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OPTICAL INSTRUMENTATION AND STUDY OF GAS-SOLID SUSPENSION FLOWS
FINAL REPORT

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ABSTRACT

A new technique and particle detecting system for the quantification of local fluid flow velocities, particle concentrations and size distributions in gas-solid suspension flows has been successfully developed and constructed. A new 2-inch diameter pneumatic-pipe test-loop facility for study of solids transport flows has been built and in operation. In order to check scaling law developed from the experimental results in the 2-inch pipe, a 4-inch pipe test-loop facility was also designed and constructed. In the past, the mechanics of suspended-solid flow have not been solved in a closed form due to the lack of a model for the turbulent field to pick up solid particles from the flow boundary. In this research project, we have identified the existence of micro-hairpin vortices as a major mechanism for the lifting of solid particles from the flow boundary. This permits one to formulate a realistic model. That is, the introduction of a particle source term in the governing transport equation for the suspended particles. The resultant solution predicts the correct critical flow conditions for the initial pickup of different sizes of solid particles and their subsequent concentrations in the flow field.

1. INTRODUCTION

The objective of this research is to develop techniques and instrumentation for the quantification of local fluid flow velocities, particle concentrations and size distributions in gas-solid suspension flows. The other equally important objective is to use the new instrument to study the mechanics of suspended-solid flows. Through our effort in developing the particle detecting system, we have succeeded in building a reliable and accurate optical instrument system. In the following, the detailed discussion of the particle detecting system and experimental setup will be given. New and unique experimental results of suspended-solid flows were obtained using the newly developed particle detecting system. On carefully studying the experimental results, we have identified the existence of micro-hairpin vortices as a major mechanism for the lifting of solid particles from the flow boundary. A recent paper entitled "A new view concerning suspended-solid flows" contained the details of experimental as well as theoretical results of this research project. Therefore, it is attached here as Appendix A. List of presentations and publications for the project is given as Appendix B. The personnel for the project is listed in Appendix C.

2. PARTICLE DETECTING SYSTEM

The particle detector used in this research is based on the unique characteristic of the reflection of uniform white light at the gas-solid interface of a micro-glass sphere, see Fig. 1. In the figure, the reflectance of light r is given for different incident light angles ϕ , where ϕ is defined as the angle of incident light with respect to the normal of the interface between the media, Jenkins and White. One notes that at $\phi = 62.5^\circ$, the reflectance of the component of polarized light which is perpendicular to the plane of the incident light r_s is 18%, and the reflectance of the parallel polarized light r_p is approximately zero; i.e., near the Brewster angle. Hence, one can improve the signal to noise ratio of the detector by filtering out the parallel component of the scattered light. Fig. 2 shows the ray of incident light with a forward scattering angle of $\theta = 2\phi = 125^\circ \pm 10^\circ$ from a glass sphere. This specific scattered light is selected for detection by the light detector. The effective light reflecting-surface of the glass sphere, as seen by the light detector, is also shown in Fig. 2. It is an intense spot of light approximately 1/10 of the diameter of the glass sphere. The intensity of other rays of light that are scattered into the specific detecting angle is negligible. Figure 3 shows the general isometric view of the particle detecting system. Two parallel white-light beams, with high uniformity in intensity, are produced from a Koehler-lamp light source. Particles crossing the sampling areas A_1 and A_2 are detected by the photomultiplier tube 1 and 2, respectively. The width of the sampling area is defined by the length of the light

masking-slit placed over the light detector. Similarly, the thickness of the detecting volume is defined by the width of the slit, see Fig. 3. The particle sampling area A_1 of the detector is designed to be a square of 1.5 mm x 1.5 mm. The thickness of the sampling volume is 0.08 mm. Thus the detector has a sampling area $A_1 = 0.0225 \text{ cm}^2$ and a sampling volume $V = 1.8 \times 10^{-4} \text{ cm}^3$. Hence, the probability of having two particles in the same volume V at the same time for a maximum concentration of particles of $C = 500/\text{cm}^3$ is

$$P = (CV)^2 = 0.81\%. \quad (1)$$

This error is greatly reduced for lower values of C . The particle-size band-spread error due to particles crossing the perimeter of A_1 and detected as half-size particles can be expressed for a maximum particle diameter $d = 50$ microns as

$$C_d/2/C_d = 0.4 d/A_1^{1/2} = 1.3\%. \quad (2)$$

This error also is reduced for smaller size particles. The dark cavities shown in Fig. 3 are used to provide a dark field for the detector.

