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Thermal-Hydraulic Analysis of Nuclear Reactors

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This book is dedicated to my family

Bahman Zohuri

*This book is dedicated first and foremost to my grandfather,
General Siavash Rahimi, and to the rest of my family*

Nima Fathi

Preface

The demand for clean, non-fossil-based electricity is growing; therefore, the world needs to develop new nuclear reactors with higher thermal efficiency in order to increase electricity generation and decrease the detrimental effects of fossil-based energy on the environment. The current fleet of nuclear power plants is classified as Generation III or lower. However, these models are not as energy efficient as they should be because the operating temperatures are relatively low. Currently, groups of countries have initiated a program of international collaboration to develop the next generation of nuclear reactors called Generation IV. The ultimate goal of developing such reactors is to increase the thermal efficiency from the current range of 30–35 % to 45–50 %. This increase in thermal efficiency would result in a higher production of electricity compared to current pressurized water reactor (PWR) or boiling water reactor (BWR) technologies.

The Generation IV International Forum (GIF) program has narrowed down the design options for nuclear reactors to six concepts. These concepts are gas-cooled fast reactors (GFRs), very high temperature reactors (VHTRs), sodium-cooled fast reactors (SFRs), lead-cooled fast reactors (LFRs), molten salt reactor (MSRs), and super critical water-cooled reactors (SCWRs). These nuclear-reactor concepts differ in their design with respect to aspects such as the neutron spectrum, coolant, moderator, and operating temperature and pressure.

There are many different types of power reactors. What is common to them all is that they produce thermal energy that can be used for its own sake or converted into mechanical energy and, ultimately, in the vast majority of cases, into electrical energy. Thermal-hydraulic issues related to both operating and advanced reactors are presented. Further, thermal-hydraulic research and development is continuing in both experimental and computational areas for operating reactors, reactors under construction or ready for near-term deployment, and advanced Generation IV reactors. As computing power increases, fine-scale multiphysics computational models, coupled with systems analysis code, are expected to provide answers to many challenging problems in both operating and advanced reactor designs.

Those that practice the art of nuclear engineering must have a physical and intuitive understanding of the mechanisms and balances of forces that control the transport of heat and mass in all physical systems. This understanding starts at the molecular level, with intermolecular forces and the motion of molecules, and continues to the macroscopic level, where gradients of velocity, temperature, and concentration drive the diffusion of momentum, heat, and mass, and the forces of pressure, inertia, and buoyancy balance to drive fluid convection.

All professors believe that there is no ideal textbook for the courses they teach. In the case of courses related to the present subject, this is actually true. Traditionally, during the years in which the authors taught courses on the present subject matter, the text has been *Transport Phenomena* by Bird, Stewart, and Lightfoot. Though this is an excellent text on the fundamentals of transport phenomena, it lacks specific examples in nuclear engineering, as well as information on two-phase flows, boiling, condensation, and forced and natural convection. In writing this book, the authors have drawn heavily on materials from *Convective Heat and Mass Transfer* by Kays and Crawford, *Convective Boiling and Condensation* by Collier, and *Nuclear Systems* by Todreas and Kazimi.

This text covers the fundamentals of thermodynamics required to understand electrical power generation systems. It then covers the application of these principles to nuclear reactor power systems. It is not a general thermodynamics text but a thermodynamics text aimed at explaining the fundamentals and applying them to the challenges facing actual nuclear power systems. It is written at an undergraduate level but should also be useful to practicing engineers.

The book also concentrates on the fundamentals of fluid dynamics and heat transfer, thermal and hydraulic analysis of nuclear reactors, two-phase flows and boiling, compressible flows, stress analysis, and energy conversion methods.

It starts with fundamental definitions of units and dimensions then moves on to thermodynamic variables such as temperature, pressure, and specific volume. It then goes into thermal hydraulic analysis, with topics from that field covered in Chaps. 2 through 16, where it finishes off with the design of a heat exchanger and shells and tubes using various techniques of verification and validation (V&V) in computational mechanics and the application of their basic principles to Brayton and Rankine cycles for power generation. Brayton cycle compressors, turbines, and recuperators are covered in general, along with the fundamentals of heat exchanger design. Rankine steam generators, turbines, condensers, and pumps are also discussed. Reheaters and feed water heaters are also covered. Ultimate heat rejection by circulating water systems is also discussed. Chapter 17 covers the analysis of reactor accidents, which is independent of other chapters and can be assigned as a standalone reading chapter for students or taught separately.

The third part of the book covers current and projected reactor systems and how thermodynamic principles are applied to their design, operation, and safety analyses.

Detailed appendices cover metric and English system units and conversions, present detailed steam and gas tables, discuss heat transfer properties, and describe nuclear reactor systems.

