2

OCT 22 1990
DOE/PC/88947--T8

Development and Utilization of New Diagnostics for Dense- Phase Pneumatic Transport

Quarterly Technical Progress Report (July 1, 1990 to September 30, 1990)

Contract number: DE-AC22-88PC88947

Contract Period of Performance: October 1, 1988 to September 30, 1991

Contractor: Cornell University, Ithaca, NY 14853

Contract Participants: Michel Y. Louge, James T. Jenkins

DOE Project Manager: Mehrdad C. Massoudi

NOV 30 1990
DOE/PC/88947--T8

DE91 004206

US/DOE patent clearance is not required prior to the publication of this document.

Summary

Dense-phase pneumatic transport is an attractive means of conveying solids. Unfortunately, because of the high solid concentrations, this transport method is a difficult regime in which to carry out detailed measurements. Hence most details of the flow are unknown.

In this context, the main objective of this work is to develop probes for local measurements of solid velocity and holdup in dense gas-solid flows. In particular, we have designed capacitance probes to measure local, time-dependent particle concentrations, and a new optical fiber probe based on laser-induced-phosphorescence to measure particle velocities.

The principles for the capacitance and optical diagnostics were given in our first and second quarterly reports. A prototype of the optical fiber probe was tested during the previous quarter. In the present reporting period, we have constructed a final version of the optical fiber probe.

Another widely used method for measuring particle volume fraction inside a transport system consists of measuring the light back-scattered from the suspension onto an optical fiber. In the present reporting period, we have simulated the performance of this optical probe using a Monte-Carlo technique. The simulations have shown that the method can be very inaccurate if the ratio of the particle to the fiber core diameter is greater than one. Guidelines are proposed for utilizing this diagnostic technique accurately.

Progress Report

1. Fiber-optic anemometer probe

In the previous quarter, we tested a prototype of the optical fiber anemometer probe described in our first quarterly progress report. We also simulated the performance characteristics of the probe using a Monte-Carlo representation of the optics at the probe tip. In the present quarter, we have designed and assembled a new probe based on the information gathered during the tests of the prototype. Because the Monte-Carlo simulation had shown that the measurement volume of the receiving fibers is confined to a slender region immediately around the optical axis, the new probe was designed with receiving fibers packed as closely as possible on a ring centered on the axis of the probe tip. In this way, the close packing of the receiving fibers ensures that all glowing particles can be detected by one of the receiving fibers. A special tool was constructed to permit easy assembly of the 18 receiving fibers at 1.5mm from the probe axis. Tests of the new probe will be carried out in the next reporting period.

2. Optical fiber measurement of voidage

A convenient method for measuring particle volume fraction in a transport system consists of inserting a single optical fiber in a suspension and recording the amount of light back-scattered onto the fiber (Figure 1). Because it is far less intrusive than other probes such as our traversing capacitance probe, this technique is attractive. However, because the probe must be calibrated *in situ*, it suffers from severe drawbacks associated with uncertain knowledge of the solid volume fraction used in the calibration (e.g., Hartge & Werther, 1988). As discussed in our 6-th quarterly report, a convenient solution to this problem consists of inserting the optical fiber into the central ground surface of a wall capacitance probe. The capacitance probe provides accurate measurements of the local solid volume fraction around the optical fiber. Once it is calibrated against these measurements, the optical probe is traversed through the transport vessel.

Encouraged by our success at simulating the optics of the optical fiber anemometer, we have developed another ray-tracing Monte-Carlo simulation to predict the amount of light back-scattered onto the fiber by a random array of uniform glass spheres at a given solid volume fraction. In this program, 'photons' are launched from the tip of the fiber with a probability consistent with a gaussian radiant intensity distribution. The 'photons' are emitted in equiprobable directions within the fiber's cone of acceptance. They proceed on straight rays in space until they hit a glass sphere. Provided that the wavelength of light is

much smaller than the diameters of the particle or that of the fiber core, this ray tracing technique is an accurate representation of the optical system.

Fig. 1. Simultaneous measurements of voidage using an optical fiber probe and a wall capacitance probe.

The space in front of the fiber is divided in a periodic array of uniform cubes. Each cube contains only one sphere. Its volume is therefore equal to the volume of the sphere divided by the average particle volume fraction. The position of the sphere within the cube is random. When a photon hits one of the spheres, it emerges from the 'collision' as either a reflected or a transmitted photon with a probability consistent with its angle of incidence on the sphere and the indices of refraction of the sphere and the surrounding medium. Similarly, the absorption of light is simulated by assigning a probability for the disappearance of the photon as it travels through the sphere. Internal reflections of the photon in the sphere are also modeled by assigning probabilities for reflection and refraction.

