Electrical capacitance tomography measurements on vertical and inclined pneumatic conveying of granular solids

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Abstract

Pneumatic conveying of granular solids in vertical and inclined risers was studied using electrical capacitance tomography (ECT). The focus of the study was on flow development past a smooth bend connecting the riser to a horizontal duct which brought the gas-particle mixture to the riser. In the vertical riser, dispersed flow manifested a core–annular structure, whose development is discussed. Three different time-dependent flow patterns were imaged. Slugging flow, which appeared to be intrinsic to riser flow, took the form of alternating bands of core–annular disperse flow and a slug with a particle-rich core. Averaging over these two structures yielded a composite distribution with high particle concentration both at the axis and the wall region. Pulsing flow, whose ECT fingerprint was similar to that of slugging flow, was largely an entrance effect. Stationary and moving annular capsules with a dilute core were also observed, and such flow patterns do not appear to have been reported previously. Our ECT measurements probing the development of disperse flow in an inclined riser past a bend revealed that the particle loading initially decreased, subsequently increased and then leveled off. Regimes such as eroding dune flow and flow over a settled layer could be easily imaged using ECT. The surface of the settled layer had a concave shape, suggesting that the particles were picked up from the settled layer by airflow at the center and deposited on the sides of the tube.

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1. Introduction

The organization of particles into rope-like structures when a gas–solid mixture flows past pipe bends and the subsequent dispersion of these ropes are well known. Huber and Sommerfeld (1994) studied the segregation of 40 and 110 μm glass beads in an 80 mm ID pipe using phase-Doppler anemometry and laser-light sheeting. In dilute-phase pneumatic conveying through pipe bends with \( R/r \) ratios of 2.78 and 5.08 (where \( R \) and \( r \) denote the bend and pipe radii, respectively), a region of high concentration and a rope-like structure were observed near the outer wall immediately after the bend. The rope disintegrated after \( \sim 1 \) m as a result of flow turbulence and secondary flow induced by the bend. These authors concluded that the motion of small particles was greatly affected by the turbulence and the interaction with mean flow, while the motion of the large particles was largely dictated by their inertia.

Levy and Mason (1998) examined through numerical simulations the flow of gas-particle mixtures past bends. They found that a core–annular distribution evolved downstream of the bend and that the path followed by the particles depended on particle size, suggesting that segregation of particles based on size is likely arise upon flow past bends.

Yilmaz and Levy (2001) conducted fiber optic measurements of rope formation during pneumatic transport of 75 μm pulverized coal particles past two different bends (\( R/r \) of 3.0 and 6.0) and two different pipes (154 mm and 203 mm ID). They concluded that the formation and dispersion of solid ropes depended strongly on \( R \) and to a lesser extent on air velocity and solids loading. Their visualization studies revealed the discontinuous nature of the ropes and the disintegration of the ropes into clusters downstream of the bend. Their simulations revealed a significant influence
of secondary flows on the dispersion of the rope into a ring-like structure.

Schallert and Levy (2000) examined through experiments and simulations the effect of two closely spaced elbows on roping behavior in a vertical pipe downstream of the second elbow, and observed a stationary rope which spiraled around the inside of the vertical pipe, adjacent to the pipe wall.

The particle concentration distribution in the post-bend region can be expected to be quite different in the case of large particles as a result of the greater influence of inertia and the stronger rebound velocities following particle–wall collisions. Capes and Nakamura (1973) observed that the 3 mm glass beads used in their pneumatic conveying experiments tended to congregate near the wall region in an annular ring. Klinzing, Marcus, Rizk, and Leung (1997) suggested that the particle distribution over the cross-section of a vertical pipe depended on the ratio of particle to pipe diameters and that less annularity would be expected as this ratio increased. Matsumoto and Harakawa (1987) examined particle concentration fluctuations using a photosensor, and were able to identify the transition from a suspended bed to slug flow.

As the mass loading of particles increases, it becomes very difficult to discriminate, through simple visual observations, between the annular region and the core and the nonintrusive optical techniques become less useful (as the system becomes progressively more opaque). Intrusive probes may end up perturbing the flow characteristics and an uncertainty remains as to whether the measurements truly reflect undisturbed flow behavior. Nonintrusive probes are attractive for studying such problems. In this paper, we have studied pneumatic conveying of large particles in vertical and inclined pipes using electrical capacitance tomography (ECT), where we have examined the flow development past bends.

Using ECT, one can image dielectric components in pipes or vessels; by measuring rapidly and repeatedly the capacitances across several pairs of electrodes mounted uniformly around an imaging section (Williams & Beck, 1995; Hammer, 1983; Huang, 1995), the temporal variation of the spatial distribution of dielectric constant can be determined. If the imaging volume contains a gas–solid mixture, one can estimate the spatial distribution of particle concentration from the spatial distribution of dielectric constant. In our study, a ring of electrodes was placed along the circumference of the conveying pipe, so that instantaneous distribution of particles over the cross-section of the pipe could be determined. By using two such rings (commonly referred to as twin-plane sensors), one can also determine the speed at which disturbances propagate through the pipe.

McKee, Dyakowski, Williams, Bell, and Allen (1995) have described the application of the ECT technique to monitor the behavior of industrial-scale pneumatic conveyors. Srivastava, Agrawal, Sundaresan, Reddy Karri, and Knowlton (1998) used ECT to image the flow of Geldart-type A particles in a vertical standpipe at various aeration levels and found a dramatic difference between the holdups estimated through ECT and pressure drop measurements under stable operating conditions. This exposed the role of wall friction in stable operation of standpipes (Srivastava & Sundaresan, 2002). Using ECT, Dyakowski, Jeanmeure, and Jaworski (2000) imaged the core–annular flow pattern during the transport of FCC particles through a riser. They found the azimuthal variation of instantaneous particle concentration to be appreciable, while this variation was much less pronounced in the time-averaged data. Rao, Zhu, Wang, and Sundaresan (2001) used ECT to image flow patterns in various regimes of horizontal pneumatic conveying of large (Geldart-type D) particles. Jaworski and Dyakowski (2002) examined flow features associated with slug/plug flow in horizontal and vertical pipes, and verified ECT measurements with high-speed video images. Their study established that quantitative ECT measurement of flow structures is possible.

In the present study, we have imaged the distribution of 3.01 mm titanium dioxide filled linear low-density polyethylene (LLDPE) particles (\(\rho_s = 1683 \text{ kg/m}^3\)) and 2.8 mm polypropylene granules (\(\rho_s = 1123 \text{ kg/m}^3\)) over the cross-section during pneumatic conveying in vertical and inclined risers following a pipe bend under various flow regimes. The permittivity ratios for LLDPE and polypropylene are almost equal (~ 2.3). Through these measurements coupled with video images, we have brought forth (a) the manner in which core–annular flow pattern develops in dispersed flow regime, (b) the quasi-periodic flow structure in slugging and pulsing flow regimes, and (c) the structure of stationary and moving annular capsules in vertical conveying.

