39th Short Courses
on
Modelling and Computation of Multiphase Flows

Zurich, Switzerland, 12-16 February 2024
hosted by ETH Zurich

Part I: Basics

Part IIA: New Reactor Systems and Methods or
Part IIB: Computational Multi-Fluid Dynamics (CMFD)

Part III: CMFD with 3D System Codes and CFD Commercial Codes

THE COURSES

Multiphase flows and heat transfer with phase change are of interest to researchers, scientists and engineers working in a multitude of industries. Courses similar to this one have been offered in the past at Stanford University, the University of California-Santa Barbara, in Washington D.C. and elsewhere. The courses have taken place at ETH Zurich since 1984 with over 2100 participants so far. Over the years, the courses have continuously evolved, reflecting on-going progress, interests, and developments; parallel sessions were introduced in 1989.

The Zurich courses not only offer the opportunity to meet and interact with outstanding lecturers, but also with colleagues working worldwide on similar topics but in different industries. The courses are organized in a modular form as an intensive introduction for persons having basic knowledge of fluid mechanics, heat transfer, and numerical techniques (introductory tutorial texts are provided to the participants before the course), but also serve as advanced courses for specialists wishing to obtain the latest information.

Part I, Basics, covers the common background material and emphasises the latest empirical and mechanistic modelling, computational and instrumentation aspects of multiphase flows. A tutorial text is provided to the participants before the course to introduce the very basic concepts and fill any basic gaps in their background, so that they can participate in the most effective way.

Part IIA, New Reactor Systems and Methods, covers multiphase flow topics of particular interest to the nuclear industry. Some of the most recently proposed advanced reactor designs and the main multiphase phenomena of importance to the nuclear industry are treated. The state-of-the-art and beyond in modelling and simulation methods (including CFD and CMFD applications) for core design and accident analysis is introduced. An article introducing Light Water Reactors will be provided to the participants as tutorial material before the course.

Part IIB, Computational Multi-Fluid Dynamics (CMFD), reflects the growing interest in the application of CMFD techniques to multi-phase flows and covers the most common computational techniques. The introductory chapters from a book authored by Tryggvason, Scardovelli and Zaleski will be provided to the participants to prepare for the lectures.

Part III, CMFD with 3D System Codes and Commercial CFD Codes, is attached to both Parts IIA and IIB. The participants will hear about the latest developments in 3D TH system codes, and commercial code developers discuss their products for both nuclear and other applications.

The emphasis in these courses is on

- A condensed, critical, and updated view of basic knowledge and future developments, in relation to systems and phenomena encountered in industrial applications
- Trends in modelling, design, analysis, CFD / C*M*FD methods and experimentation
- Sources of information, data and correlations
- Availability as well as limitations of modern modelling and computational techniques and codes
- Interdisciplinary transfer of knowledge from one area of applications to another

These limited-enrolment courses feature

- 21 well-coordinated lectures by experts *and* excellent lecturers
- Movies, videos, animations, and computer simulations illustrating the physical phenomena and the numerical techniques
- A complete set of all the lecture materials (including extensive notes) will be available for download from our website
- Tutorials as introductory texts for all parts of the course
- Handout-format hard copies of all the standardized PowerPoint presentations for use in the classroom
- Discussion time and discussions with the lecturers during and between lectures

FEES

Full course (I, IIA or IIB and III): CHF 1'950
Part I: CHF 1'400, Parts IIA or IIB and III: CHF 1'100

INFORMATION

All practical information about the course can be obtained from the course web site:
https://ns-ecmfl.ethz.ch/education/short-course-mpf.html

REGISTRATION

https://ethzurich.eventsair.com/scomf2024/reg/Site/Register

CONTACT

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COURSE VENUE

ETH Zurich, Raemistrasse 101, Zurich, main building (HG)

Monday-Friday: D floor, auditoria 7.2 (HG D 7.2)
Thursday/Friday part IIA only**:** E floor, auditoria 33.1 (HG E 33.1)

The organizers reserve the right to cancel the course on short-term notice, with full refund of the fees, in case of force majeure.

