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A HISTORICAL PERSPECTIVE OF NUCLEAR THERMAL HYDRAULICS

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THERMAL HYDRAULICS

IN

NUCLEAR REACTORS

Edited by Francesco D'Auria, University of Pisa, Italy

Rationale

Thermal hydraulics is the discipline which studies the transient evolution of engineering systems where water is the working fluid and boiling and condensing processes occur. Nuclear thermal hydraulics addresses the performance of water-cooled and water-moderated nuclear power plants. Selected peculiarities of the discipline can be listed as follows: i) its importance for design and safety has been established since the beginning of the nuclear technology era; ii) it shares with fluid dynamics the known difficulty associated with the modelling of turbulence: here the problem is even more complex because of the presence of two-phases; iii) approximation of results from numerical models and the need to bound the errors of calculations, i.e. the uncertainty, are a consequence of the item above; iv) controversy in judging the quality and the applicability of experimental and numerical findings is not surprising, as well as the need to have expertise based on decades of activity. System thermal hydraulics (SYS TH), seen as an evolution of fundamental thermal hydraulics, constitutes the subject of this book. The computational tool named SYS TH code constitutes a basket of expertise and the direct or the indirect target of the individual chapters. The use of SYS TH for demonstrating the safety and the acceptability of nuclear plants is given high priority in the book.

Proposed contents and suggested authors:

PART I – THE BACKGROUND TO NUCLEAR THERMAL HYDRAULICS

1. **INTRODUCTION TO NUCLEAR THERMAL HYDRAULICS**

The scope and framework, the objectives and the content.

F. D'Auria, University of Pisa

2. **A HISTORICAL PERSPECTIVE OF NUCLEAR THERMAL HYDRAULICS**

From fundamentals (at the beginning of the nuclear energy era - 1940) to applications (nowadays - 2020).

F. D'Auria, University of Pisa

3. **NUCLEAR HYDRAULICS DEFINITIONS**

The variables used in the equations (state, balance and constitutive equations either empirical or mechanistic model based). Key non-dimensional quantities. The void-quality relationship (fundamental equation in thermal-hydraulics) and implications (e.g. average density and mass in a boiling channel or system).

F. Reventos, BarcelonaTECH

4. **ROLE OF NUCLEAR HYDRAULICS IN NUCLEAR POWER PLANT TECHNOLOGY: DESIGN AND SAFETY**

Thermal-hydraulics and thermodynamics: the differences & the complementary role. The design of the power cycle for NPP and the thermodynamic efficiency . The design of the key nuclear components: the core, the steam generator, the pressurizer, the condenser, the turbine, the containment.

Role of thermal-hydraulics in the NPP technology and connections with different disciplines and subjects.

Processes to derive needs in thermal-hydraulics: coming from design of NPP and from Nuclear Reactor Safety:

a) *The core thermal-hydraulics.*
b) *The licensing process and the concept of Design Basis Accident at the origin of phenomena.*

R. R. Schultz, INL

PART II – THERMAL-HYDRAULICS CONNECTIONS: THE PRINCIPLES OF THERMODYNAMICS & NUCLEAR SYSTEMS

5. THE BALANCE EQUATIONS FOR TWO-PHASE FLUIDS IN NUCLEAR THERMAL HYDRAULICS

The conservation (or balance) equations derived from first principles of thermodynamics and mechanics are presented. Emphasis given to the UVUT model or the six (plus additional material) balance equations. Integral, differential and algebraic formulations discussed. UVUTUP, multi-field and interfacial area transport equations are discussed, too.

G. Yadigaroglu, formerly ETH

6. TARGET PHENOMENA IN NUCEAR THERMAL HYDRAULICS

Phenomena (mostly transient from accident analysis) and design situations derived in the previous chapter are presented with suitable detail, making use of the concepts and definitions introduced in Chapter 3. The CSNI list of phenomena is considered [heat transfer and pressure drops are presented in two devoted Chapters, respectively].

N. Aksan, formerly PSI

PART III – NUCLEAR THERMAL HYDRAULICS MODELING

7. HEAT TRANSFER IN NUCLEAR THERMAL HYDRAULICS: PRINCIPLES AND MODELING

Conduction, convection and radiation heat transfer are presented separately. Integration and/or interfaces (including issues) for the three heat transfer modes are considered. Reflood (or quench front propagation or rewet) and condensation (either fluid-to-fluid, or in the presence of a wall) are included.

P. Kirillov, formerly IPPE Obninsk & H. Ninokata, formerly Tokyo University

8. PRESSURE DROPS IN NUCLEAR THERMAL HYDRAULICS: PRINCIPLES AND MODELING

The components of pressure drops are presented. Special reference is made to the derivation of pressure drops in a closed boiling-condensing natural circulation loop.