As shown in Fig. 3, the particle detecting system has two light detectors, photomultiplier #1 and #2. As a particle first enters the sampling area A_1 , the specific 125° forward scattered light is detected by the light detector #1 as shown. The peak signal-pulse intensity is related to the square of the diameter of the particle. Hence, the square-root of the signal gives a linear output signal proportional to the diameter of the micro-glass sphere. A typical calibration curve is shown in Fig. 4, and a typical signal recording is shown in Fig. 5. The second sampling area A_2 is placed $\Delta x = 2.0$ mm downstream of the first sampling area A_1 , which provides a delay time Δt of a particle crossing the sampling areas A_1 and A_2 . Hence, the velocity of the particle is $U = \Delta x/\Delta t$. The mean flow velocity can be obtained by performing the cross correlation of the signals from the two detectors $A(t)$ and $B(t)$ corresponding to the detector #1 and #2, respectively:

$$R(\tau) = \frac{1}{T} \int_0^T A(t-\tau)B(t)dt, \quad (3)$$

where τ is the delay time, and T is the total correlation time. A typical correlation function $R(\tau)$ is shown in Fig. 6. In general, the correlation function $R(\tau)$ will indicate a typical functional peak corresponding to the mean delay time $\Delta\tau$ for the particles crossing the two light detectors. The value of $\Delta\tau$ is related to the mean velocity of the particles as $\bar{U} = \Delta x/\Delta\tau$. In addition, the correlation has the appearance of a Gaussian distribution function. From the width of the distribution function one may readily obtain both the values of the rms intensity u' and the peak intensity of turbulence u'_{peak} . The particle concentration in the suspended-flow system can be

obtained as:

$$C = q/\bar{U}A_1, \quad (4)$$

where q is the number count of particles of a given particle diameter range crossing the sampling area A_1 per unit time, and $\bar{U}$ the mean velocity of the particles.

The particle detecting system has been successfully built. Figure 7 is a photograph showing the various components inside the light-source tube, including condensing lens, projection lens, Koehler lamps and light beams defining mask. The light sensing detector tube is shown in Fig. 8 with various components displayed before final assembling. The components include image forming lens, photomultipliers and sampling volume defining slits. These two tubes had been assembled and mounted on a aluminum plate as shown in Fig. 9. The aluminum plate together with the optical particle detector assembly was then mounted on a vertical moving stage as shown in Fig. 10. Light beams and scattered lights are directed through the glass windows on both sides of the flow pipe. The optical glass windows were not in place at the time when the picture was taken. They were designed and fabricated later on as shown in Fig. 11. The optical glass windows for the detector were modified from an originally vertical orientation to a sloping one as shown in Fig. 11. This configuration eliminates the problem of the accumulation of solid particles at the bottom of the slit openings of the pipe and on the surface of the glass windows.

3. EXPERIMENTAL SETUP

A 2-inch diameter pneumatic-pipe test-loop built specifically for the present study is shown in Fig. 12. The maximum flow speed for the test system is 50 m/sec. It is driven by a 3 hp 3-stage turbopump. Photographs showing the turbo-pump/motor assembly are given in Fig. 13. The overall pipe length is 5 m long. This is to assure that both the turbulent flow field and the suspended particle load have reached a fully established state. The test system has one horizontal out going test section and one variable-slope return test section, as illustrated in the picture of Fig. 14. The optical detector for local measurements of flow speed, particle size and particle concentration is shown mounted on a two-axes traversing instrument mount, a picture of which is shown in Fig. 15. The optical detector is mounted on the vertical axis, and the pipe is mounted on the horizontal axis. This permits one to make local measurements at different radial positions in the pipe. There are two sloping slits, each 5 mm in width, on the PVC pipe to permit light from the detector to go in and out, see the detail view in Fig. 12, also see the picture shown in Fig. 11. The return flow of the test system is directed into a cyclone particle-separator to separate the particle from the air. The pictures showing the outside and inside of the cyclone particle-

separator are given in Figs. 16 and 17. Solid particles are then recycle into the test system through a feed valve and a venturi tube. However, the solid particle feed-system was later modified from the original passive venturi-feeding design to a positive screw-feeding design where the solid particle feed-rate into the flow system can be subjected to independent control. The feed rate is controlled by a precision variable-speed drive motor. A photograph of the particle screw-feed system is shown in Fig. 18. To prevent fluidization of the particle in the particle feed-column, the column is made 25 cm tall. In this manner, the equivalent hydrostatic-pressure developed by the solid particles at the bottom of the feed column is higher than the differential gas-pressure existing between the screw-feed outlet and the particle collecting cyclone. The pictures of the feed-column and feed-screw are shown in Figs. 19 and 20. The horizontal test section is 6 m long and 5.1 cm in diameter. A manometer is shown connected to two pressure taps along the pipe for monitoring the wall shear stress which is an important parameter in characterizing the turbulent flow in the pipe.