SCHEDULE AND CONTENTS OF LECTURES

PART I. BASICS

MONDAY, 12 FEBRUARY 2024 (9-12:30 and 14:00-17:30) HG D 7.2

1. Introduction to multiphase flows (09:00–10:30): *M. Corradini.* Definition of multiphase flows; types of flow (two-phase, three-phase, single component, multi-component). Applications: power generation, hydrocarbon recovery, chemical processing, etc. Differences to single phase flows; examples of characteristic multiphase phenomena (Counter Current Flow Limitation, Departure from Nucleate Boiling, Dry out, instability). History of development of the subject; principal sources of information.

2. Two-phase flow instrumentation and visualization (11:00–12:30): *A. Manera.* Objective of measurements in two-phase flows, quantities characterizing a gas-liquid flow: liquid and gas holdup ("void fraction"), phase and superficial velocities, phase slip, volume flow and volume flow ratio, bubble size, interfacial area density, statistical functions. Methods to measure gas fractions: cut-off valves, differential pressure method, local (needle) probes, mesh sensors, liquid film sensors. Animations of measured data, flow maps for vertical and horizontal two-phase flows.

3. Basic models for two-phase flows (14:00–15:30): *S. Banerjee.* Objective of thermal hydraulic modelling, 1D vs. 3D modelling of two-phase flows. Two-fluid model. Averaging of conservation quantities and fluxes. Conservation equations for mass, momentum and energy in a two-fluid formulation. Closure equations. Wall pressure drop. Interfacial friction and void fraction. Wall and interfacial heat transfer. Jump conditions at the gas-liquid interface. Role of flow regime maps.

4. Empirical and phenomenological models (16:00–17:30): *M. Bucci.* Empirical models and correlations for void fraction and pressure drop; the drift flux model. Examples of phenomenological modelling: modelling of annular flow, flooding (CCFL).

TUESDAY, 13 FEBRUARY 2024 (9-12:30 and 14:00-17:30) HG D 7.2

5. Instability of the gas-liquid interface and flow regime maps (9:00–10:00): *M. Bucci.* Basic theory of the interfacial instability (Rayleigh-Taylor and Kelvin-Helmholtz instability) and numerous applications. Flow regime maps based on phenomenological modelling; stability of stratified flow as basis of flow regime maps.

6. Basics of phase transition, pool boiling (10:00–10:30, coffee, 11:00–12:30): *J. Buongiorno*. Thermodynamics of phase transition. Bubble nucleation. Bubble growth and departure, including the effect of microlayers and conjugate heat transfer. Macroscopic view on boiling and heat transfer: saturated and subcooled pool boiling. Transition to film boiling. Rewetting. Microscopic view on boiling (novel results obtained with micro-engineered heaters and modern diagnostics such as infrared thermography). Effects of nano- and micro-scale surface features on nucleation, nucleate boiling, CHF and rewetting. Correlations and models.

7. Flow boiling and condensation (14:00–15:30): *M.L. Corradini.* Flow boiling models for heat transfer in a boiling channel, including onset of nucleate boiling, subcooled boiling, pool and flow boiling correlations, critical heat flux, introduction to post-CHF heat transfer, quenching. Condensation models for heat transfer, including laminar and turbulent films, influence of non-condensible gases.

8. Phenomenological models for the flow boiling crisis (16:00–17:30): *J. Buongiorno.* Definition of the boiling crisis or Critical Heat Flux (CHF) in flow systems. Types of flow boiling crisis: Departure from Nucleate Boiling (DNB) vs Film Dryout. Physical limits of CHF. General trends of CHF with respect to mass flux, equilibrium quality, channel length, pressure, and inlet subcooling. Mechanistic models for the DNB-type and Film Dryout-type boiling crisis.

