MEASUREMENT OF DISPERSION OF PARTICLE JETS

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ABSTRACT

Experimental results confirm earlier works that leaner particles jets dispersed more than the denser ones. At high relative velocity with a high background velocity, there was less dispersion of the particle jet. This work was based on a much higher differential velocity up to 6 times (6 m/s to 40 m/s) but with a low particle jet density of 4 kg/m^3 to 40 kg/m^3. This study has also shown that for a given particle loading and background velocity, the particle jet behaves just like the single phase jet. The centre line of the jet decreases with increasing issuing jet velocity - almost linearly. For a given velocity, the jet dispersion and acceleration decreases for increasing particle loading. Also, the higher the dispersion, the greater is the rate of acceleration of the jet and the more uniform the cross sectional velocity profile.

These results however do not allow noticeable inference to be drawn on the effect of the velocity ratio, again this might be due to the narrow velocity range achieved. More work will need to be made exploring a wider velocity range before concrete jet dispersion characteristics can be established.

INTRODUCTION

One of the main requirements in the design of a pulverized fuel burner is to get as through mixing between the air and the fuel as possible[1-5]. Some new burner designs have achieved in lowering the level of nitrogen oxides, NO_X emissions. These burners have been termed as low NO_X burners. Although there are many designs of low NO_X burners, they are however basically similar in that they are dual registers burners - with a central fuel injection system which has two annular register (rings) injecting secondary and tertiary air around the primary fuel/air system. The primary fuel/air mixture has to be swirled to keep if fluid for injecting. At the exit, it is normal to employ straighteners to reduce the mixing of the air thereby enhancing the sub-stoichiometric combustion. For similar reasons, tertiary air tends to be directed away from the flame so that it comes into play at the far end of the flame where the char is consumed.

The pulverized fuel is normally transported pneumatically to the burner arrays, in the course of transportation, as mentioned above, the mixture has to be swirled to keep it fluid. The density of the fuel-air mixture during the transport is customarily lean. When particle-jets go over a right angle bend, normally from vertical to horizontal, the jets separates into regions, the high density particles jet region, termed as the "particle rope" and the less dense region constituting of mainly air. Clearly the fluid dynamics of the process needs to be understood more in order to assess why this is the case.

Understanding the fluid mechanics of high density particle jet ribbons ("particle ropes") and the physical reasons for their formation, persistence and eventual break is important in providing data which can be used to design better pulverized fuel burners which will have high efficiencies and better flame characteristics which will limit the production of nitrogen oxides, NO_X and sulphur oxides. SO_X gases that are known to harm the environment.

The production of NOx in a pulverized fuel burner is influenced by both physical and chemical parameters. This study however was restricted to the study of the physical parameters in particular dispersion of the particle jets. The complex chemical reactions and their kinetics and the complex size reduction which occurs during devolatilisation and combustion of pulverized fuel or the flame velocities which depend not only on the temperature and concentration of fuel species but also on the ignition source (a stochastic variable in the flame surrounding the air envelope) was not studied.

The study of the basic physical parameters which affect the stability and dispersion characteristics of particle "ropes" was done by measuring particle velocities and their trajectories. The PIV velocity measurement technique was used to record the velocity information on the film, this information was later on recovered by ascertaining the separation of the particle images on the film. This was done by interrogating each point on the film using a low power laser beam. This produced, in the far field diffraction zone, a series of Young's fringes. The distance between the fringes being inversely proportional to the particle image separation at that point on the film, and their orientation is perpendicular to the flow direction. Knowing the magnification of the recording optics and the time between exposures, the flow velocity was deduced. It is possible to establish the separation of the particle images on the film by directly observing the separation using a microscope. This method is however tedious and inaccurate.

THEORY

The concept of the air-particle mixture behaving as a homogeneous fluid has been applied to air-particle jets before e.g. by[6-9]. In the laminar flow case, if both the particle diameter and the loading (concentration) is small, the spread of the particles in the jet is due to fluid motion and as the particle cloud is slowed down, its concentration increases and eventually settles down, the overall momenta of the system is conserved as in a jet of single phase fluid but the momenta of the particles is not as they are dispersed.

When the flow is turbulent, the particles, in addition to experiencing the behaviour of other particles, via particle-wake interactions, experience region of air-flow recirculation with a consequence of significantly reducing the fluid turbulent shear stress. This reduction is enhanced by the dissipating effects of the particles; accompanied by the decrease in the turbulent kinetic energy. Particles dispersion, however, depends strongly in aerodynamic response time, $t^* = \frac{\rho_p d_p}{18\mu}$, and as such large particles cannot be expected to follow the rapid fluctuations of the air phase.