Toward the end of the project, it was found that a test loop with a larger-radius pipe would be desirable in order to check the scaling law developed from the experimental results in the 2-inch pipe. Therefore, a 4-inch pipe test-loop was designed. The construction and modification of the test-loop facility were carried out during the extension period of the project. The major modifications involved the fabrication of the new glass windows for the detector and pipe connection to the cyclone particle-separator. A picture of the new glass windows on the 4-inch pipe along with the 2-inch pipe is shown in Fig. 21. The new setup for the 4-inch test-loop is now essentially completed and will serve as a valuable facility for future solids transport studies.

4. EXPERIMENTAL RESULTS

The experiment was carried out for four different groups of glass beads with mean diameter $d=1600\text{ }\mu\text{m}$, $173\text{ }\mu\text{m}$, $115\text{ }\mu\text{m}$, and $49\text{ }\mu\text{m}$. The size variation within each size group is approximately $\pm 10\%$ of the mean. Particle concentration profiles along the vertical diameter of the pipe were measured by the newly developed particle detecting system. Complete detailed experimental results together with the theoretical analysis were given in a recent paper entitled "A New View Concerning Suspended-Solid Flows".² Therefore, this paper is reproduced in its entirety and attached here as Appendix A. All the experimental and theoretical discussions and results will be referred to Appendix A.

5. CONCLUSION

A new optical particle detecting system has been successfully developed and fabricated. A pneumatic-pipe test-loop built specifically for the present study has been shown to be a useful facility for solid-suspension flow studies. A series of experiments have been carried out to study the mechanics of suspended-solid flow and to test the new detecting system. From the experimental results, we have obtained clear evidence that the micro-hairpin vortices do play a key role on the mechanics of suspended-solid flows. Hence, this work might in the future contribute to basic improvements for many other physical problems associated with turbulent flows.

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Fig. 1. Reflectance over the air-glass interface. Reflectances r_s and r_p are the polarized light components perpendicular and parallel to the plane of incident light shown in the figure, respectively.

Fig. 2. Ray of light having an incident angle of 62.5° is reflected from a micro-glass sphere with a forward scattering angle of $125^\circ \pm 10^\circ$. It is selectively detected by the light sensor. The rotated top view of the reflecting surface as seen by the detector is shown in the lower half of the figure.

Fig. 3. Isometric view of the particle detecting system.

Fig. 4. Typical calibration curve for micro-glass spheres.

Fig. 5. Typical signals of micro-glass spheres. The time delay between the pair of light detectors is clearly indicated.

Fig. 6. Cross correlation of $A(t)$ and $B(t)$ time series for different delay time τ , $R(\tau)$. The value of $R(\tau)$ is shown in arbitrary unit. The peak of $R(\tau)$ indicates the mean delay time $\Delta\tau$ of $B(t)$ with respect to $A(t)$. For this case $\Delta\tau = 0.0104$ sec, which gives a mean bubble velocity of $U = \Delta x / \Delta\tau = 0.67$ m/sec.

Fig. 7. Light-source tube with inside components displayed.
The components include condensing lens, projection lens,
Koehler lamp and light-beams defining mask.

Fig. 8. Detector tube showing internal components of image forming
lens, photomultipliers, and sampling volume defining slits.

DETECTOR TUBE

LIGHT-SOURCE TUBE

Fig. 9. Assembled light-source tube and detector tube.

Figure 10. Optical particle detector assembly mounted on the vertical moving stage. Light beams and scattered lights are directed through the glass windows (not shown) on both sides of the flow pipe.

Figure 11. Optical glass windows.

Fig. 12. Isometric view of the pneumatic test-loop designed specifically for the study of solid-suspension flows.

Figure 13. Photographs showing the turbo-pump/motor assembly. The radial guide vanes are used to guide the gas radially into the suction inlet of the pump to prevent formation of a strong swirling flow.

Figure 14. The piping loop with a horizontal 2-in PVC pipe and a sloping return pipe.

Figure 15. A photograph showing the vertical moving stage for particle detector and the lateral moving stage for pipe.

Figure 16. A photograph showing the cyclone particle-separator setup with the turbopump/motor on the top of the assembly.

Figure17. A photograph showing the inside of the cyclone particle-separator.

Figure 18. Particle screw-feed system.

Figure 19. Modified particle-feed system.

Figure 20. Feed-screw.

Figure 21. The new glass windows for the 4-inch pipe along with the old glass windows for the 2-inch pipe.

APPENDIX A.

A NEW VIEW CONCERNING SUSPENDED-SOLID FLOWS

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ABSTRACT

In the past, the mechanics of suspended-solid flow have not been solved in a closed form due to the lack of a model for the turbulent field to pick up solid particles from the flow boundary. Without a pickup mechanism, all particles will eventually fall to the boundary and no steady-state solution exists for the problem. Recently, we have identified the existence of micro-hairpin vortices as a major mechanism for the lifting of solid particles from the flow boundary. This permits one to formulate a realistic model. That is, the introduction of a particle source term in the governing transport equation for the suspended particles. The resultant solution predicts the correct critical flow conditions for the initial pickup of different sizes of solid particles and their subsequent concentrations in the flow field.

