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Workshop Findings

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Abstract

This report outlines scientific issues whose resolution will help advance and define the field of multiphase flow. It presents the findings of four study groups and of a workshop sponsored by the Program on Engineering Physics of the Department of Energy.

The reason why multiphase flows are much more difficult to analyze than single phase flows is that the phases assume a large number of complicated configurations. Therefore, it should not be surprising that the understanding of why the phases configure in a certain way is the principal scientific issue. Research is needed which identifies the microphysics controlling the organization of the phases, which develops physical models for the resultant multiscale interactions and which tests their validity in integrative experiments/theories that look at the behavior of a system. New experimental techniques and recently developed direct numerical simulations will play important roles in this endeavor. In gas–liquid flows a top priority is to develop an understanding of why the liquid phase in quasi-fully-developed pipe flow changes from one configuration to another. Mixing flows offer a more complicated situation in which several patterns can exist at the same time. They introduce new physical challenges. A second priority is to provide a quantitative description of the phase distribution for selected fully developed flows and for simple mixing flows (that could include heat transfer and phase change). Microphysical problems of interest are identified—including the coupling of molecular and macroscopic behavior that can be observed in many situations and the formation/destruction of interfaces in the coalescence/breakup of drops and bubbles.

Solid–fluid flows offer a simpler system in that interfaces are not changing. However, a variety of patterns exist, that depend on the properties of the particles, their concentration and the Reynolds number characterizing the relative velocity. A top priority is the development of a physical understanding of inertial instabilities which give rise to structural features that have a large range of scales. Important microphysical problems are the understanding of particle/particle interactions, particle/boundary interactions that include the effect of wall roughness, and the influence of particles on fluid turbulence. These behaviors can differ depending on the characteristics of the particles, their size distribution and their concentration. For large concentrations, such as exist in granular flows, instabilities associated with particle–particle

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interactions often cause separations in systems which are not homogeneous. These instabilities are not well understood.

Appropriate averaged equations could provide a way to use an understanding of the microphysics obtained in simple systems to describe more complicated flows. The formulation of these equations presents physical challenges since the structure of the phase distribution could affect the choice of averaging methods and closure relations. Universal computational approaches appear to be out of reach at present.

Keywords: Multiphase flow; Scientific issues; Workshop; Gas–liquid flows; Disperse flow; Computational physics; Microphysics

1. A road map for scientific understanding of multiphase flow

A physical understanding of flows in which more than one phase is involved offers problems of far greater complexity than encountered with single-phase flows. The reasons are that the phases do not uniformly mix and that small-scale interactions between the phases can have profound effects on the macroscopic properties of the flow. Our ability to predict the behavior of these flows is a limiting factor in scaling, in analyzing heat transfer systems, in developing new technologies, in analyzing chemical reactors and in avoiding and managing accidents. Scientific advances would have an impact on interests of the Department of Energy, such as high-power electronics, combustion, power systems, global warming, nuclear and chemical waste cleanup, solids handling, and transportation of petroleum products.

Considerable progress has been made in recent years in the development of instrumentation, in the use of direct numerical simulations, in the understanding of small-scale physics and in the development of computational tools that have the possibility of describing the behavior of complex systems. An opportunity now exists to capitalize on this progress by addressing the problem itself: multiphase flow behavior. This realization motivated the organization of a workshop to define the basic scientific problems whose solution would have a major impact on developing the field of multiphase flows.

An outcome of the deliberations from this workshop is the development of a road map for basic research. The starting point and, perhaps, the most important scientific issue is to understand the complexity that characterizes multiphase flows. This would involve a description of how the phases organize in space and how this organization is related to the microphysics. A number of configurations can be realized for a given system, depending on operating conditions such as the flow rates and the physical properties of the phases. The tasks, then, are to predict changes of the configuration and to develop a quantitative understanding of how the phases distribute for a given configuration.

The solution of this problem involves the discovery of the small-scale interactions between the phases which are controlling their distribution in space, studies of these interactions in carefully controlled laboratory experiments or direct numerical simulations, the development of physical models, and the testing of these models in integrative experiments.