The PIV velocity measurement method was used to measure the particle rope dispersion and the particle velocity distribution in the whole flow area. PIV is a velocity measuring technique which can "instantaneously" record velocity over a whole flow field. The technique relies on photographing small particles contained in and faithfully following the flow under investigation. Light from a laser source is normally expanded into a two-dimensional sheet and projected into the flow field, so that successive images can be recorded on the film plane of a camera placed at right angles to the expanded sheet of laser light. Fig. 1 shows the configuration for PIV recording. A review of PIV velocity measuring technique is discussed in[9].

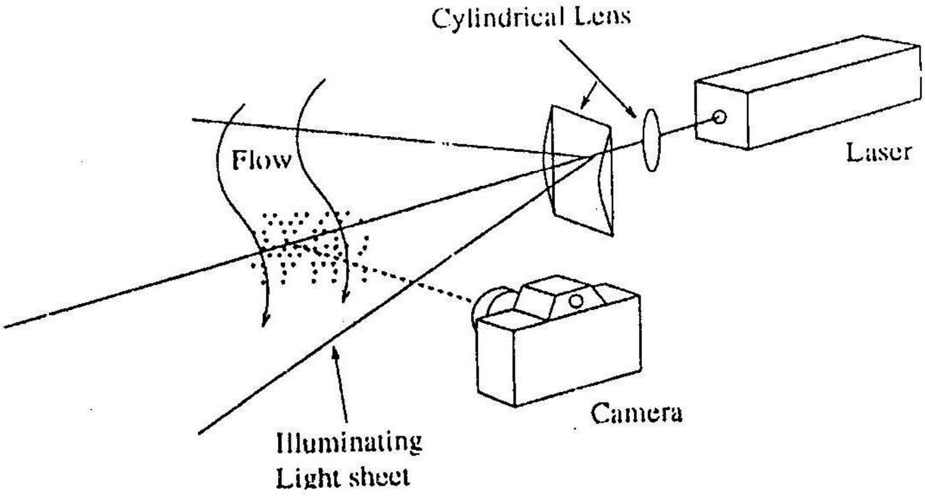


Fig. 1: PIV recording setup

EXPERIMENTAL SET-UP

In order to simulate flow characteristics similar to those in real industry, the experimental equipment had to be scaled, the scaling was based on the Froude number: $F_r = \frac{u^2}{gd}$. The Froude number scaling however relates only to the particle settling in a horizontal pipe. Also the residence time and temperature gradient scaling criteria $\frac{d}{u}$ constant were not accounted for. For these reasons, a wide range of velocity had to be investigated (from u =~ 6 to 40 m/s). Different ranges of spherical particle sizes, and of known size distribution and particle density was used.

The experimental rig used is shown in Fig. 2 while Fig. 3 shows a schematic diagram of the small wind tunnel utilised to study the particle jet dispersion. The particle jets were generated by means of a stream of air from a fan picking up the particles from the outlet of dust hopper with a screw feeder. The speed of both the screw feeder of the dust hopper and the fan were variable so that the injection velocity and particle loading of the jet could be controlled independently.

