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, March 20-24, 2006
Hosted by the
Swiss Federal Institute of Technology (ETH)
in Zurich

THE COURSES

Multiphase flows and heat transfer with phase change are of interest to researchers and engineers working in power, nuclear, chemical-process, oil-and-gas, cryogenic, space, 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 for 22 years now at ETH-Zurich; over 1300 participants attended the Zurich courses.

The courses are organised in a modular form as intensive introductory courses for persons having basic knowledge of fluid mechanics, heat transfer, and numerical techniques, but also serve as advanced courses for specialists wishing to obtain the latest information.

Part I, **Bases** covers the common background material and emphasises the latest modelling and computational aspects of multiphase flows.

The **New Reactor Systems and Methods** part reviews some of the most recently proposed advanced reactor system designs (including those in Generation IV) and introduces the state-of-the-art and beyond in modelling and simulation methods for core design and accident analysis.

The module on **Computational *Multi*-Fluid Dynamics (C*M*FD)** reflects the growing interest in the application of CFD techniques to multi-phase flows; it is continuously updated to cover most new computational techniques.

The **C*M*FD with Commercial Codes** module is attached to both Parts IIA and IIB. The participants will have the possibility to meet the main commercial code developers and discuss their products.

General discussion sessions with all the lecturers have been added this year to give to the participants the opportunity to bring their problems and discuss them in class.

The emphasis in these courses is on:

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

The limited-enrolment courses feature:

- A program of up to 22, *co-ordinated,* 90-min lectures by experts in the field
- A complete and extensive set of lecture notes plus copies of all the standardised presentations
- Movies, videos, animations, and computer simulations illustrating physical phenomena and numerical techniques

COURSE FEES

Part I alone: EUR 1100.
Parts IIA+III **or** IIB+III alone: EUR 850.
All parts (either IIA **or** IIB) taken together: EUR 1500.

The fees include the cost of all corresponding course materials but do *not* include meals and hotel accommodations. (A fee of EUR 100 will be retained in case of cancellation after March 10, 2006.)

To secure registration please make a **bank transfer** before March 10, 2006 **exactly** to

Short Course (Prof. G. Yadigaroglu)
Account No. 206-DP133534.0
Bank: UBS AG, P.O. Box, CH-8098 Zurich, Switzerland
BIC: UBSWCHZH80A
Int. Bank Account Number,
IBAN: CH16 0020 6206 DP13 3534 0

All **practical information** about the course and **hotel reservations** can be obtained from the **course Internet site:**

http://www.ascomp.ch/ShortCourse.

ADDRESS for correspondance:
Prof. G. Yadigaroglu
ETH, WEN B-13, Weinbergstrasse 94
CH-8006 Zurich, Switzerland
Telephone: +41- 44 - 632.4615
Fax: +41- 44 - 632.1105

Preferred communications mode: e-mail: yadi@ethz.ch

SCHEDULE AND CONTENTS OF LECTURES

PART I. BASES

MONDAY, MARCH 20 (9-12:30 and 14-17:45)

1. The nature of multiphase flows: *G.Hetsroni.* Classification of multiphase flows. Basic definitions. Flow regimes in two-phase gas-liquid flows; flow regime maps. Flow regimes with phase change. Liquid-liquid flows. Three-phase liquid-liquid-gas flows.
2. Basic models for two-phase flows: *G.Yadigaroglu.* Simplified, control volume derivation of continuity, momentum and energy equations for separated flows. The homogeneous flow model. Averaging. Closure requirements. Application to annular and stratified flows. Combined equations; correlation requirements. The drift flux models.
3. Pressure drop and void fraction: *G.Hetsroni.* Steady-state combined equation for pressure gradient; components of pressure gradient in straight channels. Correlations for frictional pressure gradient and void fraction. Comparison of correlation performance. Singularities (orifices, bends, T-junctions etc).
4. Phenomenological models for two-phase flows: *G.F. Hewitt.* The bases of phenomenological modelling. Some transition phenomena (stratified/slug, slug/churn, annular/wispy annular). Modelling of continuous flows (bubble, annular, stratified). Modelling of intermittent flows (slug, churn, wispy annular).

TUESDAY, MARCH 21 (9-12:30 and 14-17:45)

5. Phase change heat transfer (single component systems) *G. Hetsroni.* Boiling heat transfer; nucleate boiling, forced convection evaporation. Correlations and models. Dryout (critical) heat flux: mechanism and predictions. Condensation; falling film, tube bundles, inside horizontal tubes.
6. 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.
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. Phase change heat transfer (multicomponent systems): *G.F. Hewitt.* Occurrence of multicomponent systems; chemical industry, oil industry, etc. Vapour-liquid equilibrium. Multicomponent nucleate boiling. Forced convection evaporation; role of entrainment, modelling.

