

## TIME TABLE

TIME	Monday June 8	Tuesday June 9	Wednesday June 10	Thursday June 11	Friday June 12
9.00 - 9.45	Registration	Sun	Prosperetti	Zenit	Takagi
9.45 - 10.30	Risso	Sun	Bothe	Zenit	Takagi
11.00 - 11.45	Bothe	Risso	Magnaudet	Takagi	Zenit
11.45 - 12.30	Bothe	Risso	Magnaudet	Takagi	Sun
14.00 - 14.45	Magnaudet	Prosperetti	Zenit	Sun	
14.45 - 15.30	Magnaudet	Prosperetti	Zenit	Sun	
16.00 - 16.45	Prosperetti	Bothe	Magnaudet	Risso	
16.45 - 17.30	Prosperetti	Bothe	Takagi	Risso	

## ADMISSION AND ACCOMMODATION

The registration fee is of 575,00 Euro + VAT taxes\*, where applicable (bank charges are not included).

The registration fee includes a complimentary bag, four fixed menu buffet lunches (Friday subject to numbers), hot beverages, downloadable lecture notes and wi-fi internet access.

Applicants must apply at least one month before the beginning of the course. Application forms should be sent on-line through our web site: <http://www.cism.it> or by post.

A message of confirmation will be sent to accepted participants. If you need assistance for registration please contact our secretariat.

Applicants may cancel their course registration and receive a full refund by notifying CISM Secretariat in writing (by email) no later than two weeks prior to the start of the course.

If cancellation occurs less than two weeks prior to the start of the course, a Euro 50,00 handling fee will be charged. Incorrect payments are subject to Euro 50,00 handling fee.

A limited number of participants from universities and research centres who are not supported by their own institutions can be offered board and/or lodging in a reasonably priced hotel or students' dormitories, if available.

Requests should be sent to CISM Secretariat by **April 8, 2015** along with the applicant's curriculum and a letter of recommendation by the head of the department or a supervisor confirming that the institute cannot provide funding. Preference will be given to applicants from countries that sponsor CISM.

Information about travel and accommodation is available on our web site, or can be mailed upon request.

\* Italian VAT is 22%.

*For further information please contact:*

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 Palazzo del Torso  
 Piazza Garibaldi 18  
 33100 Udine (Italy)  
 tel. +39 0432 248511 (6 lines)  
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## DYNAMICS OF BUBBLY FLOWS

Advanced School  
 coordinated by  
**Frédéric Risso**  
 CNRS  
 and University of Toulouse  
 France

**Chao Sun**  
 University of Twente  
 The Netherlands

Udine June 8 - 12 2015

## DYNAMICS OF BUBBLY FLOWS

In many practical situations, bubbles are dispersed in a liquid phase. The understanding and the modeling of bubbly flows is therefore a major issue for many applications including chemical engineering (bubble columns), water treatment (oxygenation and purification), nuclear industry (steam generators, accidental depressurizations), naval transport (skin drag reduction) and medicine (contrast agent, micro-bubbles bursting).

Bubbly flows result from the two-way coupling between a liquid and bubbles that are randomly distributed over space. The specific properties of the bubbles make their dynamics very rich. Bubbles are inertialess and deformable, which complicates the expression of the hydrodynamic forces that act on them. They are compressible, which causes bubbly flows to be

complex media for pressure waves and allows cavitation to occur. The interface properties are influenced by the presence of surfactant molecules that may be adsorbed at the bubble surface. In addition, the size of the bubbles is often not small compared to the characteristic length scales of the flow and buoyancy forces play a significant role. This implies to consider a large range of length scales and causes the generation of a strong agitation known as pseudo-turbulence.

Owing to their complexity, different approaches have to be combined to deal with the different aspects of bubbly flows. Numerical simulations are particularly well suited to investigate phenomena at the bubble scale. In this course, the fundamentals of the numerical simulation of bubbles will be presented and, in particular, the hydrodynamic loads

acting on a bubble will be discussed in detail. Collective effects are better addressed by experimental investigations. A review of advanced experimental techniques (High-speed imaging, Particle Image Velocimetry, 3D Particle Tracking Velocimetry...) will be proposed and the dynamics of a swarm of rising bubbles will be described for both Newtonian and non-Newtonian liquids. Theoretical methods are also of great help in the study of bubbly flows. Theoretical expression of hydrodynamic forces on a single bubble will be presented for large or small Reynolds numbers. Averaged equations will be derived to handle the stochastic character of flows involving many bubbles.

The objective is to provide state-of-the-art information on bubbly flow. The principal methods of investigations will be exposed and

illustrated. The flow will be considered at different scales, from that of a single bubble to that of a bubble swarm. Major results concerning the dynamics of bubbly flows will be presented as well as several modern applications. The course is addressed to PhD students, young and senior researchers, or practicing engineers, involved in Chemical Engineering, Mechanical Engineering or Fluid Dynamics. Since it does not focus on a particular technique (numerical, experimental or theoretical), it should be of interest for a large audience.

## PRELIMINARY SUGGESTED READINGS

On bubble clustering and energy spectra in pseudo-turbulence. Martinez, Chahata, van Gils, Sun & Lohse. *J. Fluid Mech.* 650 (2010) 287–306.