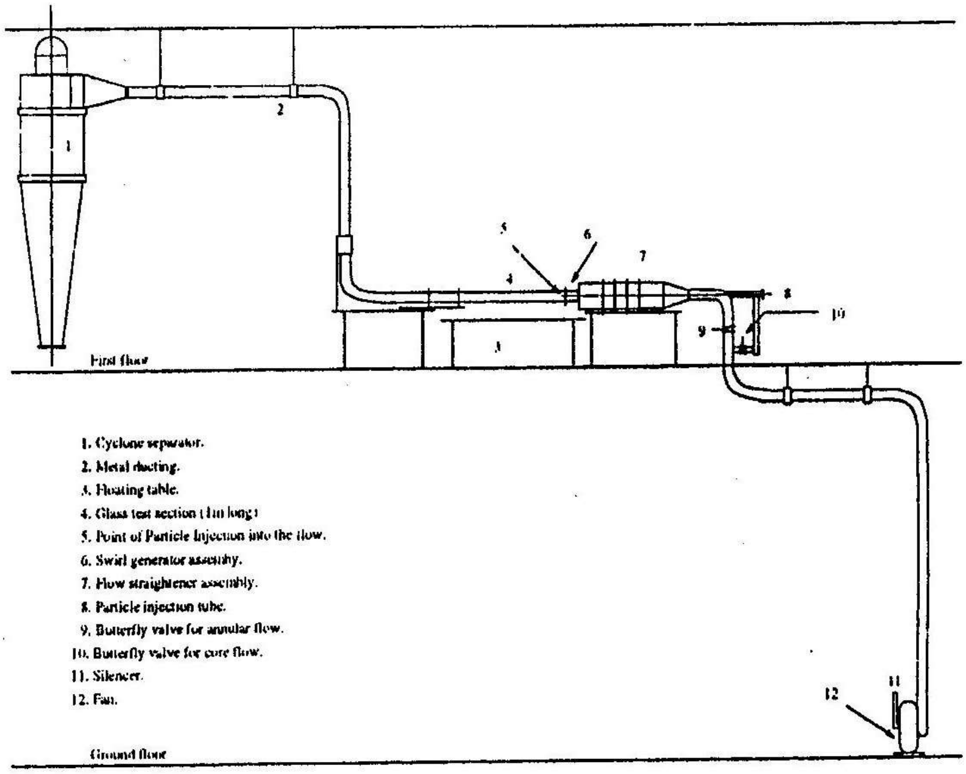


Fig. 2: Schematic layout of the experimental rig

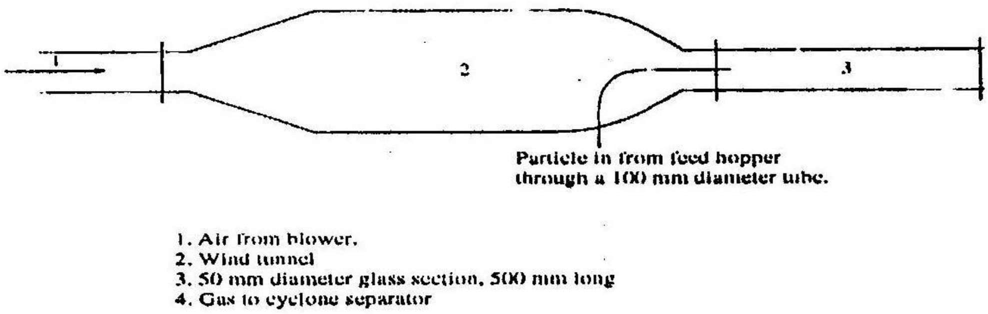


Fig. 3: Schematic diagram of wind tunnel rig

The air-particle jet was injected via a 10 mm bore tube, into the centre of the duct; coaxial with the streamwise component of the background airflow. The injection of the air particle mixture was studied under conditions with a background having a minimal turbulence and where the background airflow contained grid-generated turbulence. In the experiments, background air velocity was set at 6 ms-1 and 10 ms-1. Several particle injection velocities were used (3.5 s-1 to 12.5 ms-1). The turbulence levels were varied from 1% level (no grid- generated turbulence) and 6% for grid-generated turbulence. The background air velocity (in the absence of the particle jet) measurements, were made by Laser Doppler Anemometry, LDA, using 1 mm corn-oil droplets. This enabled the mean flow and turbulence characteristics to be determined.

A 15W Argon-Iron laser beam, collimated to 1 mm diameter using a system of lenses was used. The scanning beam method was utilised to illuminate the particle air flow field for recording the PIV negatives. The PIV technique was used to record the velocity profile of the whole flow volume. PIV and LDA measurement methods are explained elsewhere [9].

To retrieve the velocity flow information from the film, the Youngís Fringes method was used. In this method, a small local region of the negative, over which the fluid velocity is approximately constant, the recorded flow will consist of two similar but displaced random patterns of resolved particle images, the measurement of the mean displacement between these two separated sets of images is most reliably determined by autocorrelation of the local particle images distribution. The spacing and orientation of successive particle images in the area of the interrogation is directly determined from two-dimensional position of the signal peaks in the autocorrelation plane, the fourier transform was used to produce the autocorrelation plane. The position of the centroid of the signal peak is directly correlated to the inter-particle image spacing on the negative. All these tasks were done by the micro computer.

Experiments of PIV Measurement of Dispersion of a Particle Jet

The experiments were done by varying the velocity of the primary air from the blower and the velocity of the air picking up the particles. The particle loading (particles to air ratio) was also varied by varying the speed of the hopper feed screw and the velocity of the air transporting the particles. The feed hopper motor was a variable speed one. The main limitation of the rig set up was that the velocity range that gave a stable jet was very narrow and it was thus not possible to explore a wider range of both velocity and particle loadings. In this study, particle loadings of 95 kg/m3 to 198 kg/m3 were used compared to 4 kg/m3 to 40 kg/m3 used in previous work [6]. The jet was the exposed to a 15W Argon-Iron laser beam. The beam was expanded to 1 mm thick sheet using an 18 facet spinning mirror whose frequency of spin could be varied from 0 to 450 Hz.

The choice of the frequency of the spinning mirror was based on getting a particle image separation being between 1 mm and 2 mm, so that the negatives could be reliably analyzed to get the velocity vectors. The camera exposure time (the time the shutter remained open), Texp, was set such that the physical length of the track of particle images on the negative, $MV_{max}T_{exp}$ was within the minimum separation range i.e. 1 mm $\leq MV_{max}T_{exp} \leq$ 2 mm, where M is the magnification factor which was established experimentally by photographing a graph paper and measuring the length of the scale on the resulting film negative. The time between successive light flashes or time between exposures, Ts was set up so that it was possible to have four exposure during the camera exposure time. Thus using the 18 facet spinning mirror and for n film exposures, then the spinning mirror frequency is:

$$\frac{1}{18f} = T_s = \frac{T_{\exp}}{n-1} \tag{1}$$

Thus for four exposures n is equal to four in the above equation. Results of some of the experiments done are shown in figures 4 to 9.