Experimental studies present a number of difficulties because probes can interfere with the flow and because multiphase systems can be optically opaque. Major efforts to develop and deploy new instrumentation would be most useful. Techniques of interest are small angle scattering, X-ray and neutron tomography, nuclear magnetic resonance imagery, high-speed infrared thermometry, various microprobes, UV laser-induced fluorescence. Pattern recognition software includes the application of artificial intelligence methods such as neural networks, genetic algorithms and Bayesian-based image processing techniques. However, of equal importance is the availability of well designed and operated flow facilities that can investigate a range of equipment sizes, flow conditions and fluid properties.

One goal is the development of equations (analogous to the Navier Stokes equations for single phase flows) that can describe the organization of the phases both in simple and in complex situations. The basic equations of fluid dynamics, the equations of motion of particles or of bubbles, and the equations of interfacial dynamics are applicable. However, for most engineering systems, solving these equations will be impractical for the foreseeable future and their use will be limited to scientific studies. Therefore, one must employ equations which describe the behavior of a system in an average sense. The development of averaged equations, which use the correct microphysics in the required closure laws, is a central problem.

The approach outlined above would seem to be obvious since it simply acknowledges that the first-order problem is to understand the complexity that makes the analysis of multiphase systems so difficult. Yet, the scientific community has not given this issue the attention it deserves. For example: The flow regimes observed for gas and liquid flowing in a long pipeline were identified over 40 years ago, and empirical correlations of such quantities as the pressure drop and liquid holdup have been found to be more successful if they are tailored to a particular regime. However, validated physically based models that describe the transition from one regime to another are not available. Here, validation implies the direct verification of the postulated physical mechanisms and the testing of the predictions over a wide range of conditions.

A dramatic example of how large-scale phenomena are controlled by small-scale physics is the sensitivity of the behavior of a dense fluidized bed to the properties of the particles and to the polydispersity of the particles. Another is the change of an annular flow in a horizontal pipe to a stratified flow through the addition of very small amounts of drag-reducing polymers (Al-Sarkhi and Hanratty, 2001). The annular pattern is observed in gas–liquid flows at large gas velocities. Part of the liquid flows along the wall as a film and the rest as drops entrained in the gas. The additives destroy disturbance waves on the wall film. Because of this, atomization ceases and the ability of the wall film to climb around the circumference is diminished.

2. Dilute disperse flows

2.1. Phase configurations

Disperse flows of solid particles, bubbles and drops are central to the analysis of multiphase flows in that they are often used as a prototype for developing general computational approaches. They are found in nature and technology (sand and rain storms, coal combustors, paint sprays, cyclone separators, liquid fuel combustors, chemical reactors, grain conveying). The goals of theoretical analyses include the prediction of the particle distribution in space, local volume fractions of the dispersed phase, the relative velocities of the phases, particle turbulence, fluid turbulence, and deposition rates. The motion of the particles is controlled or strongly affected by the relative motion of the phases. The idealized picture of uniformly dispersed spheres, which are interacting with one another, is rarely realized. For example, the solids can often distribute close to the wall in an upwardly flowing gas–solid mixture. Such distributions of the solids are a serious consideration in the operation of catalytic reactors, since the efficiency of the contacting is affected.

When the relative motion is large enough, inertial instabilities can give rise to mesoscale structures (Agrawal et al., 2001). This behavior is manifested by the appearance of clusters of particles or bubbles (Serizawa and Tomiyama, in press). Under some circumstances the particles can assume large-scale turbulent motions that do not appear to reflect directly the turbulence patterns in the fluid.

For the cases of dispersed drops and bubbles additional complications arise because the interface between the fluid and the particles can change due to deformation, breakup and coalescence. The interfacial area density (that is, the area per unit volume) is an important variable that captures some of these effects (Kocamustafagullari and Ishii, 1995; Delhaye, 2001). However, other characteristics such as drop or bubble size distribution also need to be considered.

The understanding of the spatial distribution of the particles, the formation of large-scale structures and the evolution of the interfacial configuration in fluid–fluid flows become central issues. This understanding requires the identification/study of the controlling microphysics and the development of a theoretical framework to describe the observed behavior. Some progress has been made in this direction. However, in many situations (particularly, in complex flows) the organizing principles have not yet been discovered.

The above discussions have focused mainly on the effect of the fluid on the particles. However, the particles can cause increases or decreases (Kulick et al., 1994; Hetsroni, 1989) in the fluid turbulence, even at very small concentrations. A complete understanding of these effects is not available.

