PANELIST COMMENTS ON: OPEN QUESTIONS AND NEW DIRECTIONS IN GAS-LIQUID FLOWS

Summaries of the ideas and discussion contributed by the panelists are presented in this article. Each panelist has contributed under a separate title in order to preserve the individuality of the opinions and visions expressed on the subject.

Tickling Gas-Liquid Flows

Andrea Prosperetti
Department of Mechanical Engineering
The Johns Hopkins University
Baltimore, MD 21218, USA.
Faculty of Applied Physics, Twente Institute of Mechanics, and Burgerscentrum,
University of Twente, AE 7500 Enschede, The Netherlands

While certainly there are many new important and promising directions into which multiphase flow research can be extended (micro-devices, processing, the environment), in my mind flow regimes still remain the key unsolved problem. For perfectly legitimate reasons, much of the past research has been centered on the study of processes occurring in flows and under conditions of direct practical interest. It is my impression that it would be useful to adopt the approach used in medical animal research in which, in order to understand the system, the organism is perturbed so much as to be often killed. In other words, it may be profitable to shift attention from situations encountered in practice to highly artificial ones, which are not of direct interest in themselves, but may nevertheless reveal the underlying physics. It is in this spirit that I propose the following experiments.

Bubbly/slug flow transition. According to some scenarios, a bubbly flow transitions to slug flow when the void fraction exceeds a certain threshold. A way to cause this void fraction increase is to generate a bubbly flow in a pressurized tube and release the pressure to expand the bubbles. Is there a threshold for transition? How long does it take? What is the role of bubble size? Bubble size can be controlled pretty well e.g. by simply using salt water. Another worthwhile experiment (which has already been attempted, but which could probably stand repetition and extension) is to generate void fraction and pressure waves at the bottom of a bubbly column.

Slug stability. The same device can be used to study the stability of long bubbles: when the pressure falls, the bubble will elongate. What happens then? Does it break up? Two bubbles would both expand: do they get closer? Do they coalesce?

Horizontal stratified/slug transition. In a stratified flow, one could use a wave-maker submerged in the liquid to investigate the role of surface roughness in the transition. An insert could taper the available gas space and gradually increase its velocity. A long time ago, Jean Fabre (Toulouse) suggested that this transition could be affected by secondary flows generated in the cross-section of the tube due to the roughening influence of surface waves. These secondary flows may in some sense be similar to the Langmuir cells at the ocean surface. The surface roughness would be dependent on the local liquid depth, which could be controlled in a number of ways, e.g. by an insert on the bottom of the tube shaped so as to vary the wave amplitude in different parts of the cross section.

Atomization. The onset of atomization is likely related to the amplitude of surface waves. In a horizontal flow, rather than relying on naturally occurring waves, one could artificially generate them with a submerged wave-maker, or small, submerged vertical jets. For example, for the same gas velocity, it should be possible to investigate whether a threshold exist for the onset of entrainment.

Flow regime transition has proven to depend on very subtle physical mechanisms which are not easily understood or identified. Progress in Science has often relied on the generation of unusual situations in the laboratory studied not because they actually occur in practice, but because they help elucidate the mechanisms at work in the systems of interest. It may be time to have a greater recourse to this attitude than has perhaps prevailed in the past. Learn from the doctors: kill the patient!

Towards Strategic Research

Theofanis G. Theofanous
Center for Risk Studies and Safety
Departments of Chemical Engineering
and Mechanical & Environmental Engineering
University of California
Santa Barbara, CA 93106

Gas-liquid flow is at a critical juncture of its development as a subject. Knowledge islands created during the past fifty years have brought us to a point where sporadic, often practice-driven studies are unlikely to significantly improve basic understanding, generalization and predictive capability. The opportunity is open to enter the phase of development of the subject as a scientific discipline. What is needed is a new vision and a research agenda that can rise to the challenge. We can expect that opinions on how to best accomplish this, colored by interests, would differ. Here are my views on what is important at this high level of definition. I will address it in terms of conceiving, nurturing, and keeping on track such an endeavor.