WEDNESDAY, MARCH 22 (9-12:30 and 14-17:45)

9. 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.
10. Closure laws: *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 chocked flow, stratified flow, CCFL. Interfacial area and turbulence.
11. 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.
12. Introduction to CMFD: *G.F. Hewitt.* Applications of single-phase CFD to two-phase systems. Application of multifluid models. Interface-tracking methods; VOF, level sets, embedded interface methods etc. Turbulence modelling in two-phase flows. Examples of applications.

General discussions with all lecturers present: will take place Monday to Thursday, 17:15-17:45. The participants are encouraged to bring and discuss their problems.

PART IIA. NEW REACTOR SYSTEMS AND METHODS

THURSDAY, MARCH 23 (9-12:30 and 14-17:45)

13A. Core design for light water cooled reactors: *G.F. Hewitt.* Core configurations in conventional and advanced PWR's and BWR's. Critical heat flux in rod bundle geometries; prediction methods (global models, sub-channel models, phenomenological models); effects of non-uniform flux distribution; grid design for enhancement.

14A. 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 cooling.

15A. Advanced computational modelling of nuclear systems: *D. Bestion.* Needs and progress towards advanced simulation tools for nuclear reactor thermalhydraulic issues. Future development directions for codes. Structure, closure laws, the interfacial area, efficiency. Advances in two-phase, 1D modelling. Use of CMFD for nuclear reactor investigations.

16A. Multiphase phenomena in LWRs II: *M.L. Corradini.* Multiphase phenomena during severe accidents: vapour explosions, molten core quenching and coolability, etc. Severe accident codes and system simulation.

FRIDAY, MARCH 24 (8:30-12:30)

17A. Advanced LWR concepts and phenomena: *M.L. Corradini.* Review of advanced PWR and BWR concepts for near-term and Generation IV reactor development. Two-phase phenomena in the primary system and the containment: condensation; choking and critical flow; supercritical heat transfer and flow stability.

18A. Advanced reactor systems: *M.L. Corradini.* Overview of Generation IV liquid-metal and gas reactor systems. Multiphase flow issues: direct-contact heat transfer, solid-gas fluidisation, steam generator considerations.

19A. Future computational tools: *G. Yadigaroglu.* Trends: multi-physics and multi-scale. Examples of emerging applications of CFD and CMFD methods to reactor systems: interface tracking methods in combination with the one-fluid model (VOF, Level Sets), Large-Eddy Simulation, etc.

PART IIB. COMPUTATIONAL MULTI-FLUID DYNAMICS

THURSDAY, MARCH 23 (9-12:30 and 14-17:45)

13B. Direct simulations of multiphase systems I: *S. Banerjee*. Interfacial boundary conditions. The ghost fluid and level set methods, reinitialization. Solution techniques for discontinuous pressure, density and viscosity across interfaces. Bubbly, thin film and stratified flows. Turbulence-interface interactions.

14B. Embedded Interface methods: *G. Tryggvason.* Interface following methods using marker particles. Advancing fluid interfaces. Computing interfacial forces. Methods of solution.

15B. Direct simulations of multiphase systems II: *S. Banerjee.* The phase field method. Numerical issues and developments. Phase separation and scaling. Coalescence. Generalised two-fluid models and hydrodynamic field theoretic approaches. Viscoelastic and self assembling systems.

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

FRIDAY, MARCH 23 (9-12:30)

17B. Applications of VOF and Lattice Gas Cellular Automata: *S. Zaleski.* Flows with large interface deformation and disruption. Ligament formation, atomization and entrainment. Droplet splashing. Multiphase flow in porous media. Introduction to Lattice Gas Cellular Automata and Lattice Boltzmann.

18B. Applications of Embedded Interface Methods: *G. Tryggvason.* Simulations of dispersed bubbly flows; atomization; flows with complex physics, including boiling, solidification, and electrohydrodynamic effects.

General discussions with all lecturers present: will take place Monday to Thursday, 17:15-17:45. The participants are encouraged to bring and discuss their problems.

PART III. C*M*FD with Commercial Codes

FRIDAY, MARCH 24 (13:30-17:30)

20. Modelling of industrial multiphase flows with STAR-CD: *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 multiphase systems with Fluent: *S. A. Vasquez.* Single-fluid approach (Mixture models, VOF, cavitation). Two-fluid approach, (Eulerian, and Eulerian-granular models). Numerics. Turbulence. Transports and population balances.
22. Validation of two-phase flow models in CFX-5. *G. Scheuerer*. Solver technology; overview of model portfolio: Euler/Euler two-phase, free surface flow, Euler/Lagrange models; applicability and limitations. Applications and comparisons to data.

THE LECTURERS

Sanjoy Banerjee is Professor in both the Depts of Chem. and Mech. Engng at the Univ. of California-Santa Barbara. Previously 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 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 is a member of several Editorial Boards, and has received the ASME Melville Medal, the 1992 Cray (Italy) Prize, and the ASME 1999 Heat Transfer Memorial Award in Science. He has published extensively on multiphase fluid dynamics and turbulence.

