29th SHORT COURSES
on
Modelling and Computation of Multiphase Flows:
Part I: Bases
Part IIA: New Reactor Systems and Methods
or
Part IIB: Computational Multi-Fluid Dynamics (C*M*FD)
Part III: C*M*FD with Commercial Codes

Zurich, Switzerland, 13-17 February 2012
Hosted by the
Swiss Federal Institute of Technology (ETH Zurich)

THE COURSES

Multiphase flows and heat transfer with phase change are of interest to researchers, scientists and engineers working in power, nuclear, chemical-process, oil-and-gas, cryogenic, space, food, bio-medical, micro-technology, and other industries. Courses similar to this one have been offered in the past at Stanford University, the University of California-Santa Barbara and elsewhere. These courses have taken place annually at ETH-Zurich since 1984 with some 1700 participants so far. Over the years, the courses have continuously evolved, reflecting on-going progress, interests, and developments; the number of lecturers has gradually increased and 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 modules as intensive introductory courses for persons having basic knowledge of thermodynamics, fluid mechanics, heat transfer, and numerical techniques, but also serve as advanced courses for specialists wishing to obtain the latest information in certain areas.

Part I, Bases, covers the common background material and emphasises the latest modelling and computational aspects of multiphase flows. A tutorial text is e-mailed to the participants before the course to introduce the very basic concepts for this module and fill any basic gaps in their background, to help them participate in the courses the best possible way.

Part IIA, New Reactor Systems and Methods, covers multiphase flow topics of particular interest to nuclear engineers. This module reviews some of the most recently proposed advanced reactor designs (including reactors considered for near-term construction and those in Generation IV) and the main multiphase phenomena of importance in these designs. This module also introduces the state-of-the-art and beyond in modelling and simulation methods (including CFD and CMFD applications) for core design and accident analysis. An article introducing reactors, and in particular Light Water Reactors, will be e-mailed as tutorial material for non-nuclear specialists to the participants of this module before the course.

Part IIB, Computational Multi-Fluid Dynamics (CMFD), reflects the growing interest in the application of CFD techniques to multi-phase flows; it is continuously updated to cover the most common new computational techniques. The introductory chapters from a book authored by Tryggvason, Scardovelli and Zaleski will be emailed to the participants in Part IIB to prepare them for the lectures.

Part III, CMFD with Commercial Codes, is attached to both Parts IIA and IIB. The participants will have the possibility to meet commercial code developers and 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, computational techniques, 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:

- A program of *co-ordinated,* 90-min lectures by experts in the field
- A complete and extensive set of the lecture notes and other non-copyrighted course materials on a **CD-ROM**
- Tutorial, introductory texts for all parts of the course emailed to the participants before the course
- Handout-format hard copies of all the standardized PowerPoint presentations for use in the classroom (it is *not* advised to bring laptops)
- Movies, videos, animations, and computer simulations illustrating the physical phenomena and the numerical techniques (with non-copyrighted material included in the **CD-ROM**)
- Discussion time and discussions with the lecturers during and between lectures

FEES

All parts (either IIA **or** IIB) taken together: EUR 1600.
Part I alone: EUR 1150.
Parts IIA+III **or** IIB+III alone: EUR 900.

REGISTRATION and PRACTICAL INFORMATION

All **practical information** about the course and **hotel reservations** can be obtained from the **course web site** **http://www.lke.mavt.ethz.ch/shortcourse/index**

To register and communicate please use e-mail (**shortcourse@lke.mavt.ethz.ch**) and the **Registration Form** (from the web site) and make a bank transfer including fund number (credit cards cannot be accepted) **by 3rd February 2012 *exactly*** to:

ETH Zürich
Swiss Post, Post Finance, CH-3030 Bern, Switzerland
SWIFT/BIC (intl. bank code): POFICHBE
Int. Bank Account Number,
IBAN: CH64 0900 0000 9155 9964 8
Fund Number: 1-67587-11

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

COURSE ADDRESS (if needed):
c/o Prof. H.M. Prasser, ETH, ML K14
Sonneggstrasse 3, CH-8092 Zurich, Switzerland
Telephone: +41-44-632.8821 (with voice mail)

SCHEDULE AND CONTENTS OF LECTURES

PART I. BASES

MONDAY, FEBRUARY 13 (9-12:30 and 14-17:30)

1. Introduction to multiphase flows: *G. Hetsroni.* Definition of multiphase flows; types of flow (two-phase, three-phase). Applications; power generation, hydrocarbon recovery, chemical processing, etc. Differences to single phase flows; limiting phenomena (CHF, instability, etc). History of development of the subject; principal sources of information. Nature of multiphase flows; flow patterns (movie).