2.2. Particle tracking

Much progress has been made on the analysis of dilute particle laden flows by studying the trajectories of a large number of particles that are introduced into a direct numerical, or large eddy, simulation of a turbulent flow. When the interaction of particles and the influence of particles on the fluid turbulence are not taken into account the results essentially represent possible trajectories of small single particles. Changes of fluid turbulence have been calculated by back momentum coupling through a point-force approximation.

Invariably these methods assume the particle Reynolds number is small, that the particle size is less than the smallest turbulent scale and that drag laws in non-turbulent fluids can be used. However, in many contexts these conditions are not satisfied and it is important to have a better understanding of fluid–particle and particle–particle interactions when this is the case. Hydrodynamic and collisional interactions of particles can become important at volume fractions as small as 10^{-4} so that one needs to be cautious when neglecting their effect. More work is warranted to use the particle tracking approach to study the basic physics and, in particular, to understand the effects of particle–particle interactions on the spatial distribution of the particles. The development of an improved understanding of the physics of particle–wall interactions (that includes the effect of wall roughness), of particle–particle interactions, and of the effect of particles on the fluid turbulence emerge as major scientific problems that need to be addressed further.

The performance of particle tracking studies in a turbulent field that is generated by a direct numerical solution of the Navier Stokes equations has the disadvantage that the size of the computations can be prohibitive if a large range of variables needs to be explored. Furthermore, the calculations are limited to small Reynolds numbers and to simple flows. An alternate approach is to use large eddy simulations to represent the fluid field. Perhaps, the simplest approach is to develop a stochastic model for the turbulence seen by the particles that takes account of the effect of the particles on the turbulence in an average sense. This approach has not been used with great confidence because direct testing of the stochastic models has not received enough attention. However, the possibility of comparing them with direct simulations or detailed experiments provides motivation for more work in this direction.

2.3. Eulerian methods

Ultimately, Eulerian methods need to be developed if practical calculations are to be carried out. Impressive progress has been made in recent years by using methods outlined in Section 2.2 to simulate the behavior of disperse flow. One of the more advanced calculations is a direct numerical simulation of sedimenting particles in a non-turbulent fluid in which the drag of the fluid on the solid particles is not modeled but determined from the calculated velocity field of the fluid (Hu et al., 2001). Comparable simulations have been done for disperse bubbly flows (Bunner and Tryggvason, 2002). Not enough has been done to use numerical experiments such as these to develop the physics needed to carry out Eulerian calculations.

As indicated in Section 1, Eulerian methods, necessarily, involve the development and use of appropriately averaged momentum, mass, and mechanical energy equations. One of the more popular approaches is the "two-fluid" model which implies two interpenetrating streams. The development of these equations and the specification of closure relations continue to offer a theoretical challenge (Prosperetti, in press).

However, for fully developed flows, a simpler approach that directly relates the distribution of the dispersed phase to the microphysics is of interest, particularly in identifying the controlling physics. For example, consider a horizontal disperse flow of drops or solids in a channel—such as observed in the core of a gas–liquid annular flow. A theory for the spatial variation of the concentration of drops could be developed by equating the diffusion velocity, $= -\varepsilon \, \mathrm{d}c/\mathrm{d}y$, to fluxes associated with gravitational settling, turbophoresis, forces due to particle–particle interactions and forces due to the existence of mean velocity gradients. In dilute disperse flows the deposition constant is mainly defined by the "free-flight" flux to the wall and the gravitational settling. Models are needed for these different fluxes, for the relation of the particle turbulence to the fluid turbulence, and for free-flight deposition.

3. Gas–liquid flow regimes

3.1. A problem in complexity

In a general multifluid system, the interfaces are free to deform, break up, or coalesce. While topologically unconstrained, the forces in such systems cause a self-organization into spatio/

temporal patterns, defined by fluid distributions and physical phenomena that are observed over a large range of length scales. Since the behavior of these systems depends on the pattern, its prediction is the overriding scientific goal. Scientific understanding will be greatly enhanced if we recognize the task as being an issue of complexity that involves the definition of the organizing principles that govern these patterns.