We have also probed the development of disperse flow in inclined risers past a bend, where the particle loading initially decreased because of acceleration and subsequently increased as a result of gravitational sedimentation. Our ECT measurements have revealed a concave shape for the surface of the settled layer in the regime of flow over a settled layer, which suggests that the particles were picked up from the settled layer by airflow at the center and deposited on the sides of the tube.

Rotary valves are commonly used in industries to feed particles into pneumatic conveying lines. Gas leakage through rotary vales is quite common (Klinzing et al., 1997). The carryover leakage, in particular, can hinder the discharge of particles from the feed hopper and affect the output of the rotary valve. It may also give rise to fluctuations in solids flow rate and concentration in the conveying line. In order to overcome this problem, a vent is often added to the rotary valve, which provides an alternate path for gas leakage and facilitates smooth delivery of particles into the gas stream. In the present study, we have examined using ECT the flow characteristics with and without the vent. The ECT and pressure drop measurements revealed an oscillatory flow pattern without venting, which disappeared upon venting.
This paper is organized as follows. Section 2 gives a brief description of the experimental facility. The procedure followed to extract cross-correlation coefficient from ECT data is outlined in Section 3. The results obtained with vertical and inclined risers are detailed in Section 4 and the main contributions of this study are summarized in Section 5.

2. Experimental

The experimental facility used to carry out the measurements is shown schematically in Fig. 1. Air from the compressor was metered and sent to the rotary air lock feeder, where it entrained the particles. The rotary feeder (General Resources Corp., Hopkins, Minnesota), equipped with eight pockets and a vent at the body of the rotary valve providing the passage of the air leakage, was operated at a fixed speed of 30 rpm. The test section consisted of a 4 cm ID horizontal pipe (4.12 m long), followed by a smooth 90° elbow \((R/p = 2)\), a 3.41 m tall vertical pipe (4 cm ID) and another smooth 90° elbow \((R/p = 2)\). Static (Gems, model K054205, Basingstone, England) and differential (Stellar Technology Inc., New York, Model-ST1510-15G-000Stellar) pressure transducers were mounted on the vertical pipe at 0.58, 1.18, 2.18 and 2.78 m away from the bottom elbow. Four sets of 12-electrode (10 cm long) ECT sensors (labeled as i–iv in Fig. 1) were arranged on the vertical pipe at locations 0.47, 1.20, 2.05 and 2.66 m from the bottom elbow. Two more sets of ECT sensors mounted on the horizontal pipe (labeled v and vi in Fig. 1) were used in conjunction with i–iv to study changes across the pipe bend. Using a data acquisition module (Process Tomography, Wilmslow, Cheshire, UK) connected to the ECT sensors, capacitance data were gathered under various operating conditions. The ECT and pressure transducers were sampled at 40 and 200 Hz, respectively. The solids flow rate was measured using a load cell attached to the storage hopper. This experimental facility was used in a previous study (Rao et al., 2001) to examine flow in a much longer horizontal duct. Further details about this experimental system can be found in Rao et al. (2001). The present work examines flow in the vertical pipe following the bend.

The ECT system was calibrated for the lower (air with 0 as reference value) and upper (solids with 1 as reference value) permittivity bounds. The conveying loop was made of PVC pipes. The conveying loop and the pressure transducers were grounded by means of conducting cables. The ECT sensors were connected by 1 MΩ resistors to dissipate static charge and the sensor modules were grounded. In spite all the precautionary measures there would be still some electrostatic charge in the system that depended on the operation conditions (such as conveying velocity, solids flow rate, etc.). These static charges could have some influence on the ECT signals. The perturbation of capacitance signals due to static charge has been compensated by correcting the ECT signals for the base state drifting. This is achieved by recording the base state values immediately after the experiment.

Experiments were also conducted in a riser inclined at 45° to the vertical, which required some modification of the conveying lines. Six sets of ECT sensor electrodes were mounted on the inclined riser at distances of 0.6, 1.45, 2.16, 2.77, 3.68 and 4.27 m from a bend connecting this inclined riser to a horizontal duct at the bottom.

3. ECT measurements of particle distribution

The permittivity of mixture (air+solids) existing between the electrodes of a capacitor was quantified in our work through a series model

\[ k_m = \frac{k_i k_s}{(k_i - k_s)\tau_i + k_s} \]  \hspace{1cm} (1)

\(k_m\) was used in the post-processing of captured ECT data. This effective permittivity depends not only on the individual permittivities of gas and solids, but also on the solids volume fraction.

For a 12 sensor ECT system, a total of 66 capacitance \((\tilde{C}(66,1))\) measurements were obtained for each cycle of measurements and these capacitances were determined by the solids distribution over the cross-sectional of the conveying pipe, which was divided into 32 × 32 “pixels.” For a given solids distribution, the capacitances can be calculated as

\[ \tilde{C} = \tilde{S} \cdot \tilde{K}_m + \tilde{\phi}_1, \]  \hspace{1cm} (2)

where \(\tilde{K}_m(1024,1)\) is a vector representing a set of unknown effective permittivity \((k_m)\) values characterizing the flow.
over a pipe section, and $\tilde{S}(66,1024)$ is a matrix containing known sensitivity factors, $\tilde{S}_1$ is the measurement error. Extracting the distribution of solids particle concentration over the cross-section of the conveying pipe from capacitance data entails the solution of a complex inverse problem. Further details can be found in Yang and Peng (2003).

By post-processing the ECT data at each instant of time ($t$) using the simultaneous iterative reconstruction technique described by Su, Zhang, Peng, Yao, and Zhang (2000), we obtained $\tilde{S}(x,y,z,t)$ at a given location $z$ averaged over the length of sensor, which is defined as the local volume fraction of particles divided by the volume fraction of particles at maximum packing, $F_p$ (=0.77 and 0.75 for polypropylene and LLDPE particles, respectively). Here, $x$ and $y$ denote Cartesian coordinates in the cross-sectional plane, made dimensionless using the pipe diameter as the characteristic length, and $z$ is the axial coordinate denoting the location of the ECT electrodes. Henceforth, we will refer to $\tilde{S}$ (loosely) as particle concentration, and the particle volume fraction is simply $\tilde{S}F_p$. The time-averaged particle concentration ($\bar{\tilde{S}}_t$) was found by averaging $\tilde{S}(x,y,z,t)$ over a time period $T$ (typically 25 s):

$$\bar{\tilde{S}}_t(x,y,z) = \frac{1}{T} \int_0^T \tilde{S}(x,y,z,t) \, dt.$$  (3)