2. Basic models for two-phase flows: *G. Yadigaroglu.* Strategies in modelling two-phase flows. Averaging. Simplified, control-volume derivation of conservation equations for separated flows. The homogeneous flow model. Combined equations – separated flow models; closure requirements. Application to annular and stratified flows. The drift flux models.

3. Empirical and phenomenological models for multiphase flows I: Vertical flows: *G.F. Hewitt.* Empirical correlations for frictional pressure gradient and void fraction. Phenomenological models: Bubble flow, bubble/slug transition. Slug flow. Flooding (CCFL) and the slug churn transition. Churn flow. Churn/annular transition. Annular flow. Wispy annular flow.

4. **Empirical and phenomenological models for multiphase flows II: Horizontal and inclined flows:** *G.F. Hewitt.* Empirical correlations for frictional pressure gradient and void fraction in horizontal and inclined flows. Phenomenological models for horizontal flows: Stratified flow. Stratified/slug transition. Slug flow. Stratified/slug/annular transition. Annular flow. Critical two-phase flow

TUESDAY, FEBRUARY 14 (9-12:30 and 14-17:30)

5. Phase change heat transfer (single component systems): *G. Hetsroni.* Boiling heat transfer (movie); nucleation and nucleate boiling, forced convection evaporation. Correlations and models. Dryout (critical) heat flux: mechanism and predictions.

6. **Empirical and phenomenological models for multiphase flows III: Flows with phase change:** *G.F. Hewitt.* Single component systems; heat transfer regimes, heat transfer in slug flow (equilibrium, non-equilibrium); heat transfer in annular flow, correlations, mechanisms, models (overall, detailed, effect of nucleate boiling). Multicomponent systems (droplet effects). Dryout (critical) heat flux; low quality (bubbly) and high quality (annular) flows. Condensation; similarities and differences to evaporation.

7. Thermal non-equilibrium flows: *G. Yadigaroglu.* Importance of departures from mechanical and thermal equilibrium. Computation of non-equilibrium flows. Subcooled boiling. Post-dryout heat transfer; 3D effects.

8. Multifield models: *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.

WEDNESDAY, FEBRUARY 15 (9-12:30 and 14-17:30)

9. Advanced two-phase flow instrumentation: *H.-M. Prasser*: Instrumentation for gas fraction, velocity and interfacial area. Local probes and mesh sensors. Tomographic methods. Optical methods. Ultrasonic sensors.

10. Instabilities in two-phase flow: *G. Yadigaroglu.* Instabilities of the liquid-gas interface; applications to jets, particles, etc. Two-phase system instabilities; fundamentals, mechanisms. Computational tools, stability maps. BWR stability.

11. Experiments to develop closure relations for two-fluid models: *H.-M. Prasser.* Interfacial momentum transfer in bubbly flow; forces acting on bubbles. Bubble coalescence and break-up. Interfacial heat transfer, condensation, boiling.

12. Numerical methods: *S. Banerjee.* Introduction. Initial and boundary conditions. Method of characteristics. Finite difference methods. Stability. Explicit and implicit methods. Methods used in computer codes.

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PART IIA. NEW REACTOR SYSTEMS AND METHODS

THURSDAY, FEBRUARY 16 (9-12:30 and 14-17:30)

13A. Multiphase phenomena in LWRs I: *G. Yadigaroglu.* Loss-of-coolant accidents, transients and their simulation; uncertainty evaluation. In-vessel accident phenomenology; modelling of core cooling. Passive emergency core and containment cooling.

14A. Heat transfer in nuclear fuel elements: *G.F. Hewitt.* Critical heat flux in rod bundle geometries and prediction methods: global models, sub-channel methods, phenomenological models; effects of non-uniform heat flux distribution; grid design for enhancement. Reflood heat transfer; clad ballooning, droplet/surface interactions, rewetting.

15A. Multiphase phenomena in LWRs II: *M.L. Corradini.* Multiphase phenomena during severe accidents: vapour explosions, molten core quenching and coolability, etc. Severe accident codes; systems analyses and simulation.

16A. Closure laws in nuclear systems codes: *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

FRIDAY, FEBRUARY 17 (*8:30*-12:30)

17A. Advanced LWR concepts and phenomena: *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).

