Heat transfer between solid particles and a gas in direct contact is a subject as old as when solid fuel combustion was first observed. The combustion phenomenon was the principal application of this direct-contact process for many years and may remain so today. The thrust of the current workshop has been the examination of fundamental heat transfer phenomena, however, so the situation with chemically reacting species will not be considered here in depth. We are essentially considering the state of knowledge and continuing needs for describing the exchange between a gas and solids—either particles, solid boundaries, or both—when there are temperature differences between the media.

All of the basic heat transfer modes are present in gas-solid systems. Conduction will occur at points of contact between particle surfaces and other boundaries whether they be container walls or internal heat-exchange surfaces. Convection will naturally always be present since the gas will have some sort of motion and this motion will affect the energy transport directly. A "gas" will generally refer to a single phase, however, with quite small particles present, a more-or-less homogeneous emulsion may be treated as a dense gas phase. Radiation will be a significant heat transfer mode if relatively large temperature differences exist across a heat-transfer path. Such effects normally occur between particles that are at or close to the bed temperature and solid boundaries such as internal surfaces.
Heat transfer processes in gas-solid systems are intimately associated with the relative motions of the phases; this is the major challenge in this area—that of understanding and describing gas and solid-particle motions. When one observes, visually, a bed of particles in motion as a result of fluid interaction the complexity of this process is readily apparent. The process is chaotic and is affected by numerous variables such as particle size and distribution, fluid characteristics—principally as a function of temperature, particle properties, bed geometry, the presence and geometric arrangement of bed internals, and the manner in which the bed particles are confined and fluidized. A phenomenon of extreme importance in this regard is that involving "bubbles" of particle-free gas that exist in fluidized beds and may be fundamental in affecting the heat transfer.

Following the acceptance of the notion that this is a complex business, we are left with a range of needs to satisfy different audiences. Academicians and others whose approaches are basic wish to understand gas-solid systems sufficiently well that heat transfer and, obviously, the motions of the phases can be described from first principles, given a few system parameters. Practitioners are interested in operational information adequate for describing a process already in existence or for designing a system to satisfy a definite operational need. Unfortunately, the state of knowledge at present leaves us quite a distance from satisfying any of these needs in complete fashion.

1 FLUID FLOW MECHANISTIC CONSIDERATIONS

Some introductory remarks have already been made on this subject. Chen describes the process whereby a bed of particles becomes fluidized by the upward flow of a gas. Beyond the velocity at which minimum fluidization occurs bubbles begin to form at the distributor plate and their upward motion, whether "fast" or "slow," will influence heat transfer in a major way. "Bubbles," in the fluidized-bed sense, are regions where the gas is free of particles over a distance that is large compared with the size of particles. In contrast to "bubbles" in the usual gas-liquid sense, ours are regions through which gas is flowing. In a case where gas convection is significant in a heat transfer sense, the effective heat transfer coefficient will be much different when the gas is flowing rapidly between the interstices of adjacent particles and/or internal surfaces than when flow is relatively slow within a bubble. Bubbles themselves are subject to some complex effects. Chen describes the relative motion of bed particles when bubble flow is "fast" or "slow." This motion is, as yet, not fully predictable. Certainly, the resulting particle motion is of interest for heat transfer purposes.

It is well known that a horizontal tube immersed in a fluidized bed will, at relatively low superficial velocities, experience variable effects around its periphery. At the bottom a pseudo-stagnation point effect will exist. Around the sides the gas-solid-boundary motion is quite dynamic. Near the top a "stack" of stationary particles will form and remain in place until being displaced by a passing bubble. This stack region is one of low heat transfer; thus if the stack is not displaced relatively frequently, the average heat transfer for the cylinder will be reduced