The instantaneous value of the cross-sectional average particle concentration, $\tilde{S}_t(z,t)$, is defined as

$$\tilde{S}_t(z,t) = \frac{1}{A} \int \int \tilde{S}(x,y,z,t) \, dx \, dy$$  (4)

and the time-average value of $\tilde{S}_t(z,t)$ is denoted by $\langle \tilde{S}(z) \rangle$:

$$\langle \tilde{S}(z) \rangle = \frac{1}{T} \int_0^T \tilde{S}_t(z,t) \, dt \equiv \frac{1}{A} \int \int \tilde{S}_t(x,y,z) \, dx \, dy.$$  (5)

The cross-correlation coefficient, $C(d)$, where $d$ denotes the delay time, was then computed as

$$C(d) = \frac{1}{T} \int_0^T (\tilde{S}_t(z_1,t) - \langle \tilde{S}(z_1) \rangle)(\tilde{S}_t(z_2,t+d) - \langle \tilde{S}(z_2) \rangle) \, dt.$$  (6)

Here, $z_1$ and $z_2$ refer to upstream and downstream planes, respectively, and $d$ was taken to be positive. The dominant pattern propagation velocity, $V^*$, was estimated from $V^* = L/D$, where $L$ is the axial distance between the two ECT sensors and $D$ is the value of $d$ at which $C(d)$ assumes the largest value. $V^*$ estimated in this manner is clearly based on cross-sectional averages. One can also define pixel–pixel cross-correlation coefficient, $c(x,y,d)$, as

$$c(x,y,d) = \frac{1}{T} \int_0^T (\tilde{S}(x,y,z_1,t) - \tilde{S}_t(x,y,z_1))(\tilde{S}(x,y,z_2,t+d) - \tilde{S}_t(x,y,z_2)) \, dt.$$  (7)

The dominant pattern propagation velocity, $V(x,y)$, was estimated from $V(x,y) = L/d(x,y)$, where $d(x,y)$ is the value of $d$ at which $c(x,y,d)$ assumes the maximum value (for that $x$ and $y$).

4. Results and discussion

4.1. Flow in the vertical riser

The vertical conveying characteristics for the LLDPE and polypropylene particles without venting are summarized in Tables 1 and 2. These tables contain data on air superficial velocity ($U_\varphi$), solids mass flux ($G_s$), qualitative description of the regime of flow observed visually, ($\tilde{S}$) measured at station (ii) and (iii), averaged pressure gradient between stations (ii) and (iii) and the pressure gradient associated with

<table>
<thead>
<tr>
<th>$U_\varphi$ (m/s)</th>
<th>$G_s$ (kg/m$^2$ s)</th>
<th>Regime</th>
<th>$\langle \tilde{S} \rangle_{\text{ii and iii}}$</th>
<th>$\Delta P/L$ (Pa/m) measured across ii and iii</th>
<th>$\Delta P/L$ (Pa/m) associated with holdup</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.8</td>
<td>22.6</td>
<td>DF</td>
<td>0.012</td>
<td>183.6</td>
<td>148.6</td>
</tr>
<tr>
<td>19.5</td>
<td>21.3</td>
<td>DF</td>
<td>0.015</td>
<td>201.9</td>
<td>185.7</td>
</tr>
<tr>
<td>18.2</td>
<td>8.5</td>
<td>SF</td>
<td>0.018</td>
<td>359.1</td>
<td>222.9</td>
</tr>
<tr>
<td>16.9</td>
<td>7.5</td>
<td>AC</td>
<td>0.177</td>
<td>617.8</td>
<td>2191.7</td>
</tr>
<tr>
<td>15.6</td>
<td>3.7</td>
<td>AC</td>
<td>0.261</td>
<td>727.2</td>
<td>3231.9</td>
</tr>
<tr>
<td>23.4</td>
<td>30.9</td>
<td>DF</td>
<td>0.012</td>
<td>191.6</td>
<td>148.6</td>
</tr>
<tr>
<td>22.1</td>
<td>30.8</td>
<td>DF</td>
<td>0.014</td>
<td>201.2</td>
<td>173.4</td>
</tr>
<tr>
<td>20.8</td>
<td>29.9</td>
<td>DF</td>
<td>0.015</td>
<td>240.8</td>
<td>185.7</td>
</tr>
<tr>
<td>19.5</td>
<td>26.2</td>
<td>DF</td>
<td>0.015</td>
<td>269.9</td>
<td>185.7</td>
</tr>
<tr>
<td>18.2</td>
<td>14.3</td>
<td>SF</td>
<td>0.020</td>
<td>533.9</td>
<td>247.7</td>
</tr>
<tr>
<td>16.9</td>
<td>9.9</td>
<td>AC</td>
<td>0.192</td>
<td>626.7</td>
<td>2377.5</td>
</tr>
<tr>
<td>15.6</td>
<td>4.3</td>
<td>AC</td>
<td>0.312</td>
<td>860.4</td>
<td>3863.4</td>
</tr>
</tbody>
</table>

Solids feed valve opening: 50% (rows 1–5), 75% (rows 6–12) DF = dispersed flow; SF = slugging flow, AC = annular capsule.
Table 2
Transport of polypropylene particles in a vertical riser (without venting)

<table>
<thead>
<tr>
<th>$U_g$ (m/s)</th>
<th>$G_s$ (kg/m$^2$ s)</th>
<th>Regime</th>
<th>$\langle \tilde{z} \rangle_{ii}$</th>
<th>$\Delta P/L$ (Pa/m) measured across ii and iii</th>
<th>$\Delta P/L$ (Pa/m) associated with holdup</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.9</td>
<td>13.7</td>
<td>DF</td>
<td>0.010</td>
<td>108.8</td>
<td>84.8</td>
</tr>
<tr>
<td>15.6</td>
<td>13.0</td>
<td>DF</td>
<td>0.012</td>
<td>156.7</td>
<td>101.8</td>
</tr>
<tr>
<td>14.3</td>
<td>11.4</td>
<td>SF</td>
<td>0.015</td>
<td>246.0</td>
<td>127.2</td>
</tr>
<tr>
<td>13.0</td>
<td>7.0</td>
<td>AC</td>
<td>0.310</td>
<td>616.7</td>
<td>2629.7</td>
</tr>
<tr>
<td>20.8</td>
<td>25.2</td>
<td>DF</td>
<td>0.010</td>
<td>161.8</td>
<td>84.8</td>
</tr>
<tr>
<td>19.5</td>
<td>28.0</td>
<td>DF</td>
<td>0.014</td>
<td>174.7</td>
<td>118.8</td>
</tr>
<tr>
<td>18.2</td>
<td>32.6</td>
<td>DF</td>
<td>0.014</td>
<td>197.7</td>
<td>118.8</td>
</tr>
<tr>
<td>16.9</td>
<td>27.0</td>
<td>DF</td>
<td>0.017</td>
<td>208.9</td>
<td>144.2</td>
</tr>
<tr>
<td>15.6</td>
<td>31.4</td>
<td>DF</td>
<td>0.019</td>
<td>240.5</td>
<td>161.2</td>
</tr>
<tr>
<td>14.3</td>
<td>21.7</td>
<td>SF</td>
<td>0.033</td>
<td>369.3</td>
<td>279.9</td>
</tr>
<tr>
<td>13.0</td>
<td>8.5</td>
<td>AC</td>
<td>0.079$^a$</td>
<td>750.1</td>
<td>670.1</td>
</tr>
</tbody>
</table>

Solids feed valve opening: 50% (rows 1–4), 75% (rows 5–11) DF = dispersed flow; SF = slugging flow, AC = annular capsule.

