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Thermal Hydraulics in Water-Cooled Nuclear Reactors

Edited by Francesco D'Auria

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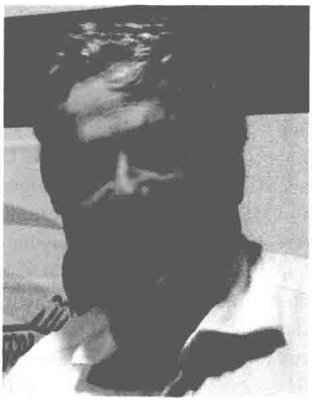

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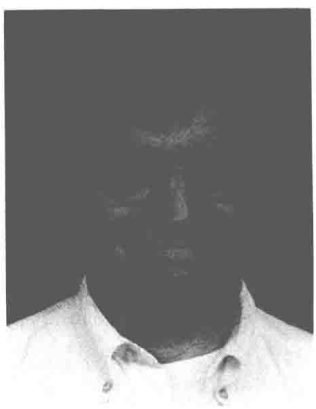
Upendra Singh Rohatgi was born in 1949 in Kanpur, India. He received his Bachelor of Technology degree in Mechanical Engineering from the Indian Institute of Technology, Kanpur. He then received his Masters and PhD degrees in Fluids and Thermal Sciences from Case Western Reserve University, Cleveland, OH in 1972 and 1975, respectively. He joined the scientific staff of Brookhaven National laboratory in 1975 in the Department of Applied Sciences. He is currently a senior scientist. He has contributed to US Nuclear Regulatory programs since 1975 in the areas of development and validation of reactor simulation codes, specifically TRAC, RELAP5, and RAMONA series of codes, and participated in the development of Code Scaling, Applicability, and Uncertainty (CSAU) methodology, the first method of estimating uncertainty in the code prediction. His expertise is in two-phase flows, nuclear simulation codes, LOCA and instabilities, scaling, and turbomachinery.



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Klaus Umminger was born on Jan. 13, 1956 in Oberlauda, Germany. After graduating from the Technical University of Munich (Diploma in Mechanical Engineering), he joined AREVA (formerly Siemens/KWU) in 1982, where he has been engaged in experimental projects in the field of reactor safety research and in the design of fluid instrumentation. Since 1995 he has been in charge of the large experimental program PKL. The PKL facility (operated at AREVA Germany) is used to investigate the T/H system behavior of PWRs during postulated accidents, since 2001 the PKL project has been continued as an international OECD project. His main areas of work include design, performance, interpretation of experiments for application in code validation, and experimental verification of AM measures for PWRs.

Preface

The technology created after the first self-sustainable nuclear chain reaction taking place in Chicago, USA, at the Chicago Pile-1, in 1942, under the leadership of Enrico Fermi (also called "architect of nuclear age") constitutes the general framework for the nuclear reactor thermal-hydraulics and the present Book. This is the initiation of the Nuclear Power Plant (NPP) technology. Related cornerstone events or achievements can be summarized as follows:

- Production of electricity by the heat released through undergoing nuclear fission of uranium dioxide
- Use of water as coolant (and also as moderator in the majority of designs) for the region where the chain reaction is sustained, i.e., the core of the reactor
- Construction of large (high power) NPP units
- Safety and design needs for NPP as well as the advent of computational science

Thermal-hydraulics is one of the pillar disciplines to make possible the exploitation of the nuclear fission for the production of electrical power. The complexity and the relevance of the discipline can be depicted by three items:

(A) *Turbulence*: The existence of turbulence is known from several hundred years in single-phase flow conditions; at least, it was noticed by Leonardo da Vinci in the 16th century. Three questions can be formulated: (1) Does turbulence exist?, (2) What is turbulence?, and (3) Can we model turbulence? "Yes" can be the easy answer to the first question. The second question can be hardly answered, i.e., not covering all details of turbulence. "No" is the generic answer to the third question if all relevant appearances of turbulence in nature or man-made systems are considered. In nuclear thermal-hydraulics the intricacy is amplified by the presence of two phases which interact by turbulence-controlled mass, momentum, and energy transfer processes.

