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DETERMINATION OF FLOW-REGIME BOUNDARIES FOR COHESIVE PARTICLES

**Project 61093 Quarterly Report
For the Period September 20 Through December 19, 1990**

by

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SUMMARY

Cohesive powders are composed of fine particles (particles generally less than 44 microns in size). Interparticle forces are extremely large and cause clumping, sticking, and channeling when attempts are made to fluidize these powders. These solids do not flow freely in pipes and bridge extremely easily.

Although flow problems can be experienced in the transport of free-flowing solids, they pale in comparison to the problems experienced with the flow of cohesive powders. Because of these flow problems, most process designers have shied away from using cohesive powders. However, cohesive powders are often produced in processes by attrition, and then concentrated in solids-collection equipment such as cyclones. Also, because cohesive solids have an extremely high surface area per unit volume, they are potentially desirable feed stocks for many processes. In addition, recent research has shown that beneficiation of oil shale and coal is possible after grinding these materials down to the cohesive size range.

Although there is much interest in cohesive powders at present, there is little information in the literature on the gas-solid, two-phase flow behavior of cohesive solids. Much information is needed in all cohesive solid flow regimes in order to characterize them. Possibly the most important information for plant designers, however, is knowledge of where the cohesive solids pass from dilute-phase flow into a dense-phase or choking flow. Cohesive solids can be handled more easily in dilute-phase than in dense-phase. In dense-phase flow, cohesive solids clump and bridge and often do not flow at all.

The purpose of this work is to develop a hydrodynamic model capable of predicting the choking/non-choking flow regime boundary for cohesive solids. There are six tasks in this study:

- Task 1. Preparation of a Project Work Plan
- Task 2. Hydrodynamic Model Development
- Task 3. Determination of Solid Rheological Properties for Incorporation Into the Hydrodynamic Model

Task 4. Small-Scale Flow Tests

Task 5. Large-Scale Flow Tests

Task 6. Comparison of Model with Data and Preparation
of Final Report

In Task 4, tests were conducted with a Laser-Doppler velocimeter (LDV) with cohesive oil shale particles to determine the particle size distribution simultaneously with the determination of the particle velocity in a pipe at a superficial gas flow rate of 5 SCFM.

Also in Task 4, the small-scale test unit with a 7.6-cm-diameter riser, was operated to determine the effect of riser height on the radial profiles of mass flux, particle velocity, and solids volume fraction using FCC catalyst. The profiles generated were similar to those reported in the literature.

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OBJECTIVES

The overall objective of this program is the development of a hydrodynamic model to predict the choking/non-choking flow regime boundary of fine, cohesive (that is, Geldart Group C) powders. Specific objectives are to:

1. Develop a two-dimensional hydrodynamic model that can be applied to cohesive solids.
2. Generate large-scale solids-flow data that will be used to verify the model.

INTRODUCTION

The objectives of this program are to -

1. Develop a two-dimensional, hydrodynamic model that can be applied to cohesive solids.
2. Generate large-scale solids-flow data that will be used to verify the model.

The research is divided into six tasks:

- Task 1. Preparation of a Project Work Plan
- Task 2. Hydrodynamic Model Development
- Task 3. Determination of Solid Rheological Properties for Incorporation Into the Hydrodynamic Model
- Task 4. Small-Scale Flow Tests
- Task 5. Large-Scale Flow Tests
- Task 6. Comparison of Model With Data and Preparation of Final Report.

In Task 1, a detailed Project Work Plan describing the tests to be conducted will be prepared and sent to the Department of Energy (DOE) for review and approval.

An existing, two-dimensional mathematical model will be extended to include interparticle forces such as exist in cohesive solids in Task 2. The equations to be programmed into the model will be derived from experimental measurements made in Task 3.

In Task 3, the rheological properties of a cohesive oil shale test material will be determined and incorporated into the hydrodynamic model to improve its capability for predicting gas and solid velocity profiles for gas and cohesive solids in two-phase flow. In addition, the fluidization and flow characteristics of the cohesive oil-shale powders will be determined.

A small-scale (3-inch-diameter), solids-flow test facility will be modified in Task 4. The facility will be operated with cohesive solids to provide solids concentration and gas velocity data to fine-tune the hydrodynamic model.

In Task 5, cohesive flow tests will be conducted in a large-scale (12-inch-diameter) solids flow unit to obtain data for comparison with model predictions. The large-diameter line should minimize wall effects that can be substantial in smaller units.

In Task 6, the hydrodynamic model will be compared with the results from both the small-scale and large-scale test units. The model will be fine-tuned, and then used to predict gas and solids velocity profiles both near and far away from choking. The final report for the project will also be prepared in this task.

TECHNICAL PROGRESS REPORT

Task 1. Preparation of Project Work Plan

This task has been completed.

Task 2. Hydrodynamic Model Development

The derivation of the two-phase gas-solid equations for continuity, momentum, and the fluctuating energy of the particle phase is complete. The model will now be used to compare its predictions with the data from the large-scale test unit when the data become available in sufficient quantities.

Task 3. Determination of Solid Rheological Properties for Incorporation Into the Hydrodynamic Model

Subtask 3.1 Parameter Determination

No work was conducted in this subtask this month.

