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SCIENTIFIC ISSUES IN THE FLOW OF GASES WITH DISPERSED SOLIDS

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Abstract. This brief document contains suggestions for scientific issues to be studied in flows of gases and dispersed solids. It begins by enunciating principles that the US Department of Energy may consider for its funding of fundamental research in this area. It then provides a partial list of general topics that continue to challenge our basic understanding.

1. PREAMBLE

Fundamental research combines theoretical development, numerical simulations and physical experiments. The three activities reinforce each other and lead to the understanding of observable phenomena. A scientific consensus on this understanding can only derive from a careful balance among the three activities.

Theories are only as good as their underlying assumptions, no matter how sophisticated the mathematics. Similarly, the outcome of numerical simulations depends upon the simplifications invoked to capture natural phenomena. Physical experiments are regarded as the ultimate arbiter of the success of theories and simulations. However, experimental observations are only as good as the instruments they employ.

In general, simplicity in a theory or simulation promotes physical understanding; likewise, simplicity in the design of an experiment facilitates its interpretation. Complex, all-encompassing theories rarely foster understanding. Intricate experiments purporting to mimic industrial processes seldom lend themselves to rational interpretation, and thus can fail in their role as an arbiter of theoretical predictions.

Unfortunately, the simplifications of fundamental research can be interpreted as irrelevance by funding agencies whose ultimate aim is to assist technological progress. To resonate with the public, research funding is often justified by invoking practical applications.

Researchers studying flows of a gas and disperse solids thus face a dilemma. Applications with dense flows, opaque suspensions, heterogeneous mixtures, large scales and non-linear phenomena are far from the reach of fundamental experiments, whose detailed instrumentation is limited to dilute conditions, small vessels, etc.

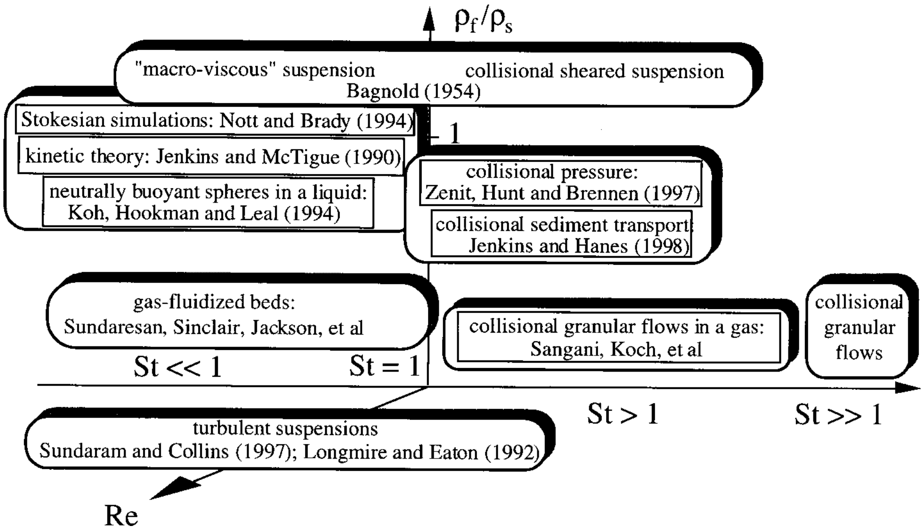
Consequently, if they address flows of practical interest (e.g., circulating fluidized beds), theories and simulations will remain untested until they focus on situations where detailed experiments can be conducted. Those situations are seldom directly related to practical devices.

To encourage and reward creativity, a successful funding strategy should avoid over-directing research topics. It is hoped that funds can remain available for orthogonal thinking that does not fall within a few selected, fashionable topics.

Finally, funding should be coordinated with agencies offering special facilities or complementary resources. For example, a number of fundamental experiments on gas-solid flows can be carried out on microgravity platforms operated by NASA.

2. FRONTIER TOPICS FOR RESEARCH IN GAS-SOLID FLOWS

The Figure shows a simple mapping of flows involving a fluid and a dispersed solid, in which hydrodynamic and contact forces are important. The horizontal, vertical and oblique axes represent, respectively, the Stokes number, the ratio of fluid and solid material densities, and the Reynolds number based on vessel size. This discussion reflects the limits of my own knowledge. It focuses attention on flows involving a gas



and a dispersed solid phase i.e., $\rho_f/\rho_s << 1$, and it only addresses hydrodynamic or particle-particle interactions.