(B) *Bubble motion*: I was visiting an Institute of National Academy of Science in Siberia at the time of Soviet Union. During my presentation about capabilities of thermal-hydraulic system codes a senior researcher who had a "personal" lab underground in the building asked: "How is it possible to predict transient evolutions of two-phase mixtures in complex systems when I cannot calculate the motion of a single bubble?" The problem is more challenging if production, growth coalescence, and collapse of a multitude of bubbles are concerned. Averaging is the answer to the question, but unpredictable errors are introduced.

(C) *Void fraction and neutron flux*: Massive boiling occurs in the core in design conditions of some reactors: two-phase mixture is responsible for generating thermal neutrons by the moderation process other than removing the fission energy. One key-affecting parameter is the amount of water mass in the region. In a high-velocity two-phase flow conditions, void fraction associated with flow regimes determines the fluid mass. Expertise in thermal-hydraulics is needed to determine void fraction with acceptable error including transient conditions: this is directly connected with a variety of flow configurations (flow regimes).

An attempt is made in the Book to provide a vision of nuclear thermal-hydraulics as it appears following more than half-a-century development. The idea is to cover from fundamentals to applications. This implies the consideration of a universe of topics, as discussed in Chapter 1, which may need an encyclopedia rather than a book. So, a window is opened to describe selected elements with emphasis to phenomena and basic principle equations on the side of fundamentals and nuclear reactors accident scenarios on the side of applications.

Currently system thermal-hydraulics codes are used to predict accident scenarios in nuclear reactors. Possibly in some future date computational fluid-dynamics codes (or sets of equations ready to be solved by computers) could be able to predict similar accident scenarios. In this respect, the computer codes constitute one of the central elements in the Book.

The processes of thermal-hydraulic phenomena identification and characterization, code development and validation, as well as scaling demonstration and prediction of errors of code calculations, i.e., uncertainty evaluation, may appear a matter for guru: rigorous procedures are not always applied or simply do not exist. This is also a consequence of some inadequate modeling of aspects in nature, behaviors like turbulence, and bubble motion and coalescence, already noted.

The vision provided in the Book is expected to be helpful in demonstrating the ability of thermal-hydraulics to address the needs in design and safety evaluation of existing nuclear reactors although this is achieved by those complex processes involving averaging techniques, validation, scaling, uncertainty, etc. Consequently, the Book may resemble as the description of a dynamic target rather than an archival product. However, inspiration for moving further the barriers of knowledge shall be attained from various discussed topics: the thermal-hydraulic phenomena and the accident scenarios are relevant in this connection.

The enormous research investment in the period 1970–1990 or 1970–2000, i.e., the golden period for research in nuclear thermal-hydraulics, provided the major source of knowledge to justify the Book. Sufficient understanding of phenomena for technological purposes and worldwide declining interest toward nuclear fission caused sharp decrease in financing and support of research in thermal-hydraulics in subsequent decades.

The grown expertise, sometimes of guru-type, is going to be lost because of retirement of top scientists acting during the golden period. The knowledge built may resemble a small town: the small town is now at risk to become a "Pompeii of the year 2020"; it can be buried by the dust of oblivion. Accidents like Chernobyl and, in a more powerful way, Fukushima mined the trustworthiness of nuclear technology: they are capable of producing the dust which is responsible for clouding the mind of decision makers. The Book contributes to the hope for knowledge preservation although coordinated efforts from all the stake-holders of nuclear technology are needed in this connection.

F. D'Auria
September 2016
Pisa, Italy

Acknowledgments

The adventure involved in producing a book like the present one may be undertaken by authors after decades of engagement where fundamental research and technology applications are intimately merged. The complexity of the topic "promotes" deep international cooperation.