$^a$Measuring station was only partially covered by the capsule.

Fig. 2. Differential pressure (across sensors ii and iii) fluctuations and their corresponding power spectra: 75% valve opening; (a, b): $U_g = 19.5$ m/s; (c, d): $U_g = 16.9$ m/s; (e, f): $U_g = 15.6$ m/s; (g, h): $U_g = 14.3$ m/s. Operating flow regime and the solids feed rate are as given in Table 2.
particle holdup. The last quantity, was estimated as 
\[ \rho_s g F_p \langle x \rangle_{iii} \]
where \( \langle x \rangle_{iii} = \langle x \rangle \) measured at station (iii).
The difference between the last two columns of numbers in these tables is an approximate measure of wall resistance to flow. Experiments were done by simply keeping the solids feed control valve opening at one of two different levels (50% or 75%). At each opening level, the solids flow rate varied appreciably with gas flow rate, as is readily apparent from Tables 1 and 2. Dispersed flow regime was observed at high gas flow rates, at both valve-opening levels. Upon decreasing the gas flow rate, the system first entered into a slugging and then to an annular capsule flow regimes.

Matsumoto and Harakawa (1987) examined the flow regime transition from dispersed to slug due to the intrinsic instability of suspension. The probability density function of differential pressure fluctuations exhibited a unimodal to bimodal distribution variation while the superficial air velocity was gradually reduced to dense phase operation. The periodic components were attributed to the transition flow into slugging mode. Their pressure measurements were consistent with the concentration signal measurements from a photosensor. In the present study, similar analysis is performed on the pressure and solid concentration measurements. Fig. 2 shows the differential pressure fluctuations and the power spectra at gas velocities 19.5, 16.9, 15.6 and 14.3 m/s (‘a’ through ‘h’) and the corresponding solids concentration fluctuations are given in Fig. 3 (‘a’ through ‘h’). At 19.5 m/s the fluctuations are dominated by feeder characteristics with a strong spectral peak representing the feeding frequency. However, intrinsic fluctuations due to solids movements are evident at \( U_g < 16.9 \) m/s. The appearance of dominant spectral peak closer or away from the zero value could be due to the core–annular structure. At 14.3 m/s the flow enters into slugging identified by a significant secondary peak in the differential

Fig. 3. Particle concentration (sensor location ‘iii’) fluctuations and their corresponding power spectra: 75% valve opening; (a, b): \( U_g = 19.5 \) m/s; (c, d): \( U_g = 16.9 \) m/s; (e, f): \( U_g = 15.6 \) m/s; (g, h): \( U_g = 14.3 \) m/s. Operating flow regime and the solids feed rate are as given in Table 2.
pressure spectra. The power spectra of solids concentration fluctuations identify very well the onset of slugging with multiple periodic peaks as a result of the intense solids circulation.

4.1.1. Dispersed flow

Figs. 4a and b show two snapshots (in the dispersed flow regime) of vertical pipe segments at sensor locations (i) and (iii), respectively. Figs. 4c and d show grayscale plots of $\bar{z}_r$ at these sensor locations. The values of $\langle z \rangle$ in disperse flow regime were generally very small and it was hard to establish the quantitative accuracy of ECT measurements in this regime. Nevertheless, the qualitative features revealed by Figs. 4c and d suggest that particle distribution over the cross-section was nonuniform at both locations—the particle concentration was low in the wall region, peaked at a distance away from the wall and became small in the central core. A comparison of Figs. 4c and d suggests that the peak in the particle concentration migrated closer to the wall as the particles moved downstream of the bend. This is seen more clearly in Fig. 5, which shows the time-averaged particle distribution over the cross-section at the four sensor locations downstream of the bend for a different set of operating conditions in the dispersed flow regime. The core–annular structure is visible at all four locations, but the pronounced peak seen in Fig. 5a gradually disappears with distance from the bend.

The particle distribution contours from the four ECT stations (i)–(iv) obtained during pneumatic transport of LLDPE particles in the disperse flow regime are shown in Figs. 6a–d. In this case, particle-rich regions (henceforth referred to as clusters) were scattered near the pipe wall forming either continuous or discontinuous annular ring-like structures.

It is interesting to compare Figs. 5 and 6, obtained with polypropylene and LLDPE particles at the same air velocity and comparable particle mass flux. The LLDPE particles, which are $\sim 85\%$ heavier than the polypropylene beads, distributed themselves in a narrower region near the wall than the polypropylene beads.
Fig. 5. Distribution of polypropylene particles in a vertical riser. $U_g = 19.5 \text{ m/s} \quad G_s = 28.0 \text{ kg/(m}^2 \text{s)}$. (a)–(d): Particle concentration contours at sensor locations (i)–(iv), located at distances of 0.47, 1.32, 2.05 and 2.66 m past the bend, respectively. The values of $\langle S \rangle$ at these locations are 0.017, 0.013, 0.014 and 0.014, respectively. Data were obtained by time averaging the ECT results. A horizontal pipe brought the gas–solid mixture to the vertical riser from the west side. Smooth 90° bend with $R/r = 2$. Rotary valve vent remained closed in this experiment.

Huber and Sommerfeld (1994) and Yilmaz and Levy (2001) have reported the presence of rope-like structures in the post-bend region, but such ropes were not observed in our study involving much larger particles.

It is clear from Tables 1 and 2 that the weight of the particles in the pipe contributed significantly to the measured pressure drop in the disperse flow regime. Furthermore, the actual pressure drop was invariably larger than that associated with the weight of the suspension, and hence the wall resistance was pointing down in this regime (opposing flow).