Dominique Bestion is research director at Commissariat à l'Energie Atomique, at CEA-Grenoble, in France. He has been working a long time in modelling two-phase flow for the CATHARE code and has been project manager of CATHARE development for three years. He is now involved in the development of the NEPTUNE thermalhydraulic platform as a coordinator of the R&D for two-phase flow modelling. He is also coordinator of the Thermalhydraulic Subproject of the NURESIM European Integrated Project for a multi-disciplinary and multi-scale software platform. As a member of the GAMA working group of OECD-CSNI, he coordinates a Writing Group about the extension of CFD to two-phase nuclear reactor safety issues.

Michael L. Corradini is Chair and Wisconsin Distinguished Professor of Nuclear Engng at the Univ. of Wisconsin-Madison. Previously, at Sandia Natl Laboratories he was principal investigator for the LWR vapour explosion research programme and for other severe accident research projects. He has been a consultant for fifteen years to the US NRC Advisory Committee on Reactor Safeguards in reactor safety. Member of NRC safety review panels and of the DoE Generation IV Roadmap Project. He has published widely in areas related to vapour explosion phenomena, jet spray dynamics and transport phenomena in multiphase systems.

Gad Hetsroni is the Danciger Professor of Engng at the Technion - Israel Inst. of Technology. 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 Research and Development in Israel, and as Dean of the Faculty of Mechanical Engng 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*.

Geoffrey F. Hewitt is Professor emeritus of Chem. Engng at Imperial College, London. He was formerly head of the Thermal Hydraulics Division and founder of the Heat Transfer and Fluid Flow Service (HTFS) at the Harwell Laboratory. He has authored and edited many books and published over 400 papers and reports, mainly on gas-liquid flow and evaporative heat transfer. He is Editor of *Multiphase Science and Technology* and Executive Editor of the *Heat Exchanger Design Handbook.* He is the recipient of the AIChE Donald Q. Kern, the ASME Max Jacob awards, the Nusselt Reynolds Prize, the Luikov Medal and the IChemE Council and Armstrong medals. He has received Hon. Doctorates from Louvain, UMIST and Heriot Watt. He is Fellow of the Royal Academy of Engng, Fellow of the Royal Society, and Foreign Associate of the US Natl Academy of Engng.

Simon Lo is the Sector Manager for Chemical and Process Industries at CD-adapco. He received his PhD from Imperial College, London in 1984. Since then he has been actively involved in the development of commercial CFD codes (CFX and STAR-CD) and their application to industrial multiphase flows.

Georg Scheuerer is Managing Director, ANSYS Germany. He has obtained his doctorate at the Univ. of Karlsruhe on turbulence modelling (with Prof. Rodi). Lecturer at Univ. of Erlangen-Nürnberg, GRS Garching (two-phase flow modelling). Founder of Advanced Scientific Computing GmbH (1990).

Gretar Tryggvason is Professor and Head of Mech. Engng at the Worcester Polytechnic Institute. Previously, he was Professor of Mechanical Engng at the Univ. of Michigan in Ann Arbor. He has published on multiphase and free surface flows, vortex dynamics and combustion, boiling, solidification, and numerical methods. He is a fellow of the American Physical Society and of the ASME, an Assoc. Editor of the *Int. J. of Multiphase Flow* and the Editor-in-chief of the *J. Comp. Physics.*

Sergio A. Vasquez, Ph D in turbulence modelling at the Univ of Sheffield in the UK, is Principal Development Engineer and Technical Lead in Multiphase Software Development, Fluent Inc., Lebanon, NH. He has worked on the development and application of numerical methods and physical models for single and multiphase problems for over 20 years.

George Yadigaroglu is Professor emeritus of Nuclear Engng, ETH-Zurich and President and founder of ASCOMP, an ETH spin-off company specializing in CMFD simulations. Has also headed the Thermal-Hydraulics Laboratory at the Paul Scherrer Institute. He was previously Professor of Nuclear Engng at the Univ. of California-Berkeley, and served as Head of the Nucl. Regulatory Service in Greece. He is active in research and consulting for various organisations and national laboratories and is a member of several international committees dealing with nuclear safety issues. ANS Technical Achievement Award. ANS and ASME Fellow. Former Assoc. Editor of the *Int. J. of Multiphase Flow*.

Stéphane Zaleski is Professor of Theor. Mechanics at Univ. Pierre et Marie Curie (Paris 6). His interests are in chaos and turbulence in fluids, predictability of dynamical systems, and numerical simulation of flows. He investigates various methods for the simulation of interfaces between fluids in collaboration between his own team at the Laboratoire de Modélisation en Mécanique (LMM) in Paris and other organizations, including groups at Worcester Polytechnic Inst., MA, USA and the Univ. of Bologna, Italy. He is Associate editor of the *J. Comput. Physics;* received the Victor Noury prize of the Paris Academy of Sciences and the Silver Medal of CNRS; fellow of the American Physical Society.

Course Directors: G. Hetsroni and G. Yadigaroglu