The outcome of this is the unavoidable recognition that the work of several hundreds or even thousands of scientists and technologists contributed to the understandings depicted in this book. I feel profoundly indebted to each of them: everyone created or inspired a small stone of the mosaic which is described in the Book. An attempt to create a meaningful list of individuals to be acknowledged would imply an effort comparable to the effort set for producing the Book and still will not eliminate the risk of incompleteness.

Let me create below a pyramid of categories of persons to acknowledge.

The tip of the pyramid is constituted by:

(a) The authors of chapters who have an expertise in the area far beyond my expertise and accepted the challenge to depict a new vision in the area.

(b) The authors of documents listed in the references of each chapter: a few thousands names are now listed in alphabetic order at the end of the Book; they provide a sample picture of the expertise in nuclear thermal-hydraulics; I take the occasion here to apologize to the many leading scientists who are not considered in the list.

Further categories down to the base of the pyramid are:

(c) Scientists and technologists who attended international working groups where I participated, namely at the Organization for Economic Cooperation and Development (OECD) premises in Paris and at the International Atomic Energy Authority (IAEA) in Vienna: they provided unquantifiable amount of invaluable ideas, research results, and related information.

(d) Secretaries, managers, and directors of a variety of institutions I entered in contact: they ensure, sometimes by hidden efforts, the sustainability of research or the financing of knowledge.

(e) Members of international groups which have been functional for the activities I had the privilege to perform ranging in the areas of development, training, and application in nuclear thermal-hydraulics.

(f) Scientists part of established international contexts like American and European Nuclear Societies; Conferences frameworks like Nuclear Reactor Thermal-Hydraulics (NURETH), International Conference on Nuclear Engineering (ICONE), and International Congress on Advances on Nuclear Power Plants; and Journals like Nuclear Engineering and Design (NED), Science and Technology of Nuclear Installations (STNI), and Nuclear Engineering and Technology (NET).

(g) Colleagues (who tolerated my aversion to unnecessary red tape) and coworkers including Master and PhD students (a few hundreds) and technicians, in various universities of the world (mostly at University of Pisa).
(h) Teachers in Italy and at University of Pisa who opened the doors of knowledge and planned the bases for my professional career.
(i) My parents, relatives, and friends who created or accepted the conditions to perform the activities.

It is my pleasure here to remember my friends and leading scientists Nusret Aksan, Yassin Hassan, and Dominque Bestion who inspired or continuously drove or supervised many of the activities in nuclear thermal-hydraulics where I took part for including in the present Book.

I wish also to acknowledge the work done by Alessio Capperi at University of Pisa in deriving the list of authors of all references and in contributing to improve the editing of individual chapters.

The challenging (nuclear) technology supported by committed and dedicated people revealed the perfect environment for developing a research career. It is my privilege to belong to this environment and, after decades of the working life, it is my pleasure to invite young generation scientists to enter this community and to tackle the many remaining issues in nuclear reactor thermal-hydraulics field.

However, for the sake of completeness of information, namely for young readers, I will not refrain to bring an unusual acknowledgement remark: this is for those who created hitches and tried to slow-down and stop research initiatives. This revealed an easier task for a technology which became unpopular and vulnerable during the last years (at least in some countries) because of and throughout misinterpreting, or putting within an obscure light, accidents which happened and are also discussed in the Book. Young researchers should expect artificial (man-created, external to the research environment) challenges and be ready to react.

Dedication

This book is dedicated to my teacher Bruno Guerrini and to my friend Emilio Vitale. Both were leaders who embraced the spirit of the Renaissance, paving the way for outstanding endeavors like the one resulting in this current effort. The passing away of Prof. Guerrini from natural causes was preceded by a tragic accident that, in the prime of his life, left Emilio in a twilight world. An easy path has been adopted by their successors that would appear to lead directly toward a new Middle Age. I can still tell Emilio this but he cannot react to the havoc that has been wreaked on great wisdom.

The Editor

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