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Last but not least, special thanks go to our parents, wives, children, and friends for their constant encouragement, without which this book could not have been written. We especially appreciate their patience and understanding for the authors' frequent absence from home and long hours in front of the computer during the preparation of this book.

Contents

Authors

Bahman Zohuri is currently at Galaxy Advanced Engineering, Inc., a consulting company he founded in 1991 when he left both the semiconductor and defense industries after many years of working as a chief scientist. After graduating from the University of Illinois in the field of physics and applied mathematics, he joined Westinghouse Electric Corporation, where he performed thermal hydraulic analysis and natural circulation for inherent shutdown heat removal systems (ISHRS) in the core of a liquid metal fast breeder reactor (LMFBR) as a secondary fully inherent shutdown system for secondary loop heat exchanges. All these designs were used for nuclear safety and reliability engineering for self-actuated shutdown systems. Around 1978, Dr. Zohuri designed a mercury heat pipe and electromagnetic pumps for large pool concepts of LMFBRs for heat rejection purpose in such reactors, for which he received a patent. Subsequently, he was transferred to the defense division of Westinghouse, where he was responsible for the dynamic analysis and launch method and handling of MX missiles from canisters. The results were applied to MX launch seal performance and muzzle blast phenomena analysis (i.e., missile vibration and hydrodynamic shock formation). Dr. Zohuri was also involved in conducting analytical calculations and computations in the study of nonlinear ion waves in rarefying plasma. The results were applied to the propagation of soliton waves and the resulting charge collector traces in the rarefactions characteristic of the corona of a laser-irradiated target pellet. As part of his graduate research work at Argonne National Laboratory, he performed computations and programming of multi-exchange integrals in surface physics and solid state physics. Dr. Zohuri holds patents in areas such as diffusion processes and the design of diffusion furnaces, which he obtained while working as a senior process engineer for various semiconductor companies such as Intel Corp., Varian Inc., and National Semiconductor. Later on he joined Lockheed Missile and Aerospace Corporation as Senior Chief Scientist and was responsible for research and development (R&D) and the study of vulnerability, survivability, and both radiation and laser hardening of various components of the Strategic Defense Initiative, also known as Star Wars. This included of payload (i.e., IR sensors) for the Defense Support Program, Boost Surveillance and Tracking Satellite, and Space Surveillance and Tracking Satellite against laser or nuclear threats. While at Lockheed, he also studied and analyzed how laser beams and nuclear radiation interact with materials and investigated transient radiation effects in electronics, electromagnetic pulses, system-generated electromagnetic pulses, single-event upsets, blasts, and thermomechanical, hardness assurance, maintenance, device technologies.

He spent a few years consulting under the auspices of his company, Galaxy Advanced Engineering, with Sandia National Laboratories, where he supported the development of operational hazard assessments for the Air Force Safety Center in collaboration with other interested parties. The intended use of the results of his consulting work was their eventual inclusion in Air Force Instructions issued specifically for directed energy weapons operational safety. Dr. Zohuri completed the first version of a comprehensive library of detailed laser tools for airborne lasers, advanced tactical lasers, tactical high-energy lasers, and mobile/tactical high-energy laser, for example.

He also oversaw SDI computer programs related to Battle Management C^3, artificial intelligence, and autonomous systems. He is the author of several publications and holds various patents such as Laser Activated Radioactive Decay and Results of Thru-Bulkhead Initiation.

Finally, Dr. Zohuri recently published two books with CRC/Francis Taylor, *Heat Pipe Design and Technology: A Practical Approach* and *Directed Energy Weapons Technologies*, and has published the following book with Springer Publishing Company as listed below:

1. Dimensional Analysis and Self-Similarity Methods for Engineers and Scientists, March 2015
2. Thermodynamics in Nuclear Power Systems with Dr. Patrick McDaniel, June 2015
3. Combined Cycle Driven Efficiency for Next Generation Nuclear Power Plants, May 2015

Nima Fathi holds an MSc in mechanical engineering, focusing on multiphase-flow modeling for particle interaction in Stokes flow. He is an expert in computational fluid dynamics (CFD) and verification and validation (V&V) in computational mechanics. Nima has many years of experience in industry, where he designed more than 86 different types of heat exchangers and pressure vessels for the various projects in which he participated over the years. His outstanding industrial and engineering experiences and accomplishments include successful collaboration with various Asian and U.S. companies on projects related to thermal, structural, and CFD analysis.

His technical experience includes design, industrial drafting, procurement, and fabrication, all related to fluid dynamics and thermal hydraulic analysis of multiphase flows. He also holds two patents pending in the optimization of heat transfer in solar chimney power plants and increasing thermal hydraulic performance in power plants.

Presently, Mr. Fathi is at the University of New Mexico in the Department of Mechanical Engineering, where for the past several years he has been teaching courses in heat transfer while pursuing his PhD in mechanical engineering and his MSc in nuclear engineering.