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Combined Cycle Driven Efficiency for Next Generation Nuclear Power Plants

An Innovative Design Approach

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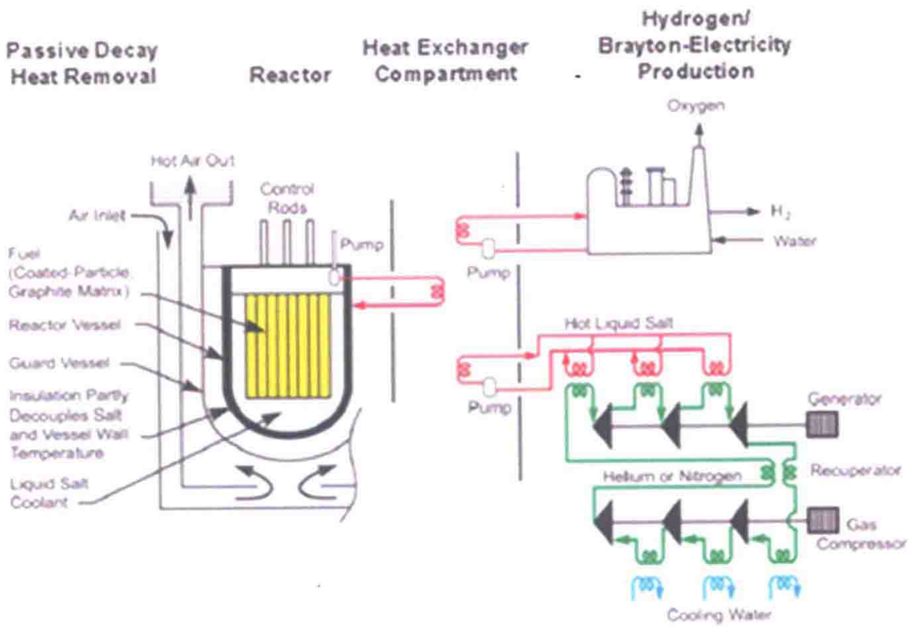

Passive Decay Heat Removal
Reactor
Heat Exchanger Compartment
Hydrogen/ Brayton-Electricity Production
Hot Air Out
Air Inlet
Control Rods
Pump
Fuel (Coated-Particle, Graphite Matrix)
Reactor Vessel
Guard Vessel
Insulation Partly Decouples Salt and Vessel Wall Temperature
Liquid Salt Coolant
Oxygen
H_2
Water
Pump
Hot Liquid Salt
Pump
Generator
Helium or Nitrogen
Recuperator
Gas Compressor
Cooling Water

Preface

Today's global energy market places many demands on power generation technology including high thermal efficiency, low cost, rapid installation, reliability, environmental compliance, and operation flexibility.

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 on the environment. The current fleet of nuclear power plants is classified as Generation III or less. 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 an 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 what currently is in the 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.

A number of technologies are being investigated for the next generation nuclear plant that will produce heated fluids at significantly higher temperatures than current generation power plants. The higher temperatures offer the opportunity to significantly improve the thermodynamic efficiency of the energy conversion cycle. One of the concepts currently under study is the molten salt reactor. The coolant from the molten salt reactor may be available at temperatures as high as 800–1000 °C. At these temperatures, an open Brayton cycle combined with Rankine bottoming cycle appears to have some strong advantages.

Combined-cycle thermal efficiency increases as gas turbine-specific power increases. The gas turbine firing temperature is the primary determinant of specific power.

Gas turbine engines, both in aircraft and industrial power generation, represent one of the most aggressive applications for structural materials. With ever growing demands for increasing performance and efficiency, all classes of materials are being pushed to higher temperature capabilities. These materials must also satisfy stringent durability and reliability criteria. As materials are developed to meet these demanding requirements, the processing of these materials often becomes very complicated and expensive. As a result, the cost of materials and processes has become a much larger consideration in the design and application of high-performance materials. Both the aircraft engine and power generation industries are highly cost competitive, and market advantage today relies on reducing cost as well as increasing performance and efficiency.