Subtask 3.2 Fluidization and Flow Testing

The testing in this task has now been completed.

Task 4. Small-Scale Flow Tests

Small-Scale Riser Test Unit

During the last several quarters, the small-scale test unit (Figure 1) was operated to determine the radial profiles of mass flux, solids volume fraction, and particle velocity for FCC catalyst as a function of solids mass flux and superficial gas velocity. This quarter, the small-scale test unit was operated to determine the effect of riser height on the radial profiles of mass flux, particle velocity, and solids volume fraction.

The radial mass flux profile was measured using an extraction probe, and the solids volume fraction was measured using an X-ray densitometer. Because the particle velocity, solids volume fraction, and mass flux are related, knowing any two of the three parameters enables the calculation of the other parameter. The radial particle velocity profile was calculated from the measured radial mass flux and the solids volume fraction data.

The FCC catalyst used in the testing this quarter had an average particle size of approximately 75 microns. The actual particle-size distribution of the catalyst is given in Table 1.

Figure 1. SCHEMATIC DRAWING OF SMALL-SCALE TEST UNIT

Table 1. PARTICLE-SIZE DISTRIBUTION OF FCC CATALYST MATERIAL

Particle Size Range, <u>microns</u>	Weight, <u>%</u>
3/4	0.28
4/6	0.71
6/8	0.31
8/10	0.50
10/20	4.55
20/40	50.67
40/50	27.21
50/70	12.31
70/100	1.41
100/200	1.40
200/286	0.65

The catalyst had a vibrated bulk density of 68.4 lb/ft³, and a loose bulk density of 63.4 lb/ft³. The particle density of the material (as determined by mercury porosimetry) was determined to be 103.2 lb/ft³.

A description of the techniques and equipment used to determine the radial profiles of solids volume fraction, mass flux, and particle velocity is given below.

Radial Solids Volume Fraction Profile

X-Ray Densitometer

The radial solids volume fraction profile in the test unit was determined with an X-ray densitometer. A schematic drawing of this device is shown in Figure 2. The probe contains a 200-mCi Curium 244 source centered at the capped-off outlet of a 2.66-cm-I.D. pipe. The cap of the pipe is covered with lead, 1.27-cm-thick, to prevent X-ray scatter. A 0.635-cm tube that is approximately 15 cm in length extends through the lead to the center of the X-ray source. A collinear X-ray beam travels through the pipe. Since the outlet of the tube is inserted into the CFB, it is capped off to prevent particles from flowing into it. A 0.635-cm-diameter plug of Karvex

Figure 2. SCHEMATIC DRAWING OF X-RAY DENSITOMETER

(jeweler's) wax is used to accomplish this objective. To fix the wax into position, the inside surface of the tube was roughened before the wax was melted into place. Karvex wax was used because it does not severely attenuate the X-ray beam. Also, the wax is robust and has a high (121°C) melting point.

The tube extends through a male run tee into the CFB. Plastic ferrules are used in the tee so that the tube may be continuously repositioned. When positioning the tube, air is continuously purged through the tee to prevent particles from causing the tube to bind.

A block diagram of the X-ray spectrometer is shown in Figure 3. The collinear X-ray beam traverses from the tip of the X-ray probe, through the absorbing material (CFB particles and gas stream) and CFB acrylic pipe, to a thallium-activated, sodium iodide scintillation counter. The X-rays are absorbed in the scintillator, which is powered by a regulated dc potential of 960 V. Each X-ray photon transfers its energy to a photoelectron, which in return, expends its energy producing 4100-Å light photons. The more energetic the X-ray photon, the more light photons will be produced. Thus, detector output is proportional to X-ray photon energy. A preamplifier and amplifier are used to amplify the detector output pulse to potentials high enough to pass through the window of the pulse-height selector. The window for the selector is set as narrowly as possible to eliminate noise that may distort the final count rate. Output from the selector is fed to a counter and timer that provides readout and display of the X-ray intensity data in an accumulative digital mode over a selected time interval.

Theory of Operation

The Beer-Lambert law is the mathematical basis used to analyze the experimental data obtained with the X-ray densitometer. It can be expressed as -

$$I = I_0 \exp (-\delta t) \quad (1)$$

where I is the radiation intensity, I_0 the initial radiation intensity, and δ and t are the linear-absorption coefficient and thickness of the absorber, respectively. The negative sign indicates that the radiation intensity always decreases (that is, the X-rays are attenuated as they pass through solids). A more useful form of this equation is -

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Figure 3. BLOCK DIAGRAM OF X-RAY SPECTROMETER

$$I = I_0 \exp (-\gamma \bar{\rho} t) \quad (2)$$

where
$$\bar{\rho} = \frac{1}{t} \int_0^t \rho dt \quad (3)$$

and
$$\gamma = \delta / \bar{\rho} \quad (4)$$

and γ is the mass-absorption coefficient (cm^2/g) of the absorber, and ρ the absorber density (g/cm^3). The mass-absorption coefficient is an intrinsic property of materials, and is a measure of their x-ray opacity. For the same wavelength (α), γ is different for every element; and for the same element, γ is different at every wavelength. The wavelength is related to the photon energy (E_x) by the equation -

$$a = 12.396/E_x \quad (5)$$

where E_x and α are in keV and Angstroms, respectively. The principal photon energy of the 200-mCi X-ray source used in this experiment is 18 keV.