DISCUSSION OF PIV RESULTS

The experimental results are presented in vector plots, the vectors depict both the relative magnitude and direction of the particle velocity at that particular position. These velocity vector plots are that of the particle velocity with the mean axial velocity having been subtracted. The vectors are principally uni-directional confirming the absence of any significant reverse flow or swirling flow except for figure 4. The vectors can actually be considered as representing instantaneous particle velocities.

The velocity vector plots Figs. 4(a) to 9(a) do not show any significant difference, this might be due to the fact that the velocity range achieved was very narrow. It would be expected that the jet would disperse more quickly when velocity (both the jet and the primary air) was higher or indeed when one of the two streams was at higher velocity level.

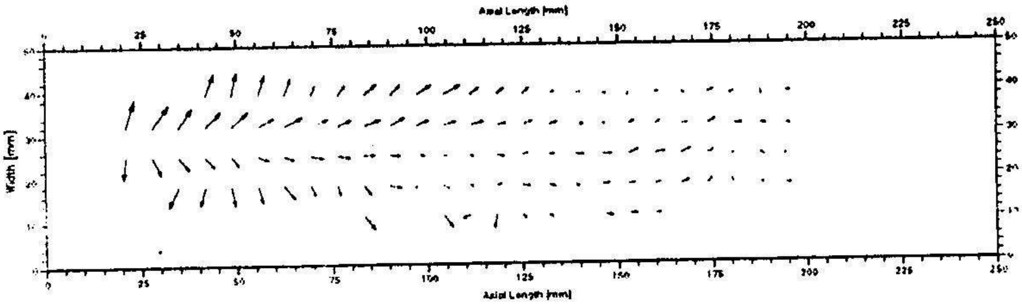
Velocity differentials in this work are in fact all fairly low. The velocity vectors shows that the jet spreads (particles therefore dispersing).

There is however no noticeable inference that can be drawn on the effect of the velocity ratio, again this might be due to the narrow velocity range achieved, the velocity fluctuation at the central axis is minimum, Figs. 4(b) to 9(b), these plots show the axial velocity at different position across the width of the flow volume. The velocity magnitudes in the caption refer to values calculated from the Pitot-static measurement at the inlet of the respective streams on the basis of inlet pipe area. When the two streams are of about equal magnitude, the fluctuations are minimum, Figs. 4(b), 6(b) and 9(b). The dip towards the end of the plot corresponds to positions where a significant deposit of particles occur, visually particles could be seen sitting on the base of the duct (sand dune effect), and had the effect of reducing the air flow, see Fig. 10.

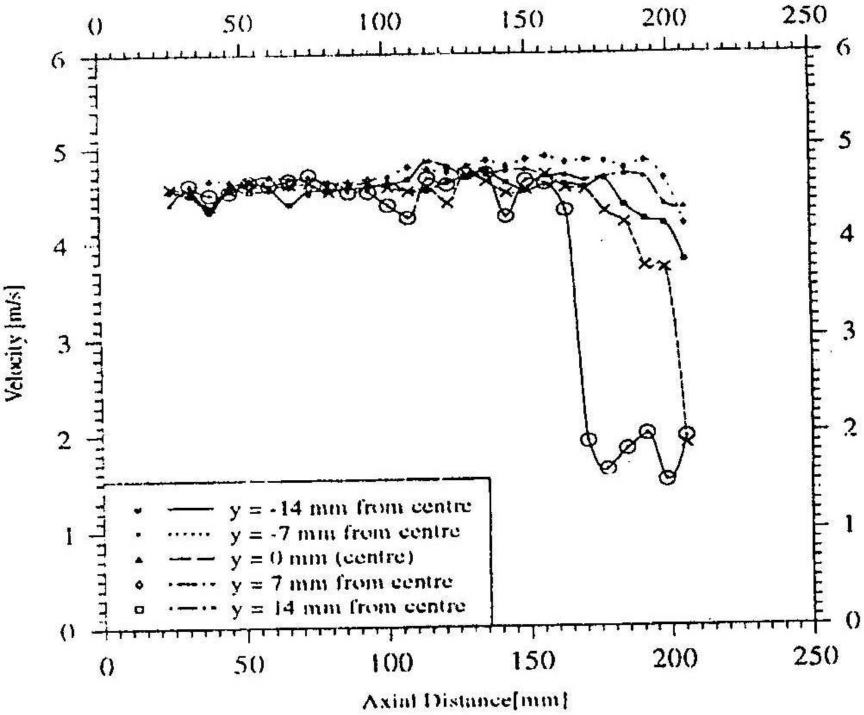
CONCLUSIONS

In conclusion it can be said that the PIV measurement results are consistent with earlier work by McCluskey [6] in which she found that leaner particle jets dispersed more than the denser ones. Also in agreement is the fact that at high relative velocity with the a high background velocity, there was less dispersion of the particle jet. McCluskey work was based on a much higher differential velocity up 6 times (6 m/s to 40 m/s) but with a low particle jet density of 4 kg/m3 to 40 kg/m^3.