Development of high-temperature/high-strength materials, corrosion-resistant coatings, and improved cooling technology has led to increases in gas turbine firing temperatures. This increase in firing temperature is the primary development that has led to increases in combined-cycle gas turbine (CCGT) thermal efficiencies. The improvements in combined-cycle thermal efficiencies and the commercial development of combined-cycle power plants have proceeded in parallel with advances in gas turbine technologies.

The Generation IV International Forum (GIF) Program has narrowed design options of the nuclear reactors to six concepts. These concepts are gas-cooled fast reactor (GFR), very high temperature reactor (VHTR), sodium-cooled fast reactor (SFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), and super critical water-cooled reactor (SCWR). These nuclear reactor concepts differ in their design in 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–hydraulics 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 the computing power increases, the fine-scale multi-physics computational models, coupled with the systems analysis code, are expected to provide answers to many challenging problems in both operating and advanced reactor designs.

Compact heat exchangers, filters, turbines, and other components in integrated next generation nuclear power plant combined-cycle system must withstand demanding conditions of high temperatures and pressure differentials. Under the highly sulfiding conditions of the high temperature, such as inlet hot steam or other related environmental effects, the performance of components degrades significantly with time unless expensive high alloy materials are used. Deposition of a suitable coating on a low-cost alloy may improve its resistance to such sulfidation attack and decrease capital and operating costs. A review of the literature indicates that the corrosion reaction is the competition between oxidation and sulfidation reactions. The Fe- and Ni-based high-temperature alloys are susceptible to sulfidation attack unless they are fortified with high levels of Cr, Al, and Si. To impart corrosion resistance, these elements need not be in the bulk of the alloy and need only be present at the surface layers.

Those that practice the art of Nuclear Engineering must have a physical and intuitive understanding of the mechanisms and balances of forces, which 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 convection of fluids.

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 is 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.

Chapters 3 and 4 were provided to me by Prof. Bill Garland of Department of Engineering Physics at McMaster University Ontario, Canada, and his permission was given to this author exclusively to use his lecture, class notes, and other related materials that he wrote during the time he was teaching at this university.

This book also concentrates on fundamentals of fluid dynamics and heat transfer; thermal and hydraulic analysis of nuclear reactors; two-phase flow and boiling; compressible flow; stress analysis; energy conversion methods.

It starts with the fundamental definitions of units and dimensions, then thermodynamic variables such as temperature, pressure, and specific volume. Then, approaches to start of thermal hydraulic analysis with the topics in that field from Chap. 2 through Appendix 16, where it finishes off with design of heat exchanger and shell and tube using different Verifications and Validations (V&V) in computational mechanics and their applications of the fundamentals 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 discussed. Reheaters and feed water heaters are also covered. Ultimate heat rejection by circulating water systems is also discussed. Appendix 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 can be independently taught.

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

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

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The author would like to acknowledge all the individuals for their help, encouragement, and support. We have decided not to name them all since some of them may not be around to see the end result of their encouragement, but we hope they can at least read this acknowledgment wherever they may be.

Last but not least, special thanks to my parents, wife, children, and friends for providing constant encouragement, without which this book could not have been written. We especially appreciate their patience with pure frequent absence from home and long hours in front of the computer during the preparation of this book.

My sincere appreciation goes to Professor Bill Garland of Department of Engineering Physics at McMaster University Ontario, Canada, who provided me the entire materials and text that are provided in Chaps. 3 and 4 of this book along with his exclusive permission granted to me to utilize them. I am also very grateful to my mentor and teacher, Professor Patrick McDaniel for what he taught me.