(a) *Conception.* The essence of the subject is Flow Regimes – the space-time distribution of phases and their length scales. This has always been, and remains THE Open Question.

(b) *Nurturing.* Viewed as Flow Regimes the subject falls into the realm of complexity – self organization, adaptation, emergent behavior. Accordingly resolution requires very special efforts. Never having been realized as THE main thrust, this should be the dominant consideration in defining New Directions.

(c) *Operational Framework.* Even if we all were to agree on the above, we would still have to face the choice of strategic steps appropriate to achieving a pertinent degree of focus over such a broad domain of scientific and practical needs. And even if this was agreed upon, we would still need effective means for communication and debate, appropriate incentives both for synergisms and independence, and track records that would foster responsibility and accountability over the whole spectrum of activity, from providing advice to making decisions.

In my opinion it is this third aspect that has been, and is likely to remain, a critical missing link to success. To put it differently, in an otherwise favorable technical situation (however hard, but enabled with modern advances in physics, mathematics, and digital technologies – computation, instrumentation) the principal impediment I see is human factors related, over the whole spectrum of those involved, from the researcher to administrative personnel in various industries and governmental agencies.

Significant change in this respect would require the great and focused attention arising from an overwhelming need, such as that of Nuclear Safety in power reactors in the seventies. Rather, the situation now is one of comparatively low level, but highly diversified/diffuse needs, of commercial significance for the most part. To create a focus in this environment, a focus that is helpful to all, would require an enormous amount of leadership and risk taking. Previous sporadic efforts indicate that odds for success are not favorable.

To address Flow Regimes properly we would need an unrestricted view of the multidimensional, multiscale, and in come cases (boiling and burnout, cavitation, etc.) even multiphysics aspects of multiphase flow. This in turn would require the synergistic, adaptable use of precise and detailed measurements and a panoply of theoretical and computational tools (from direct numerical simulation to effective field models), in wisely-conceived, scrupulously-controlled, and independently verified experiments. The task of uncovering the organizing principles, that is, the dominant features of the flow that create organization, involves much, much more than showing the agreement of an analytical or numerical model with selected features of a flow, in selected experiments. It needs a much more developed (than what has been the case in the past) sensibility on matters of falsification (as Karl Popper would say), for this is just as powerful a force for progress as are new ideas or concepts that purport to explain nature. This is the path to resolving complexity, and it is for this reason that an Operational Framework, as noted above, is absolutely essential.

Let us call this strategic research. It could be an important complement to individual investigator, ad hoc inspired efforts that marked the landscape in the past. A recent DOE Basic Energy Science workshop [1] came up with a whole list of such specific scientific issues in multiphase flow. It also led to a vision for pursuing strategic research on Flow Regimes [2]. Briefly, the idea is that consideration of "steady, fully-developed gas-liquid flows in conduits", and "mixing flows" (including heat transfer and phase change) can be viewed as the canonical elements, and starting points, of an approach for anchoring a general quest for capability that would eventually address multidimensional, unsteady flows in general.

In my view, the overwhelming need is that we do not continue to lose the forest for the trees, and this is why I chose to approach the subject of this panel in the manner outlined above. In these metaphorical terms, complexity, that is, the forest being much more than the sum total of its trees, makes this view even more imperative. For completeness I should conclude by noting that key influences on these views are recent experiences in the very old subject of Boiling and Burnout [3], and a rather new one on Compressible Multihydrodynamics [4], as well as my experiences with the Institute for Multifluid Science and Technology (IMuST, www.crss.ucsb.edu/imust)

Multi-Scale Dynamics in Bubbly Flow

Yoichiro Matsumoto
Department of Mechanical Engineering
The University of Tokyo Hongo, Bunkyo-ku
Tokyo 113-8656, Japan

Bubbly flow has multiple structures in terms of time and spatial scales. The macro-scale flow structure in bubbly flow is affected by both mezzo-scale and micro-scale phenomena. A multi-scale analysis is required to solve bubbly flows reasonably. It is well known that a very small amount of surfactant can drastically change the terminal velocity of a bubble. When the liquid is contaminated, the bubble motion is affected by the Marangoni effect due to the variation of surface tension along the bubble surface caused by the gradient of the contaminant concentration. Numerical results reveal that the flow pattern around the contaminated bubble becomes similar to that of a rigid particle and the drag coefficient increases from that of clean bubble to that of rigid particle.