The mass-absorption coefficient of a mixture of elements of weight fractions $W_a, W_b, W_c, \dots$ is given by:

$$\gamma_{\text{mix}} = \sum W_i \gamma_i \quad (6)$$

The weight fraction of a component i is related to its volume fraction by:

$$\gamma_i = \epsilon_i \rho_i / \rho_{\text{mix}} \quad (7)$$

where
$$\bar{\epsilon}_i = \frac{1}{t} \int_0^t \epsilon_i dt \quad (8)$$

where ϵ_i , ρ_i , and ρ_{mix} are the volume fraction and density of component i , and the density of the mixture, respectively. Substituting Equation 7 into Equation 6 yields:

$$\gamma_{\text{mix}} = \sum \epsilon_i \rho_i \gamma_i / \rho_{\text{mix}} \quad (9)$$

For a mixture, the Beer-Lambert law is expressed as -

$$I = I_0 \exp (-\gamma_{\text{mix}} \rho_{\text{mix}} t) = I_0 \exp (-\sum \epsilon_i \rho_i \gamma_i t) \quad (10)$$

For a mixture consisting of air and solids the Beer-Lambert law becomes:

$$I = I_0 \exp (-(\bar{\epsilon}_s \rho_s \gamma_s + \bar{\epsilon}_a \rho_a \gamma_a) t) \quad (11)$$

and

$$\ln I = \ln I_0 (-(\bar{\epsilon}_s \rho_s \gamma_s + \bar{\epsilon}_a \rho_a \gamma_a) t) \quad (12)$$

where

$$\bar{\epsilon}_a + \bar{\epsilon}_s = 1 \quad (13)$$

Differentiating Equation 11 with respect to t and solving for $\bar{\epsilon}_s$ explicitly results in -

$$\bar{\epsilon}_s = (\partial \ln I / \partial \ln t + \gamma_a \rho_a) / (\gamma_a d_a - \gamma_s \rho_s) \quad (14)$$

From this equation the solid volume fraction can be obtained from the experimental values of $I(t)$, because all other components in the expression are constant.

Experimental Techniques

To apply Equation 14 in the test unit operating with air and FCC catalyst, the absorption coefficients for FCC catalyst and air were first determined. The catalyst coefficient was determined by adding catalyst into the riser of the test section in a packed-bed mode. Intensity measurements were obtained every 0.159 cm across the pipe. The natural log of the measured intensity versus distance for the catalyst is shown in Figure 4.

The slope of Figure 4 is nearly linear for radiation intensities resulting in counts exceeding 190 counts/s. It is over this range that the curve obeys Beer-Lambert's law. The linear-absorption coefficient of the catalyst is equal to the negative of the slope and has a value of 2.372 cm^{-1} . The mass-absorption coefficient of the catalyst is equal to the linear-absorption coefficient divided by the density of the solids at calibration. The coefficient was determined to be $2.335 \text{ cm}^2/\text{g}$.

It is important that the Beer-Lambert Law hold over the range of applicability. Because the largest and smallest values of the intensity over the range of applicability are, respectively, 975 counts/s and 190 counts/s, the area density (ρ_{st}) should be less than -

$$\rho_{st} = \ln(975/190)/2.335 = 0.7 \text{ g/cm}^2 \quad (15)$$

to avoid significant error in the calculations. A higher energy radiation source should be used for the measurement of particle area densities that are greater than this value.

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Figure 4. X-RAY DENSITOMETER CALIBRATION CURVE FOR FCC CATALYST

A curve similar to that of Figure 4 was also obtained for air. This curve is shown in Figure 5. The curve in Figure 5 is linear and obeys the Beer-Lambert Law. The linear and mass-absorption coefficients for air were determined to be 0.0096 cm^{-1} and $6.79 \text{ cm}^2/\text{g}$, respectively.

Radial Mass Flux Profile

Extraction Probe

Mass flux profiles in the riser were monitored with the extraction probe shown in Figure 6 using the equipment schematically depicted in Figure 7. The probe consists of a brass tube that has a outside diameter of 0.635 cm and a 0.472-cm inside diameter. The tube is bent at a 90-degree angle to align its opening parallel to the flowing solids-gas mixture. Unfortunately, because of its 90-degree bend, the probe could not be pulled back completely flush with the near riser wall. Therefore, flux measurements spanned only 6.99 cm of the 7.5-cm riser inside diameter.

Two circular levels were attached to the probe to align its inlet with the wall of the riser. Radial probe alignment was accomplished by measuring the distance between a marker on the probe and the male run tee. When aligning the probe, compressed air was passed through the male run tee to prevent binding of the probe.

After extraction of the solids by the probe, the solids/gas mixture was separated by a filter. The filter was equipped with a removable solids collection chamber fabricated of clear PVC for visual observation. Air leaving the filter flowed through a finer secondary filter to protect the downstream rotameter and vacuum pump. The flow of air exiting the extraction probe was regulated by a globe valve located downstream of the rotameter used to measure the extraction gas flow rate.

