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Appendix 1: Report of study group on flow regimes in multifluid flow ☆

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Abstract

Pattern formation is identified as the principal scientific issue permeating essentially every aspect of multifluid flow. An overall strategy for addressing the issue is proposed, and subsidiary scientific issues of high priority are identified. This summary is written in the spirit that it will be read in conjunction with the study group member contributions identified by the list of references.

Keywords: Flow regime; Pattern; Phase distribution; Regime transition; Multifluid flow

1. Introduction

In a multifluid system, the interfaces are free to deform, break up, or coalesce. While topologically unconstrained, we find that under the influence of the relevant forces such systems tend to self-organize into spatial/temporal patterns, defined by fluid distributions and length scales. Since much of the behavior depends on these patterns, their prediction is the overriding scientific goal in pursuit of our subject. Unfortunately it is a goal that remains largely unfulfilled, despite intense investigations beginning over half a century ago.

There is an opportunity that, if taken, will prevent a similar kind of statement being made 50 years from now. The opportunity is created by tremendous advances made in infrastructure crucial to the task—instrumentation from nano and micro technologies, materials science, digital

☆ Members of the Study Group on Flow Regimes in the Workshop on Scientific Issues in Multiphase Flow (7–9 May 2002, Champaign-Urbana, IL) are Theo Theofanous (chair), Thomas J. Hanratty (co-chair), Jean-Marc Delhaye, Geoffrey Hewitt, Mamoru Ishii, Daniel D. Joseph, Richard T. Lahey, Jr., Andrea Prosperetti, Akimi Serizawa.

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technologies, numerical simulations capability (that result from leveraging clever schemes with hardware speed and capacity). However, the opportunity will escape us unless we see the task for what it is—an issue of complexity—and unless we take steps to approach it accordingly. This would involve searching, discovering, and verifying conclusively the "laws" (or organizing principles) that govern these patterns.

It is suggested that this challenging task will require a highly collaborative atmosphere that has to be anchored in experimentation. Our interpretation of experimental results should involve theory and simulations of all kinds, from molecular dynamics, to DNS, to effective field (EF) models, and ultimately to true multiscale treatments. The aim should be understanding the key physics behind the phenomena being studied. The necessary discoveries cannot be a priori guaranteed. Thus we need to allow patience with others' efforts and to have an attitude that is more collaborative and less exclusive. This may also require some structural changes by the sponsors (of research) to catalyze and promote synergisms and collaborations.

With this perspective, the individual contributions of the Task Group must be considered only as indicative; that is, we want to emphasize the goal and the process (the way of doing), rather than the specifics. The contributions are highly complementary. Hanratty (in press), Joseph (in press) and Prosperetti (in press) address mechanisms and criteria for regime transitions in fully-developed, steady-state, adiabatic pipe flows. Serizawa and Tomiyama (in press) and Lahey and Drew (in press) address the detailed characteristics of bubbly flows. Theofanous and Dinh (in press) bring out the importance of mixing flows and suggest that these, as well as disperse flows, could be viewed as the canonical components in a multiscale treatment that is focused to understand self-organization in multifluid systems. Ishii and Kim (in press) discusses interfacial area transport within a multifield formulation and Lahey and Drew (in press) consider a constitutive treatment of forces as a way of distributing the phases within a multifield model. These two approaches are complementary since the basic source terms for the formation of interfacial area density are also the source terms for the field-to-field exchanges which may, in turn, lead to flow regime transitions. Significantly, these sources must be developed from an understanding of microphysical phenomena. The above summary could suggest that there is no uniformity of opinion; actually there are considerable synergisms and complementarities, as discussed below.

2. An overall view

The overall organization indicated in Fig. 1 emerged. Each of the three rectangular boxes indicates the scope of a particular (broad) domain of investigation. Again, the aim within each of these domains is to determine the physics (laws) that govern self-organization and, by implication, transitions. At the center are the enabling tools, that is, instrumentation and dynamic numerical simulations software. The instrumentation is critical to reveal patterns and the numerical simulations are essential in interpreting what is revealed by the experiments. They are centrally positioned because what is learned in one context is available for use in another. The double arrows suggest the important interplay between specific analytic activities (scaling laws, theory, simple ad hoc models) and the numerical simulation task. As mentioned above, these central tasks include any kind of simulation tool that exists or could be developed and fruitfully applied.