4.1.2. Slugging flow

Fig. 7a presents a snapshot of polypropylene particles in the slugging flow regime. The corresponding time-averaged concentration distribution, $\bar{z}_p$ at station (iii) is shown in Fig. 7c as a surface plot. In a time-averaged sense, the particle distribution was fairly uniform in the azimuthal direction, but the measurements revealed distinct peaks in the wall region and near the axis of the pipe. The origin of the central peak is better understood by examining a sequence of ECT images shown in Fig. 7b. This figure shows clearly the alternating passage of two patterns: one where the particles are predominantly in the wall region (pattern A) and a second one with a particle-rich core ("slug"). These two patterns were found to be rather robust. Time-averaging over these two patterns produced the two peaks seen in Fig. 7c. Pattern A was very similar to the distribution recorded in the disperse flow regime; however, unlike purely disperse flow, the particles in pattern A were generally found to be falling down at least near the wall region. The slugs, with predominantly upward movement of the particles, appeared in a quasi-periodic manner. The flow pattern in this regime was reminiscent of a slugging fluidized bed. Figs. 7d and e show the corresponding temporal variations of cross-sectional average particle concentration, $\bar{z}_p(t)$, and the pressure gradient. It is clear from Fig. 7d that the concentration of particles was appreciably higher in the slugs. The passage of slugs was also evident from the pressure gradient fluctuations.
It is seen from Tables 1 and 2 that the actual pressure gradient in slugging flow regime was larger than that due to the average suspension weight. Thus, on an average, the wall friction was pointing down in this regime, opposing net upflow of gas-particle suspension. Since the particles in the dilute region between the slugs were falling down (at least in the wall region), one can expect the wall to offer a small resistance pointing upwards in the dilute region. As the net force due to the wall was pointing down, one can conclude that the slugs experienced an appreciable downward force due to wall friction.

4.1.3. Annular capsule
As the air velocity was decreased even further, the slugging flow gave way to a rather unusual annular capsule flow pattern, which is illustrated in Fig. 8. Fig. 8a shows two (of the five) capsules which were observed in our vertical pipe. These capsules were stationary although the particles were in motion. The capsules had an annular structure, which is visible in the snapshot shown as Fig. 8b and in the time-averaged concentration distribution, \( \bar{z}_t \), shown as Figs. 8c and d. An upflow of dilute gas-particle suspension could be observed (visibly) in the core region. This upflow picked up particles from the bottom of the capsules and deposited them at the top of the capsules. Downward motion of particles near the wall could be seen in the capsules. Thus, the downward motion of particles in the annular capsule was balanced by a carry over of the particles from the bottom of the capsule to the top through core flow.

It is clear from Tables 1 and 2 that the actual pressure drop was considerably smaller than that due to the weight of the suspension in the annular capsules. It immediately follows that the wall exerted a large frictional resistance to support the weight of the capsule.

To qualitatively describe the role electrostatic forces plays on this unusual capsule flow, a simple test run was carried out to examine the induced current from the wall of pipe. The extra devices consisted of a coaxial cable linking the outer wall of pipe (which was tightly wrapped by an aluminum foil) and a digital electrometer. All...
Fig. 7. Distribution of polypropylene particles in a vertical riser flow. $U_g = 14.3$ m/s; $G_s = 21.7$ kg/(m² s). Slugging flow. (a) Snapshot showing a slug. (b) A sequence of ECT images showing the passage of a slug. (c) A surface plot of particle concentration contours at sensor location (iii)—2.05 m past the bend, obtained by time averaging the ECT results. (d) Temporal variation of cross-sectional average particle concentration at sensor location (iii). (e) Temporal variation of pressure gradient at this location. A horizontal pipe brought the gas–solid mixture to the vertical riser from the west side. Smooth 90° bend with $R/r = 2$. Rotary valve vent remained closed in this experiment. In Fig. 6c, the locations (0,0) and (1,1) denote the west and east sides, respectively.

All the above observations indicated qualitatively that electrostatic force did contribute to the formation of the annular capsule flow pattern.

4.1.4. Pattern velocities

Cross-correlation coefficient, $C(d)$, was extracted from twin-plane ECT data for the disperse flow of LLDPE particles for the operating conditions described earlier in Fig. 6. These results for three different ECT sensor pairs (i–ii, ii–iii, iii–iv) were calculated and clearly showed distinct peaks in the curves of cross-correlation coefficient against time delay. From the value of $d$ at which $C$ assumed its largest value (data not shown), we estimated the pattern propagation
Fig. 8. Distribution of polypropylene particles in a vertical riser flow. \( U_g = 13.0 \text{ m/s}; \ G_s = 7.0 \text{ kg/(m}^2\text{ s)} \). Flow in the presence of stationary annular capsules. (a) Photograph showing two stationary capsules. (b) Photograph revealing the annular structure of the capsule. (c) Particle concentration contours at sensor location (iii)—2.05 m past the bend, obtained by time averaging the ECT results. (d) A surface plot of particle concentration contours in Fig. 7c. A horizontal pipe brought the gas–solid mixture to the vertical riser from the west side. Smooth 90° bend with \( R/r = 2 \). Rotary valve vent remained closed in this experiment. In Fig. 7d, the locations (0,0) and (1,1) denote the west and east sides, respectively. Capsule extended all the way through the ECT sensor.

velocities to be 2.1 m/s (i–ii), 2.9 m/s (ii–iii) and 2.0 m/s (iii–iv). Such a trend, where the pattern velocity increased at first and then decreased, was observed at several operating conditions; however, a satisfactory explanation remains elusive.

Fig. 9. Dominant pattern propagation velocity, \( V^+ \text{ (m/s)} \), ■ N–S, ▲ E–W, based on twin-plane ECT data at sensor locations (iii) and (iv). Transport of polypropylene particles in a vertical riser without venting. (a) \( U_g = 16.9 \text{ m/s}; \ G_s = 27.0 \text{ kg/(m}^2\text{ s)} \) (b) \( U_g = 15.6 \text{ m/s}; \ G_s = 31.4 \text{ kg/(m}^2\text{ s)} \).

Pixel–pixel correlations of twin-plane ECT data along the E–W and N–S diagonals at sensor locations (iii) and (iv) in the disperse flow regime were obtained for the transport of polypropylene particles described earlier in Fig. 4. The existence of a dominant delay time, and hence a dominant pattern propagation velocity, could be seen at almost every pixel. The pattern propagation velocities estimated in this manner are presented in Fig. 9b. Fig. 9a shows similar results for a different set of operating conditions. Although there is some scatter, one can see that the pattern velocities are larger in the core region where the conditions are more dilute. The lower velocities in the wall region are consistent with the retarding effect of particle–wall interaction. The propagation velocities estimated from cross-sectional average ECT data and from pixel–pixel correlations were generally comparable in magnitude, as one would indeed expect.

