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ROPE FORMATION FOR GAS SOLID FLOW IN A 90 DEGREE BEND WITH VARYING PARTICLE SIZE DISTRIBUTIONS

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ABSTRACT
Pneumatic conveying, the process of transporting particulate materials through pipelines with gas as the carrier, is a commonly-used means of material transport in industry. In order to simplify the layout of the plant, the materials are frequently transported through ducts with numerous bends and pipe sections. For instance, coal-fired power plants operate on a continuous supply of pulverised coal which is transported from the mill through these ducts. The piping used in these transport systems commonly includes bends that have a significant effect on the gas-solid flow structure. As a result of centrifugal forces within these pipe bends, the gas and solid particles segregate and the particles form a dense structure known as a rope. This region has relatively high particle concentration. Additionally, deposition of particles occurs due to deceleration of particles. These particle behaviors lead to difficulties for plant operators in maintaining optimal conditions for combustion in furnaces as a result of irregularities in the pulverised fuel supply.

Experimental studies have been conducted in a 90-degree vertical-to-horizontal pipe bend. The solid particles used in this study are high density polyethylene (HDPE) beads and ground flaxseed, with diameters ranging from 686 to 1171 microns, and with a mean diameter of 871 microns. The particle densities are 0.86g/cc and 1.2g/cc respectively. Experiments have been performed for a range of gas velocities and solids loadings, and the results of these experiments show that the particles form a thick rope at high solids loadings. The rope formation conditions for the different particle size distributions were analysed and computational fluid dynamics (CFD) simulations are performed to supplement the experiments. Preliminary comparisons between the experimental and CFD simulation results show that both the flaxseed and HDPE particles exhibit a roping behaviour at solids loadings as low as 0.4; however, experimental results indicate that only the flaxseed exhibits roping at this loading. The reasons for this unexpected behaviour are being investigated.

INTRODUCTION
Pneumatic conveying is a major means of transporting granular or powdered materials in industrial settings. Power plants, chemical industries and food industries rely greatly on this mode of material transport. The plant layout of these industrial facilities includes a number of ducts and pipe bends in order to make the layout simpler. Though these bends provide flexibility, they affect the gas–solid flow significantly. On account of the centrifugal forces, the solid particles and the gas segregate in the bends. Due to their inertia, the solid particles move towards the outer wall, then reflect back and form a dense structure known as a rope. This region has relatively high solids concentration compared to the rest of the pipe. When this happens, the particles slow down significantly and can get deposited along the bottom wall. This leads to number of problems. Among these, the pipe conveying area is reduced and may lead to blockages, and there will be irregularities in the particle feed supply. In major power plants, the roping phenomenon will induce irregularities in the supply of pulverised coal to the furnace leading to inefficient and dangerous operating conditions. Yilmaz and Levy [1] have clearly discussed the formation and disintegration of the rope in their experiments with a horizontal to vertical elbow. Huber and Sommerfeld [2] have discussed in detail the concentration profiles, particle velocities and mean particle diameter distributions along the pipe cross-sections at various locations in a vertical pipe after a horizontal to vertical pipe bend. Akilli *et al*. [3] have performed experiments and simulations which discuss the roping phenomenon and concentration profiles in the horizontal pipe after a vertical to horizontal pipe bend. Ibrahim *et al.* [4] have discussed the effects of various parameters like mass loading, bend curvature and particle

diameter on the gas – solid flows through bends. Yilmaz and Levy [5] studied the solid flow non-uniformities that develop in a lean phase upward flow after a horizontal-to-vertical elbow. In each of these previous studies, pulverized coal was used as the solids material. Unfortunately, coal does not lend itself well to visual studies due to its tendency to leave dirt and dust deposits on the inside surfaces of the pipes, thus making visual observation difficult. Because of this, alternate materials were used in the present study.

