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MEASUREMENT OF THE LOCAL PARTICLE CONCENTRATION IN FULLY TURBULENT DUCT FLOW

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Abstract—Measurement techniques are reported for determining the average local particle concentration. Typical-local concentration measurements in fully turbulent duct flow are reported.

This study reports on a miniaturized probe which allows the measurement of the local particle concentration in a glass bead–air suspension. Typical results are given for the concentration profile in a fully turbulent direct flow.

A miniaturized optical system which relies upon the attenuation of a collimated light beam passing through a particulate suspension was used to measure the local particle concentration in the flow. This measurement technique is based upon the well known relationship between the transmitted and incident fluxes as given by the Lambert–Beer Law. For a polydisperse suspension of spherical particles,

$$\frac{f}{f_0} = \exp - \frac{3}{2} \frac{EL}{\bar{d}_p} \frac{\rho_p}{\bar{\rho}_p} \qquad [1]$$

where (f/f_0) is the transmittance, L is the optical path length, ρ_p is the particulate density in the suspension, $\bar{\rho}_p$ is the material density, $\bar{d}_p$ is the mean particle diameter of the polydisperse suspension and E is the extinction coefficient.

In the literature, the extinction coefficient, E, has been calculated for materials of different refractive index utilizing the parameter (Van de Hulst 1957; Penndorf 1958).

$$\alpha = \frac{2\pi a}{\lambda} \qquad [2]$$

where (f/f_0) is the transmittance, L is the optical path length, ρ_p is the particulate density in the suspension, $\bar{\rho}_p$ is the material density, $\bar{d}_p$ is the mean particle diameter of the polydisperse normalized size parameter, $2\alpha(n-1) > 20$ (Hodkinson 1966). With the particles employed in this work, the normalized size parameter was always greater than 29. Van de Hulst (1957) indicates an interparticle spacing of three times the particle radius as a sufficient condition of independent scattering. With the dilute suspension utilized in this study, the condition for independent scattering was always exceeded.

Since the particle diameter is large relative to the wavelength of light, that part of the light beam which actually collides with the particle is either absorbed within it or scattered by reflection or refraction, while a further equal quantity of light is scattered from the remainder of the light beam by diffraction. But the diffracted light is scattered very little from the forward direction, and therefore it would not be distinguishable from the light beam itself. If this were the case, the extinction coefficient would appear to be one. The miniature optical system depicted in figure 1 eliminates this problem with the use of lenses and pinholes. Theoretically, any light that is

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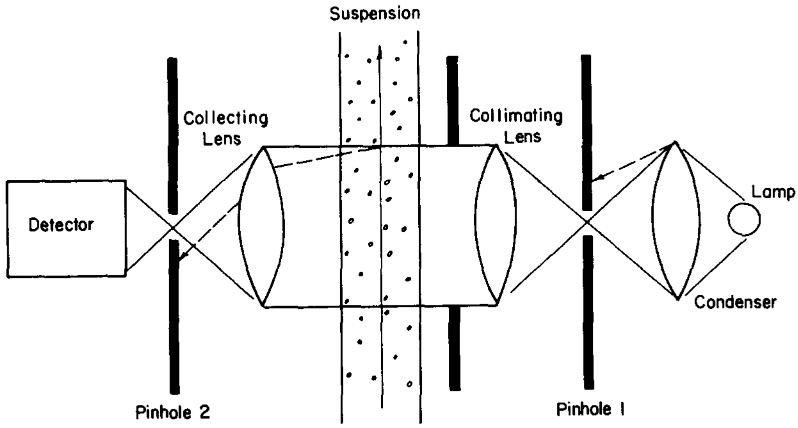

Figure 1. Optical system for measurement of particulate density.

scattered or absorbed cannot affect the detector which is placed beyond the second pinhole. In construction of an actual device, however, the second pinhole must subtend a finite angle and therefore will admit a small portion of the scattered light. The relationship between the angle within which light is collected and the reduction in extinction coefficient caused by the transmitted, reflected, and diffracted light striking the detector has been published (Heller 1957). With the system constructed, the semiangle subtended at the collecting lens is approx 1/2 degree. Hence, the contribution of this source of error was estimated to be less than 10%. Reductions in the extinction coefficient due to light externally reflected from the particle and collection of light transmitted through the particle are neglibible compared to the reduction due to the collection of diffracted light.