One can readily expect that the flow patterns in the post-bend region will be closely coupled to the flow behavior in the horizontal pipe leading to the bend. Fig. 10 shows a comparison of the flow characteristics before and after
Fig. 10. Transport of LLDPE particles from a horizontal pipe to a vertical riser. $U_g = 20.8 \text{ m/s}$; $G_s = 29.9 \text{ kg/(m}^2 \text{ s)}$. Rotary valve vent remained closed in this experiment. (a) Particle concentration contours at sensor location (vi); (b) Particle concentration contours at sensor location (iii).

the bend. For the operating conditions considered here, the flow in the vertical pipe was in disperse flow regime, while a small eroding dune was present in the horizontal pipe over which the gas-particle mixture traveled in a dilute dispersed state. These are illustrated in the time-averaged particle concentration contours in Figs. 10a and b, which show results obtained at sensor locations (vi) in the horizontal duct and (iii) in the vertical pipe. The cross-correlation coefficients evaluated between twin-plane ECT sensors (v) and (vi) in the horizontal duct and (ii) and (iii) in the vertical pipe (data not shown) manifest strong peaks at comparable delay times, clearly showing that the disturbances whose propagation velocities were being detected through twin-plane ECT sensors in the vertical pipe were closely coupled to those in the horizontal duct.

4.1.5. Effect of rotary valve venting

The beneficial effects of rotary valve venting are generally well known. Air vents provided in the intermediate and feed recycle hopper reduce pressure build up in the system. The feeder characteristics are one of the key subjects in the pneumatic conveying operation. Most commonly used rotary feeders are known for leakages, which hinder the solids supply into the system. Providing a vent to the rotary feeder largely reduces the resistance to solids supply hence allowing smooth delivery into the air stream. The solids transport rates observed with vent case are more consistent for a given flow regime compared to no-vent case. In the absence of venting, the solids feed rate depended rather strongly on air flow rate (for a given rotary feeder rotation speed and valve opening level), and this can be seen from the results summarized in Tables 1 and 2. Venting reduced the back-pressure at the feed end and modified the rotary valve feeding characteristics. Specifically, much larger solids feed rate could be obtained (for a given rotary feeder rotation speed and valve opening level) and the solids feed rate was much less sensitive to air flow rate. This can be seen clearly by...
Fig. 12. Pneumatic conveying characteristic state diagram in a vertical pipe for polypropylene particles with venting. The pressure gradient is plotted against superficial gas velocity for different values of solids mass flux. Also refer to Table 3.

Comparing the fluxes reported in Tables 2 (without venting) and 3 (with venting). Furthermore, venting altered the nature of the fluctuations observed in the flow. This is illustrated in Fig. 11, which shows the effect of venting on cross-sectional average particle concentration, $\bar{z}_p(t)$, and its power spectrum. Figs. 11a and b were obtained with closed vent, while Figs. 11c and d correspond to open vent. The air velocity, rotary feeder rotation rate and valve opening were maintained constant in every case. Opening the vent increased the solids circulation by a factor of $\sim 2.5$. Fig. 11a reveals the presence of low-frequency fluctuations, which can be seen prominently in the power spectrum shown in Fig. 11b. This low-frequency fluctuation was absent when the vent was open (Figs. 11c and d). Fig. 11d reveals a clear peak at $\sim 3.5$ Hz. With a rotary feeder having eight pockets operating at $\sim 30$ rpm, one would expect pulsations at a frequency of $\sim 4$ Hz, which is quite close to the observed peak. Fig. 12 shows a characteristic state diagram of pneumatic conveying of polypropylene particles with venting.

Fig. 13. Distribution of polypropylene particles in a vertical riser flow. $U_g = 24.7$ m/s; $G_s = 74.5$ kg/(m$^2$ s). (a)–(d): Particle concentration contours at sensor locations (i)–(iv), located at distances of 0.47, 1.32, 2.05 and 2.66 m past the bend, respectively. The values of $\bar{z}$ at these locations are 0.0288, 0.0214, 0.016 and 0.014, respectively. Data were obtained by time averaging the ECT results. A horizontal pipe brought the gas–solid mixture to the vertical riser from the west side. Smooth 90° bend with $R/r = 2$. Rotary valve vent was open in this experiment.
4.1.6. Pulsing flow

When vertical pneumatic conveying experiments were performed with open vent, disperse flow, pulsing flow and moving annular capsule flow regimes were observed. Fig. 13 shows the time-averaged particle distribution, $\tilde{z}$, at sensors (i)–(iv) for an air velocity of 24.7 m/s and polypropylene particle flux of 74.5 kg/(m$^2$.s). It is clear from Figs. 13c and d that a core–annular distribution of particles emerged downstream of the bend. At low elevations (i.e. soon after the bend, Fig. 13a), one could identify a core and an annular ring rich in particles. This appears similar to the particle distribution presented earlier in Fig. 7. The annular ring is indicative of the developing disperse flow, discussed earlier (see, for example, see Fig. 5a). The particle-rich core seen in the time-averaged distribution (Fig. 13a) was a result of quasi-periodic pulsing at the bottom of the vertical pipe. At higher elevations, this pulsing became weaker (Fig. 13b) and eventually disappeared (Figs. 13c and d), revealing that...
Table 3
Transport of polypropylene particles in a vertical riser with venting

<table>
<thead>
<tr>
<th>(U_g) (m/s)</th>
<th>(G_s) (kg/(m^2) s)</th>
<th>Regime</th>
<th>(\langle Z \rangle_{ii})</th>
<th>(\Delta P/L) (Pa/m) measured across ii and iii</th>
<th>(\Delta P/L) (Pa/m) associated with holdup</th>
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</thead>
<tbody>
<tr>
<td>24.7</td>
<td>48.2</td>
<td>DF</td>
<td>0.010</td>
<td>214.9</td>
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<tr>
<td>23.4</td>
<td>34.8</td>
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<td>0.012</td>
<td>231.7</td>
<td>101.8</td>
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<tr>
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<td>34.1</td>
<td>DF</td>
<td>0.012</td>
<td>217.8</td>
<td>101.8</td>
</tr>
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<td>242.5</td>
<td>118.8</td>
</tr>
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<td>19.5</td>
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</tr>
<tr>
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<tr>
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<td>34.6</td>
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<td>491.2</td>
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<td>DF</td>
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</tr>
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<td>DF</td>
<td>0.025</td>
<td>307.2</td>
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<tr>
<td>19.5</td>
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<td>DF</td>
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<td>306.6</td>
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<td>16.9</td>
<td>65.3</td>
<td>PF</td>
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<tr>
<td>15.6</td>
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<td>MAC</td>
<td>0.120</td>
<td>1007.9</td>
<td>1017.9</td>
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</tbody>
</table>

Solids feed valve opening: 50% (rows 1–8), 75% (rows 9–16) DF = dispersed flow; PF = pulsing flow; MAC = moving annular capsule.