The primary purpose of the current study is to determine whether or not the Fluent CFD software is able to accurately predict the roping phenomena in a simple 90° vertical-to-horizontal pipe bend for various particle size distributions. A secondary objective is to provide more detailed experimental data including well resolved flow visualization. A series of experiments have been conducted using both high density polyethylene (HDPE) and ground flaxseed. The results of these experiments provide the benchmark to which the simulations are compared.
The HDPE particles were selected based upon previous experience suggesting the ease with which they can be recorded and analysed via high speed video. However, as will be discussed in the following sections, the HDPE did not exhibit roping conditions at the solids/air mass loadings of interest to this study. As a consequence, selection of a second solids material was required. , Thus the ground flaxseed was selected because it exhibited both the desired roping behaviour at lower solids loadings, and was shown to not cause erosive damage to the borosilicate glass observation section of the experimental apparatus (erosion of the glass was a significant consideration that lead to the rejection of many other common materials used for gas-solid flow studies, such as sand, silica beads and spent FCC catalyst). The particle densities for the HDPE and ground flaxseed are 0.86 g/cc and 1.2g/cc, respectively. Both of the particulate materials used in the experimental system have a size distribution ranging from 600 to 1200 microns in diameter. In order to examine the effects of varying particle diameters upon the simulation results, size ranges have been considered for the CFD simulation component of this study for both of the materials used: the first range comprises of 201-400 microns, the second range 401-600 microns and the third range of 686-1171 microns respectively. This paper reports on the preliminary results of a study whose long-term objective is to measure particle velocities and concentrations via high speed video image analysis for the purposes of CFD model validation.

NOMENCLATURE

C_P	[kg/ m^3]	Particle mass concentration
D	[m]	Inside pipe diameter
G/S	[-]	Gas to solid mass flow ratio
Y/D	[-]	Distance from lower wall to upper wall
L/D	[-]	Distance from bend exit
R	[m]	Bend radius
U_g	[m/s]	Velocity of gas
U_p	[m/s]	Velocity of particles
Rho_p or ρ_p	[kg/ m^3]	Density of particles

EXPERIMENTAL SETUP

The experimental setup consists of the solid particle feeding mechanism, a vertical pipe, a 90 degree bend which transitions the flow between the vertical pipe and a horizontal one, and finally a cyclone that is used to separate and collect the solids material from the airflow for reuse. The feeding mechanism comprises of a hopper and an attached screw feeder that feeds the solids particles into a pneumatic transport line that feeds a spouted air/solids distributor located at the bottom of the vertical pipe section. In addition, high pressure air from an air compressor is supplied to the air distributor via a series of variable-area flow meters, allowing for precise control of airflow rates into the system. The pipe sections consist of a combination of clear acrylic and glass pipes; where the observation section is made of 3-inch ID borosilicate glass pipe. The total lengths of the horizontal and vertical pipe sections (including the borosilicate glass) are approximately 46 and 60 inches, respectively. The borosilicate glass elbow has a bend radius of 1.8 inner diameters (1.8D). The horizontal pipe is connected to the cyclone to reclaim the particles. The entire setup is mounted on a steel frame. Figure 1 shows the experimental setup and Figure 2 shows the size distribution of the HDPE particles used in the experiments. Similar distribution has been used for the flax seed also.

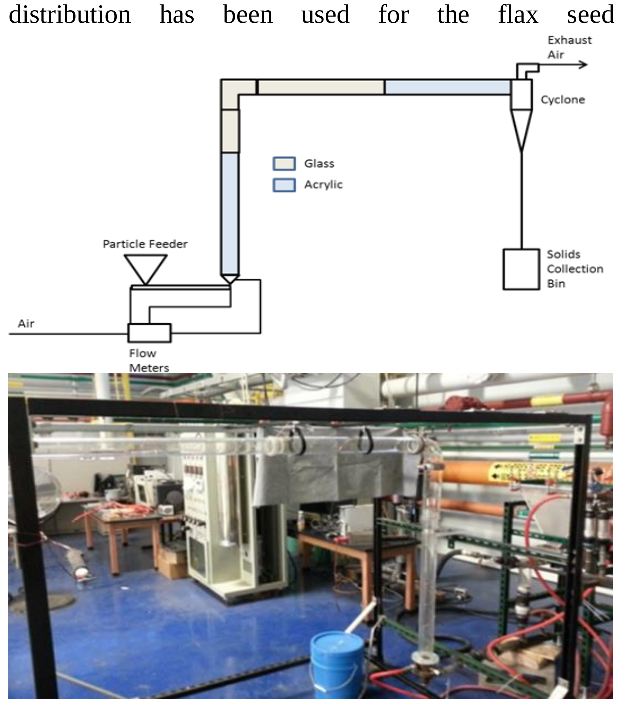

Figure 1: Experimental setup

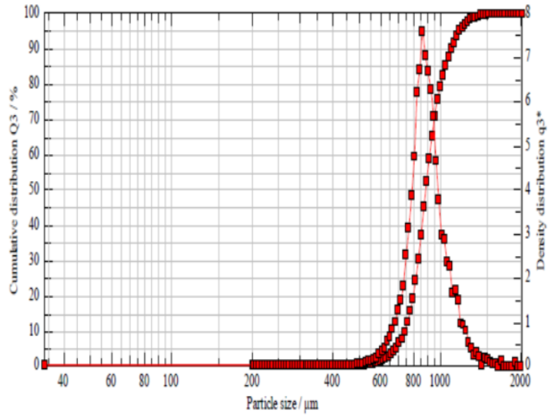

Figure 1: HDPE particle size distribution for experiments (characterization courtesy of Jonathan Tucker of the U.S. Department of Energy National Energy Technology Laboratory, Morgantown, WV)