The construction of the particulate density probe allowed the actual measurement to be made in the flow field itself. The probe design minimized any induced disturbance of suspension characteristics. To accomplish this, the projected area of the probe normal to the direction of flow was minimized in the vicinity where the light beam passes through the suspension.

One of the major restrictions on similar particulate density probe designs over the years has been the propensity of particles to deposit on the optical surfaces within the probe and thus introduce error in the measurement. By utilizing a carefully designed purging system coupled with a special flow tripping device (the beveled projection shown in figure 2) in the measurement region, the deposition of particles on optical surfaces was markedly reduced. Air purging rates were such that the ratio of air velocity in the purge supply tubes to the local gaseous velocity in the gas stream was approx 20%. A simplified schematic of the particulate density probe is given in figure 2.

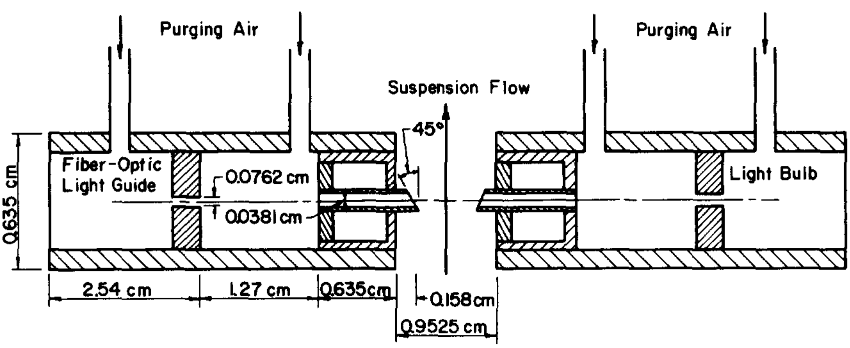

Figure 2. Details of particulate density probe.

A miniature incadescent light bulb was used as the light source. By means of a fiber-optic light guide, a Clairex 705 L/2 photoconductive cell was illuminated. The circuit constructed to monitor the changes in resistance incorporated the photoconductive cell as the feedback resistor of the amplifier is given in figure 3. In this way, the output voltage was always linear regardless of the magnitude of change from the nominal resistance of the photoconductive cell.

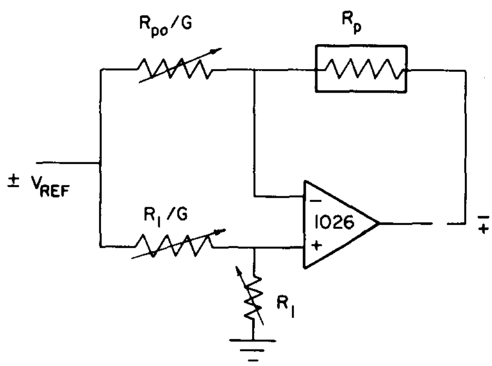

Figure 3. Circuit for monitoring photocell resistance.

The output voltage of the amplifier circuit can be characterized as

$$\Delta V = k_v \frac{\Delta R}{R_{P_0}} \quad [3]$$

where R_{P_0} is the nominal photoconductive cell resistance and ΔR is some change in resistance from R_{P_0}. Photoconductive cell response typically takes the form

$$\frac{R}{R_0} = \frac{(f)^{-k_i}}{f_0}. \quad [4]$$

Substituting the circuit and photocell relations above into the extinction equation for a polydisperse system yields

$$\ln\left(\frac{\Delta V}{k_v} + 1\right) = \frac{k_i EL}{\bar{d}_p} \frac{\rho_P}{\bar{\rho}_P}. \quad [5]$$

Expanding and keeping only the first term of Maclaurin's expansion results in

$$\Delta V = \frac{3}{2} k_v k_i \frac{EL}{\bar{d}_p} \frac{\rho_P}{\bar{\rho}_P}. \quad [6]$$

Calibration of the particulate density probe involved isokinetic sampling at the duct centerline to determine the particulate density in conjunction with measuring the voltage output from the particulate density probe 2.59 m upstream also at the duct centerline. Isokinetic sampling at the duct centerline yields a good indication of ρ_p in that the particulate slip velocity is small. This procedure permitted simultaneous measurement of both ρ_p and voltage output. The particulate density was changed by altering the dust loading within the duct and observing the particulate density probe output for each loading. The results of this calibration can be seen in figure 4 where the output is seen to be linear as predicted [1] and not dependent on gas velocity.