The starting points are studies of quasi-fully-developed adiabatic flow in pipes with different inclinations and of well-defined mixing flows (that can include heat transfer). These flows are important in practice and they are simple systems in which the controlling physics can be studied. The enabling tools are dynamical numerical simulations and appropriate local and global instrumentation that can provide quantitative information about flow patterns.

In the long term it is desirable to use newly acquired physical insights to analyze more complex systems. This will, necessarily, require the development of imaginative computational approaches.

3.2. Quasi-fully-developed flows

Some examples of fully developed adiabatic flows are bubbly (discussed in Appendix 1—Report of study group on flow regimes in multiphase flow), annular, slug, stratified, and churn patterns.

The annular pattern is one for which part of the liquid flows along the wall and the remainder as drops in the gas. It is extremely important (particularly in heat transfer problems) but its description offers a number of physical challenges which include the development of theories for the rate of atomization, the rate of deposition and drop size. At large liquid flows a wispy annular regime occurs in vertical pipes whereby the liquid in the gas core forms agglomeration structures, which are poorly understood. In horizontal flows gravity causes the liquid in the film and the drops in the core to distribute asymmetrically. A quantitative description of these effects is extremely important, particularly in heat transfer applications where one is concerned about dryout of the wall film. Such descriptions are not available because the turbulent processes which oppose the influence of gravity have not been defined.

The slug pattern, which exists in horizontal or near-horizontal applications, is of interest because it can be accompanied by large vibrations in equipment. It is characterized by the intermittent appearance of aerated slugs of liquid that move at velocities that are slightly larger than the gas velocity. (They, therefore, have large momenta.) There is a need to predict when this behavior will occur and the distribution of slug lengths. These, in turn, require an understanding of how slugs are formed and a model for the slug which describes the rate at which liquid is shed and the influence of slug length on stability.

A stratified pattern exists in horizontal pipelines whereby all of the liquid flows along the bottom of the pipe and the gas, cocurrently to it. It would seem to be the simplest pattern. Yet, considerable errors can be made in predicting the liquid holdup, the pressure drop and the liquid flow at which a transition to slug flow occurs. The main reason for this is that sound theories relating the drag of the gas on the liquid to the wave pattern on the interface are not available.

The idealized bubbly flow pattern, observed in vertical pipes, is described in Appendix 1—Report of study group on flow regimes in multifluid flow. As the volume flow of gas increases, coalescence causes the appearance of cap-like bubbles. In relatively small diameter tubes bullet shaped (Taylor) bubbles, which fill the whole tube, are formed. At still larger flows this gives way to a churn pattern. A liquid film exists at the wall. Portions of the film are carried downward by gravity and other portions are carried upward by surface waves. A haphazard flow of the gas–liquid mixture exists over the main part of the pipe cross-section. Churn flow can be different in large diameter pipes or large vessels, where Taylor bubbles are not formed and wall films are not an important consideration. Not enough attention has been given to the churn pattern, particularly when we consider that it usually exists over a wider range of flow conditions than does bubbly flow.

3.3. Flow regime transitions

The development of an improved physical understanding of transitions from one flow regime to another could be the most important problem that needs to be addressed. Success would provide a basis for developing a much needed sound physical theory for predicting flow patterns. It would also establish basic physical laws that define the science of multiphase flow.

Early workers presented maps, with coordinates such as the superficial gas velocity and the superficial liquid velocity to define flow patterns. This empirical approach has failed to produce a general method to predict transitions. Taitel and Dukler (1976) were the first to attempt a general analysis in which physical mechanisms were used. This work has had a strong impact and its predictions are often used—even though they are unreliable because the physics is incorrect or only partially correct.

Some progress has been made in predicting the transition from a stratified flow to a slug flow by considering the stability of a stratified flow and the stability of a slug (Woods and Hanratty, 1996). The main task for completing this analysis is to put together a synthesis of the work that has been done and to test it over a range of conditions.

Unfortunately, our understanding of the transitions amongst other flow regimes is not so well developed.

3.4. New issues introduced in mixing flows

Mixing flows are common in a large number of applications that involve gas–liquid systems. These include jet breakup, developing flows in short pipes, pool boiling, bubble reactors, and inertial-confinement fusion. A general approach to these types of problems is desirable. A starting point is the incorporation of an understanding of the microphysics obtained from studies of quasi-fully-developed flows in pipelines into an appropriate computational scheme. However, additional problems arise that are not seen in fully developed pipe flow. For example, more than one pattern can exist in the same field so one must be able to define local patterns from internal variables.