NUMERICAL VALIDATION STUDY

The numerical simulations in this study were performed using the commercial CFD package Fluent. The CFD model setup for this study will be discussed in the next section. In order to justify the results from our study, numerical simulations have been performed and compared with previously published data. These validation simulations have been performed to replicate the work of H.Akilli *et al*. [6] for gas-solid flow through a pipe bend at a loading of 0.3 with the same CFD model used in this study. The Discrete Phase Model (DPM) in Fluent has been used for this study. The particle size distribution of the pulverized coal was not mentioned in the above work. So the size distribution from [3] has been used. The particle size varies from less than 45 microns to 125 microns with a mean diameter of 50 microns. The established experimental and numerical data is for coal for a similar setup with 6 inch inner diameter for all the pipes and a bend radius of 3 pipe diameters. Figures 3 and 4 show the concentration profiles at various locations in the horizontal pipe after the bend exit. The results obtained are very close to the previously published data.

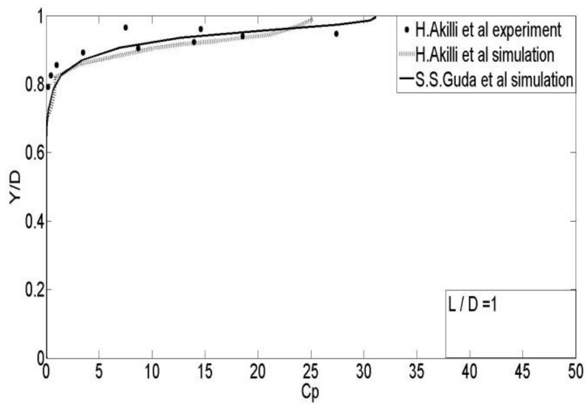

Figure 3 Concentration profiles at L/D=1

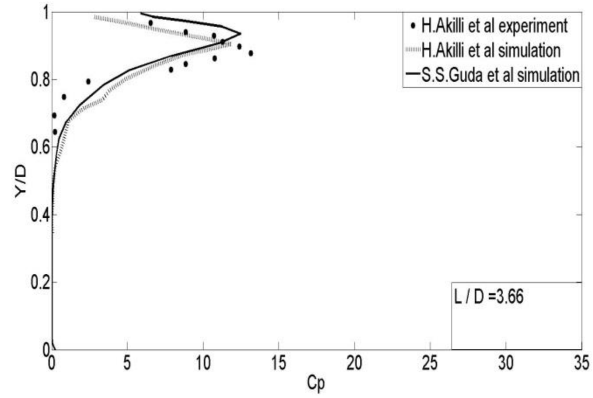

Figure 4 Concentration profiles at L/D=3.66

NUMERICAL SETUP

The numerical simulations were performed using Ansys Fluent. The inner diameter of the pipes is 3 inches (D). The computational models consisted of a vertical pipe of 5 pipe diameters (5D), a horizontal pipe of 30 pipe diameters (30D) and a bend of radius 1.8 pipe diameters (1.8D). An Eulerian–Lagrangian model was used for this study; where the gas phase is modelled by the Eulerian method and the particle tracking is done via the Lagrangian method. RNG K- Epsilon model with standard wall functions was used for turbulence modelling. The coefficient of restitution has been taken as 0.9. A relatively coarse mesh with 91530 cells was used. All of the simulations completed were three-dimensional. The mass flow rates of gas and particles are 0.068 kg/s and 0.02834 kg/s, which results in a solids-to-air ratio (or solids loading) 40 percent (G/S). The particles were injected with a velocity of 10.114 m/s considering the slip and gravitational effects. The computational mesh is shown in Figure 5. The numbers in this figure indicate the locations at which the solids concentrations are examined.