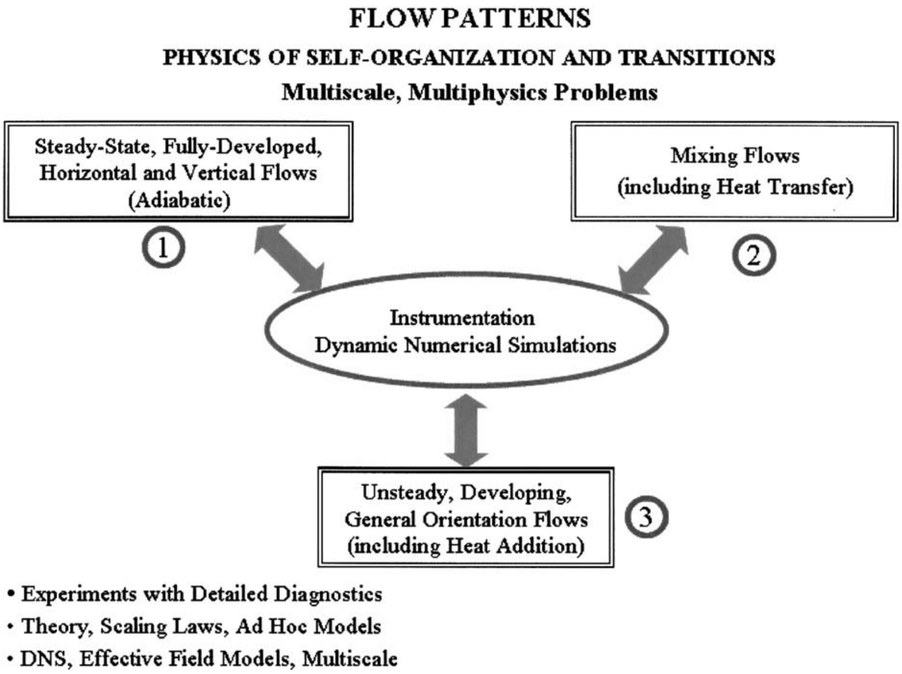

Fig. 1. Key elements of an overall strategy.

The numbers indicate the order of priority. On one hand, steady, fully-developed adiabatic pipe flows are the cornerstone whose understanding is overdue. Besides being very important for practice in their own right, they also provide the simplest possible anchor for developing and testing numerical simulation tools. Moreover, we can expect that what is learned (by such simulations) could substantially aid the discovery of the organizing principles being sought. Simple mixing flows are the other important cornerstone to develop. Besides being practically important, these need to be understood before anything more complex, such as unsteady, developing flows in complex geometries can be addressed in a sound fundamental way. Since the prediction of such complex flows (Box 3 in Fig. 1) requires a panoply of dynamic simulation tools, it is suggested that developments and applications in all three areas are mutually beneficial and are indispensable features of an overall "integrative" approach.

The remaining three sections of this report discuss in slightly greater detail what is contained in the two basic thrusts (the two top Boxes in Fig. 1) and the enabling central thrust. The presentation is for the most general case of gas–liquid flows that can include phase changes due to heat transfer (boiling, condensation). However, the analogous and important case of liquid–liquid systems should also be kept in mind. Detailed discussions are found in contributions by different members of this Study Group that are identified in the last paragraph of the Section 1.

3. Steady, fully-developed, adiabatic flows

An overall view of steady, fully-developed adiabatic flows is depicted in Fig. 2. The top line gives a classification that is simplified by first considering dispersed and separated flows. The latter

STEADY-STATE, FULLY-DEVELOPED, ADIABATIC FLOWS

	Dispersed	Stratified	Annular	Intermittent
Horizontal	D	B	A	B
Vertical	C, D		A	C
Inclined	D	B	A	B

A. **Phase distribution**. Drop entrainment and deposition? Film shear/waves and redistribution mechanisms? Drop dynamics and gas turbulence?

B. **Slug Formation and Dynamics**. Interfacial shear and holdup? Mechanism of formation and sustenance? Linear or Non-Linear behavior? Role of viscosity? Surfactants and drag-reducing polymers?

C. **Transition from Dispersed to Intermittent**. Gradual coalescence. Limits of slug flow with channel diameter? Using dynamic response for identification of mechanisms?

D. **Phase Distribution in Bubbly Flow**. Coping with many types interactions generically?

Fig. 2. An overview of Element 1 in Fig. 1 and related issues.

can be either (gravity) stratified or annular. Clearly there are in-between patterns. The most important of these are intermittent flows that exhibit temporally varying large scale structures. Examples are slugs (in horizontal/near horizontal or in small diameter vertical pipes) and gas/vapor-dispersed subregions (churning) in large diameter vertical flows. A key aspect of the topology is the extent of the continuity of the gas/vapor flow path, which defines the degree of coupling between the gas/vapor (which normally has a much higher volumetric throughput) and the liquid streams. The two extremes, in this viewpoint, are dispersed and separated; the intermittent is transitional. By dispersed, we mean both bubbly and droplet flows, although it should be noted that the vapor core of annular flows normally contains drops.