Theory of Operation

At any particular position within the riser, the time-averaged mass flux consists of both an upward and downward component. The magnitude of the upward mass flux minus the magnitude of the downward mass flux is equal to the net upward mass flux. Both components of the mass flux are measured with the extraction probe. The upward and downward mass flux components are measured

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Figure 5. X-RAY DENSITOMETER CALIBRATION CURVE FOR AIR

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Figure 6. SCHEMATIC DRAWING OF MASS FLUX EXTRACTION PROBE

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Figure 7. SCHEMATIC DRAWING OF MASS FLUX MEASUREMENT SYSTEM

with the inlet of the extraction probe pointing in the upstream and downstream directions, respectively. Because the solids flow in the riser fluctuates, all flux measurements were time-averaged over periods that ranged from 1.5 to 6 minutes. Mass flux components were calculated by dividing the weight of solids recovered in the filtration collection chamber by the area of the tip of the probe and sample time.

The magnitude of both mass flux components appears to be a linear function of the flow of gas through the extraction probe; however, the net mass flux does not. That is, the difference between the upward and downward components of the mass flux does not vary with extraction gas flow when the extraction gas flow rate is the same for both components. An exception to this rule has been when the gas extraction rate has been low enough for slugging to occur in the line between the probe and the filter.

Other investigators have assumed that the components of net mass flux are the flux axis intercept of the gas flow versus mass flux curve, because this is the hypothetical zero gas extraction velocity (that is, where there is no influence of gas velocity on the rate of solids extraction). This method is labor intensive in that it requires several (3 to 5) data points to correctly determine the mass flux axis intercept. In this investigation, the net mass flux was taken to be the difference between the two (2) components of the mass flux, measured at the same gas extraction rate. To compensate for experimental error, the readings were averaged over two (2) gas extraction rates. Measurements were obtained at gas flows that were high enough to prevent line plugging. Relatively low gas flows were used so that the measured mass flux components would be as close as possible to their zero gas extraction velocity value.

Experimental Results

During the last several quarters, radial profiles of mass flux, particle velocity, and solids volume fraction were determined as a function of solids mass flux and superficial gas velocity. These data were determined at a height of 4.18 m above the solids feed point in the riser. This quarter, the radial profiles of mass flux, particle velocity, and solids volume fraction were also determined at riser heights of 1.86 and 5.52 m above the solids feed point. The results of the testing are presented in Figures 8, 9, and 10.

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Figure 8. RADIAL SOLIDS MASS FLUX PROFILES AS A FUNCTION OF RISER HEIGHT

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Figure 9. RADIAL SOLIDS VOLUME FRACTION PROFILES AS A FUNCTION OF RISER HEIGHT

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Figure 10. RADIAL SOLIDS PARTICLE VELOCITY PROFILE AS A FUNCTION OF RISER HEIGHT

In Figure 8, radial profiles of solids mass flux are shown as a function of riser axial location at a constant riser superficial gas velocity of 2.89 m/s, and a constant solids mass flux of 32.8 kg/s-m². The profiles are parabolic, with higher mass fluxes in the center of the riser than at the wall. However, the radial mass flux profiles obtained at the two higher riser locations, were "flatter" than the profile obtained at the lower location. The data also indicate that the annulus layer of downward flowing solids at the wall is thicker at the lower riser location, and then thins out at higher levels in the riser.

The measured radial profiles of solids volume fraction in the riser as a function of height are also parabolic, and are shown in Figure 9. These data were obtained at a constant superficial gas velocity of 2.61 ft/s and a constant solids mass flux of 20.4 kg/s-m².

The curves in Figure 9 show that the solids volume fraction is highest along the wall (in the annular region) and lowest in the center of the riser. The solids volume fraction radial profile obtained at the lowest riser height (1.86 m) was more parabolic than the curves obtained at the two higher riser levels. Also, the values of the solids volume fraction were higher at the lower riser location than at the higher riser locations. This difference was especially pronounced near the wall.

The radial profile of solids velocity across the riser was determined by calculation from the experimental values obtained for the solids volume fraction and the solids mass flux. The relationship between solids particle velocity, solids volume fraction, and the solids mass flux is given at each radial position by

$$V_p = G/(\rho_p \epsilon_s) \quad (16)$$

The effect of riser axial location on the radial solids velocity profiles are given in Figure 10. These curves were obtained at a constant superficial gas velocity of 2.89 m/s, and a constant solids mass flux of 12 kg/s-m². As with the mass flux and solids volume profiles, the particle velocity radial profiles were parabolic. Also, the particle velocity radial profiles were significantly "flatter" at the higher axial positions.

It is apparent from the data obtained at the different riser heights, that the radial profiles for mass flux, solids volume fraction, and solids

velocity tend to become "flatter" at higher axial locations. This implies that the central core of the riser expands with height. This causes the various riser parameters to vary less with radial position.