WEDNESDAY, 14 FEBRUARY 2024 (9:00-12:30 and 14:00-17:00) HG D 7.2

9. Thermal non-equilibrium flows (09:00–10:30): *J. Buongiorno*. Importance of Departure from Mechanical and Thermal Equilibrium. Subcooled Boiling: Net Vapor Generation, Fully-Developed Subcooled Flow Boiling. Post-CHF Heat Transfer: Inverted-Annular and Dispersed-Flow Film Boiling. Quenching.

10. Multifield models (11:00–12:30): *S. Banerjee.* The need for multifield models. Interpenetrating continua and Lagrangian-Eulerian approaches. Closure requirements. One-dimensional form – structure, strengths, and weaknesses. Multidimensional aspects – applicability and limitations.

11. Advanced two-phase flow instrumentation (14:00–15:30): *A. Manera.* Void fraction measurement by attenuation of ionizing radiation. Phase distribution and flow structure: Gamma, X-ray and neutron tomography, dual energy tomography, impedance tomography. Velocity measurements: hot film probes, laser methods, ultrasonic sensors.

12. Numerical methods (16:00–17:30): *D. Lakehal.* Introduction. Initial and boundary conditions. Method of characteristics. Finite difference methods. Stability. Explicit and implicit methods. Methods used in computer codes.

PART IIA. NEW REACTOR SYSTEMS AND METHODS

THURSDAY, 15 FEBRUARY 2024 (8:30-13:00 and 14:00-17:30) HG E 33.1

13A. Introduction and multiphase phenomena in Design Basis Accidents (8:30-9:50): *M. Corradini*. Introduction to thermal-hydraulics in reactor safety and historic developments. Loss-of-coolant accidents and reactor transients; their simulation and uncertainty evaluation. In-vessel accident phenomenology; modelling of core cooling.

14A. Advanced reactor concepts and phenomena (10:00-11:20): *M.L. Corradini.* Review of advanced LWR concepts for near-term and Generation IV reactor development. Two-phase phenomena in passive safety systems (natural circulation, condensation, critical flow).

15A. Closure laws in nuclear systems codes (11:40-13:00): *D. Bestion.* Development and validation of closure laws dependent on flow regime. Hydrodynamic and heat transfer closure relationships in system codes and their limitations. Predicting choked flow, stratified flow, CCFL.

16A. PIRT and Scaling methods for complex reactor transient analysis (14:00-15:30): *D. Bestion.* Phenomena Identification Ranking Table (PIRT), Scaling analysis for integral test facilities (ITFs) design criteria, design of ITFs, use of system codes in scaling analysis, scaling analysis of PWR LOCAs and SBLOCAs, building integral and separate effect test validation matrices, code scalability conditions, uncertainty quantification.

17A. Instabilities in two-phase flows (16:00 – 17:30): *A. Manera.* Two-phase flow system instabilities. BWR Stability, stability maps, computational tools, practical applications.

FRIDAY, 16 FEBRUARY 2024 (8:30-12:30) HG E 33.1

18A. Applications of two-phase RANS CFD models to complex nuclear safety problems: (8:30–10:00): *E. Baglietto.* Computational thermal-hydraulics in the practice using a variety of modelling techniques for different problem configurations. From statistical average models to scale-resolving strategies. A brief review of CFD usage in the nuclear industry, including detailed modelling of a PWR, single-phase and two-phase flows in fuel bundles, critical discharge, pebble bed reactor, spent fuel transport and storage, and environmental flow around reactor buildings.

19A. Multiphase phenomena in severe accidents (10:30–12:30): *M.L. Corradini.* Multiphase phenomena during severe accidents: vapour explosions, molten core quenching and coolability, etc. Severe accident codes, systems analyses and simulation.