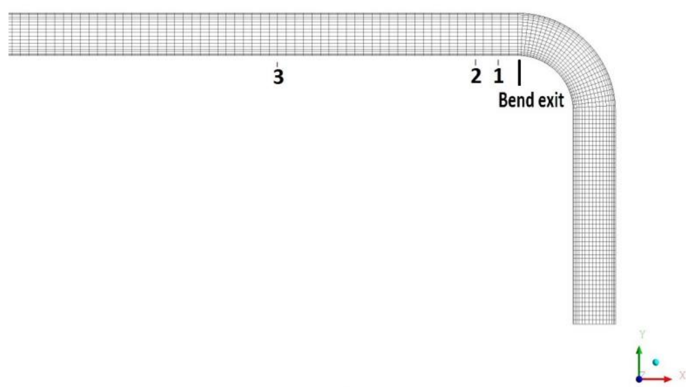

Figure 5 Pipe bend mesh

Transient simulations have been performed with steady particle tracking. Once the gas phase has reached a steady (or pseudo-steady) state, the particles are then injected and their trajectories solved for. Ansys Fluent predicts the trajectory of a discrete phase particle by integrating the particle equation of motion written in a Lagrangian reference frame; the force balance (Eq. 1) equates particle inertia with the forces acting on the particle.

$$\frac{dU_p}{dt} = F_D\left(U_g - U_p\right) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F} \qquad \text{(Eq. 1)}$$

$F_D\left(U_g - U_p\right)$ is the drag force per unit particle mass and

$$F_D = \frac{18\,\mu\, C_D\, Re}{\rho_p d_p^2\, 24} \qquad \text{(Eq. 2)}$$

d_p is the particle diameter and Re is the relative Reynolds number

$$Re = \frac{\rho\, d_p\, |U_p - U_g|}{\mu} \qquad \text{(Eq. 3)}$$

The inlet size distributions for the three ranges are shown in Figures 6. The same distributions have been used for studies with the ground flaxseed. The results of HDPE and Flaxseed have been compared only for the third range. For each of the particle size ranges simulated, the mean diameter (based upon mass) was determined to be 279, 479 and 865 microns, respectively.

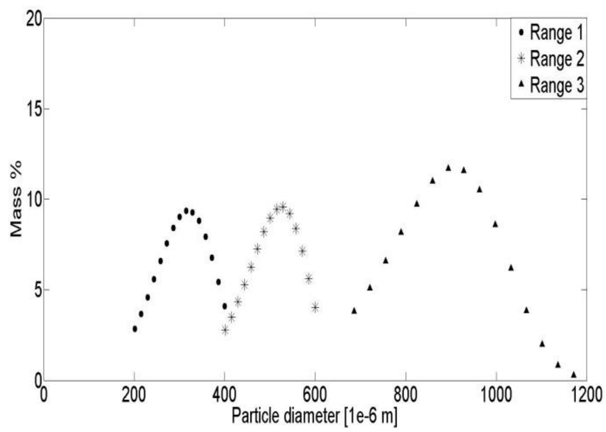

Figure 6 Inlet size distributions

RESULTS AND DISCUSSION

For the each of the size distributions simulated; non-dimensional solid particle concentration profiles were plotted for several locations downstream of the outlet of the pipe elbow. These locations are shown in the Figure 5 and mentioned in Table 1.

Table 1: Locations at which concentrations are plotted

Location	Pipe diameters downstream of bend exit (L/D)
1	0.5
2	1
3	7

L/D is the number of pipe diameters downstream of the bend exit. The plots show concentrations along the diameter from top wall to bottom wall (Y/D). The concentrations have been non-dimensionalised by dividing the resulting concentration by the density of the appropriate material.

Case A: HDPE

Figures 7-9 show concentrations at various locations for the HDPE particles. The profiles show a much higher concentration of particles in the upper portion of the pipe section at a distance of 0.5 diameter (L/D = 0.5) downstream of the elbow (Figure 7). This higher concentration is indicative of rope formation. Additionally, the data shows that the resulting rope is much more concentrated for the smaller particle size ranges than for the larger ones. The rope slowly disperses and progresses downwards towards the lower wall further away from the bend, as evidenced by the changing concentration profiles for locations further downstream of the elbow. At the L/D=7 location, the rope totally disintegrates for both the ranges.

