# SHORT COURSES
## on
## Modelling and Computation of Multiphase Flows:
## Part I: Bases
## Part IIA: New Reactor Systems and Methods
## Part IIB: Computational Multi-Fluid Dynamics (C*M*FD)

*Zurich, Switzerland, March 22-26, 2004*
*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, at the University of California-Santa Barbara and for 20 years now at ETH-Zurich; over 1200 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** has been updated again and modified to emphasise the latest modelling and computational aspects of multiphase flows. Flows in micro-channels and molecular dynamics have been added this year.

The **New Reactor Systems and Methods** part reviews the most recently proposed advanced reactor system designs (such as 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 (CMFD)** reflects the growing interest in the application of CFD techniques to multi-phase flows. The module has been expanded this year to cover most new computational techniques.

**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 CMFD 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 nineteen, 90-min, *co-ordinated* lectures by experts in the field
- A complete and extensive set of lecture notes plus copies of all the standardised presentation materials used
- Movies, videos, animations, and computer simulations illustrating physical phenomena and numerical techniques

### COURSE FEES
Part I alone: EUR 1050. Parts IIA or IIB alone: EUR 750.
Parts I *and* IIA *or* IIB taken together: EUR 1450.

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 12, 2004.)

To secure registration please make a bank transfer before March 12, 2004 **exactly** to

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

Information on **hotel accommodations** can be obtained from the **course Internet site** and can also be provided to all participants.

**COURSE ADDRESS** for all correspondence:
**Prof. G. Yadigaroglu**
**ETH-Zentrum, CLT**
**CH-8092 Zurich, Switzerland**
**Telephone: (+41-1) 632.4615; Fax (+41-1) 632.1166**
**e-mail:** yadi@ethz.ch
**Internet: http://www.lkt.mavt.ethz.ch/courses.html**

# SCHEDULE AND CONTENTS OF LECTURES

## I. BASES

### MONDAY, MARCH 22

**1. Introduction to two-phase flows and modelling strategies:** *G.F. Hewitt.* Nature of two-phase flows. Introduction to flow patterns. Key design and scientific parameters in two-phase flows; definition and methods of measurement. Modelling methods - empirical, phenomenological, multifluid, computational fluid dynamics.

**2. Empirical models I: Flow regimes, pressure drop and void fraction:** *G. Hetsroni.* Description of flow regimes. Flow regime maps. Analytical bases for the flow regime transitions. Methods for estimating pressure drop and void fraction.

**3. 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).

**4. Empirical models II: Heat transfer:** *G. Hetsroni.* Boiling heat transfer; nucleate boiling, forced convection. Correlations and models. Dryout (critical) heat flux: mechanism and predictions.

### TUESDAY, MARCH 23

**5. 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: inverted-annular and dispersed-flow film boiling; liquid phase distribution.

**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. Multicomponent systems:** *G.F. Hewitt.* Occurrence of multicomponent systems; chemical industry, oil industry, etc. Vapour-liquid equilibrium. Multicomponent evaporation and condensation. Computer modelling of multicomponent systems.

**8. 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.

### WEDNESDAY, MARCH 24

**9. Closure laws:** *M. Ishii.* Need for closure laws according to the flow regime. Interfacial area; importance, definition, measurement. Hydrodynamic closure relationships. Closure laws in codes and their limitations.

**10. 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.

**11. Flow and heat transfer in micro-channels:** *G. Hetsroni.* Applications of flow in micro-channels as enabling technology in the electronic and optical industries; single-phase flow and heat transfer; two-phase flow regimes. Multi-micro-channels.

**12. Fundamentals of micro and nanoscale fluid mechanics:** *P. Koumoutsakos*. Flows in the nano and microscale: flows in nanopores, flows with micro and nanoparticles; hydrophobicity, wetting, no-slip boundary conditions. Computational methods for micro-nano fluid dynamics.

## IIA. NEW REACTOR SYSTEMS AND METHODS

### THURSDAY, MARCH 25

**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. Post-dryout heat transfer.

**14A. Advanced computational modelling and scaling capability:** *M. shii.* The interfacial area transport equation as an alternative to flow regime maps; one- and two-group approaches. Scaling of two-phase systems; systematic establishment of code scaling capability.