About the Author

Dr. Bahman Zohuri is currently at the Galaxy Advanced Engineering, Inc. a consulting company that he stared himself in 1991 when he left both semiconductor and defense industries after many years working as a chief scientist. After graduating from University of Illinois in the field of Physics and Applied Mathematics, as well as University of New Mexico from Nuclear Engineering Department, he joined Westinghouse Electric Corporation where he performed thermal hydraulic analysis and natural circulation for inherent shutdown heat removal system (ISHRS) in the core of a liquid metal fast breeder reactor (LMFBR) as a secondary fully inherent shut system for secondary loop heat exchange. All these designs were used for nuclear safety and reliability engineering for self-actuated shutdown system. He designed the mercury heat pipe and electromagnetic pumps for large pool concepts of LMFBR for heat rejection purpose for this reactor around 1978 where he received a patent for it. He was later transferred to the defense division of Westinghouse where he was responsible for the dynamic analysis and method of launch and handling of MX missile out of canister. The results are applied to MX launch seal performance and muzzle blast phenomena analysis (i.e., missile vibration and hydrodynamic shock formation). He also was involved in analytical calculation and computation in the study of nonlinear ion wave in rarefying plasma. The results are applied to the propagation of "soliton wave" 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 computation and programming of multi-exchange integral in surface physics and solid-state physics. He holds different patents in areas such as diffusion processes and design of diffusion furnace while he was senior process engineer working for different semiconductor industries such as Intel, Varian, and National Semiconductor corporations. Later, 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 different components of Strategic Defense Initiative known as Star Wars. This included payload (i.e., IR sensor) for Defense Support Program (DSP), Boost Surveillance and Tracking Satellite (BSTS), and Space

Surveillance and Tracking Satellite (SSTS) against laser or nuclear threat. While there, he also studied and performed the analysis of characteristics of laser beam and nuclear radiation interaction with materials, transient radiation effects in electronics (TREE), electromagnetic pulse (EMP), system-generated electromagnetic pulse (SGEMP), single-event upset (SEU), blast and, thermomechanical, hardness assurance, maintenance, device technology.

He did a few years of consulting under his company Galaxy Advanced Engineering with Sandia National Laboratories (SNL), where he was supporting development of operational hazard assessments for the Air Force Safety Center (AFSC) in connection with other interested parties. Intended use of the results was their eventual inclusion in Air Force Instructions (AFIs) specifically issued for directed energy weapons (DEW) operational safety. He completed the first version of a comprehensive library of detailed laser tools for airborne laser (ABL), Advanced Tactical Laser (ATL), Tactical High Energy Laser (THEL), Mobile/Tactical High Energy Laser (M-THEL), etc.

He also was responsible for SDI computer programs involved with Battle Management C^3 and artificial Intelligent, and autonomous system. He is the author of a few publications and holds various patents such as Laser-activated Radioactive Decay and Results of Thru-Bulkhead Initiation.

Recently, he has published two other books with CRC and Francis Taylor on the subject of:

1. Heat Pipe Design and Technology: A Practical Approach, Published by CRC Publishing Company
2. Dimensional Analysis and Self-Similarity Methods for Engineering and Scientist Published by Springer Publishing Company
3. High Energy Laser (HEL): Tomorrow's Weapon in Directed Energy Weapons Volume I, Published by Trafford Publishing Company
4. Thermodynamics In Nuclear Power Plant Systems, Published by Springer Publishing Company
5. Thermal-Hydraulic Analysis of Nuclear Reactors, Published by Springer Publishing Company.

Acronyms

AECB	Atomic Energy Control Board
AECL	Atomic Energy of Canada Ltd.
AESOP	Atomic Energy Simulation of Optimization (computer code)
AFCI	Advanced Fuel Cycle Initiative
AHTR	Advanced High Temperature Reactor
ASDV	Atmospheric Steam Discharge Valve
ASSERT	Advanced Solution of Sub-channel Equations in Reactor Thermal hydraulics (computer code)
ASTM	American Society for Testing Materials
BLC	Boiler Level Control
BLW	Boiling Light Water
BPC	Boiler Pressure Controller
CBA	Core Barrel Assembly
CCP	Critical Channel Power
CHF	Critical Heat Flux
CHP	Combined Heat and Power
CPR	Critical Power Ratio
CRL	Chalk River Laboratories
CRT	Cathode Ray Tube
CS	Core Structures
CSA	Canadian Standards Association
CSC	Core Structure Ceramics
CSDV	Condenser Steam Discharge Valve
CSNI	Canadian Standards for the Nuclear Industry
DBE	Design Base Earthquake
DCC	Digital Control Computer
DF-ET	Drift Flux-Equal Temperature
DF-UT	Drift Flux-Unequal Temperature
DHX	Dump Heat Exchanger
DNB	Departure from Nucleate Boiling
DRACS	Direct Reactor Auxiliary Cooling System
EBR-II	Experimental Breeder Reactor