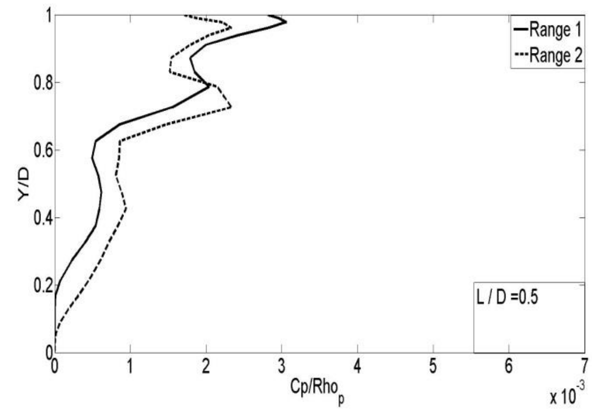

Figure 7 Concentrations at L/D =0.5

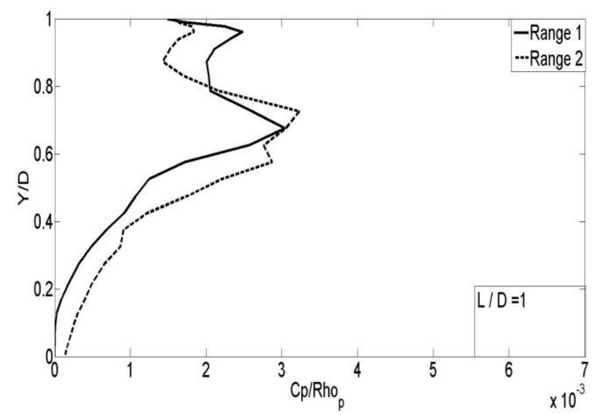

Figure 8 Concentrations at L/D = 1

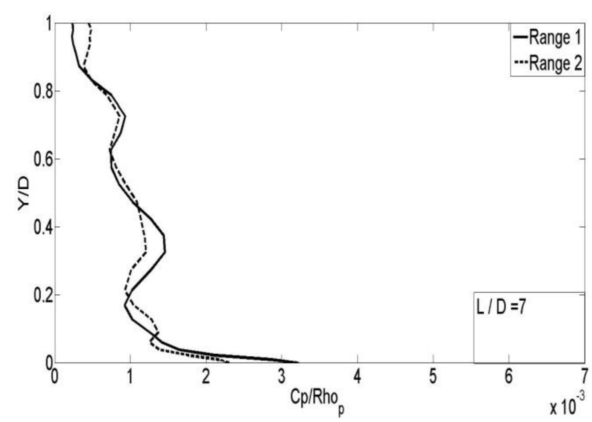

Figure 9 Concentrations at L/D = 7

Preliminary experiments were conducted with a solids feed rate of 0.0283 kg/s and airflow rates leading to solids loadings of 0.4, 0.5, 0.67 and 1.0. Figures 10-13 show the resulting two-phase flow patterns in the region of the elbow exit. Contrary to the CFD results for HDPE, no roping was observed to have taken place. While not shown, additional experimentation led to the conclusion that, for the given particle size distribution, roping was not present at loadings below ~1.5 for the HDPE.

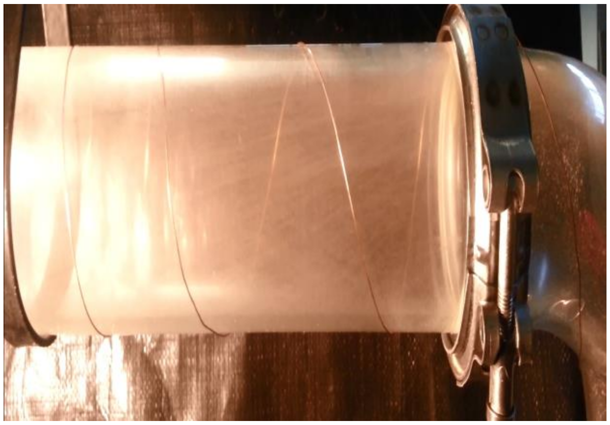

Figure 10 Experimental run with solids loading of 0.4.

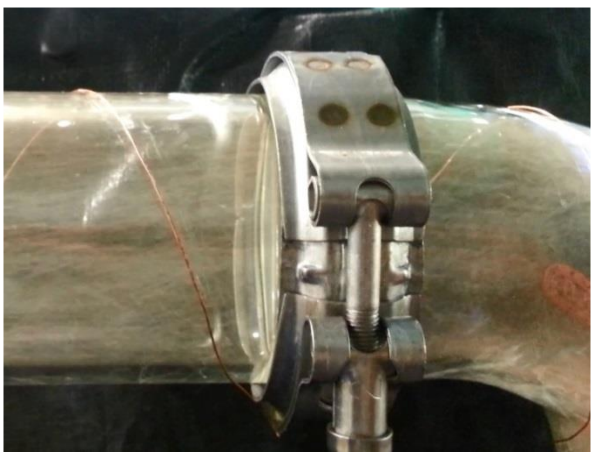

Figure 11 Experimental run with solids loading of 0.5.