**15A. Multiphase phenomena in LWRs I:** *G. Yadigaroglu*. Loss-of-coolant accidents and transients and their simulation; uncertainty evaluation. In-vessel accident phenomenology; modelling of core cooling. Passive emergency cooling.

**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 26

**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.* Emerging applications of Computational Multi-Fluid Dynamics (CMFD) methods to nuclear reactor systems: interface tracking methods in combination with the one-fluid model (VOF, Level Sets), Large-Eddy Simulation, etc.

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

### THURSDAY, MARCH 25

**13B. Computational modelling of multi-dimensional phenomena in two-phase flow:** *G.F. Hewitt.* Multifield formulation and phenomena. Interpenetrating-media versus one-fluid, interface-tracking methods; embedded interface methods. Turbulence modelling in two-phase flows. Examples of applications.

**14B. Direct simulations of multiphase systems:** *S. Banerjee.* Combined flow-structure equations for direct simulation – level set/ghost fluid, phase-field and self-consistent field theory models. Computational approaches. Applications to phase-separating and self-assembling formulations. Inertial effects and turbulence.

**15B. Volume of Fluid (VOF) method:** *S. Zaleski.* Volumetric tracking, piecewise linear interface reconstruction. Recent advances in unsplit and exactly conserving VOF methods. Surface tension with VOF methods.

**16B. Embedded Interface methods:** *G. Tryggvason.* Interface following methods using marker particles. Advancing fluid interfaces. Computing interfacial forces; constant and variable surface tension, Methods of solution.

### FRIDAY, MARCH 26

**17B. Applications of VOF and Lattice Gas Cellular Automata:** *S. Zaleski.* Flows with large interface deformation and disruption. Ligament formation, atomization and entrainment. Simulations of droplets and bubbles. Introduction and applications of Lattice Gas Cellular Automata.

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

**19B. Multiscale flow simulations using particle methods:** *P. Koumoutsakos*. Fundamentals of particle methods for multiscale flow simulations: Molecular dynamics, dissipative particle dynamics, smooth particle hydrodynamics and vortex methods; applications to multiphase flows and nanofluidic device simulations.

## THE LECTURERS

**Sanjoy Banerjee** is Professor in both the Depts of Chemical and Mechanical 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.

**Michael L. Corradini** is Chair and Wisconsin Distinguished Professor of Nuclear Engng and Engng Physics at the Univ. of Wisconsin-Madison. Previously, at Sandia Natl Laboratories he was principal investigator for the LWR vapour explosion research program 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 and multiphase flow, as well as to the DOE Natl Laboratories. 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 Engineering 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*. He was the Vice President for Region 13 and past governor of ASME International.

**Geoffrey F. Hewitt** is Emeritus Professor of Chemical 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 Honorary 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.

**Mamoru Ishii** is Walter H. Zinn Distinguished Professor of Nuclear Engng at Purdue University. He is also Director of the Inst. of Thermal-Hydraulics established by the US NRC at Purdue, with eight major participating universities. Before joining Purdue, he was a senior scientist and group leader at the Reactor Analysis and Safety Division at Argonne Natl Laboratory and served as deputy director of the ANL Multiphase Flow Research Institute. His interests in thermal-hydraulics and reactor safety include two-phase flow fundamentals, formulation, multiphase flow instrumentation, interfacial transfer, and subcooled boiling. In 1988, he received the Technical Achievement Award from the ANS Thermal Hydraulics Division.

**Petros Koumoutsakos** is Professor of Computational Sciences at ETH Zurich and the director of the ETHZ CoLab (Computational Laboratory). During 1992-1994 he was a National Science Foundation postdoctoral fellow in parallel supercomputing at Caltech. Since 1994 he is senior research associate and maintains an active affiliation with the Center for Turbulence Research (CTR) at NASA Ames/Stanford Univ. His research activities are in the areas of particle methods, machine learning, biomimetics, biologically inspired computation, and the application of these techniques to problems of interest in the areas of Engng and Life Sciences.

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

**George Yadigaroglu** is Professor of Nuclear Engng at ETH in Zurich. Until recently, he has also been heading 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 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. ANS and ASME Fellow. He was until recently Assoc. Editor of the *Int. J. of Multiphase Flow*.

**Stéphane Zaleski** is Professor of Theoretical Mechanics at Université 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 various groups at CRS4, Cagliari and the University of Bologna.