Laser-Doppler Velocimeter Experimental Unit

Last quarter, the Laser-Doppler Velocimeter (LDV) experimental test unit construction was completed, and the test unit was shaken down. This quarter, tests were conducted with cohesive oil shale particles to determine the particle size distribution simultaneously with the determination of the particle velocity at a superficial gas flow rate through the pipe of 5 SCFM. Particle size and particle velocity distributions of the cohesive oil shale were determined as a function of radial position in the pipe. A description of the operating principle of the LDV and the test results to date are presented below.

Theory of Operation

Light scattered by a moving particle is "Doppler" shifted in frequency. By measuring the amount of this shift, the velocity of the particle may be determined. The high intensity and monochromaticity of laser light is well suited for this type of measurement. The method is non-intrusive, and can measure particle velocities accurately and with high spatial resolution.

The principal advantages of this method of measurement are the lack of probes, which could otherwise disturb the flow, and the ability to measure a wide range of velocities (from a few millimeters per second to supersonic flow), without the need for calibration. The drawback, however, is that optical access is a necessity, and thus, applying the method to complex geometries is difficult. A schematic diagram of the Laser Doppler Velocimeter is shown in Figure 11.

In a dual-beam LDV, the laser beam is split by a beam splitter into two beams of equal intensity, both of which are focused at the measuring point. The LDV used in this study utilized a beam from a Helium-Neon Laser (15 mW at a wavelength of 6328 Å). The two beams were 50 mm apart, and passed through a focusing lens of 250 mm focal length. Inside the focusing volume, the two light beams intersect, and interfere with each other to form a fringe, where light intensity varies periodically in space (Figures 12 and 13).

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Figure 11. SCHEMATIC DRAWING OF LASER-DOPPLER VELOCIMETER

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Figure 12. SCHEMATIC DRAWING OF LASER-DOPPLER VELOCIMETER OPERATING PRINCIPLE

F9006 19

Figure 13. LIGHT INTENSITY VARIATION IN THE LDV

The fringe space, d_f , is given by -

$$d_f = \frac{\lambda}{2 \sin \kappa} \quad (17)$$

where λ is the wavelength of the laser light, and κ is the half angle between the two beams.

When a moving particle passes through this fringe area, the intensity of the scattered light reflected from the particle surface varies in time to form the Doppler Burst Signal. This Doppler burst is received by the photodetector, and its frequency, f_d , is proportional to the velocity of the moving particle. The frequency is given by the relation,

$$f_d = \frac{U}{d_f} = \frac{2 U \sin \kappa}{\lambda} \quad (18)$$

where U is the particle velocity component perpendicular to the optical axis. The Doppler signal output from the photomultiplier tube typically has a Gaussian envelope. The mean value, which also has a Gaussian shape, is referred to as the pedestal, and is usually filtered out.

Thus, by measuring the Doppler frequency, it is possible to determine the particle velocity without any calibration. When measuring the velocity of gas flowing through a pipe, the gas must be seeded with small particles, since the LDV actually measures a particle velocity. The particles must be small enough (usually less than 1 micron) in order to ensure that its velocity is essentially the same as the gas velocity.

Measurement of Particle Size With an LDV

There have been several attempts to measure the particle-size distribution simultaneously with measuring particle velocity with the LDV. It can be demonstrated theoretically, that the shape of the Doppler Burst signal is determined by the size, shape, and the surface properties of the particles, the optical system alignment, the optical properties of the particle, and the actual path that the particle takes while passing through the focusing volume.

For a fixed optical system alignment, the Doppler signal still depends on the individual particle size in a complex way. There are two approaches

discussed in the literature which deal with the attempt to obtain the relationship between the particle size and certain signal characteristics:

1. the visibility of the Doppler-Burst signal (1,2), and
2. the amplitude of the Doppler-Burst signal (3).

In this work, a new theory was developed to interpret the Doppler signal which is based on obtaining particle-size information from the amplitude of the Doppler-Burst signal.

It is assumed that no more than one particle can pass through the focusing volume at any time. This means that each Doppler-Burst will correspond to only one particle in the focusing volume at the precise measuring moment. When several particles appear in the focusing volume, they are considered to be moving as clusters, and are treated as one big particle. This assumption should be true in the case of very dilute gas-solidflows, and when the optical focusing volume very small.

The dual-beam LDV used in this work has an oval-shaped focusing volume, with a short-axis length of 184 microns and a long-axis length of 1890 microns. The fringe space length, d_f , is 3.2 microns. Light intensity is distributed across the focusing volume in a Gaussian distribution.

In a system with a fixed optical alignment, the amplitude of the Doppler-Burst, A_d , then depends only on the particle size, D_p , and the position of the path as it travels through the focusing volume. Let l be the effective path-length. Then different path-lengths will represent a different position of the path (Figure 13). Therefore,

$$A_d = \text{function } (D_p, l) \quad (19)$$

In general, a larger particles will generate a stronger signal than smaller particles. For the same size of particle, when it travels through the center of the focusing volume, the strongest signal will be generated. Farmer (1) obtained an expression for the light intensity distribution in the focusing volume based on the Mie Scatter Theory. It is given below:

$$I_o = 2 I \exp \left[-2 \left(\frac{x^2}{b_o^2} + \frac{y^2}{b_o^2} + \frac{z^2 \kappa^2}{b_o^2} \right) \right] \left[\cosh \left(\frac{A y z \kappa}{b_o^2} \right) + \cos \left(2\pi \frac{y}{d_f} \right) \right] \quad (20)$$

where b_0 is the e^{-2} dimension of the focusing volume in the direction perpendicular to the light axis.