An example of a bubbly flow where the mezzo-scale phenomena can be clearly observed is the rise of bubbles in quiescent contaminated water. There is much to be learnt on the subject by conducting Direct Numerical Simulations (DNS) on fundamental flows such as this. We have adopted this approach, and the Navier-Stokes equations by the finite difference method and tracking the bubble motion within a rectangular grid system. The relation between drag coefficient, Reynolds number and void fraction is thus investigated at moderate Reynolds numbers. Present results on void fraction dependence on the drag coefficients show good agreement with experiment and theory. Information on the turbulence structure and related averaged quantities in a multi-bubble system is obtained from simulations of the flow around swarms of spherical bubbles rising in a periodic box, leading to conclusions such as that the turbulent energy in the surrounding liquid increases with the void fraction.

To simulate large-scale, more realistic turbulent bubbly flows Large Eddy Simulations (LES) become necessary. This requires application of Sub-Grid Scale (SGS) modeling in bubbly flows. Currently we are carrying out two-fluid LES under the same conditions as the DNS of bubble swarm motion in quiescent liquid for comparisons and validation. Constitutive equations, where not only SGS stresses but also boundary conditions of the pressure and the vorticity on the interface are taken into account, are derived for the LES. The energy spectrum obtained by the present bubbly flow model reproduces the DNS result well. In contrast, the result by the conventional model, where the SGS stress and the boundary conditions on the interface are neglected, shows considerable differences relative to the DNS one.

The development of SGS models for conducting LES in bubbly flows is a topic of considerable interest and still an open problem. Conducting DNS on simpler bubbly flows including the essential physics is a very useful tool in aiding this development.

Drag and Lift Forces Acting on Bubbles

Akio Tomiyama
Faculty of Engineering, Kobe University
Rokkodai, Nada, Kobe 657-8501
Japan

Drag and lift forces acting on single bubbles are of fundamental importance in modeling gas-liquid two-phase flow phenomena. Even after several decades' efforts, our knowledge on them is still rudimentary due to the presence of time-dependent gas-liquid interfaces and the nonlinearity intrinsic to fluid motion. As an example, it has been believed that the balance between the drag and buoyancy forces uniquely determines the terminal velocity of a single bubble in stagnant liquid. However, it has emerged out of recent experimental works [5], [6] that one can easily obtain various terminal velocities and shapes just by slightly changing the way of bubble release. It has been also pointed out that the instantaneous bubble shape uniquely determines the instantaneous rise velocity of a bubble in a low viscosity system [5]. Though a single bubble is a trifle entity in practical bubbly flow systems, the presence of multiple states in terminal velocity and shape might be one of the dominant sources of the diversity in bubbly flow. Physical explanation of multiple terminal conditions, therefore, has to be made in the near future.

The same applies to the lift force, which plays a significant role in the transverse motion of a bubble. Due to the highly complex nature of the lift force, most of the research on it has been restricted to the simplest case, i.e., the lift force acting on a bubble in a simple shear flow. According to a semi-theoretical model for a spherical bubble [7], the lift coefficient C_L increases up to more than 10 as the bubble Reynolds number decreases. On the other hand, measured data showed an opposite tendency [8]. It is recently confirmed by our recent experiments that the cause of this discrepancy is the bubble shape, that is, a slight departure from spherical bubble shape results in a large difference from C_L of a spherical bubble.

The aforementioned two examples clearly demonstrate that the time-dependent bubble shapes and nonlinearity would cause the diversity even for the motion of a single bubble in a simple flow condition. Despite the fact that the problems with respect to single bubbles and drops are old, it is also true that they are still open to question due to the diversity.