INTRODUCTION

The well known equation for sedimentary transport originally developed by O'Brien¹ and later by Rouse² is incomplete. The equation contains no mechanism for the flow field to pick up heavy particles from the flow boundary. From the recent study of the coherent structure of turbulence near the flow boundary, it was found that there are strong micro-vortices³ existing near the flow boundary where the mean velocity-gradient is most intense. These micro-vortices are the key mechanism by which heavy particles are being picked up from the flow boundary and subsequently entrained into the main turbulent-flow field. Without this key mechanism the theory for solid suspension flows cannot be successfully expressed in a closed form; i.e., there will be no steady-state solution for the problem. Because all suspended solids eventually will settle to the bottom of the flow boundary. Unlike the turbulent heat-transfer problem where the molecular diffusivity of gas dominates the transfer of heat from the flow boundary, the same mechanism cannot lift heavy particles. The success of the transport theory for heat has caused scientists to neglect the existence of the micro-hairpin vortices which are crucial for the lifting of solid particles from the flow boundary. To account for this lifting mechanism, we proposed to add a simple source term $S(y)$ to the basic transport equation as

$$\frac{d}{dy} K(y) \frac{dC}{dy} + W_f \frac{dC}{dy} + S(y) = 0, \quad (1)$$

where C is the concentration of solid particles; $K(y)$ the eddy diffusivity of the turbulent flow which is a function of the distance y from the flow boundary; and W_f the mean fall-velocity of particles due to gravitational acceleration. The first term in Eq. 1 is the rate of particles diffusing in or out of a control volume by the action of turbulence, and the second is the rate of particles falling out under the action of gravitational force. These are the two original terms proposed by O'Brien and Rouse. The third term $S(y)$ in Eq. 1 is the newly proposed particle-source due to the lifting action by the micro-hairpin vortices. Presently, the unknown factors in Eq. 1 are W_f and $S(y)$. This is because the mean free-fall velocities for large particles may not achieve full terminal velocity due to the finite depth of a flow system. Also, the number density of micro-hairpin vortices and other details relating to the source term $S(y)$ are still unknown. These factors will have to be determined through experimental measurements and analytical simulations.

Through the successful development of an optical detector for the measurement of particle-size concentrations⁴, we are able to obtain particle concentration data over a wide range of flows and particle

Fig. 1. Isometric view of the particle detecting system.

parameters. From these data we can further determine some of the unknown functional characteristics for the governing parameters. Since the details for the optical detector and the experimental setup had previously been described in the Proceedings of DOF Solid Transport Contractors' Review Meetings⁴, no further description for these will be given in this paper. However for a quick reference, the isometric layout for the optical detector is shown in Fig. 1, and the experimental setup is shown in Fig. 2.

From the experimental results, we have obtained clear evidence that the micro-hairpin vortices do play a key role on the mechanics of suspended-solid flows. Hence, this work might in the future contribute to basic improvements for many other physical problems associated with turbulent flows.

MICRO HAIRPIN VORTICES

In the past treatment for the turbulent boundary-layer theory, the role played by the micro-hairpin vortices has been neglected without noticeable undesirable consequences. This is no longer true when the transport of suspended solid particles is involved. For clarity, one should differentiate the micro-hairpin vortices from the large hairpin vortices commonly observed in the wake zone of a turbulent flow-field⁵. The micro-hairpin vortices that exist in the zone of the intermediate sublayer is physically small and short

Fig. 2. Isometric view of the pneumatic test-loop for the study of suspended-solid flows.

in development time, typically millimeter in size and millisecond in time. However, they have the highest velocity field within a turbulent boundary-layer. In fact, they are the very source of turbulence. It is only through recent study of the inception of cavitation within a turbulent boundary-layer that the evolving characteristics of the micro-hairpin vortices were clearly observed⁶.

Micro-hairpin vortices are developed as flow instability at the laminar sublayer. They started out as parallel line vortices transverse to the flow direction. These vortices tend to pair up and interact with one another. The leading vortex line tends to lift the trailing line, while the trailing line tends to depress the leading line. Due to uneven spacing between the pair of interacting lines, the lines tend to evolve into loosely twisted strands as a rope. The lifted parts are immediately subjected to high speed dragging action of the mean flow field, while the reverse is true for the depressed parts. The straining of the vortex lines by the mean flow field produces very intense micro-hairpin vortices. For a typical boundary-layer flow, the peak velocity attained by these vortices can be estimated from the known data of root-mean-square velocity fluctuation⁷, $\sqrt{\bar{u}'^2}$, in this zone as

$$U_v = 3 \sqrt{\bar{u}'^2} + U_0 = (3 \times 0.11 + 1) U_0 = 1.3 U_0, \quad (2)$$

where U_0 is the mean flow velocity of the system; i.e., one may assume that the peak fluctuating velocity to be 3 times the root-mean-square value at one standard deviation.