If it is assumed that the velocity component of the particle perpendicular to the laser-beam plane can be neglected, the expression above results in the following expression for $A_d(D_p, l)$

$$A_d(D_p, l) = A_{d0}(D_p) \exp \left[-2 \left(1 - \frac{l^2}{l_{\max}^2} \right) \right] \quad (24)$$

where $A_{d0}(D_p)$ is the Doppler signal amplitude generated by a particle with diameter, D_p , passing through the center of the focusing volume. Because the effective path length, l , is proportional to the actual number of peaks within one Doppler-burst, N , the equation above may be written as:

$$A_{d0}(D_p) = A_d(D_p, l) \exp \left[2 \left(1 - \frac{N^2}{N_{\max}^2} \right) \right] \quad (22)$$

Thus, for any Doppler-Burst, A_{d0} calculated from this burst will be proportional to the size of the particle which caused the burst.

Noise Rejection

Even after implementing the techniques described above, there is substantial noise (from the various electronic devices employed in the testing) among the received Doppler signals. Two criteria (time and period discrimination) are used to discriminate the electronic noise.

Time Discrimination

Reasonable Doppler signals should last longer than a certain minimum time duration, i. e.,

$$\tau_{\min} \leq \tau \quad (23)$$

where τ is the duration of the individual Doppler burst, and $\tau_{\min}$ is the required minimum time duration to minimize noise. $\tau_{\min}$ is determined from the experimental measurements.

Period Discrimination

All Doppler bursts oscillate at the same frequency. Therefore, they all have the same period. For accelerating particles, the relative standard

deviation of the periods of each Doppler burst should be less than some critical value (determined from measurements). If not, the bursts are treated as noise. Thus,

$$\frac{\left[\frac{1}{N} \sum_{i=1}^N (\Delta\tau_i - \overline{\Delta\tau})^2 \right]^{1/2}}{\overline{\Delta\tau}} \leq \text{Critical Value} \quad (24)$$

where $\Delta\tau_i$ is the i th period in the Doppler burst, and $\overline{\Delta\tau}$ is the average period in the Doppler burst.

Only after both the time and the period criteria are satisfied can a particular Doppler burst be considered as a reasonable signal.

In actual testing, an HP 5404 digitizing oscilloscope was used to record the Doppler signals. The signals were then stored and transferred to an IBM 386-type computer for data processing.

Particle-Size Calibration Curve

It is nearly impossible to determine the particle-size versus electric signal voltage curve theoretically. This is because the light intensity/voltage signal relationship is unknown, and the electric signals have been amplified before they are recorded. Therefore, the following procedure was used to obtain a calibration curve for particle-size analysis:

1. The actual particle-size distribution of the particles being used in the experiment were determined using a Coulter Counter or other particle-size analyzer.
2. A reference flow condition was then chosen, and a large number of random Doppler signals were recorded with solids flowing through the experimental pipe, to make data processing statistically significant.
3. An electronic filter was used to remove the very high frequency components of the signal which are considered as noise, as well as the low-frequency components (pedestals).
4. The time and period criteria were then used to discriminate the remaining signal to remove further noise.
5. The burst amplitude of each Doppler burst, A_{d0} , was then calculated using Equation 22.

6. A statistical analysis was then performed to determine the accumulative signal number distribution as a function of signal amplitude.
7. The signal-amplitude distribution was then compared with the reference particle-size distribution obtained in Step 2.
8. The particle-size calibration curve was then constructed by choosing the signal amplitude and particle size values corresponding to the same accumulative signal number distribution (signal number percentage).

The resulting calibration curve allows the determination of the size of particle which causes a particular Doppler burst.

A TSI photodetector and frequency counter amplified the signals and filtered out the high and low frequency components of the raw signals. However, waveforms on the HP 5404 digitizing oscilloscope showed that some high and low frequency components still existed after filtering. Therefore, a computer program was developed to further filter the signals. After being filtered via the computer, the resulting signals were acceptable.

Solid Concentration Measurement Using LDV

As well as obtaining the particle size distribution, it is also possible to obtain information about the solid-phase volume (number) concentration at the measuring point. Because the particle velocity and the particle size are measured, it is possible to calculate the solid flux and then obtain the solid volume concentration from the solid flux and velocity. Solid volume concentrations may be determined by two methods, the flux-velocity method and the time-averaging method.

Experimental Equipment

A schematic drawing of the experimental test unit is shown in Figure 14. The test unit consists of five major parts: 1) the primary gas flow inlet, 2) the solids feed section, 3) the solids/gas mixing chamber, (4) the measurement (test) section, and 5) the cyclone and solids recirculation section.

The primary gas flow inlet section consists of four filters to remove water and oil droplets from the compressed air, a pressure regulator to lower the high-pressure air (80 to 120 psig) to the desired operating pressure (20 to 30 psig), and a flow meter to measure the total air flow rate.