Shock Waves in Dilute Bubbly Liquids. Watanabe & Prosperetti. *J. Fluid Mech.* 274 (1994) 349-381.

Modeling and VOF-based numerical simulation of mass transfer processes at fluidic particles. Bothe & Fleckenstein. *Chem. Eng. Science* 101 (2013), 283-302.

The motion of high-Reynolds-number bubbles in inhomogeneous flows. Magnaudet & Eames. *Annual Review of Fluid Mechanics* 32 (2000) 659-708.

Experimental characterization of the agitation generated by bubbles rising at high Reynolds number. Riboux, Risso & Legendre. *J. Fluid Mech.* 643 (2010) 509–539.

## INVITED LECTURERS

**Dieter Bothe** - Technische Universität Darmstadt, Germany  
*5 Lectures on:* Modeling and Direct Numerical Simulation of Bubbles: (1) continuum thermodynamics of two-phase systems employing sharp-interface approach; (2) discussion of various numerical methods for DNS, with emphasis on VOF; (3) applications to bubble dynamics and multi physics with emphasis on mass transfer.

**Chao Sun** - University of Twente, The Netherlands  
*5 Lectures on:* Advanced experimental techniques for bubbly flows are presented and discussed: high-speed imaging, flow visualizations, phase-sensitive hot-film anemometry, laser-Doppler anemometry, particle image velocimetry and tracking. A particular emphasis is put on 3D characterization.

**Jacques Magnaudet** - Université de Toulouse, France  
*5 Lectures on:* The physical origin of the hydrodynamic forces on bubbles is discussed: added-mass, shear-induced lift, viscous drag, history drag and wall effect. Theoretical or semi-empirical expressions are given for all Reynolds numbers. Their predictions are compared with available data in practical situations.

**Andrea Prosperetti** - Johns Hopkins University, Baltimore, MD, USA  
*5 lectures on:* Pressure waves in bubbly flows: (1) Fundamental of bubble dynamics; (2) Simple averaging approaches for linear waves; (3) Nonlinear waves and shocks; (4) Ensemble averaging tools; (5) Derivation of averaged equations by ensemble averaging.

**Frédéric Risso** - CNRS and Université de Toulouse, France  
*5 lectures on:* Statistical and spectral features of the liquid agitation induced by moving bubbles are described. Underlying physical mechanisms are explained by distinguishing localized spatial disturbances from collective flow instability. Practical consequences on mixing and interfacial transfer are presented.

**Shu Takagi** - The University of Tokyo, Japan  
*5 lectures on:* Engineering and medical applications of bubbly flows are discussed with an emphasis on fundamental physics: water purification using microbubbles; skin friction reduction for ship propulsion by bubble injection; microbubbles as contrast agent of ultrasound diagnosis with application to the therapy.

**Roberto Zenit** - Universidad Nacional Autónoma de México, Mexico  
*5 lectures on:* Starting from fundamental rheological concepts, the influence of viscoelasticity and shear-dependent viscosity on the motion of single bubbles and pair interactions are analyzed. Then, the original key features of non-Newtonian bubbly liquids, such as cluster formations, are discussed.

## LECTURES

All lectures will be given in English. Lecture notes can be downloaded from the CISM web site, instructions will be sent to accepted participants.

**DYNAMICS  
OF BUBBLY FLOWS**

**Udine, June 8 - 12, 2015**

**Application Form**

(Please print or type)

Surname \_\_\_\_\_

Name \_\_\_\_\_

Affiliation \_\_\_\_\_

Address \_\_\_\_\_

\_\_\_\_\_

E-mail \_\_\_\_\_

Phone \_\_\_\_\_ Fax \_\_\_\_\_

**Method of payment upon receipt of confirmation (Please check the box)**

*The fee is 575,00 Euro + 22% Italian VAT taxes, where applicable (bank charges are not included).*

I shall send a check of Euro \_\_\_\_\_

Payment will be made to CISM - Bank Account No. 094570210900,  
VENETO BANCA - Udine (CAB 12300 - ABI 05035 - SWIFT/BIC  
VEBHIT2M - IBAN CODE IT46 N 05035 12300 09457 0210900).  
Copy of the receipt should be sent to the secretariat

I shall pay at the registration counter with check or VISA Credit Card  
(Mastercard/Eurocard, Visa, CartaSi)

**IMPORTANT: CISM is obliged to present an invoice for the above sum.  
Please indicate to whom the invoice should be addressed.**

Name \_\_\_\_\_

Address \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

C.F.\* \_\_\_\_\_

VAT/IVA\* No \_\_\_\_\_

(\* Only for EU residents or foreigners with a permanent business activity in Italy.

**Only for Italian Public Companies**

I ask for IVA exemption (ex law n. 537/1993 - art. 14 comma 10).

**Privacy policy:** I understand that data received via this form will be used only to provide information about CISM and its activities, within the limits set by the Italian legislative decree no. 196/2003 and subsequent amendments.

Complete information on CISM's privacy policy is available at [www.cism.it](http://www.cism.it).

I have read the "Admission and Accommodation" terms and conditions and agree.

Date \_\_\_\_\_ Signature \_\_\_\_\_