PART IIB. COMPUTATIONAL *MULTI*-FLUID DYNAMICS (C*M*FD)

THURSDAY, 15 FEBRUARY 2024 (8:30-13:00 and 14:00-17:30) HG D 7.2

13B. Introduction to CMFD and Direct Numerical Simulations (8:30-9:50): *D. Lakehal*. Overview of single fluid modelling (surface tracking by VOF, Level Set, etc.) and multi-fluid models in C*M*FD. Turbulence in multiphase flows: scale separation; averaging and filtering; methods for low and high Reynolds numbers – from RANS to LES; coupled sub-scale approaches.

14B. Introduction to RANS modelling of two-phase flows (10:00-11:20): *E. Baglietto*. Theory or Reynolds Averaging Navier Stokes equations models for two-phase flows, including boiling, and evaporation/condensation with applications to nuclear engineering.

15B. Introduction to Interface Tracking (11:40-13:00): *G. Tryggvason.* Need for numerical simulations and history. Overview of the governing equations and standard solution methods. Introduction to the various methods used to track sharp fluid interfaces.

16B. Volume of Fluid (VOF) method (14:00-15:30): *S. Zaleski.* Volumetric tracking, piecewise linear interface reconstruction. Advanced VOF methods: unsplit, exactly-conserving VOF methods, oct-tree adaptive mesh refinement, height-function methods. High-density ratio and momentum-conserving methods.

17B. Applications of VOF, Phase Field and Lattice Boltzmann (16:00 – 17:30): *S. Zaleski.* The Gerris, ParisSimulator and Basilisk free codes. Flows with large interface deformation and disruption. Ligament formation, atomization and entrainment. Droplet splashing. Multiphase flow in porous media. Introduction to the Phase-Field / Cahn-Hilliard model. Multiphase Lattice Boltzmann. Lattice Boltzmann at high density ratio.

FRIDAY, 16 FEBRUARY 2024 (8:30-12:30) HG D 7.2

18B. Embedded Interface Methods (8:30 – 10:00): *G. Tryggvason.* Interface tracking for direct numerical simulations (DNS) of multiphase flows. Applications to bubbly flows and flows with phase change and mass transfer. Multiscale issues.

19B. Application of CFD codes to complex multiphase flow systems (10:30-12:30): *D. Lakehal***.** Introduction to different modelling approaches for multiphase flows, including Multi-component systems with mass transfer. Treatment of local heat transfer with phase change, using Interface Tracking and Phase averaging. Compressible multiphase flows with phase change. Applications: PTS, Condensing jets, Nucleate and convective flow boiling, Water hammer.

PART III. CMFD WITH 3D SYSTEM CODES AND COMMERCIAL CFD CODES

FRIDAY, 16 FEBRUARY 2024 (14:00-17:00) HG D 7.2

20. 3D Modelling in system codes and multiscale approaches (14:00 – 15:00): D. *Bestion.* 3D phenomena in LWRs RPV, 3D equations in a porous body approach, CMFD models in open medium, multiscale approaches, 3D modeling validation.

21. Modelling of industrial multiphase flows with commercial codes (15:10 – 16:10): Overview of models in commercial codes and validation A selection of examples illustrating some of the challenges and advanced multiphase models used in the oil & gas, chemical & process and nuclear industries. NN. Solver technology; Overview of model portfolio: Euler/Euler two-phase flow, free surface flow, Euler/Lagrangian models, DDPM; Applicability and limitations. Applications and model validation including comparisons to data

22. General discussion (16:10 – 16:30)

23. Closing coffee break (16:30 – 17:00)

LECTURERS

Emilio Baglietto is Professor in the Department of Nuclear Science and Engineering at the Massachusetts Institute of Technology (MIT) and . His research focuses on advancing the accuracy and reach of high-fidelity computational fluid flow and heat transfer simulations, and improving the effectiveness of 3-D, first-principles computational tools for nuclear reactor design. He earned a MSc from the University of Pisa, and a PhD from the Tokyo Institute of Technology, both in nuclear engineering. Prior to his arrival at MIT he was Director of Nuclear Applications at CD-adapco, the engineering simulation software company.