Micro-hairpin vortices can be made visible under various cavitating conditions within a water tunnel³. By using a strobe light having a pulse duration of $10 \mu s$ and repeating at a rate of less than 15 per second, one can observe the existence of these vortices. At the very inception of cavitation, one can clearly see the legs of the vortices as fine cavity lines sticking out from the flow boundary. They all incline approximately at a forward angle of 45° from the wall, and appear like short hairs growing out of the wall. By lowering the pressure in the tunnel very slowly, one begins to see the strange phenomenon of cavitating bubbles with twin tails, see Fig. 3. That is, the head of the hairpin vortex has transformed into a bubble, while the tails remain distinct under the intense straining by the mean flow. From this figure, one may examine with care the cavity surfaces of the twin tails. There are counter rotating spiral waves with a spiral angle of 45° . Hence, they are part of a micro-hairpin vortex with a strong three-dimensional flow field. That is, there exists a high axial velocity component equal to the peak of the circulating velocity field. From the known inception cavitation index, one can also estimate the peak velocity vector for the tails to be approximately 1.3 times of the mean flow velocity⁶ U_0 . This will be shown later to be a key value for the problem of suspended-solid transport. By continued slow decrease of the pressure in the tunnel, the various early stages of evolution for the vortices can be made visible in a backward sequence.

The cycle of straining action for the hairpin vortices can be expressed by a simple geometric analysis. Assume a leg of the vortex with a length L_0 has been lifted into the vertical position shown in Fig. 4(a). Starting from here, the vortex line is subjected to the convective action of the mean flow field with an intense velocity gradient dU/dy . As shown, the vortex line L will continue to be stretched with time. The forward angle θ of the line with respect to the flow boundary will decrease with time from 90° to 0° . The rate of strain for the vortex line as a function of the angle θ can be expressed from the figure as

$$\frac{dL/L}{dt} = \frac{U}{L_0} \cos \theta \sin \theta = \frac{1}{2} \frac{dU}{dy} \sin 2\theta. \quad (3)$$

Fig. 3. Cavitation of a micro-hairpin vortex over a flow boundary.

The normalized rate of strain can be written as

$$2 \frac{dL/L}{dt} \frac{dy}{dU} = \sin 2\theta . \quad (4)$$

This is plotted in Fig. 4(b). It is clear that at $\theta = 45^\circ$ the rate of strain is the maximum. This should correspond to the development of the maximum velocity in the vortex line due to the conservation of angular momentum. It is the very reason for the inception of cavitation to be seen at this very angle. It is also where the solid particles are being sucked up by the intense up lifting velocity field. The time of this energizing action can be estimated from the time the angle θ moves from 60° to 30° . If one assume the mean velocity at the height of 0.5 cm from the flow boundary is 10 m/s, the elapse time for this action is approximately equal to $\Delta t = 0.5/1000 = 5 \times 10^{-4}$ s. High-speed photography by Zinng⁸ has also confirmed that sand particles being lifted by wind takes place mostly at an angle of approximately 40° . Furthermore, a small spiralling motion for the particle can also be observed. There is beyond any doubt that these are the very action of the micro-hairpin vortices. It should also be noted that the flow field where the vortex leg touches the flow boundary is not a closed circulating field. It is an open inward-spiralling field that can gather particles towards its center over an area greater than the area of the vortex core. This in turn produces a high lifting velocity along the axis of the vortex.

The preceding description of the micro-hairpin vortices is intended to provide a base for the following analyses of the suspended-solid flows.

THEORY

The basic transport equation for suspended-solid flows in a horizontal pipe is approximated as a two dimensional channel flow. This is assumed permissible, since no high precision is required for this preliminary study. Hence, the particle-concentration profile along the vertical diameter of a pipe is expressed by Eq. 1. The eddy diffusivity $K(y)$ in the equation is expressed through the mixing-length concept as

$$K(\bar{z}) = \sqrt{\tau_0/\rho} K R (1 - |\bar{z}|) = U^* K R (1 - |\bar{z}|) , \quad (5)$$

where τ_0 is the wall-shear stress, ρ the mass density of fluid, $U^* = \sqrt{\tau_0/\rho}$ the shear velocity, $K = 0.4$ the Karman constant, R the radius of pipe, and $\bar{z} = z/R$ the normalized radial distance from the center of pipe. The mixing length of turbulence is expressed as $\ell = K R (1 - |\bar{z}|)$; i.e., ℓ increases linearly with distance from the flow boundary as $(1 - |\bar{z}|)$. We further define the following nondimensional