There is a need to carry out studies of well conceived mixing flows to test the generality of theories developed in pipe flows and to understand new problems that arise in more complex flows. A characteristic of mixing flows is that topological changes can occur over relatively small spatial regions. The understanding of the behavior of these large-scale discontinuities introduces a new element of considerable importance (that needs to be understood) because the behaviors of the flow on the two sides could be qualitatively different. When the mean flow is normal (e.g., in pool boiling, shock-induced mixing, and bubble columns) the discontinuity sweeps into the mean flow and its ensemble-averaged configuration changes with time. When the flows on the two sides are parallel (e.g., annular flow and flow boiling) the ensemble-averaged behavior need not change with time.

Examples of engineering applications where large-scale discontinuities play a role are the shattering of fuel drops in internal combustion engines and liquid-fuel detonation engines, jet atomizers, and the three phase flows (oil–water–natural gas) that occur in long distance hydrocarbon pipelines. In the latter the mixing of the liquid phases can lead to the formation of an emulsion of very high viscosity, which can restrict the flow. A related problem is a phase inversion where the continuous phase in the emulsion changes.

3.5. Numerical experiments

As mentioned in Section 3.3, recent advances in direct numerical simulation offer the opportunity to carry out experimental studies of the microphysics of gas–liquid flow, which are not possible in the laboratory. The development of methods to track interfaces that include the physical processes of coalescence and breakup is particularly exciting. Other studies of interest are wave growth and atomization, vapor occlusion in films, some aspects of nucleate boiling, flow patterns in slugs, solidification, effect of polymer or surfactant additives, and annular flow liquid film dryout at critical heat flux (CHF).

For example, theoretical work on the rate of atomization and on the transition from a stratified flow to a slug flow are, largely, based on linear theory. There is a need to extend this work to include non-linear effects and the possibility of bifurcations. When one considers the stability of a stratified flow in order to predict the initiation of slugging, linear theory cannot tell whether subcritical bifurcations (i.e., multiple stable solutions) will occur. Experiments and numerical simulations are urgently needed to determine the outcome of these instabilities.

3.6. Averaged conservation equations

Section 2.3 has outlined the use of appropriately averaged equations to describe the velocity field in disperse flows. In gas–liquid systems these equations have been mainly developed for bubbly flows. These allow for breakup and coalescence and a change of interfacial area that does not occur in solid–fluid flows. A two-fluid approach is generally employed in which separate averaged equations are used for the gas and the liquid. Some success has been experienced in using these equations to describe the mean properties of a fully developed flow in circular and wedge-shaped conduits (Lahey and Drew, 2001).

The development of universal equations which describe a large range of gas–liquid flow patterns could be an impossible task. It is not the focus of this report. Nevertheless, averaged equations will be useful in demonstrating how models for the microphysics control the phase distribution. These equations will probably need to be tailored to a particular application—so their formulation is a physical challenge.

4. Concentrated solid–fluid systems

4.1. Concentrated 'fluid-like' solid–fluid suspensions

When the particle concentrations become large, such as exist in fluidized beds, granular flows and some slurry flows, the influence of particle–particle interactions (mediated by continuous-phase fluid motion and direct collisions) become important or dominant. Some progress has been made in analyzing these flows by using two simplifying approaches which are based on analogies with the kinetic theory of dense gases but allow for dissipative effects of fluid viscosity and inelastic particle collisions. The theory of "rapid granular flows" neglects all influence of the continuous phase. The theory of "gas–solid suspensions" adds the effect of a low Reynolds number gas. While there are some problems in accounting for particle–particle collisions and for boundary conditions, the major issue in extending these theories is to account for the influence of the continuous phase when the particle Reynolds number is large.

This can result in stronger dissipative effects associated with enhanced dissipation of particle kinetic energy and enhanced dissipation in the fluid due to turbulence. However, the most important and intriguing problem is a consideration of the instabilities associated with the finite Reynolds number (discussed in Section 2.1). This involves a physical understanding of these instabilities, their influence on the formulation of averaged equations, and a theoretical understanding of particle turbulence. The latter provides a challenge both to the theorist and the experimentalist.