ECC	Emergency Core Cooling
ECI	Emergency Core Injection
EFPH	Effective Full Power Hours
EVET	Equal Velocity Equal Temperature
EVUT	Equal Velocity-Unequal Temperature
EWS	Emergency Water Supply
FBR	Feed, Bleed and Relief
FHSS	Fuel Handling and Storage System
FP	Fission Product
FP	Full Power
GFR	Gas-Cooled Fast Reactor
GTHTR	Gas Turbine High Temperature Reactor
GT-MHR	Gas Turbine-Modular Helium Reactor
HEM	Homogeneous Equilibrium Model
HRSG	Heat Recovery Steam Generators
HTGR	High Temperature Gas-Cooled Reactor
HTR	High Temperature Reactor
HTS	Heat Transport System
HWP	Heavy Water Plant
HX	Heat Exchanger
HYDNA	Hydraulic Network Analysis (extinct computer code)
I&C	Instrumentation and Control
IBIF	Intermittent Buoyancy Induced Flow
ICRP	International Commission on Radiological Protection
IGCC	Integrated Gasification Combined Cycle
IHX	Intermediate Heat Exchanger
LEU-TRISO	Low Enriched Uranium Triple-Coated Isotropic
LFR	Lead-Alloy Cooled Fast Reactor
LOC	Loss of Coolant
LOC/LOECC	Loss of Coolant with Coincident Loss of Emergency Core Cooling
LOCA	Loss of Coolant Accident
LOP	Loss of Pumping
LOR	Loss of Regulation
LWR	Light Water Reactor
MCCR	Ministry of Corporate and Consumer Relations
MCS	Maintenance Cooling System
MHD	Magneto hydrodynamics
milli-k	Unit of reactivity for reactor physics
NERI	Nuclear Energy Research Initiative
NGNP	Next Generation Nuclear Plant
NGNP	Next Generation Nuclear Power Plant
NPD	Nuclear Power Demonstration
NPSH	Net Positive Suction Head
NUCIRC	Nuclear Circuits (computer code)
OECD	Organization for Economic Co-operation and Development

OH	Ontario Hydro
PBMR	Pebble Bed Modular Reactor
PCS	Power Conversion System
PGSA	Pickering Generating Station A
PHTS	Primary Heat Transport System
PHW	Pressurized Heavy Water
PHWR	Pressurized Heavy Water Reactor
PRESCON2	Pressure Containment (computer code)
QA	Quality Assurance
R&M	Reliability and Maintainability
RAMA	Reactor Analysis Implicit Algorithm
RB	Reactor Building
RCS	Reactivity Control System
RIH	Reactor Inlet Header
ROH	Reactor Outlet Header
RSS	Reserve Shutdown System
RTD	Resistance Temperature Detectors
RU	Reactor Unit
SDM	Safety Design Matrices
SG	Steam Generator
SOPHT	Simulation of Primary Heat Transport (computer code)
SOX	Sarbanes Oxley
SRV	Safety Relief Valve
THTR	Thorium High Temperature Reactor
TMI	Three Mile Island
TOFFEA	Two-Fluid Flow Equation Analysis (computer code)
TRIS	Triple-Coated Isotropic
TRISO	Tristructural-Isotropic
UVUT	Unequal Velocity Unequal Temperature
VB	Vacuum Building
VC	Vacuum Chamber
VHTR	Very High Temperature Reactor
WRE	White-shell Research Establishment

Contents