The operation procedure with the particulate density probe was as follows. The probe was placed in a region (duct centerline) where the particle slip was small such that ρ_p could be

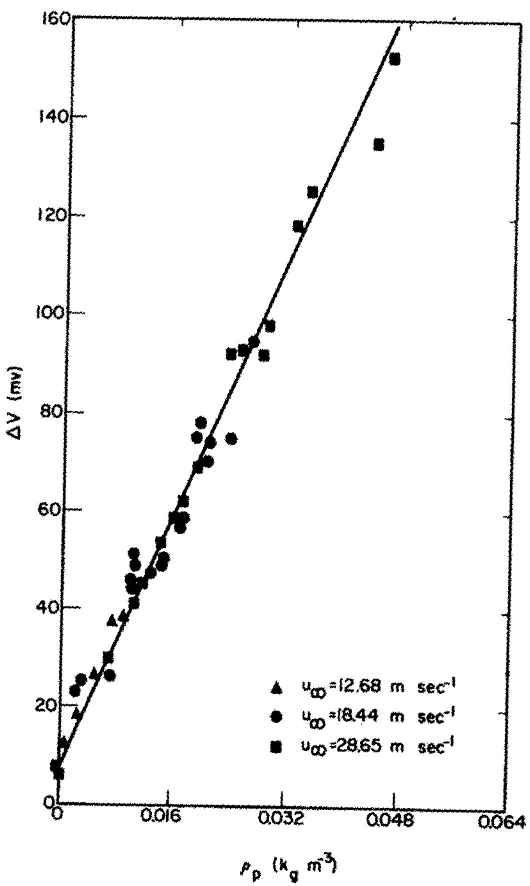

Figure 4. Density probe calibration curve.

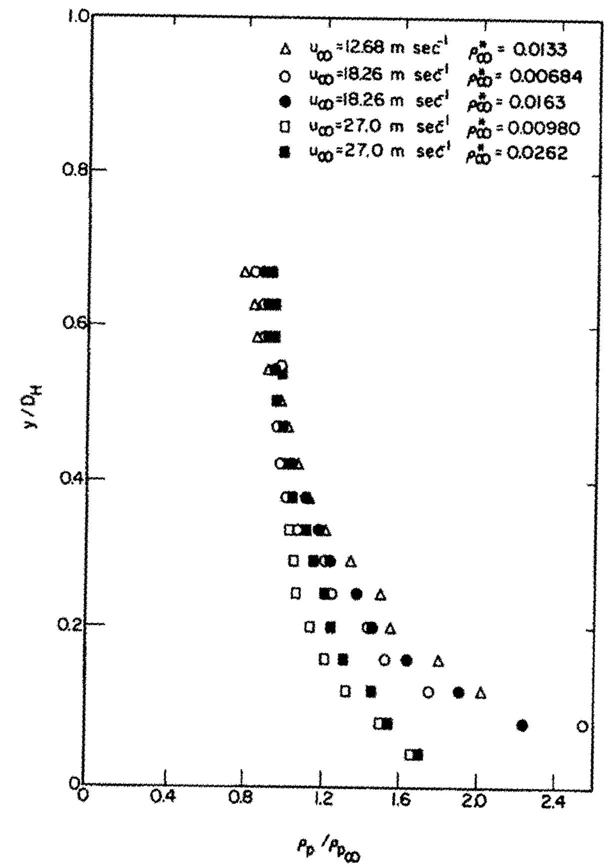

Figure 5. Vertical entrance profiles for the local particulate density.

measured by isokinetic sampling techniques. The density probe voltage output was then nulled at this location. As the density probe traversed the duct, the voltage output changed and was recorded. Since the particulate density calibration was linear, deviations in ρ_p were readily calculated. By adding this deviation in ρ_p to the initial ρ_p at the nulled location, the local particulate density was determined. This operational procedure permitted great sensitivity in the particulate density measurement.

The particulate polydisperse suspension material used was glass beads (specific gravity 2.65) where the mean particle diameter was 11 μm. Typical concentration profiles for a gas–solid flow in a fully turbulent duct flow are shown in figure 5 where D_H is the height of the duct and ρ^* is the ratio of the particulate cloud density to the density of the carrier gas.

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