Fig. 4. (a) Straining of a vortex line L by the mean velocity-gradient field.
(b) Normalized rate of strain of a vortex line with respect to forward angle θ .

parameters:

$$\bar{C} = C/C_0, \quad \bar{W} = W_f/U^*, \quad \text{and} \quad \bar{S}(\bar{z}) = \frac{S(z)R}{C_0 U^*}$$

where C_0 is the particle concentration at the bottom of the flow boundary. Substituting these parameters into Eq. 1, we have

$$0.4(1 - \bar{z}) \frac{d^2 \bar{C}}{d\bar{z}^2} + (0.4 \operatorname{sgn}(-\bar{z}) + \bar{W}) \frac{d\bar{C}}{d\bar{z}} + \bar{S}(\bar{z}) = 0. \quad (6)$$

Equation 6 can numerically be solved for different $\bar{W}$ and $\bar{S}(\bar{z})$ parameters. The boundary conditions are $\bar{C} = 1$ at $\bar{z} = -1$ and $\bar{C} = 0$ at $\bar{z} = 1$. Various combinations of $\bar{W}$ and $\bar{S}(\bar{z})$ were tried to find the best fit with the experimentally measured $\bar{C}(\bar{z})$ for various known combinations of shear velocities U^* and particle sizes d . From these results, one can determine the functional characteristics for W_f and $S(z)$.

RESULTS AND DISCUSSIONS

The experiment was carried out for four different groups of glass beads with mean diameter $d = 1600 \mu\text{m}$, $173 \mu\text{m}$, $115 \mu\text{m}$, and $49 \mu\text{m}$. The size variation within each size group is approximately $\pm 10\%$ of the mean. Particle concentration profiles along the vertical diameter of the pipe were measured for the largest size group with shear velocities $U^* = 46.5 \text{ cm/s}$, 72.9 cm/s , and 93.6 cm/s . For the smaller size groups the concentration profiles were measured at $U^* = 23.2 \text{ cm/s}$, 35.1 cm/s , 51.4 cm/s , 72.9 cm/s , and 93.6 cm/s . The maximum particle concentration studied is less than $0.03 \text{ particles/cm}^3$ for the largest particle size studied and less than $300 \text{ particles/cm}^3$ for the smallest one. This is to assure that the turbulent flow field will not be significantly modified by the suspended particles. The results of the measurements are shown in Fig. 5 for particle size $d = 1600 \mu\text{m}$; Fig. 6 for $d = 175 \mu\text{m}$ and $115 \mu\text{m}$; and Fig. 7 for $d = 49 \mu\text{m}$. It is remarkable to note that under the same shear velocity U^* the concentration profiles are almost identical for the different particle sizes. This can be explained through the following analyses.

The corresponding best analytical fit for the measured data are shown as the solid curves in Figs. 5, 6, and 7. Through these analytical simulations we hope to find answers for the experimental observations. There are two unknown basic-parameters in the analytical expression for the distribution of particle concentration, Eq. 6. They are the mean free-fall velocity to the shear velocity ratio $\bar{W} = W_f/U^*$ and the normalized particle source distribution function $\bar{S}(\bar{z})$. The $\bar{W}$ parameter has a dominant effect on the particle concentration at the upper level of the pipe, while the source parameter $\bar{S}(\bar{z})$ effects the lower level. These characteristics permits one to adjust the two parameters for a best fit to the

Fig. 5. Particle-concentration profiles for $d = 1600 \mu\text{m}$ particles.

Fig. 6. Particle-concentration profiles for $d = 175 \mu\text{m}$ and $115 \mu\text{m}$ particles.

experimental results.

For particle sizes $d = 1600 \mu\text{m}$, $175 \mu\text{m}$, and $115 \mu\text{m}$, the best fitted values for the mean free-fall velocity were found to be the same $W_f = 20 \text{ cm/s}$. It is much less than the respective terminal fall-velocity of $W = 880 \text{ cm/s}$, 116 cm/s , and 68 cm/s for the particles. This is due to the fact that the pipe of this experiment is too small for these large particles to achieve their full terminal fall-velocities. To achieve the terminal velocity, these particles will require a respective free-fall height of 2000 cm, 24 cm, and 14 cm. These distances are noted to be larger than the pipe diameter of 5.2 cm for this experiment. To achieve a mean free-fall speed of $W_f = 20 \text{ cm/s}$, the particle will require an equivalent free-fall height of $h_f = 0.3 \text{ cm}$. At this low falling speed, the falling characteristic is mainly related to the gravitational acceleration with negligible effect due to the induced aerodynamic-drag. Hence, the effective mean free-fall velocity in a small pipe is governed by the size of pipe, and it can be taken as a constant for a wide range of particle sizes whose falling velocities are limited by the pipe. If this is true, a large pipe will be less efficient for the transport of large solid particles. That is, the $\bar{W}$ parameter will be larger, and the particle concentration will be less uniform. This will have to be verified in the future by experiments using larger pipes. For the smallest particle size $d = 49 \mu\text{m}$, we have found that these particles can reach their full terminal fall-velocity of $W = 16.7 \text{ cm/s}$ within the mean free-fall distance of $h_f = 0.3 \text{ cm}$ dictated by a 5.2 cm pipe. Hence for pipes larger than $D = 5 \text{ cm}$ and particle sizes less than $d = 49 \mu\text{m}$, one may apply the full terminal velocity in formulating the $\bar{W}$ parameter.

