fluids and supercritical cycles. Based on the current understanding of supercritical transport mechanism (heat, mass, chemical reaction, etc.), system scale analysis is focused for chapters in the discussion of power efficiency and generation system designs. The compact and high efficiency in power engineering, chemical engineering, thermal engineering as well as nuclear engineering would be attractive for scientists and engineers in this field. Still, the contribution of green energy harvestation and other related supercritical energy systems are also included.

Chapter 13 is "Application of Supercritical Pressures in Power Engineering". This chapter discusses the use of SuperCritical Fluids (SCF) based thermal power plants and their various applications including nuclear power plants for Generation IV reactors. The historic development (since 1930s) and recent challenges of SuperCritical Fluids (SCF) in nuclear reactors, power generation systems and others are introduced. The primary objectives for using SuperCritical Water (SCW) as a coolant in nuclear reactors are introduced in this chapter. Generation IV nuclear reactors with SCF are introduced and discussed into detail on the basic system designs, features, and future challenges.

Chapter 14 is "Energy Conversion Using the Supercritical Steam Cycle". A supercritical steam (or Rankine) cycle is used for new coal-fired power plants, and it has also been proposed for future water-cooled nuclear reactors to enhance their efficiency and to reduce their costs. This chapter provides the technical background explaining this technology. Some criteria for boiler design and operation, like drum or once-through boiler design, fixed or sliding pressure operation and coolant mixing, are discussed in general to explain the particular challenges of supercritical steam cycles.

Chapter 15 is "The Basic Thermal Hydraulic Issues of Applying Supercritical Fluid to Nuclear Reactors". This chapter is mainly focused on illustrating some major progress on thermal hydraulic issues of supercritical water performed in Nuclear Power Institute of China (NPIC). An analytical method and in-house code are proposed to predict the heat transfer coefficient and friction coefficient based on the two layer wall function. Flow instability experiments in a two-parallel-channel system with supercritical water are made to provide an up-to-date knowledge of supercritical flow instability phenomena and initial validation data for numerical analysis.

Chapter 16 is "Supercritical Fluids as a Tool for Green Energy and Chemicals". Hydrothermal conversion of biomass is a promising technology for the conversion of biomass into biofuels and bio-based chemicals. This chapter is focused on the waste biomass conversion for production of biofuels and chemicals by applying sub- and supercritical fluids. The target is to reduce the operating temperature and energy requirements by processing biomass with water. Methods developed in this chapter for determination of thermodynamic and transport properties for multicomponent systems of different solid compounds under extreme conditions are described.

Chapter 17 is "Application of Supercritical Technologies in Clean Energy Production: A Review". In this chapter the authors seek to acquaint the reader with unusual properties of supercritical fluids, and how these properties are used for various applications in the synthesis of biofuels and the intensification of energy processes and thermal cycles. The review includes the studies of leading scientists from around the world related to effective and environmentally friendly methods and technologies of energy acquisition and conversion involving the synthesis of motor fuels, materials and chemicals, solar energy conversion and thermal cycle efficiencies using supercritical fluids.

TARGET OF THE BOOK

This book is focused on gathering and organizing the current developments in supercritical fluid related energy conversion studies and engineering developments. There are several books published in supercritical fluids, however, nearly all of them are focused in chemical extraction fields or fundamental physical aspects of supercritical fluids. Such demand in the current status-of-art in this field triggered the thinking of gather the main researchers together for publication of a book that summarizing the aspect of increasingly important field in heat transfer and energy conversion. Therefore, this book tries to cover from the very basics to the current applications of supercritical fluids. The understanding of the fundamentals will surely contribute to the development in related system designs.

It is hoped that this book will not only contributions to scientific world but also to the engineers. Indeed, such new applications of the supercritical field are also related to the energy efficiency enhancement and greenhouse gas emission reduction, which will be of great importance to the general wellbeing of humankind. For the above reason, the editors tried their best to invite the major research groups of supercritical fluids around the world to discuss and contribute to the current book. The research and publication in supercritical fluid dynamics and engineering should be of great importance in both scientific advancement and industrial innovations. The following research topics are well covered in this book:

- Supercritical fluid based heat transfer mechanisms,
- Numerical development of supercritical/near-critical fluids,
- Experiments on supercritical/near-critical fluid flow and heat transfer,
- Natural circulation flows and heat mass transfer and applications,
- Supercritical fluid based chemical reaction and manufacturing processes,
- Supercritical fluid based energy conversion and harvestation,
- Supercritical fluid utilization and performances in nuclear engineering,
- Efficiency analysis and apparatus design in supercritical fluid based systems,
- Design and optimizations of supercritical fluid/binary fluid based apparatus.

The target audience of this book will be composed of graduate students, young and professional researchers, engineers and other public policy makers interested in the field of supercritical fluids, energy conversion and environmentally friendly systems. In addition, the book could be used as handbook or reference for supercritical fluid and energy conversion related researches and engineering.

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