In general, flows of gases and solids are inherently inhomogeneous and the suspended solids exhibit agitation. Agitated solids are rarely far away from boundaries or from borders between dilute and dense regions of the flow. Therefore, a successful description of particulate flows must incorporate proper boundary conditions.

Because solids interact with one another through frictional contacts over a wide range of relative velocities, the particle spin may be important, particularly near boundaries, and the interaction may involve friction that might not be as simple as that described by Coulomb laws.

The organizers of the workshop have already identified a number of important subjects that warrant additional research in gas-solid flows. On the theoretical side, they have recommended research on hydrodynamic interactions between gas and solids, boundary conditions for the disperse phase, collisional interactions amongst particles (Jenkins and Savage, 1983; Lun, et al, 1984), and the role of inhomogeneities (Wang, et al, 1996; Agrawal, et al, 2001). On the numerical side, they have suggested further development of direct numerical simulations for large systems (e.g., Ladd, 1990, 1991, 1992).

I agree with the scope of these suggestions. To those I would add the design of experiments aimed at verifying key assumptions and constitutive relations upon which theory and simulations must rely.

For example, it is unclear whether or how drag laws commonly used in theoretical models depend upon the agitation of solid particles. Although recent numerical simulations and theory have begun addressing this question (Koch, 1990; Gopinath, et al, 1993; Koch and Sangani, 1999; Wylie and Koch, 2000; Wylie et al, 2000; Sundararajakumar and Koch, 1996; Tsao and Koch, 1995; Mo and Sangani, 1994; Sangani, et al, 1996), experimental verification should be sought. In general, drag laws are simple extensions of expressions for single spheres immersed in an infinite fluid (Clift, et al, 1978), or for porous media. Because gas-solid flows are inherently inhomogeneous (Babic, 1993; Goldhirsh, et al, 1993; Hopkins and Louge, 1991; Wang et al, 1996), it is still unclear how these laws are affected by the proximity of other agitated particles.

Considerable research has focused upon flows where the Reynolds number is large and/or the Stokes number is low. Insight should also be gained in situations where the Stokes number is of order unity or greater. Such situations arise in gas-solid flows near solid boundaries, for example.

Another crucial aspect of gas-solid or granular flows concerns the derivation of appropriate boundary conditions that incorporate interactions of solid particles amongst themselves or with boundaries (Jenkins, 1992; Jenkins and Askari, 1993; Jenkins and Louge, 1997; Louge, 1994). This interaction involves solid friction and particle spin (Lorenz, et al, 1997). Unfortunately, few treatments take particle rotation into account. Formal theories predicting the transport of particle angular momentum near boundaries are beginning to emerge (e.g., Hayakawa, 2002; Mitarai, et al, 2002). These should be extended to gas-solid flows and tested with simulations and experiments.

Solid friction is another topic that challenges our understanding. For example, in granular flows, friction can vary with relative contact speed. It can also be hysteretic or intermittent, and it depends upon the age of contact (Baumberger and Caroli, 1998). Its understanding is crucial to predict the interaction force that is tangent to a solid surface. More globally, it is important to understand flows in which particles interact with boundaries through a combination of long-lasting frictional contact as well as more ephemeral impulsive interactions. This coexistence is crucial to gravity-driven granular flows (Louge and Keast, 2001; Louge, 2003). It may also be important in gas-solid flows where particles remain in contact with walls (e.g., Louge, et al, 1991; Tsuji, et al, 1993; Dasgupta, et al, 1994; Bolio, et al, 1995; Boëlle, et al, 1995; Griffith and Louge, 1998).

Finally, the research should not be limited to hydrodynamics. This is because most applications also involve heat transfer, mass transfer and chemistry. To incorporate heat transfer, exiting theories assume that particles have uniform temperature (small Biot number). In this case, the form of the gas-solid thermal interaction term is simply proportional to the mean temperature difference between gas and solids (Louge, et al, 1993). However, there are applications where the Biot number is of order unity. In this case, the temperature history can affect the thermal exchange. In this limit, the solid phase behaves as a macrofluid. Experiments and theory should begin to address these issues.

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