Two-Phase Flow in Microchannels

Masahiro Kawaji
University of Toronto
200 College Street
Toronto, Ontario M5S 3E4
Canada

Microchannels with 1 ~ 200 μm diameters embedded in thin plastic and glass plates or silicon wafers are used in lab-on-a-chip devices, micro-reactors, Micro Total Analysis Systems (μTAS), MEMS, micro-heat exchangers, and so on. Many novel applications are being developed, e.g., insulin delivery by atomization, sperm selection, and various types of sensors and analytical systems for use in biomedical engineering, health care, chemical production, environmental analyses, among others. It is a new field that bridges the gap between the conventional technology and nanotechnology. Fortunately, our current knowledge of transport phenomena and reaction engineering is applicable to microchannels, however, some new physico-chemical phenomena need to be better understood including the effects of an Electric Double Layer, wall roughness, and greater heat dissipation in channel walls. In addition, microchannel flows are predominantly laminar for both phases, lack mixing which may be both problematic and advantageous.

At the First International Conference on Microchannels and Minichannels held in Rochester, NY, in April, 2003, 185 participants came from around the world. There were more than 100 papers presented that covered adiabatic two-phase flow, boiling, condensation, micro heat exchangers, microfluidics, and device fabrication. The activity level is high, and more papers are expected at the next Conference in 2004.

The challenges facing the microfluidics and microchannel two-phase flow research include the development of microscale devices such as pumps, valves, heat exchangers, as well as new measurement principles, sensors and control devices. Due to the small size, many conventional technologies are not directly applicable, and new methods based on optical and microfabrication techniques need to be fully utilized. For gas-liquid two-phase flow studies in microchannels, measurement of extremely low gas and liquid flow rates is challenging, and for heat transfer studies, measurements of local fluid and channel wall temperatures and heat flux require advanced instrumentation. The effects of surface wettability and fluid properties on two-phase flow characteristics as well as flow rate distributions in micro heat exchangers, thermal and hydraulic aspects of PEM fuel cells with small flow channels are additional topics that need to be investigated in connection with the microchannels.

References

[1] Hanratty T.J., Theofanous T., Delhaye J.M., Eaton J., McLaughlin J., Prosperetti A., Sundaresan S., Tryggvason G. (2003) Workshop on scientific issues in multiphase flow. Workshop findings. International Journal of Multiphase Flows, Vol. 29(7), p. 1047-1059, 2003.

[2] Theofanous T.G. and T.J. Hanraty (2003). "Appendix 1: Report of study group on flow regimes in multifluid flow", International Journal of Multiphase Flows, Vol. 29(7), p.1061-1068, 2003

[3] Theofanous, T.G., T.N. Dinh, J.P. Tu, and A.T. Dinh (2002). "The Boiling Crisis Phenomenon – Part 1: Nucleation and Nucleate Boiling Heat Transfer", V.26 (6-7), pp.775-792. Part 2: Dryout Dynamics and Burnout", J. Experimental Thermal and Fluid Science, V.26 (6-7), pp.793-810.

[4] Theofanous, T.G., R.R. Nourgaliev, and T.N. Dinh (2004). "Compressible Multi-Hydrodynamics: Emergent Needs, Approaches and Status", IUTAM Symposium "Computational Approaches to Disperse Multiphase Flow".

[5] A. Tomiyama, G. P. Celata, S. Hosokawa and S. Yoshida, "Terminal velocity of single bubbles in surface tension force dominant regime", Int. J. Multiphase Flow, 28, 1497 (2002).

[6] M. Wu and M. Gharib, "Experimental studies on the shape and path of small air bubbles rising in clean water", Phys. Fluids, 14, L49 (2002).

[7] D. Legendre and J. Magnaudet, "The lift force on a spherical bubble in a viscous linear shear flow", J. Fluid Mech., 368, 81 (1998).

[8] A. Tomiyama, H. Tamai, I. Zun and S. Hosokawa, "Transverse migration of single bubbles in simple shear flows, Chemical Engineering and Science, 57, 1849 (2002).