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Figure 14. SCHEMATIC DRAWING OF SOLIDS RECIRCULATION LDV TEST LOOP

In the solids feed section, solids particles from a storage hopper were fed into the test unit via a feed screw. A Penberthy jet-pump eductor (Figure 15) was used to create the pressure gradient required to overcome the cohesiveness of the particles and cause the solids to flow. The jet pump creates a negative pressure zone after the nozzle, which causes the particles to flow into the test unit.

The mixing chamber consisted of a 2-foot-long section of 2-inch-diameter pipe. The mixing section was added to the test unit to allow the solids to mix well with the gas before the mixture entered the test section.

A 10-foot-long section of 2-inch-diameter clear PVC pipe oriented vertically, served as the test section in the unit. The test section was located after a 3.5-foot-long section which allowed the solids and the gas to accelerate to their steady-state value. A pair of optical-glass windows 180 degrees apart were mounted in the test section after the acceleration section, to allow the laser beam to penetrate into the test section. The 20-mm-diameter window was designed to prevent accumulation of particles in front of the window. Differential pressure transmitters and gauges were distributed along the riser to measure the axial pressure distribution and pressure fluctuation during the tests. Near the bottom of the riser, spherical polystyrene tracer particles (0.96 microns in size) were added to the riser by a TSI atomizer, to allow the measurement of the gas velocity.

Following the test section, the solids were collected in two cyclones connected in series. A cloth filter captured the extremely fine particles which escaped through the cyclone. The solids collected by the cyclones were recirculated back to the feed system through two standpipes. Ball valves in the standpipes enabled the solids circulation rate to be controlled.

In a typical test, both ball valves in the recirculation standpipe were opened completely, and 300 grams of soil shale particles were loaded into the system. The frequency shift of the laser beam was set at zero. After this adjustment was completed, all of the settings on the photodetector and the frequency counter were set. The gas volumetric flow rate was then adjusted to the desired value. The LDV was then used to measure the particle velocity and the particle size. The axial pressure profile and the pressure fluctuations in the riser were also measured.

Figure 15. SCHEMATIC DRAWING OF JET-PUMP EDUCTOR

Different steady-state gas and solid flow rates were obtained by adjusting the gas flow rate through the system or by adjusting the ball valves in the cyclone recirculation standpipes.

Experimental Results

As described above, the calibration of the LDV to measure particle size distribution requires a reference flow condition. It was assumed that the reference particle-size distribution obtained using a Coulter Counter was the same as that obtained at a gas flow rate of 5 SCFM.

It was found that the shale particle-size ranged from 0.3 microns to 70 microns, with an average size of 13.6 microns. The calibration curve (Figure 16) showing the relationship between particle size and the amplitude of the signal from the LDV, was obtained using the technique described above.

Due to different mixing characteristics near the wall compared to the center of the pipe, the particle-size distribution is not uniform across the diameter of the pipe. Therefore, the particle-size distribution and the particle velocity were measured with the LDV at six different radial positions in the 2-inch-diameter test section: 0.032, 0.226, 0.290, 0.548, 0.806, and 0.935 inches from the centerline of the pipe. At each location, 1000 Doppler bursts were collected for statistical analysis of the data. The experimental particle-size distributions obtained at each radial location at a gas flow rate of 5 SCFM are shown in Figures 17, 18, 19, 20, 21, and 22.

The radial profile of the particle size obtained at a gas flow rate of 5 SCFM is given in Figure 23. Very few large particles (or agglomerates) were found near the wall probably because of particle collision (and subsequent breakup) with the wall. Large particles were measured at other radial locations except at the location 0.290 inches from the centerline. At this location, only very small particles were detected. At this location, it was found that there was a sharp change in the particle velocity. This indicates a shear interaction within the particle phases, and would tend to cause agglomerates at these locations to be more unstable and break up. This could explain why larger particle sizes were rarely measured at this location. It is not known at this time why the particle shear interaction exists at this location.

Figure 16. PARTICLE SIZE CALIBRATION CURVE FOR THE LDV PARTICLE

Figure 17. PARTICLE SIZE DISTRIBUTION OBTAINED WITH THE LDV
 (Gas Flow Rate: 5 SCFM, Dimensionless Radius: 0.032)

Figure 18. PARTICLE SIZE DISTRIBUTION OBTAINED WITH THE LDV
 (Gas Flow Rate: 5 SCFM, Dimensionless Radius: 0.226)

Figure 19. PARTICLE SIZE DISTRIBUTION OBTAINED WITH THE LDV
(Gas Flow Rate: 5 SCFM, Dimensionless Radius: 0.290)

Figure 20. PARTICLE SIZE DISTRIBUTION OBTAINED WITH THE LDV
 (Gas Flow Rate: 5 SCFM, Dimensionless Radius: 0.548)

Figure 21. PARTICLE SIZE DISTRIBUTION OBTAINED WITH THE LDV
(Gas Flow Rate: 5 SCFM, Dimensionless Radius: 0.806)