Sanjoy Banerjee is Distinguished Professor of Chemical Engineering and Director of the Energy Institute at the City University of New York. Previously he was Professor of Chem. Engng. at the Univ. of California – Santa Barbara. Member of the US NRC Advisory Committee on Reactor Safeguards, ACRS. Earlier in Canada, he occupied the positions of Westinghouse Professor of Engng Physics at McMaster Univ. and of Acting Director of Applied Science in the Whiteshell Nucl. Research Est. He was a founding member of the Canadian Advisory Committee on Nuclear Safety and serves as a consultant to governmental and industrial organisations in several countries. He has received the ASME Melville Medal, the IChemE (UK) Danckwerts Lectureship, the AIChE Kern Award, and the ASME Heat Transfer Memorial Award. He has published extensively on multiphase fluid dynamics and turbulence. Fellow of ANS.

Dominique Bestion has been Research Director at CEA-Grenoble, in France, Professor at the Ecole Polytechnique, and Editor at Nuclear Engineering and Design. Has worked extensively in modelling two-phase flow for system and CFD codes, and has been project manager of the CATHARE code development. He coordinated two-phase flow modelling in the NEPTUNE French multi-scale thermalhydraulic platform and he was coordinator of Thermalhydraulic activities of the NURESIM, NURISP and NURESAFE European Projects for a multi-disciplinary and multi-scale simulation platform. As a member of the OECD-CSNI- WGAMA, he coordinated a Task Group on the application of CFD to nuclear reactor safety issues. He is now Scientific Advisor at CEA-Saclay and chairman of the FONESYS international network of system code developers.

Matteo Bucci is the Esther and Harold E. Edgerton Associate Professor of Nuclear Science and Engineering at the Massachusetts Institute of Technology (MIT). His experimental research group studies two-phase heat transfer mechanisms in nuclear reactors and space systems, develops high-resolution non-intrusive diagnostics and surface engineering techniques to enhance two-phase heat transfer, and creates machine learning tools to accelerate data analysis and conduct autonomous heat transfer experiments. He has won several awards for his research and teaching, including the MIT Ruth and Joel Spira Award for Excellence in Teaching (2020), ANS/PAI Outstanding Faculty Award (2018 and 2023), the UIT-Fluent Award (2006), the European Nuclear Education Network Award (2010), and the 2012 ANS Thermal-Hydraulics Division Best Paper Award. Matteo serves as the Editor of Applied Thermal Engineering, is the founder and coordinator of the NSF Thermal Transport Café, and works as a consultant for the nuclear industry.

Jacopo Buongiorno is the TEPCO Professor of Nuclear Science and Engineering at the Massachusetts Institute of Technology (MIT), the Director of the Center for Advanced Nuclear Energy Systems (CANES), and the Director of Science and Technology of the MIT Nuclear Reactor Laboratory. He has published over 100 journal articles in the areas of reactor safety and design, two-phase flow and heat transfer, and nanofluid technology. For his research work and teaching he won several awards, among which recently the 2022 ANS Presidential Citation. Jacopo is a consultant for the nuclear industry in the area of reactor thermal-hydraulics, and a member of the Accrediting Board of the National Academy of Nuclear Training. He is also a Fellow of the American Nuclear Society, a member of the ASME, past member of the Naval Studies Board (2017-2019), and a participant in the Defense Science Study Group (2014-2015).

Michael L. Corradini is Distinguished Emeritus Professor of Nuclear Engineering at the University of Wisconsin-Madison. Previously he was chair of the US NRC Advisory Committee on Reactor Safeguards (ACRS), and member of NRC safety review panels and of the DoE Generation IV Roadmap Project. Currently he is a member of the CEA DES Scientific Committee, Canadian Nuclear Lab Science Advisory Board and National Academy of Engineering. He has published widely in areas related to vapour explosion and severe accident phenomena, jet spray dynamics and transport phenomena in multiphase systems.