Fig. 7. Particle-concentration profiles for $d = 49 \mu\text{m}$ particles.

The nondimensional source parameter $\bar{S}(\bar{z})$ is by intuitive reasoning to be a function of

$$\bar{S}(\bar{z}) = f(C_0, U^*, R, h_v, W, d, d_v), \quad (7)$$

where C_0 is the concentration of particles at the wall, U^* the shear velocity, R the pipe radius, h_v the height of the hairpin vortices, W the terminal fall-velocity of particles, d the diameter of particles, and d_v the diameter of the micro-hairpin vortices. From the fitting of this parameter with the experimental results, we have found that $\bar{S}(\bar{z})$ can simply be expressed as

$$\bar{S}(\bar{z}) = \frac{S(z)R}{C_0 U^*} = 30 d \bar{z} \bar{B}(\bar{z}). \quad (8)$$

The function $\bar{B}(\bar{z})$ is related to the height of the micro-hairpin vortices h_v . For best fitting, $\bar{B}(\bar{z})$ is taken to be 1.0 from $\bar{z} = -1.0$ to -0.8 and tapered off to zero at $\bar{z} \geq -0.65$. Hence, from this experiment, the height of the micro-hairpin vortices should be approximately $h_v = 0.2 R$ and independent of the thickness of the intermediate sublayer. The distribution function $\bar{B}(\bar{z})$ is consistent with the nature in which particles are being lifted by the micro-hairpin vortices. The source function was found to be independent of W , d , and d_v . That is, within the ranges of flow speeds and particle sizes covered in this study, both the lifting velocity U_v and diameter d_v of the micro-hairpin vortices are larger than the respective terminal fall-velocity W and particle diameter d . This is analogous to the action of a vacuum cleaner. Most particles that can be sucked up will be taken up at the same rate, because the intake velocity is much greater than the terminal fall-velocities for the particles being sucked up.

It was further found that the critical shear-velocity U_c^* required to initiate the transport of solid particles is also independent of the particle size up to at least $d = 400 \mu\text{m}$. For particle sizes $d = 175 \mu\text{m}$, $115 \mu\text{m}$, and $49 \mu\text{m}$ studied, the value of U_c^* for picking up particles was found to be the same, $U_c^* = 16 \text{ cm/s}$. This is equivalent to a mean pipe flow speed of $U_0 = U_c^* / 0.047 = 340 \text{ cm/s}$ and a corresponding pipe flow Reynolds number of $Re = 10^4$. It is well known that $Re = 10^4$ is the limit for the development of a fully turbulent flow in a pipe⁹. Hence without a fully developed turbulent flow, no particles can be picked up from the flow boundary. At the initiation of a fully turbulent flow at $U_c^* = 16 \text{ cm/s}$, for a pipe of 5.2 cm , the lifting velocity component U_v for a micro-hairpin vortex is approximately equal to

$$U_v = 1.3 U_0 = \frac{1.3 U_c^*}{0.047} = 440 \text{ cm/s}. \quad (9)$$

Hence, any particles with a terminal fall-velocity less than 400 cm/s will be picked up from the flow boundary. This explains why all particles less than $400 \mu\text{m}$ in diameters are picked at the same critical shear-velocity $U_c^* = 16 \text{ cm/s}$. One should note that this value will be reduced with the increase in pipe size. One also notes in Figs. 6 and 7 that at the lowest value of $U^* = 23.2 \text{ cm/s}$ studied, the concentration profiles are the same for all sizes of particles. That is, any particles with a terminal velocity W much less than the lifting velocity U_v of the micro-hairpin vortices will be lifted and distributed in a similar way.

For the largest particle size studied $d = 1600 \mu\text{m}$, the critical shear-velocity U_c^* is dictated by its terminal fall-velocity of $W = 880 \text{ cm/s}$. Similar to Eq. 9, the lifting velocity U_v must be greater than W . Hence,

$$U_c^* > \frac{W}{1.3} 0.047 = 0.036 W = 32 \text{ cm/s}. \quad (10)$$

The measured critical shear-velocity for $d = 1600 \mu\text{m}$ is $U_c^* = 33.8 \text{ cm/s}$. This is very close to the predicted value. It should be noted that in this case the particle diameter d is almost the same as the diameter of the hairpin vortices d_v . Hence, for d/d_v greater than unity, U_c^* is expected to be a function of this ratio.