The narrow velocity range achieved make it difficult to establish concrete jet dispersion characteristics and more work would need to be done where a wider velocity range will be explored. The rig's particle delivery system will need significant redesign to make sure that a steady stream of particles was delivered to the point where the particles are picked up by the air. This might entail acquiring a new powerful blower.

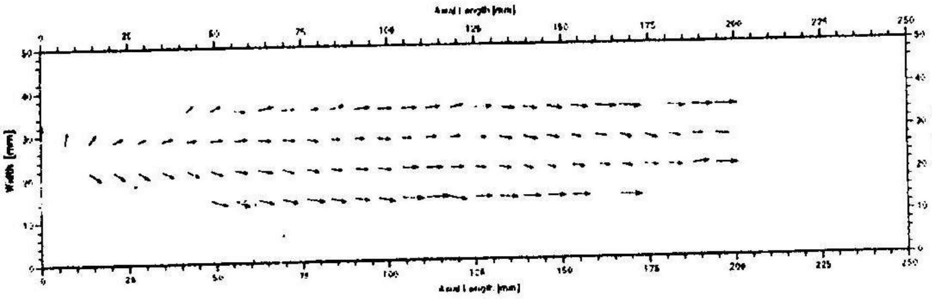


(a) Velocity vectors (mean velocity subtracted)



(b) Axial velocity

Fig. 4: **Primary velocity = 9.1 m/s; particle jet velocity = 9.4 m/s and particle jet density = 135 kg/m^3**



(a) Velocity vectors (mean velocity subtracted)

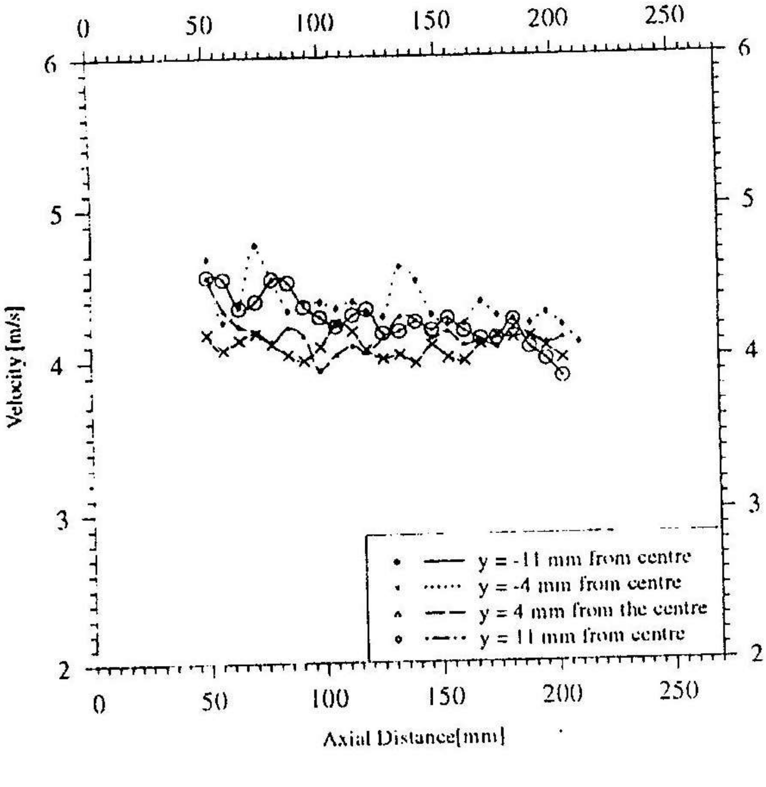
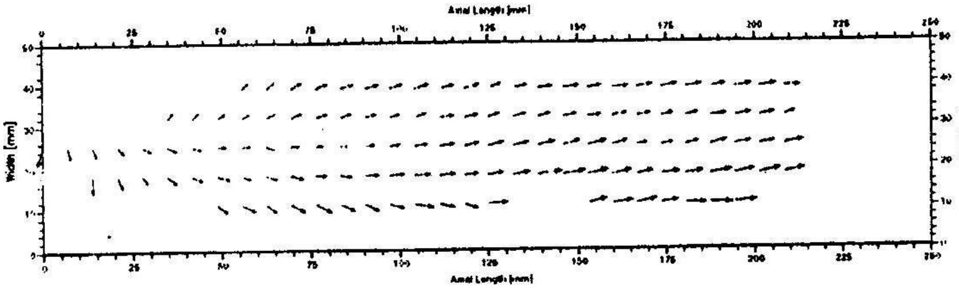