Fig. 2. Relative uncertainty associated with the finite number of photons launched. The conditions of the simulation are: ratio of particle to fiber core diameter 0.25; numerical aperture 0.37, solid volume fraction 50%.

In order to predict the amount of light back-scattered onto the optical fiber, the program counts the fraction of photons returning within the cone of acceptance of the fiber. A measure of the uncertainty that is associated with the finite number of rays launched in the simulation is shown in figure 2. There we have plotted the sample standard deviation of the result from five consecutive runs with N rays launched, normalized with the average result from the five runs. This ratio tends to zero as N becomes infinite. From figure 2 it is clear that an acceptable uncertainty less than one percent is achieved once 10^5 photons have been launched.

Figure 3 compares predictions of the simulation to data gathered with the set-up sketched in figure 1. In this experiment, particles are released near the inside surface of a vertical tube where the wall capacitance probe and the optical fiber have been inserted. The capacitance probe provides a quantitative measurement of the local time-dependent solid volume fraction seen by the optical probe. Simultaneous samples are selected at random from the signals of the capacitance and optical probes. Because the absolute voltage signal from the optical probe depends on several unpredictable, but linear, effects such as the extinction through the fiber and the characteristics of the photodiode detector, the probe signals must be normalized before comparing them with predictions from the simulation. In figure 3, we have normalized the signal and the predictions for $210\mu\text{m}$ particles at $(1-\epsilon)=50\%$. After normalization, excellent agreement is achieved between the predictions of the simulation and the corresponding relative signals detected by the optical probe.

Therefore, the simulations can be used to establish the optical performance of the probe with confidence.

Fig. 3. Relative intensity back-scattered onto the optical fiber vs. solid volume fraction ($1-\epsilon$). The open circles and squares represent glass spheres of $70\mu\text{m}$ and $210\mu\text{m}$ diameter, respectively. The optical fiber core diameter is $200\mu\text{m}$ and its numerical aperture is 0.37. The solid lines are the predictions of the simulation. The data and the simulation are normalized at $(1-\epsilon)=50\%$ for $210\mu\text{m}$ spheres.

The error bars plotted in figure 3 represent the sample standard deviation from ten consecutive runs with different random arrays of spheres of identical volume fraction. From these runs it is clear that uncertainties due to the random placement of the particles increase with the particle diameter. This result is intuitive: for particles of diameter comparable to the fiber core diameter, small random displacements have a larger effect on back-scattered light intensity than for small particles.

Figure 4 shows predictions of the back-scattered energy collected by the fiber for different particle volume fractions and ratio of the sphere to fiber core diameters. For each point on this graph, ten consecutive runs with 10^5 photons each and different random placements of the spheres were averaged. From this figure it is clear that the fraction F of light back-scattered can be represented by a function of the form: $F=k(1-\epsilon)^a$. Figure 5 is a plot of the predicted values of k and a for various ratios of fiber core to particle diameters.

Because with larger ratios of particle to fiber core diameters the intensity of back-scattered light decreases and the uncertainty from the particle random placements increases, this technique for measuring solid volume fraction is inaccurate when these ratios exceed approximately one.

Fig. 4. Predicted fraction of light back-scattered onto the optical fiber vs. solid volume fraction for ratios of particle to fiber core diameters of 0.1 (triangles), 0.35 (circles), and 1.0 (squares). The fiber numerical aperture is 0.37. Each point represents the average fraction from ten consecutive simulations of 10^5 rays with different random particle placements.

Fig. 5. Predicted exponent and pre-exponential factor vs. ratio of fiber core to particle diameter for the empirical expression $F=k(1-\epsilon)^a$.

References

- M.Y. Louge & J.T. Jenkins: "Development and Utilization of New Diagnostics for Dense-Phase Pneumatic Transport", 7 Quarterly Technical Progress Reports to the DOE (October 1, 1988 to June 30, 1990), Contract number: DE-AC22-88PC88947.
- E. Hartge, D. Rensner and J. Werther, in *Circulating Fluidized Bed Technology II*, Pergamon (1988), pp. 165-180.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

END

DATE FILMED

12 / 13 / 90