N. Cavlina, Zagreb University

9. **CONSTITUTIVE EQUATIONS FOR NUCLEAR THERMAL HYDRAULICS**

The equations and models needed to solve the balance equations (Chapter 5) which are consistent with the target phenomena are presented.

J.J. Jeong, Pusan University

10. **SPECIAL MODELS FOR NUCLEAR THERMAL HYDRAULICS**

The special models, i.e. the models which are not part of constitutive equations (and not included in heat transfer or pressure drops) are presented. For instance, Two-Phase Critical Flow (TPCF), Counter-Current Flow Limitation (CCFL), impeller pump, jet-pump, Separator, etc.

U.S. Rohatgi, BNL

11. **THE STRUCTURE OF SYSTEM THERMAL-HYDRAULIC (SYS TH) CODE FOR NUCLEAR ENERGY APPLICATIONS**

Whatever in Chapters from 5 to 8 is integrated in the SYS TH code, the coupling with three-dimensional neutron physics and the resulting multi-physics multi-scale numerical tool.
The (numerical) solution methods. The need for averaging in space and time.
The "nodalization" concept, or the connection between the code and the NPP reality.
The relation between SYS TH code and containment and sub-channel codes.

D. Bestion, CEA

12. **THE STRUCTURE OF COMPUTATIONAL FLUID DYNAMICS (CFD) CODE FOR NUCLEAR ENERGY APPLICATIONS**

Emphasis given to single-phase CFD. Bases for two-phase CFD presented. Coupling practices of CFD and SYS TH codes.
The numerical solution methods and the convergence in time and space.

Y. Hassan, T A&M University

PART IV – APPLICATIONS OF THERMAL HYDRAULICS IN NUCLEAR TECHNOLOGY

13. **VERIFICATION AND VALIDATION AND UNCERTAINTY APPROACHES IN SYSTEM THERMAL HYDRAULIC (SYS TH) CODES FOR NUCLEAR ENERGY APPLICATIONS**

The Verification bases. The Validation needs. The scaling issue. The outcomes from Validation impose the evaluation of calculation errors or Uncertainty. The current Uncertainty approaches and methods.

H. Glaeser, formerly GRS

14. THE BEST-ESTIMATE PLUS UNCERTAINTY (BEPU) APPROACH IN THE NUCLEAR INDUSTRY

The BEPU constitutes the natural evolution of the initially adopted conservative approach. The BEPU is also the only possible framework where the knowledge gained in the development and Validation of SYS TH codes is exploited.

F. D'Auria, University of Pisa

15. SELECTED APPLICATIONS OF SYS TH CODES TO NUCLEAR DESIGN AND ACCIDENT ANALYSIS

Making reference to selected DBA, sample calculated accident scenarios are illustrated, a) to demonstrate the importance of the SYS TH code, b) to provide the reader with reference bases to understand the transient performance of selected NPP unit(s).

M. Zimmermann, formerly PSI

16. THERMAL HYDRAULICS ASPECTS OF KEY NUCLEAR ACCIDENTS

Thermal-hydraulic aspects of TMI-2 (1979), Chernobyl-4 (1986), La Salle (1988), Fukushima Daichii1-4 (2011), are presented.

B. Mavko, formerly IJS

POSSIBLE LIST OF KEY AUTHORS

Chapter No.	Title (key-words)	Suggested Main Author	Address	Notes
1	INTRODUCTION	*F. D'Auria*	Pisa Univ, I	
2	HYSTORICAL PERSPECTIVE	*F. D'Auria*	Pisa Univ, I	
3	DEFINITIONS	*F. Reventos*	Barcelona Univ, E	
4	NEEDS	*R. R. Schultz*	INL, US	
5	BALANCE EQUATIONS	*G. Yadigaroglu*	ETH*, CH	
6	PHENOMENA	*N. Aksan*	PSI*, CH	
7	HEAT TRANSFER	*P. Kirillov – H. Ninokata*	IPPE Obninsk*, Ru – Tokyo Univ*, J	The Chapter may be divided into two parts

8	**PRESSURE DROPS**	*N. Cavlina*	Zagreb Univ, HR	
9	**CONSTITUTIVE EQS**	*J.J. Jeong*	Pusan Univ, Kr	
10	**SPECIAL MODELS**	*U.S. Rohatgi*	BNL, US	
11	**SYS TH CODE**	*D. Bestion*	CEA, F	
12	**CFD CODE**	*Y. Hassan*	T A&M Univ, US	
13	**V & V AND UNCERTAINTY**	*H. Glaeser*	GRS*, G	
14	**BEPU APPROACH**	*F. D'Auria*	Pisa Univ, I	
15	**DBA CALCULATIONS**	*M. Zimmermann*	PSI*, CH	
16	**TH FOR KEY ACCIDENTS**	*B. Mavko*	IJS*, SLO	

*** formerly, now retired**