18A. Advanced reactor systems: *M.L. Corradini.* Overview of Generation IV liquid-metal and gas reactor systems. Multiphase flow issues, supercritical flow and heat transfer phenomena.

19A. Advanced computational modelling of nuclear systems: *D. Bestion.* Needs of advanced simulation tools for thermalhydraulic issues. The multiscale analysis of reactor thermalhydraulics, New models for system codes. Use of C*M*FD for nuclear reactor investigations.

PART IIB. COMPUTATIONAL *MULTI*-FLUID DYNAMICS

THURSDAY, FEBRUARY 16 (9-12:30 and 14-17:30)

13B. Introduction to CMFD: *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.

14B. Computational modelling of turbulent multiphase flows: *D. Lakehal.* Multidimensional, multifluid modelling. Turbulence in multiphase flows: scale separation; averaging and filtering; methods for low and high Reynolds numbers – from RANS to LES; coupled sub-scale approaches.

15B. Direct simulations of multiphase systems: *S. Banerjee.* Interfacial boundary conditions. The Ghost Fluid and Level Set methods. Numerical issues and developments. Boundary fitting. Direct numerical simulations of separated and dispersed flows.

16B. Volume of Fluid (VOF) method: *S. Zaleski.* Volumetric tracking, piecewise linear interface reconstruction. Advanced VOF methods: unsplit, exactly-conserving VOF methods, oct-tree adaptive mesh refinement. Recent advances in surface tension with VOF methods: height-function methods.

FRIDAY, FERUARY 17 (9-12:30)

17B. Applications of VOF and Lattice Boltzmann: *S. Zaleski.* The Gerris Flow Solver open source code, development and perspectives. Flows with large interface deformation and disruption. Ligament formation, atomization and entrainment. Droplet splashing. Multiphase flow in porous media. Introduction to Multiphase Lattice Boltzmann.

18B. Embedded Interface Methods: *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.

PART III. C*M*FD WITH COMMERCIAL CODES

FRIDAY, FEBRUARY 17 (13:30-17:30)

20. Modelling of industrial multiphase flows with STAR-CD and STAR-CCM+: *S. Lo.* A selection of examples illustrating some of the challenges and advanced models used in the analyses of industrial multiphase flow problems.

21. Modelling of multiphase flow with ANSYS CFD: *Sergio A. Vasquez* Solver technology overview of model portfolio: Euler/Euler, free surface flow, applicability and limitations. Applications and comparisons to data.

22. Simulating Industrial Multiphase Flows with TransAT: *D. Lakehal.* Solver, models and algorithms. Examples and validation using the Eulerian-Eulerian field approach, Level Set and VOF, Lagrangian particle tracking and three-phase flows.

THE LECTURERS

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. Engineering 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 Engineering Physics at McMaster Univ. and of Acting Director of Applied Science in the Whiteshell Nuclear Research Establishment. 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 Lecturership, 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 is research director at CEA-Grenoble, in France. Worked extensively in modelling two-phase flow and has been project manager of CATHARE development. He is now coordinator for two-phase flow modelling in the NEPTUNE thermalhydraulic platform and coordinator of the Thermalhydraulic subproject of NURISP, the European Integrated Project for a multi-disciplinary, multi-scale software platform. As a member of the OECD-CSNI GAMA working group, he coordinates the Writing Group on the extension of CFD to two-phase nuclear reactor safety issues.

Michael L. Corradini is Chair and Wisconsin Distinguished Professor of Nuclear Engineering at the Univ. of Wisconsin-Madison. He is also a member of the US NRC Advisory Committee on Reactor Safeguards (ACRS), member of NRC safety review panels and of the US Department of Energy, DoE, Generation IV Roadmap Project. He has published widely in areas related to vapour explosion and severe accident phenomena, jet spray dynamics and transport phenomena in multiphase systems.

Gad Hetsroni is the Danciger Professor emeritus of Engineering at the Technion, Israel. He has occupied positions at Westinghouse, EPRI, Univ. of California-Santa Barbara, and Stanford University in the US. He has also served as the Director of the Natl Council for R&D in Israel, and as Dean of the Faculty of Mech. Engineering at the Technion. He has worked on many different aspects of two-phase flow and is the founder and Editor of the *Int. J. of Multiphase Flow* and Editor of the *Handbook of Multiphase Systems*. Recipient of the 2010 Int. Conference on Multiphase Flow (ICMF) Senior Award. Fellow of ASME.