The instabilities cover a wide range of scales involving fluctuations with a spatial scale of several particle diameters to spatial scales which are of the same size as the dimensions of the equipment. The analysis of these systems necessarily involves the use of equations which average the small-scale fluctuations (analogous to large eddy simulations used in single phase turbulence). The modeling of the small-scale particle turbulence emerges as a major problem, particularly because instabilities make experiments on the rheology of high Reynolds number suspensions difficult.

In some circumstances, instability leads to the appearance of pockets in the continuous phase, such as observed in dense fluid beds. Then, it is probably advantageous to use two-field equations, which analyze the pockets and fluid–solid suspension separately, and appropriate conditions in the regions separating the two fields.

4.2. Dense 'solid-like' systems

It is important to understand the conditions leading to transition from a fluid-like to a solid-like behavior, where the particles interact through enduring contacts between each other and the boundaries. These transitions are important in granular flows and have been observed in fluidized beds. Primary problems are to understand cohesive interparticle forces, frictional contact between particles, and the stability of the system. Quantitative predictions of the performance of many devices, such as fluidized beds, spouted beds, standpipes, dense phase pneumatic conveying and mixing equipment depend on our knowledge of frictional stresses.

An interesting aspect of this problem is that interparticle forces depend on the shape of the particles, the size distribution and frictional contact. A knowledge of this dependency opens the possibility of manipulating the flow behavior by tailoring particle characteristics. Constitutive models developed in soil mechanics are a good starting point but there is growing evidence that these should be modified to bring in the effect of strain rate fluctuations on the transition between quasi-static and rapid flow regimes.

An important aspect of all these systems is the tendency of granular materials to segregate because of small differences in size, density, surface roughness and shape (Ottino and Khakhar, 2000). This is a complex and imperfectly understood phenomenon of practical importance. To describe segregation we not only need models for the flow but also constitutive models for segregation fluxes under various flow states. An understanding of this issue is relevant to a wide cross-section of industries.

5. Microphysics

5.1. Identification of important microphysics

The relevance of microphysical studies needs to be measured by improvements in our ability to describe large-scale phenomena of interest. Many aspects of the microphysics have been discussed in Sections 2–4. This section gives examples of problems that have not been directly mentioned.

The coupling between molecular and macroscopic phenomena is a feature of many multiphase flows. For example, it is well known that relatively small concentrations of surfactants can promote the breakup of bubbles or drops in turbulent flows. However, there is also experimental evidence that some surfactants have the opposite effect. This coupling is a theme in much of what is presented in this section. This includes nucleate boiling, contact lines, the effects of surface active agents and drag-reducing polymers, microscopic conditions at the point of breakup or coalescence of interfaces.

5.2. Coalescence and breakup

An improved basic understanding of breakup and coalescence of interfaces would have an impact on a number of problems involving fluid–fluid flows. These include the prediction of bubble size and interfacial area per unit volume, drop size distribution, the breakup of liquid jets, the formation of sprays, and the atomization of flowing liquid layers. Direct numerical simulations and innovative experiments can provide information needed to formulate equations that define the rate processes.

An important consideration in developing predictive models is the microscopic conditions at points of breakup and coalescence. Breakup of drops and bubbles involves intermolecular forces acting at micro- or nano-scales. For example, if one considers a highly deformed bubble in a liquid, breakup may occur if a sufficiently thin neck forms between two portions of the bubble. Intermolecular forces between the liquid molecules are an important factor—determining when the neck pinches off and two child bubbles result. The modelling of final aspects of breakup and coalescence is particularly important in computational experiments. However, it is quite possible that instabilities dictate the initiation of breakup and coalescence so that analyses need not go down to the molecular level.

5.3. Altering the behavior of a multiphase system

An area of research that has not been fully exploited is the possibility of altering the behavior of multiphase systems by modifying the microphysics. Examples are the use of structured surfaces in heat transfer, the addition of fines in fluidized beds, the addition of surfactants and drag-reducing polymers. Such studies test our current physical understanding of multiphase flows and suggest technological opportunities.

The influence of surfactants on bubbly flows is an example of how molecular scale processes affect the behavior of multiphase systems (Zhang et al., 2001). They affect the final stages of coalescence and breakup and, therefore, bubble and drop size distributions. They also affect small wavelength waves which are important in understanding interfacial instabilities. Drag-reducing polymers affect both interfacial properties and the bulk flow. Their role in changing annular gas–liquid flows, in modifying the liquid flow and interfacial stresses in stratified gas–liquid flows and increasing the stability of slugs has been discussed in other sections of this report. A theoretical explanation of these results is needed.