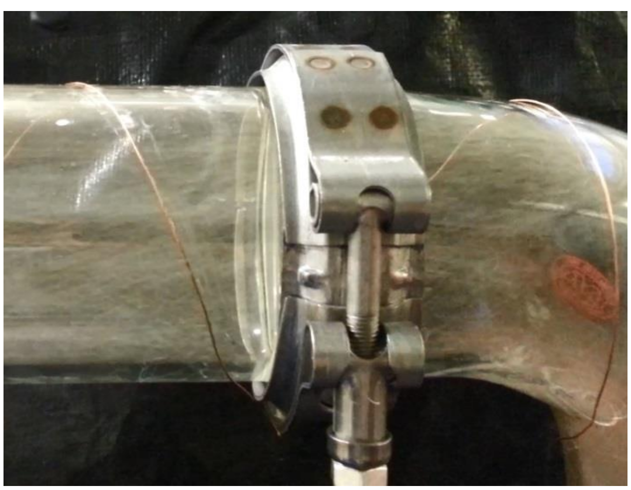

Figure 12 Experimental run with solids loading of 0.67

Figure 13 Experimental run with solids loading of 1.0.

Case B: Ground Flaxseed

Figures 14-16 show concentrations at various locations for the ground flaxseed. The concentration profiles show once again that the roping is more pronounced for the smaller particle size ranges. As was the case with the HDPE, the rope moves down towards the lower wall and disperses farther away from the bend. As will be shown in the next case, the non-dimensionalised concentration profiles resulting from the CFD simulations show small differences between the HDPE and ground flaxseed.

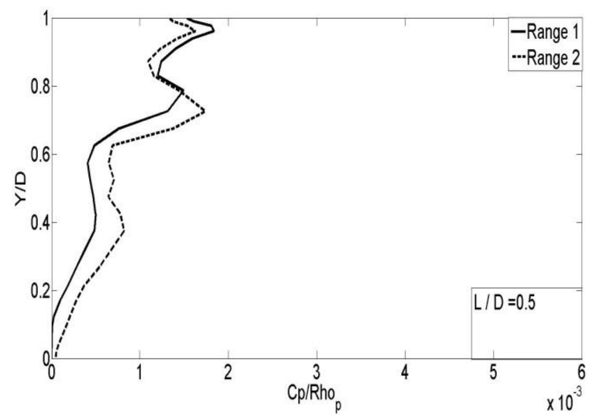

Figure 14 Concentrations at L/D =0.5 (ground flaxseed)

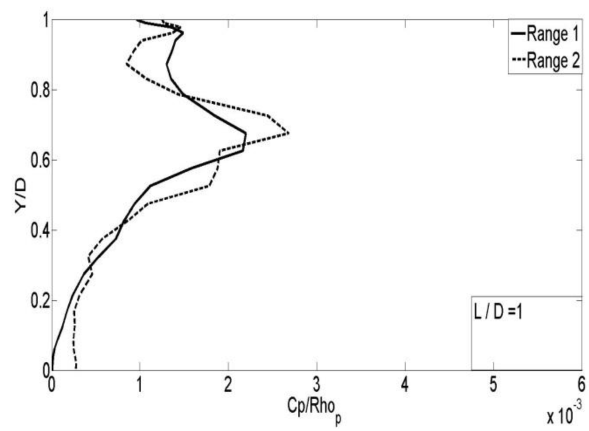

Figure 15 Concentrations at L/D =1 (ground flaxseed)

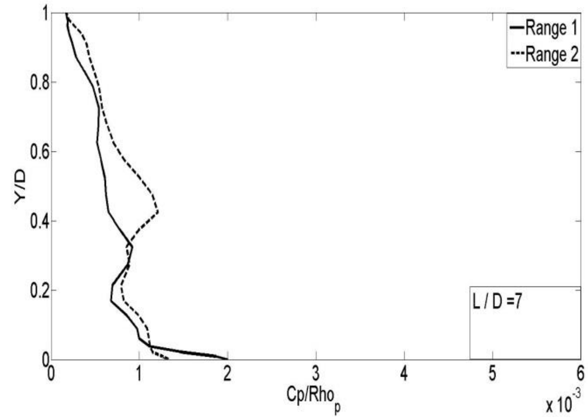

Figure 16 Concentrations at L/D =7 (ground flaxseed)

Additional experiments were conducted using the flaxseed with a solids feed rate of 0.0283 kg/s and airflow rates leading to solids loading of 0.4. Figure 17 shows the resulting two-phase flow patterns in the region of the elbow exit. Unlike the HDPE experiments, roping was observed with the ground flaxseed, as seen in Figure 17.