Fig. 15. ECT images of particle concentration at station (iii), located 2.05 m downstream of the bend, at various times. The time lag between each frame is 0.025 s. Transport of polypropylene particles in a vertical riser. A horizontal pipe brought the gas–solid mixture to the vertical riser from the west side. Smooth 90° bend with \(R/r = 2\). Rotary valve vent was open in these experiments. \(U_g = 16.9\) m/s, \(G_s = 65.3\) kg/(m² s).

Pulsing was restricted to the bottom of the riser under this operating condition.

Pulsing flow differed in a significant way from slugging flow described earlier in the context of closed vent. Slugging was observed throughout the riser and appeared to be a regime intrinsic to vertical conveying; in contrast pulsing was clearly attributable to entrance effect. In particular, pulsing flow was observed when the particle transport in the horizontal duct occurred in the form of moving or eroding dunes, so that the particles arrived at the bottom of the riser in a pulsating manner. These pulses became weaker as they traveled up through the riser. The height in the riser to which the pulsing flow could be observed depended on the operating conditions (gas velocity and particle flux).

As the gas velocity was decreased (while holding the particle flux roughly constant), the pulsing became more and more pronounced, and could be observed at greater heights. This can be recognized from Fig. 14, where we present the time-averaged particle concentrations along the N–S and E–W diagonals at sensor location (iii). Figs. 14a–f correspond to six different air velocities; the particle flux decreased slightly as the gas velocity was lowered, but the percent change in solids flux was much smaller than that in the gas velocity. As the gas velocity was decreased, the average concentration of particles increased gradually, as one would expect. It is clear from these figures that the flow was reasonably symmetric in the core region at all these flow conditions. Although this was not the case in the
annular ring, the presence of such a ring could indeed be seen in both the N–S and E–W diagonals in all these figures. Note that the prominence of the peak in the core region increases as we go from Fig. 14a–f. This is simply a consequence of increased frequency of the pulses and the fraction of time for which a pulse was seen at a given location in the pipe. Thus, a small degree of pulsing was present under most operating conditions labeled as disperse flow in Table 3. (The label in this table was based purely on visual observations.)

The passage of a pulse shown in Fig. 15 is similar to that shown earlier in Fig. 7b. However, as stated above, the visually observable dynamics in the riser were quite different in the pulsing and slugging regimes. The time-averaged particle concentrations along the N–S and E–W diagonals for the operating conditions shown in Fig. 15 are shown in Fig. 16a. It is clear that Fig. 16a is similar to Figs. 14a–f. The particle concentration levels at this operating condition were quite large, and the quantitative accuracy of the ECT measurements was generally much better (when compared to the conditions described earlier in Fig. 14). The similarity between Figs. 14 and 16a lends credence to the usefulness of the ECT system even at low concentrations, at least in a qualitative sense.

Figs. 16b and c show the temporal variations of cross-sectional average particle concentration, \( \overline{\rho}(t) \), and the pressure gradient at this location. Both reveal clearly the pulsating flow. No dramatic difference could, however, be seen between Figs. 7d and 16b, and between 7e and 16c (or the corresponding power spectra). Thus, the distinction between pulsing and slugging flow was not apparent in the ECT and pressure gradient measurements. However, visual observation did reveal appreciably different character between these two regimes, as noted above.

It is clear from Table 3 that in the dispersed flow, the pressure gradient was larger than that due to the weight of the suspension. In pulsing flow, the pressure drop was roughly comparable to the weight of the suspension or greater. This implies that the wall resistance was pointing upward at some operating conditions, which would be possible only if there was a downhill flow near the wall region.

4.1.7. Moving capsule flow

Upon lowering the airflow rate further, a transition occurred from pulsing flow to moving capsule flow. Sequences of ECT images obtained at sensor locations (ii) and (iii) are presented in Fig. 17. The moving capsule can be readily identified from these figures, and one can also compute the velocity of these capsules. The capsules had a core–annular structure, with particle concentration in the annular region being larger than that in the core. This is quite different from the pulses (open vent) or slugs (closed vent), where the core was richer in particles. The capsule illustrated in Fig. 17 is more like the capsule shown earlier in Fig. 8, the major difference being that the capsule in Fig. 8 was stationary.

Stationary capsules were not observed in our experiments with open vent. The moving capsule is quite different in character to the commonly reported moving bed flow, where there is no dilute core.

The time-averaged particle concentrations along the N–S and E–W diagonals for the case shown in Fig. 17 are presented in Fig. 18. It is clear that, in a time-average sense,
the flow was symmetric in the azimuthal direction and had a strong core–annular character.

4.2. Flow in an Inclined Riser

Tables 4 and 5 summarize results obtained in an inclined riser with and without venting. As expected, venting allowed more uniform and larger flux of particles. A variety of flow regimes were again observed. In the dispersed flow regime, the particle concentration was generally low; one

<table>
<thead>
<tr>
<th>$U_g$ (m/s)</th>
<th>$G_s$ (kg/m$^2$ s)</th>
<th>Regime</th>
<th>$\langle \delta \rangle_{\text{iii}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.2</td>
<td>25.0</td>
<td>DF</td>
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<td>EDD/FSL</td>
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</tr>
<tr>
<td>11.7</td>
<td>(−)</td>
<td>EDD/FSL</td>
<td>0.348</td>
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</table>

DF = dispersed flow; ED = eroding dunes; EDD = eroding dunes with downflow; EDD/FSL = transition from eroding dunes to flow over a settled layer, with downflow; FSL = flow over a settled layer; (−) = negligible value. Solids feed valve opening: 50% (rows 1–6), 75% (rows 7–14).
Table 5
Transport of polypropylene particles in an inclined riser with venting

<table>
<thead>
<tr>
<th>(U_g) (m/s)</th>
<th>(G_s) (kg/m(^2) s)</th>
<th>Regime</th>
<th>(\langle \xi \rangle_{av})</th>
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<td>22.1</td>
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<td>20.8</td>
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<td>19.5</td>
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<td>FSL/SFD</td>
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<td>61.6</td>
<td>FSL/SFD</td>
<td>0.286</td>
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DF = dispersed flow; ED = eroding dunes; EDD = eroding dunes with downflow; EDD/FSL = transition from eroding dunes to flow over a settled layer, with downflow; FSL/SFD = transition from flow over a settled layer to slug flow, with downflow. Solids feed valve opening: 50% (rows 1–5), 75% (rows 6–12).