Djamel Lakehal is the head of the Advanced Modelling & Simulation Department (AMS; link) of AFRY Switzerland, providing simulation & data-analytics based services for industry. He is the founder and former CEO of ASCOMP, an R&D company specialized in industrial thermal-fluid dynamics, which developed and maintains the CMFD solver TransAT. He obtained his MS & PhD in Fluid Mechanics from Ecole Centrale of Nantes, France. After four years of research on turbulence modelling at the Univ. of Karlsruhe (with Prof. W. Rodi) and TU-Berlin (with Prof. F. Thiele), he joined the Laboratory of Nuclear Energy Systems at ETH as Senior Scientist and Lecturer, where he obtained the Venia Legendi (Habilitation) jointly with Ecole Centrale Lyon. Dr Lakehal contributed substantially to the research on multiphase flow, namely in the LES and DNS areas. He acts as an adjunct lecturer at ETH Zurich and ENS Paris, as an referee expert for various international institutions, and as an associate editor of Int. Journal Multiphase Flow.

Annalisa Manera is Professor of Nuclear Systems and Multi-phase Flows Laboratory at ETH Zurich since July 2021. She is the recipient of the ANS Bal-Raj Sehgal Memorial Award and the US Department of Energy CASL Director’s award. She is also a Fellow of the American Nuclear Society. Between 2011 and 2021 she was Professor in the Nuclear Engineering Department of the University of Michigan. At the University of Michigan and ETH-Zurich she has established a research program in nuclear systems thermal-hydraulics and is the co-director of the Experimental and Computational Multiphase Flow Laboratory (ECMF) and the High Resolution Imaging Lab. Her research group focuses on high-resolution experimental techniques and CFD-based high-fidelity, multiphysics simulations of nuclear systems. She holds a M.Sc. in Nuclear Engineering from the University of Pisa (110/110 summa cum laude) and a Ph.D. in Nuclear Engineering from the Delft University of Technology.

Gretar Tryggvason Gretar Tryggvason is the Charles A. Miller Jr. Distinguished Professor and Head of the Department of Mechanical Engineering at the Johns Hopkins University. He received his PhD from Brown University in 1985 and has earlier been on the faculty at the University of Michigan in Ann Arbor, Worcester Polytechnic Institute, and the University of Notre Dame. He is well known for the development of methods for direct numerical simulations of multiphase flows and their applications. He served as the editor-in-chief of the Journal of Computational Physics 2002-2015, is a fellow of APS, ASME and AAAS, and the recipient of several awards, including the 2012 ASME Fluids Engineering Award and the 2019 ASTFE Award.

Stéphane Zaleski is Professor at Sorbonne Université in the Jean Le Rond d'Alembert Institute. He studied for his doctorate at the Physics Department of Ecole Normale Supérieure in Paris. In 1992 he joined the Laboratoire de Modélisation en Mécanique which later became the Jean Le Rond d’Alembert Institute. He investigates various numerical methods for the simulation of multiphase flow with applications for atomization, cavitation, porous media flow, boiling, hydrometallurgy and droplet impact. He currently investigates several variants of the Volume of Fluid method for interface tracking and the phase field method for interface tracking. He has written several computer codes for the simulation of two-phase flow including PARIS Simulator with R. Scardovelli and G. Tryggvason and he participates in the development of the Basilisk code. He is Associate editor of the Journal of Computational Physics and of Computers and Fluids. He created with Patrick Huerre a PhD and Master Degree program in Fluid Mechanics taught entirely in English, a rarity at a French University. He received the Victor Noury prize of the Paris Academy of Sciences and the Silver Medal of CNRS; he is a Fellow of the American Physical Society.