3.1. Phase distribution in annular flow

Annular flows are especially important in power equipment, where a first order problem is the prediction of the fraction of liquid that flows as a film along the wall. In horizontal flows, we also need to be concerned about gravity-induced asymmetries in the local film thickness and flow rate. Dryout of this film defines a point of markedly lower heat transfer coefficients and, possibly, burnout. As Hanratty's (in press) summary indicates, we have a reasonably good qualitative understanding of the phenomena, but the quantitative treatment remains empirical. Furthermore, the data base is insufficient to claim a good understanding of the scaling laws. The treatment of annular flows mainly considers interfacial shear, and rates of entrainment of drops and deposition (which in steady, fully developed flow are the same). We do not know how entrainment occurs under varying flow conditions and fluid properties. We do not know the origin and extent of validity of the concept of a minimum film thickness, below which entrainment ceases. We do not know the effect of a wall heat flux on the entrainment and deposition processes. We do not understand the wispy annular flow for which agglomerative structures develop in the entrained droplet field at high liquid flows. Finally, we do not know how annular flow arises from stratified or intermittent flows, and we certainly do not have a numerical simulation that is capable of predicting this transition.

3.2. Slug formation and dynamics

The starting point for a consideration of slug formation is usually a stratified flow. A key need is the prediction of interfacial friction since it controls the liquid holdup and, therefore, the base flow for slug development. While some success has been realized by using descriptive approaches, a first-principles understanding of how waves grow to become slugs and how slugs sustain themselves is still lacking. Initial efforts that use linear stability theory need to be complemented by a consideration of non-linear effects in the framework of bifurcation theory (Joseph, in press), and by special purpose numerical simulations (Theofanous and Dinh, in press). The interesting effects of liquid viscosity, gas density and surface tension could help discriminate among approaches.

3.3. Transition from disperse to intermittent flow

As gas velocity in a vertical disperse pattern increases the two-phase flow needs to "expand", so as to provide a degree of gas-continuity in the flow path that is needed for "venting". In small pipes this gives rise to rapidly-moving slugs of liquid. In large diameter pipes, or vessels, we have something akin to channeling which, being unsteady, gives the appearance of churning. The idea that this occurs by gradual coalescence of bubbles is addressed by Ishii and Kim (in press) within the context of his interfacial area transport formulation. Prosperetti (in press) suggests other kinds of dynamic mechanisms and special experiments, with dynamically varying flows at the inlet, as a way of discriminating. Actually, before any real progress can be made, we need to carefully characterize the patterns by measured properties of the flow. In view of the need to use large scale equipment, the complexity of the patterns, and the inherently opaque setting, this is a major challenge.

3.4. Phase distributions in bubbly flow

Bubbly flow is the most extensively studied regime. Two different perspectives emerge at this time, and it is very important that they be reconciled. On one hand, Lahey and Drew (in press) present a fully-defined multifluid, multiphase CFD model for fully developed monodisperse flows that is shown to predict all key internal ingredients of bubbly flows, including complex geometries, such as wedge-shaped channels. On the other hand, Serizawa and Tomiyama (in press) present a comprehensive experimental study that makes evident the variability and sensitivity of such flows to entry conditions. They conclude that a proper description would require a consideration of many types of interactions, as well as a careful specification of how the bubbles are formed at the inlet. Lahey suggests that these types of interactions may be accommodated within the structure of a multifield, multifluid model. However this remains to be demonstrated.

4. Mixing flows

Mixing flows are the opposite of fully-developed flows, in that one is concerned with the very early stages of creating new multifluid/dispersed topologies. As indicated in Fig. 3, a convenient classification is in terms of the direction of mixing relative to the directions of the mean flows involved in the mixing process. The topological changes of interest occur over relatively sharp spatial regions. Theofanous and Dinh (in press) refer to them as large scale discontinuities (LSDs). When the mean flows are normal to LSDs, these surfaces (that demarcate the mixing fronts) sweep into the parent flows. When the mean flows are parallel, the LSDs may be steady, as in annular flow, or may sweep into the parent flow, as in flow boiling. Furthermore, the LSDs may be in effect stationary, as in pool or flow boiling, or they may be free to move, as in slug flow or mixing jets (both in parallel as well as in cross flow).