Geoffrey F. Hewitt is Professor emeritus of Chem. Engineering at Imperial College, London. Founder of the Heat Transfer and Fluid Flow Service (HTFS) at the Harwell Laboratory. He has authored and edited many books and published over 500 papers and reports. He served as Editor for many international journals and handbook. Recipient of the AIChE Donald Q. Kern, the ASME Max Jacob awards, the Nusselt Reynolds Prize, the Luikov Medal, the IChemE Council and Armstrong medals, the Senior Multiphase Flow Award and the Global Energy Prize. He has Hon. Doctorates from Louvain, UMIST and Heriot Watt. Fellow of the Royal Academy of Engineering, Fellow of the Royal Society, and Foreign Associate of the US Natl Academy of Engineering.

Djamel Lakehal is founder and CEO of ASCOMP GmbH, an ETH spin-off company specialized in industrial thermal-fluid dynamics. He obtained his M.S. and Ph.D. in Fluid Mechanics from Ecole Centrale of Nantes in France. After four years of research on turbulence at the Univ. of Karlsruhe and TU-Berlin, he joined the Nuclear Engineering Laboratory of ETH as Group Leader and Lecturer. Dr Lakehal authored numerous papers in the area of thermal-fluid dynamics. Since March 2010, Dr Lakehal acts as an affiliate Senior Researcher at the MIT (Nucl. Eng. Department). He provides lectures on fundamental fluid mechanics at EPFL Lausanne as an Adjunct Lecturer.

Simon Lo is the Director for Multiphase Flow Models Development at CD-adapco and a Honorary Professor in CMFD at The University of Nottingham, UK. He received his PhD from Imperial College, London in 1984. Since then he has been actively involved in the development of commercial CFD codes (STAR-CD and STAR-CCM+) and their application to industrial multiphase flows.

Horst-Michael Prasser is Professor of Nuclear Energy Systems at ETH-Zurich and Head of the Thermal-Hydraulics Laboratory at PSI. He graduated from the Moscow Institute of Power Engineering and obtained his PhD in 1984 in Zittau. During the German reunification, he took part in the foundation of the Res. Center Dresden (Rossendorf), where he later headed the group "Experimental Thermal Fluid Dynamics." He worked on multiphase flow instrumentation and the closure relations necessary for C(*M*)FD codes, as well as on nuclear reactor safety studies.

Gretar Tryggvason is the Viola D. Hank Professor in the Aerospace and Mechanical Engineering Department at the University of Notre Dame. He is well known for his research on numerical simulations of multiphase and free-surface flows, vortex flows, and flows with phase changes. He is an active member of several professional societies, a fellow of the American Physical Society and the American Society of Mechanical Engineers, and the editor-in-chief of *J. Comp. Physics.*

Sergio A. Vasquez, is Development Fellow and Technical Lead in Multiphase Software Development, ANSYS Fluid Dynamics, He received his Ph.D. in turbulence modelling at the Univ. of Sheffield in the UK. He has worked on the development and application of numerical methods and physical models for single and multiphase problems in the commercial code ANSYS FLUENT.

George Yadigaroglu is Professor emeritus of Nuclear Engineering at the Swiss Federal Institute of Technology in Zurich (ETH-Zurich) and President and co-founder of ASCOMP, an ETH spin-off company specializing in CMFD simulations. For the period 1988-1999, he was also heading the Thermal-Hydraulics Laboratory at the Paul Scherrer Institute. He was previously Professor of Nuclear Engineering at the Univ. of California-Berkeley, and served as Head of the Nuclear Regulatory Service in Greece. He is active in research and consulting for various organisations and national laboratories on a range of multi-phase flow and heat transfer topics and is a member of several international committees dealing with nuclear safety issues. Since 2004 he is member of the Scientific Board of IRSN (Institute for Radiological Protection and Nuclear Safety) in France. ANS Technical Achievement Award. ANS and ASME Fellow. Former Assoc. Editor of the *Int. J. of Multiphase Flow.*

Stéphane Zaleski is Professor of Mechanics at Univ. Pierre et Marie Curie (UPMC, Paris 6). He investigates various methods for the simulation of multiphase flow. He is director of the Institut Jean Le Rond d'Alembert of UPMC and CNRS. He is associate editor of the *J. Comput. Physics.* 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.

Course Directors: S. Banerjee, G. Hetsroni, G. F. Hewitt, H.-M. Prasser, G. Yadigaroglu