Fig. 5: **Primary velocity = 9.1 m/s; particle jet velocity = 9.4 m/s and particle jet density = 189 kg/m^3**



(a) Velocity vectors (mean velocity subtracted)

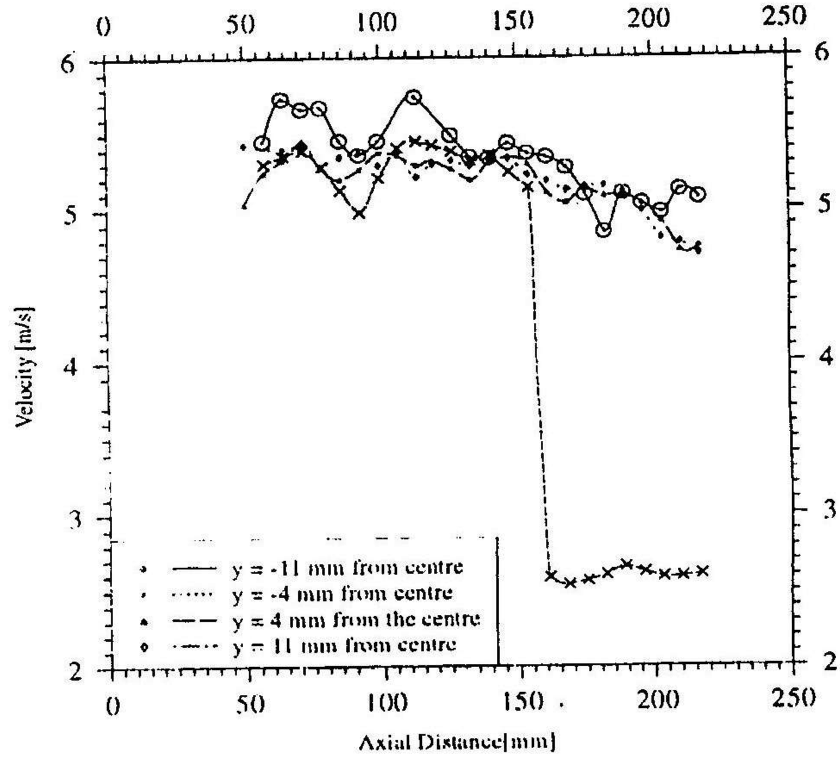
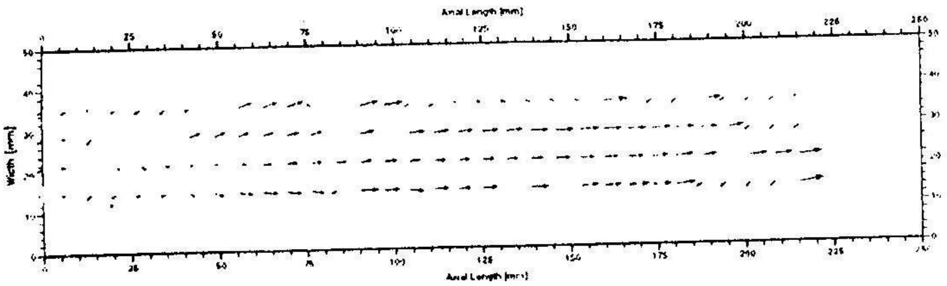


Fig. 6: **Primary velocity = 11.4 m/s; particle jet velocity = 9.4 m/s and particle jet density = 95 kg/m³**



(a) Velocity vectors (mean velocity subtracted)