Figure 22. PARTICLE SIZE DISTRIBUTION OBTAINED WITH THE LDV
(Gas Flow Rate: 5 SCFM, Dimensionless Radius: 0.935)

Figure 23. PARTICLE SIZE VARIATION WITH RADIUS
(Gas Flow Rate: 5 SCFM)

Probability density distributions of the particle velocity at each radial location in the test section were also obtained at a gas flow rate of 5 SCFM. A typical plot of probability density versus particle velocity is shown in Figure 24. The average (mean) as well as the fluctuating (standard deviation) velocity were calculated for five different particle size ranges from the probability function. The particle size ranges used were:

- Group 1: less than 7 microns
- Group 2: from 7 to 15 microns
- Group 3: from 15 to 30 microns
- Group 4: from 30 to 45 microns
- Group 5: greater than 45 microns

Figures 25, 26, 27 and 28, show the radial profiles of the mean and fluctuating particle velocities as a function of particle size, for a gas flow rate of 5 SCFM. In general, plug-flow occurs throughout the pipe, except at the location 0.29 inches away from the centerline. At this location, the mean and fluctuating particle velocities in particle-size Groups 2 and 3 went through a minimum. As discussed above, no particles from Groups 4 and 5 were measured at this location. The same type of behavior can be seen from a plot of particle velocity versus particle size at each radial position (Figures 29, 30, 31, 32 and 33).

Task 5. Large-Scale Flow Tests

This quarter, work continued on modifying the large-scale test unit to enable it to operate with cohesive solids. The gas distributor of the 5-foot-diameter fluidized bed was modified to allow higher gas flow rates. This involved removing several hundred "bubble caps" and replacing them with larger ones. In addition, aeration taps were added to the 12-inch-diameter downcomer to help control the recirculation rate of the cohesive solids.

Next quarter, tests will be conducted in an auxiliary unit to determine the optimum way to control the recirculation rate of the cohesive solids.

Task 6. Comparison of Model With Data and Preparation of Final Report

No work was performed on this task this quarter.

Figure 24. PROBABILITY DENSITY AS A FUNCTION OF PARTICLE VELOCITY
 (Gas Flow Rate: 5 SCFM)

PWSR7

Figure 25. MEAN AND FLUCTUATING GAS VELOCITY AS A FUNCTION OF PIPE RADIUS
(Particle Size < 7 Microns)

PW5R15

Figure 26. MEAN AND FLUCTUATING GAS VELOCITY AS A FUNCTION OF PIPE RADIUS
(Particle Size < 7 to 15 Microns)

Figure 27. MEAN AND FLUCTUATING GAS VELOCITY AS A FUNCTION OF PIPE RADIUS
(Particle Size < 15 to 30 Microns)

Figure 28. MEAN AND FLUCTUATING GAS VELOCITY AS A FUNCTION OF PIPE RADIUS
(Feed Distribution)

Figure 29. PARTICLE VELOCITY AS A FUNCTION OF PARTICLE SIZE
(Q = 5 SCFM, Dimensionless Radius: 0.032)

Figure 30. PARTICLE VELOCITY AS A FUNCTION OF PARTICLE SIZE
(Q = 5 SCFM, Dimensionless Radius: 0.226)

Figure 31. PARTICLE VELOCITY AS A FUNCTION OF PARTICLE SIZE
(Q = 5 SCFM, Dimensionless Radius: 0.29)

Figure 32. PARTICLE VELOCITY AS A FUNCTION OF PARTICLE SIZE
(Q = 5 SCFM, Dimensionless Radius: 0.548)

Figure 33. PARTICLE VELOCITY AS A FUNCTION OF PARTICLE SIZE
(Q = 5 SCFM, Dimensionless Radius: 0.806)

NOMENCLATURE

A_d	= Doppler burst amplitude
A_{do}	= amplitude of Doppler signal generated by particle passing through the center of the focusing volume
b_o	= e^{-2} dimension of focusing volume
d_f	= fringe space
d_p	= particle diameter
E_x	= photon energy
f_d	= Doppler burst frequency
g_o	= radial distribution function
G	= solids mass flux
I	= radiation intensity
I_o	= initial radiation intensity
l	= path length of particle
l_{max}	= maximum path length of particle in fringe space
P	= pressure
Q	= gas volumetric flow rate
t	= thickness of absorbing material
U	= particle velocity component perpendicular to optical axis
V	= volume
V_p	= solids velocity
W_i	= weight fraction of component i
W_p	= weight of powder
α	= radiation wavelength
$\bar{\Delta\tau}_i$	= average time period of a Doppler burst
$\Delta\tau_i$	= i^{th} period in a Doppler burst
δ	= linear-absorption coefficient

ϵ_i = volume fraction of component i
 ϵ_s = solids volume fraction
 γ = mass absorption coefficient
 γ_{mix} = mixture absorption coefficient
 γ_a = mass absorption coefficient for air
 γ_s = mass absorption coefficient for solid
 γ_i = mass absorption coefficient for component i
 ρ = absorber density
 ρ_{mix} = density of absorbing mixture
 ρ_p = particle density
 ρ_s = solid absorber density

Subscripts

g = gas phase
 s = solid phase

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