Case C: Comparison of HDPE and Flaxseed

The concentrations for HDPE and Flaxseed for the third range (600 – 1200 microns) are compared at various locations in Figures 18-20. For each location, the non-dimensionalised concentration profiles suggest that the HDPE particles will generate larger "bulges" that correspond to higher particle concentrations than those of the flaxseed. It can be concluded that these "bulges" in the concentration profiles indicate the location of the rope at that horizontal position. However, these results contradict the experimental results. From the experiments, it was determined that the ground flaxseed would generate visible ropes at loadings as low as 0.4, but the HDPE did not produce a rope at below approximately 1.5. This suggests that the simulations are not accurately representing the physics of the particle flow. The fact that the concentration profiles for the given materials were non-dimensionalised by the respective density may play a part; however, plotting the raw simulation data for concentration profiles did not significantly alter the results as presented here. Another likely explanation for this discrepancy is the fact that the simulation results that are presented here represent the concentration profiles along the vertical line corresponding to centreline of the pipe cross section at each horizontal location, whereas the images show the entirety of the pipe. It is entirely possible that the roping that is seen in the experiments is not located at the centreline of the pipe, and is thus not captured in the solid concentration profiles derived from the simulation results. This is further addressed in Case D.

Figure 17 Experimental run with solids loading of 0.4.

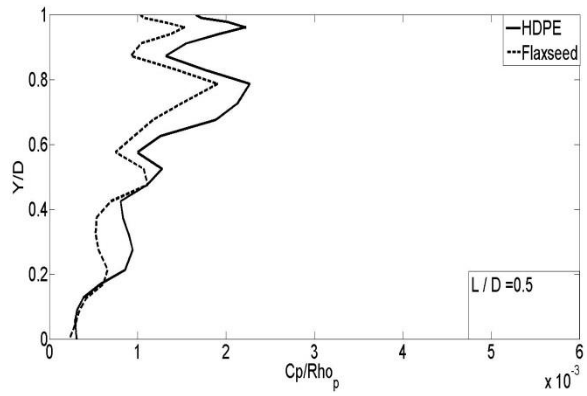

Figure 18 Concentrations at L/D =0.5

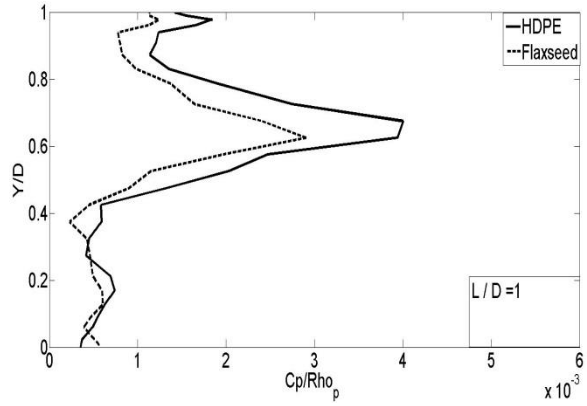

Figure 19 Concentrations at L/D =1

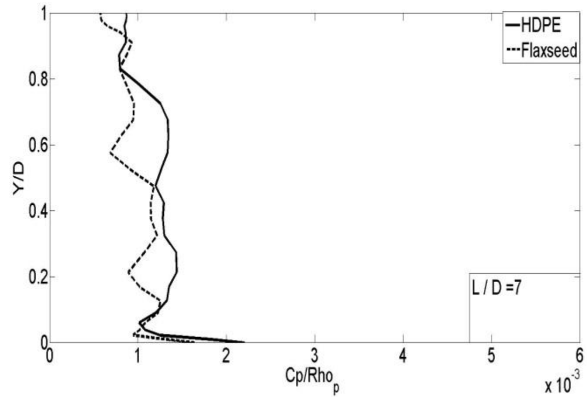

Figure 20 Concentrations at L/D =7

The cause for this discrepancy will need to be investigated further.

Case D: Study of nature of the rope along depth of the pipe

In all of the above discussed cases, concentration profiles were plotted along the centre line from the upper wall to the lower wall. One of the possible reasons for the discrepancy in the simulations is that the rope might be skewed towards one side of the pipe as opposed to being located along the centreline. In an effort to explore this possibility, a series of non-dimensionalised concentrations have been plotted at location 1 for HDPE for the third range along lines which are parallel and spaced symmetrically with respect to the centre line. These lines originate at angles of 45^o and 69^o in the counter clockwise direction along the pipe circumference. Figure 21 clearly shows the concentrations varying along the depth. There is higher concentration along the line at 45^o which tends to decrease at 69^o and again increases towards the centre line. This is clearly evident in Figure 22 which shows the concentration profiles for the same range and material but along the diameter in horizontal direction at various locations. The resulting profile shows clear variations in the solids concentration when traversing from one wall to the other at all locations.