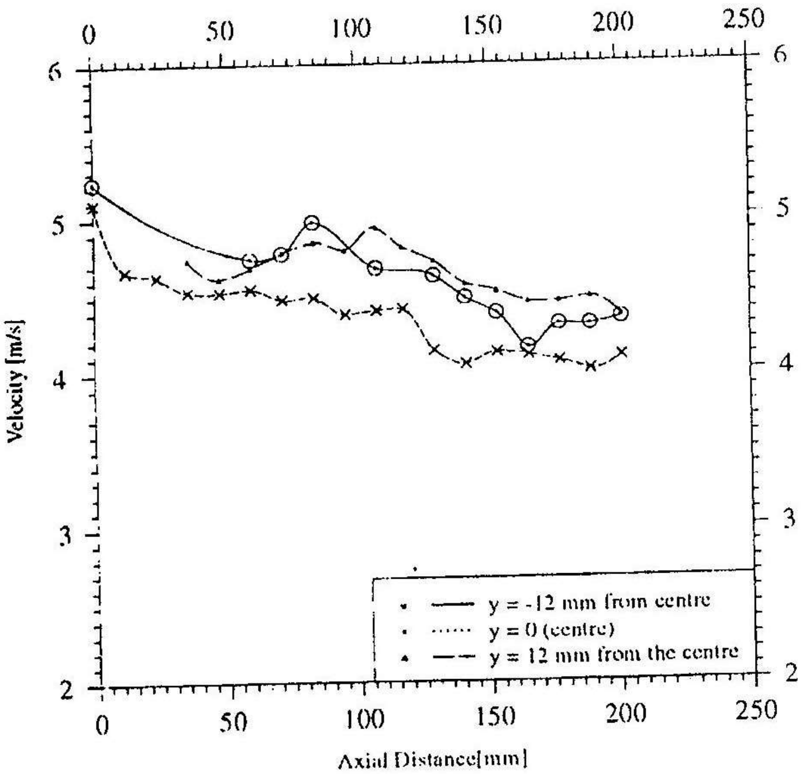
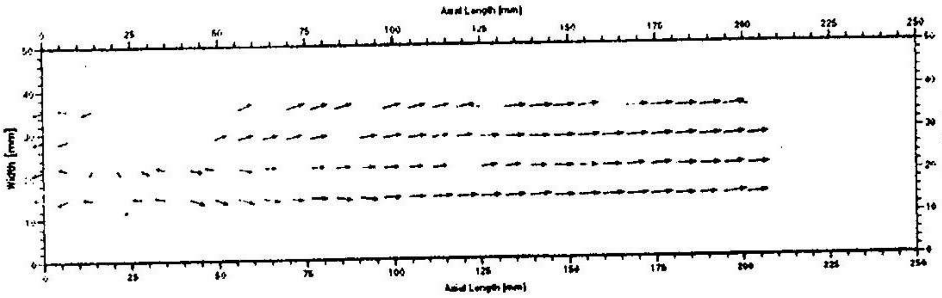


Fig. 7: **Primary velocity = 11.4 m/s; particle jet velocity = 9.4 m/s and particle jet density = 190 kg/m3**



(a) Velocity vectors (mean velocity subtracted)

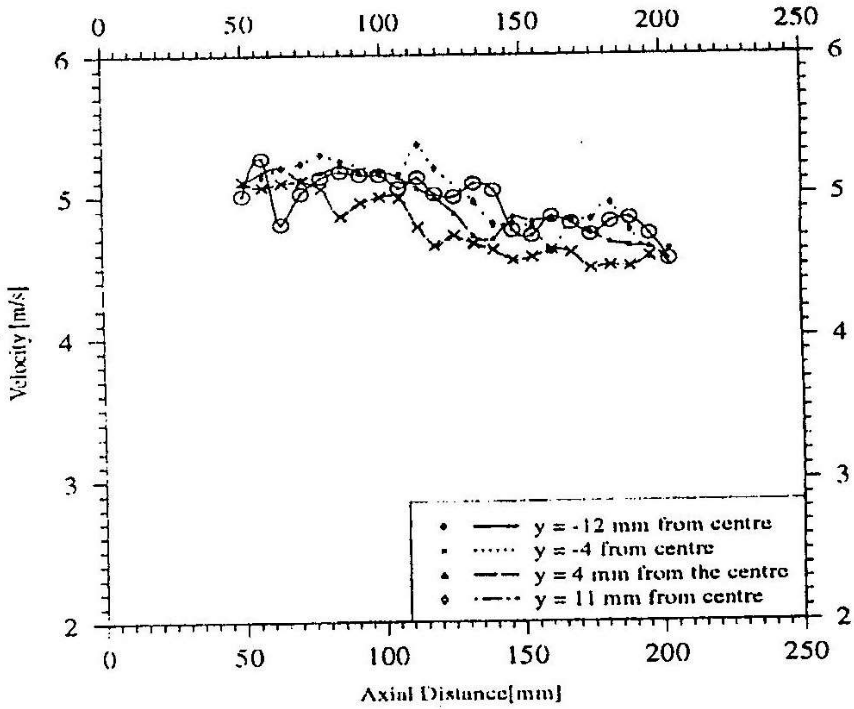
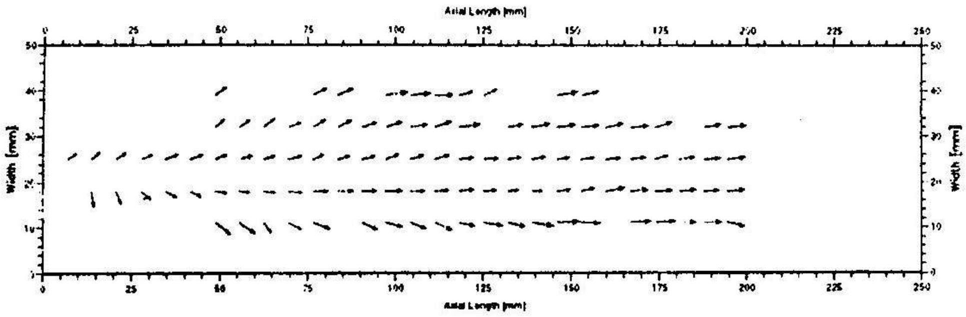