Although not previously seen as such, classical examples of mixing flows are pool and flow boiling, and annular flow. The creations of topological changes along the LSDs constitute scientific problems of great importance for the basic understanding of these flows. Shock-induced mixing flows are a relatively new topic of interest. They occur in inertial confinement fusion (ICF), internal combustion engines (ICE), and liquid-fuel detonation engines (LFDE). The latter two are concerned with the shattering of fuel drops, and their mixing and reacting with a gaseous oxidant. Among many examples of an engineered mixing device an example is the jet atomizer discussed by

MIXING FLOWS

Generic Issue: Transition from the interface to two-phase regions? Local topological changes – Length scales? Velocities? Definition of the "interfacial region" (or Large Scale Discontinuity, LSD) that demarcates rheologically homogeneous regions (single phases, gas-dispersed, liquid-dispersed, etc.)

Mixing Flows Normal to LSD

- **Pool Boiling (CHF). Scale separation characterization (Theofanous et al., 2002a,b)**
- **Shock- and/or acceleration-induced mixing (ICF, ICE, LFDE).**
- **Bubble columns**

Mixing (or Demixing) Flows Parallel to LSD

- **Droplet entrainment (Annular Flow, Film Dryout, Breakup of Jets)**
- **Droplet deposition (Annular Flow, Film Dryout)**
- **Flow Boiling (DNB)**

Mixing of Cross Flows

- **Jets into cross flow**
- **Engineered mixing devices and complex geometries**

Fig. 3. An overview of the issues for Element 2 in Fig. 1.

Reitz (in press) in his contribution to the Workshop's Microphysics Thrust. Another important case, where mixing phenomena are crucial, is in three-phase liquid–liquid–gas flows. These occur in hydrocarbon recovery where oil–water–natural gas mixtures flow for long distances in pipelines. Mixing of the liquid phases can form emulsions with very high viscosity, that restrict the flow through a pipe. A related problem is phase inversion where there is a changeover of the continuous phase.

The central issues in all of these flows are the definitions of the rate and length scale of mixing, the evolution of topological changes, and descriptions of transitions from the LSDs to the main flow regions that would be amenable to an EF treatment. Again, while many tools are needed to understand and describe the flow patterns, special attention needs to be paid to interfacing such LSD-related behaviors to appropriate EF computational frameworks.

5. Simulations: approaches and issues

Our view of the role of simulations in the overall task of discovering the physics of self-organization in multifluid flows has been described above. Here, we would like to emphasize the following:

(a) The one-suit-fits-all idea, as embodied in the two-fluid model, is not compatible with the level of complexity of the task.
(b) It is not a priori clear how to do simulations that are consistent with the physics in a reasonably general way, and at a scale that is relevant practically.

As a result, we suggest that the development of appropriate simulations is a scientific undertaking of major significance that is on par with experiments. This view is consistent with the conclusions of the Thrust Group on Computational Physics, who discuss the data mining necessary to capitalize on DNS for developing constitutive laws and gaining ideas about the (small scale) organization of the phases. Further, both the Computational Physics and the disperse flow thrusts address, in considerable depth, issues that arise in the EF framework for disperse flow simulations. Here, we only need to stress the need to simulate other (than disperse) regimes.

One approach is to capture patterns and transitions via a local application of constitutive laws within an EF (two-fluid model) framework (Lahey and Drew, in press; Ishii and Kim, in press). Ishii and Kim (in press) developed constitutive equations for coalescence and breakup events and used them to calculate interfacial area transport. Lahey and Drew (in press) propose the ensemble averaging of flow-regime-specific DNS results to help describe forces within the multi-field, multifluid model interactions that avoid the need for a separate interfacial area transport equation. Another approach is to track LSD by matching the flows on either side in a general 3D framework (Theofanous and Dinh, in press). This approach builds on the disperse flow formalisms and requires constitutive laws on the LSDs.

The stratified-to-slug transition in horizontal flows would make an ideal case to test these ideas and would contribute to the experimental and analytical efforts described in Section 3.

6. Concluding remarks

We believe it is important to emphasize again the role of experiments, pattern-revealing diagnostics, and pattern recognition software. The hardware includes instrumentation such as X-ray and neutron tomography, nuclear magnetic resonance imaging, high-speed infrared thermometry, UV (laser)-induced fluorescence. Pattern recognition software includes artificial intelligence methods such as neural networks, genetic algorithms, and Bayesian-based image processing techniques. However, without proper flow facilities, these techniques cannot be utilized. The availability of such facilities must be considered an integral part of the research needs in this area.

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