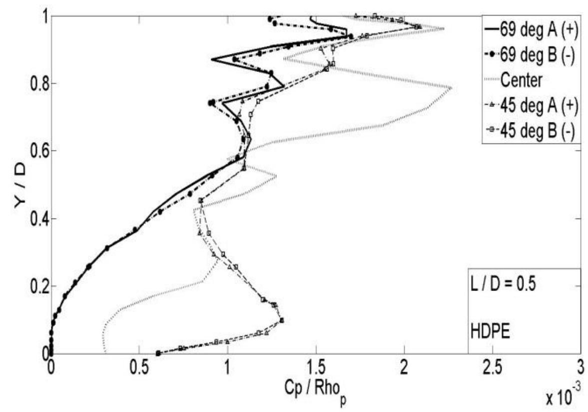

Figure 21 Concentration profiles along vertical lines on either side of the centre line

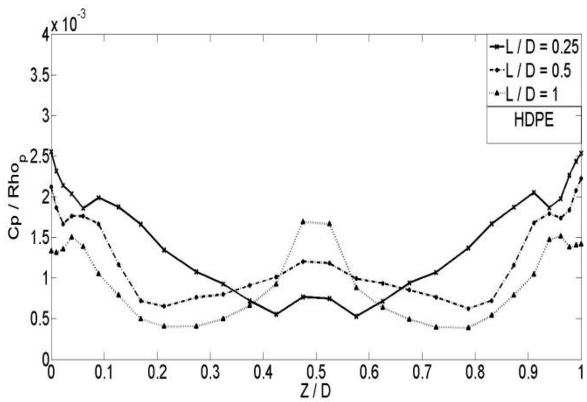

Figure 22 Concentration profiles along diameter in the horizontal direction at various locations

CONCLUSIONS

Investigation of the particle flow characteristics after a 90-degree horizontal-to-vertical elbow in a horizontal pipe was carried out. In the CFD simulations, rope formation was clearly observed for all the three ranges. It initially forms near the outer wall (with respect to the bend curvature) just after the bend exit and clearly moves towards the lower wall and then disperses as we move away from the bend exit. The particle concentration, and thus roping, is highest for the smallest particle size ranges.

However, unlike the simulations results, the experiments conducted with HDPE at solids loadings below 1.5 did not result in roping conditions. It is believed that the two most likely reasons for this discrepancy between the simulation and experimental results for the case of HPDE (and the fact that experiments show roping with the flaxseed and not the HDPE) lies either in the differences in material properties that are not currently being accounted for in the Fluent simulations, or in the transverse variations in solids concentrations seen in Case B. The experimental results depict the net effects of the particle concentrations, whereas the simulation-derived concentration profiles are limited to a single line. Among the material property differences are the likelihood electrostatic charging and particle reactions to transport gas humidity (i.e. hydro-phobic vs hydro-philic). Although other, currently unidentified, factors could be the cause. Additional testing is underway to identify the source of these differences.

Finally, the long-term objective of this study is to obtain in-situ measurements of particle velocities and concentrations under roping conditions for the purpose of CFD model validation. To achieve this goal, future plans include collaboration with the National Energy Technology Laboratory (NETL) to provide more detailed experimental data through the use of high resolution, high speed video recording of experiments in order to determine particle concentrations and velocity profiles. Figure 23 shows an example of this future work. The work currently being presented is preparatory to that effort.

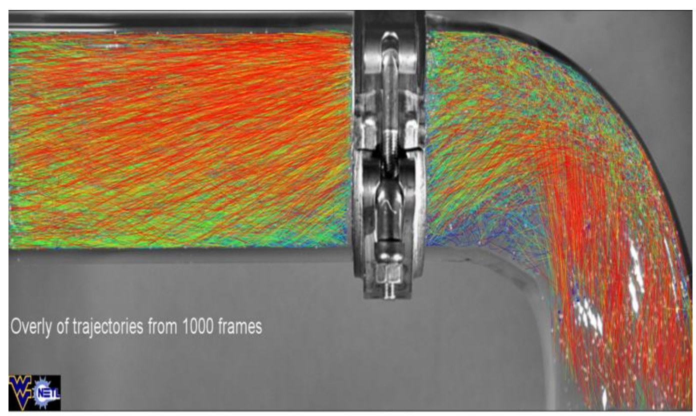

Figure 23 High speed imaging of particles in gas-solid flow at a loading of 0.5 with HDPE

(image courtesy : Frank Shaffer, NETL)

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