Fig. 8: Primary velocity = 11.4 m/s; particle jet velocity = 9.4 m/s and particle jet density = 198 kg/m^3



(a) Velocity vectors (mean velocity subtracted)

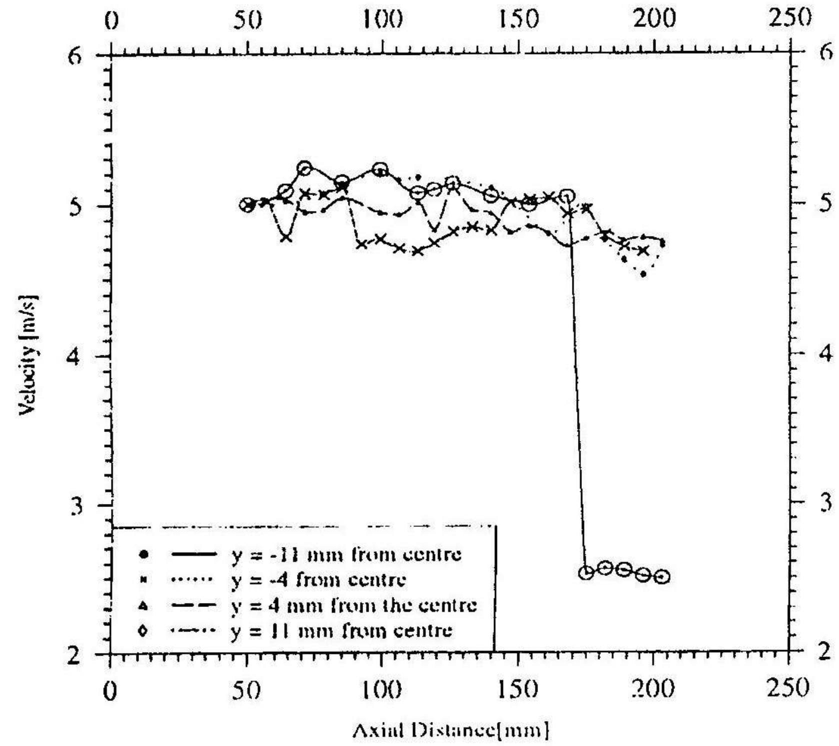


Fig. 9: **Primary velocity = 11.4 m/s; particle jet velocity = 10.4 m/s and particle jet density = 147 kg/m^3**

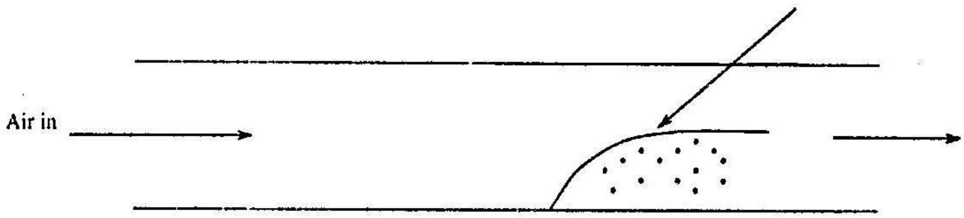


Fig. 10: Sand dune effect

This study has shown that for a given particle loading and background velocity, the particle jet behaves just like the single phase jet. The centre line velocity of the jet decreases with increasing issuing jet velocity - almost linearly. For a given velocity, the jet dispersion and acceleration decreases for increasing particle loading. Also, the higher the dispersion, the greater is the rate of acceleration of the jet and the more uniform the cross sectional velocity profile.

RECOMMENDATIONS

The main problem of the experimental set up was that of the particle delivery system. This system had a tendency to deliver an uneven supply of particles which produced an unstable jet of uneven density. Also the velocity range achievable that gave a stable jet was also very narrow. This was due to the fact that the blower delivering air for picking up the particles was not powerful enough.

NOMENCLATURE

d = pipe diameter, m
dp = particle diameter, m
f = frequency, s^{-1}
Fr = Froude number
g = gravitational accelaration, ms^{-2}
n = number of mirror facets
t* = particle relaxation time, s
Ts = time between exposures, s
Texp = camera exposure (shutter time) time, s
u = fluid velocity, m/s

Greek letters
p = particle density, kg/m^3
μ = fluid viscosity, mPa

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