5.4. Contact lines

An understanding of the motion of contact lines plays an important role in many aspects of multiphase flow. These include the wetting of the pipe wall in a horizontal gas liquid flow, the stability of dropwise condensation, the behavior of gas cavities and CHF in boiling, and the behavior of liquid films. The motion of contact lines depends on the local environment in ways that are not fully understood. Experiments on rapid condensation of steam onto surfaces with wettability gradients indicate that the motion of drops can be dramatically different from their motion in the absence of condensation (Daniel et al., 2001). Also, it has been speculated that contact line pinning occurs when a moving contact line encounters a geometrical irregularity or a hydrophobic patch (de Gennes, 1985), but this has not been verified.

5.5. Nucleate boiling

In many situations the most difficult part of analyzing a heat transfer problem is the prediction of how the phases distribute, so adiabatic experiments can provide a basis for analysis. An example is burnout caused by the disappearance of the wall film in an annular flow. This is not the case when phase changes alter the boundary condition at the wall. Considerable work has been done on nucleate boiling and on dropwise condensation but major problems need to be resolved involving the prediction of nucleation sites, and of the effects of apparent contact angle and contact line motion on heat flux.

It is well established that nucleate boiling occurs at cavities that contain entrapped gas and that the rate of heat transfer depends on the number of active cavities. Progress has been made in understanding this process but more needs to be done, particularly for situations in which the liquid is flowing. Recent experiments (Theofanous et al., 2002) have shown that nucleate boiling can occur on nanoscopically smooth surfaces. Here, molecular scale surface inhomogeneities may be expected to play an important role. Clearly, the relation of nucleation and resistance to burnout to the surface characteristics needs much deeper consideration. Also studies aimed at understanding the role of surfactants in enhancing nucleate boiling (Hetsroni et al., 2001) could be rewarding.

5.6. Heat transfer in microchannels

Networks of microchannels with hydraulic diameters in the 100 μm to 1 mm range have the capability for sustaining very large transport rates in small volumes. Consequently they are becoming increasingly important. They are characterized by large effects of surface tension, of surface wetting and of contact line movement. Inertia cannot be ignored. Surprisingly, many aspects of the flow patterns are similar to those observed in macroflows. However, quantitative descriptions of the behavior are not available. For example, it would be of interest to extend our understanding of annular flow in macroflows to microflows—and, in particular, to predict liquid film dryout (i.e., CHF). Because the small channel size could alter bubble growth, it would be expected that flow boiling could be quite different from what is observed in macroflows.

6. Closure

The central issue in multiphase flow is the understanding of the mechanisms and processes which determine the spatio-temporal distribution of the phases. Successes in meeting this challenge would have an immense impact on engineering practice and, indeed, the world's economy.

As emphasized in this report, reaching this understanding requires an integration of progress made on sub-problems, such as the behavior of particles in a turbulent field, bubble dynamics, interfacial phenomena, phase change, breakup and formation of new interfaces, boundary effects, granular flows, contact line motion, nucleation, and many others. Progress can be expected to be much swifter than in the past, given the availability of better experimental techniques (e.g., X-ray tomography, infrared photography, atomic-force microscopy), more powerful computational capabilities (e.g., parallel computers, larger memory, modern algorithms), and a deeper theoretical understanding (e.g., multiscale integration, non-linear analysis).

A feeling, broadly shared by the Workshop participants, was that the best way to proceed is to promote an understanding of the basic physics of multiphase flows. In other words, the emphasis of research in this area should change from a strictly engineering viewpoint (which has had limited success in developing general approaches) to a science-oriented one. Coupled with the remarkably powerful new experimental and computational tools that are now available, this shift of emphasis promises major advances in a relatively short time.

Progress would be further accelerated if a focused research effort could be promoted. The contemporary research enterprise is inherently complex and expensive. Encouraging researchers from different institutions to pool resources and expertise would ultimately benefit the entire community. The fostering of medium to large-scale collaborative efforts, that includes joint mentoring of students, would greatly benefit the discipline of multiphase flow.

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