The preceding analyses explain why for all the particle sizes studied the source function $\bar{S}(\bar{z})$ is only proportional to the particle concentration at the wall and the shear velocity as expressed by Eq. 8. This give further proof for the existence of the micro-hairpin vortices and the important role they play in the mechanics of sediment transport.

CONCLUSION

We have through this study discovered the important role played by the micro-hairpin vortices for the transport of suspended solids. This has made possible for the problem to be solved in a closed form. For the problem of suspended-solid flows in a smooth pipe, we have found the critical shear-velocity required for maintaining a suspension flow to be:

$$U_c^* = 500 \nu / D \quad (11)$$

and

$$U_c^* = 0.04 W, \quad (12)$$

where ν is the kinematic viscosity of fluid, and D the diameter of pipe. Equation 11 is related to the condition for a fully developed turbulent flow at $Re = 10^4$, and Eq. 12 is related to the condition for the lifting velocity of micro-hairpin vortices U_v to be greater than the terminal fall-velocity W of the solid particles. The larger of the two equations dictates the critical condition.

For flows in which the shear velocity is greater than the critical shear-velocity, the concentration of particles can be expressed by the following differential equation:

$$0.4(1 - |\bar{z}|) \frac{d^2 \bar{C}}{d\bar{z}^2} + (0.4 \operatorname{sgn}(-\bar{z}) + W) \frac{d\bar{C}}{d\bar{z}} + 30 d\bar{z} B(\bar{z}) = 0, \quad (13)$$

where $B(\bar{z})$ is taken to be 1.0 for $\bar{z} = -1.0$ to -0.8 and tapered to zero for $\bar{z} \geq -0.65$. For large particles, where the mean free fall-velocity W_f is limited by the equivalent free fall height $h_f = 0.06 D$ for the flow field, $\bar{W}$ is taken to be W_f / U^* . For very fine particles, in which the full terminal fall-velocity W is achieved within the free-fall height h_f , $\bar{W}$ is expressed as W / U^* .

This paper is only intended as a preliminary presentation of the new discoveries concerning suspended-solid flows. A more refined study is yet to follow.

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APPENDIX B. LIST OF PRESENTATIONS AND PUBLICATIONS FOR
THE PROJECT

- Ling, S.C., Pao, H.P., and Zhang, X.S., "Mechanics of suspended-solid flows in a smooth pipe," Presented as a Keynote Address at the 4th International Symposium on Refined Flow Modeling and Turbulence Measurements, Wuhan, China, 20-23 Sept. (1990).
- Ling, S.C., Pao, H.P., and Zhang, X.S., "A new view concerning suspended-solid flows," Presented at the Symposium on Multiphase Flow and Separation Processes, 21st Annual Meeting of the Fine Particle Society, San Diego, Calif., 19-25 Aug. (1990).
- Ling, S.C., Pao, H.P., and Zhang, X.S., "On the mechanics of suspended-solid flows in a smooth pipe," Presented at DOE/NSF Workshop on Fluid/Solids Transport, Pleasanton, Calif., May (1989).
- Ling, S.C., and Pao, H.P., "Ideal combustion of solid fuels," Presented at 1988 Fall International Symposium, American Flame Research Committee, International Flame Research Foundation-- Coal: Fuel for Today for the Future, Pittsburgh, PA, 46 Oct. (1988).
- Ling, S.C., and Pao, H.P., "Optical instrumentation and study of gas-solid suspension flows," Proc. DOE Solids Transport Contractors' Review Meeting, Pittsburgh Energy Technology Center, Pittsburgh, PA., p. 95-102 (1988).
- Ling, S.C., "The optimum method for combustion of solid fuels," Presented at Workshop on Emissions Control Technology for Small-Scale Combustors, Pittsburgh, PA, 4 Nov. (1987).
- Ling, S.C., and Pao, H.P., "Optical instrumentation and study of gas-solid suspension flows," Proc. DOE Solids Transport Contractors' Review Meeting, Pittsburgh Energy Technology Center, Pittsburgh, PA., p. 130-144 (1987).
- Ling, S.C., and Pao, H.P., "Optical instrumentation and study of gas-solid suspension flows," Presented at the 18th Annual Meeting of the Fine Particle Society, Boston, MA, 3-7 Aug. (1987).
- Ling, S.C., and Pao, H.P., "Optical instrumentation for local measurements of gas-solid suspension flows," Presented at ASCE 6th Engineering Mechanics Division Specialty Conference, State University of New York, Buffalo, NY, 20-22 May (1987).

APPENDIX C. PERSONNEL

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