Fig. 19. Eroding dunes in a 45\(^\circ\) inclined pipe. Transport of polypropylene particles by air. \(U_g = 16.9\) m/s. Negligible net transport of particles. (a) snapshot of the flow pattern. (b) ECT images sequence with number on the top left showing the frame number. (c) Variation of time-averaged particle concentration along the \(x\) direction marked in the figure. \(x/d_i = 0\) and 1 correspond to the top and the bottom of the pipe, respectively. Rotary valve vent was closed in these experiments. The ECT measurements were made at distance of 2.16 m downstream of the bend.

would expect the lower half of the pipe’s cross-section to contain a larger concentration of particles as a result of gravitational sedimentation, and this could be seen visually and also picked up through ECT measurements. At somewhat lower gas velocities, the sedimenting particles formed discontinuous dunes. These dunes eroded at the upstream end, with particles being picked up by the flowing air. Particles were deposited at the downstream end of the dunes, and through such erosion, the dunes gradually drifted up through the riser. (Under other operating conditions, the particles in the dune were also sliding down, so that the net movement of the dunes were actually downward. This is noted in Tables 4 and 5.)

An eroding dune is illustrated in Figs. 19a–c, showing a snapshot of the dune (Fig. 19a), ECT images at four different times (Fig. 19b), and the variation of the time-averaged particle concentration (Fig. 19c) from the top to the bottom of the pipe (along the direction \(x\) shown in Fig. 19a).
At somewhat lower airflow rates, the dunes transformed into an essentially continuous settled layer (Fig. 20a). The time-averaged particle concentration profile (Fig. 20c) is similar to that seen earlier for eroding dune flow, except that the height of the settled layer was now significantly larger. Above the settled layer, the particles were transported up the pipe in a disperse state. The net airflow rate for this operating condition was negligible, so the upflow of particles in the dilute region was compensated by the sliding flow of particles in the settled layer. ECT images shown in Fig. 20b and visual observations revealed that the top surface of the settled layer had a distinct curvature. This suggests that the particles or particle clusters were picked up by air from the settled layer at the center and were deposited along the sides of the pipe.

Fig. 21 shows the evolution of cross-sectional average particle concentrations (filled symbols) for a range of operating conditions in the disperse airflow regime. Also shown in this figure are the pattern propagation velocities extracted from twin-plane ECT measurements. Rao et al. (2001) found that pattern propagation velocities for pneumatic transport through horizontal pipes in disperse airflow regime were quite close to the particle velocities themselves and proposed an empirical approach to determining solids airflow rate from the ECT measurements. The present study on vertical and inclined risers suggested that a similar approach may be devised for flow in vertical and inclined pipes. This can be seen in Fig. 21, where an inverse relation between the particle concentration and pattern propagation velocity is evident. In three of the four operating conditions shown in Fig. 21, the particle concentration initially decreased with axial distance and then increased. The initial decrease in particle concentration can be understood as a kinematic effect associated with acceleration of particles past the bend. The subsequent increase in particle concentration may be due to gravitational settling over the pipe cross-section.

5. Summary

We have presented results of detailed ECT measurements of gas-particle flows in vertical and inclined risers. The focus of our work has been to apply ECT as a characterization tool and develop a qualitative picture of the manner in which flow patterns develop after a smooth bend connecting the vertical or inclined riser to a horizontal pipe feeding the gas-particle mixture.

Dispersed flow of large particles is shown to develop in vertical risers in an interesting manner. Time-averaged data ECT measurements at a location shortly after the bend revealed the presence of an annular ring of particles with a peak location away from the wall. At further downstream distances, the peak migrates to the wall region, yielding a familiar core–annular structure. Heavier (more inertial) LLDPE particles appear to form a core–annular structure with a narrower annulus than the polypropylene particles. Pattern velocity measurements revealed faster (slower) velocities of disturbance propagation in the core (annulus).

It is well known that rotary valve feeder venting can have a dramatic effect on particle feed rates. In the absence of venting, the backpressure which built up in the valve affected the solids flow adversely. Not only were the fluxes lower without venting, but the flow also manifested low-frequency oscillations. In the absence of venting, and at low air flow rates, the
gas-particle mixture traveled through the riser in a slugging flow pattern. The slugging flow was seen throughout the riser, suggesting that this flow pattern was intrinsic to riser flow. We have reported the spatio-temporal structure of slugging flow and rationalized the peaks in the time-averaged concentration of particles observed in the wall region and at the axis. With closed vents, we observed a peculiar flow pattern at low gas velocities, where a number of stationary annular capsules were present in the riser.

With open vents, the particle feed rates were much larger and we observed dispersed flow at high carrier gas velocities. As the gas velocity was lowered, a pulsing flow resulted in the vertical riser, which was clearly an entrance effect. In particular, pulsing flow was observed when the particle transport in the horizontal duct occurred in the form of moving or eroding dunes, so that the particles arrived at the bottom of the riser in a pulsating manner. Although pulsing and slugging left similar fingerprints on ECT and pressure gradient measurements, they differed considerably. ECT measurements revealed that pulsing got progressively weaker with increasing distance downstream of the bend.

Our ECT measurements probing the development of dispersed flow in an inclined (45°) riser past a bend revealed that the particle loading initially decreased as a result of acceleration (a purely kinematic effect) and subsequently increased (possibly as a result of gravitational sedimentation). At further distances downstream, the particle concentration appeared to level off, signaling the approach of a fully developed flow. Regimes such as eroding dune flow and flow over a settled layer could be easily imaged using ECT. Our ECT measurements revealed a concave shape for the surface of the settled layer in the regime of flow over a settled layer, which could be confirmed visually. This shape suggests that the particles were picked up from the settled layer by airflow at the center and deposited on the sides of the tube.

\begin{equation}
S = \text{density of the power spectrum, dimensionless}
\end{equation}
\begin{equation}
t = \text{time, s}
\end{equation}
\begin{equation}
T = \text{time duration for averaging, s}
\end{equation}
\begin{equation}
\Delta T = \text{time shift of the periodic wave, s}
\end{equation}
\begin{equation}
U_g = \text{superficial velocity of air, m/s}
\end{equation}
\begin{equation}
V^* = \text{pattern velocity, m/s}
\end{equation}
\begin{equation}
x, y = \text{dimensionless coordinates in the cross-section of a pipe, dimensionless}
\end{equation}
\begin{equation}
z = \text{dimensionless coordinate along the axis of the pipe, dimensionless}
\end{equation}

**Greek letters**

\begin{equation}
\bar{\bar{s}}_s = \text{instantaneous particle concentration averaged over the pipe cross-section, dimensionless}
\end{equation}
\begin{equation}
\bar{s}_t = \text{time-averaged particle concentration at a given pixel, dimensionless}
\end{equation}
\begin{equation}
\langle \bar{s} \rangle = \text{space- and time-averaged particle concentration, dimensionless}
\end{equation}
\begin{equation}
\Delta p/L = \text{pressure drop per unit length, Pa/m}
\end{equation}
\begin{equation}
\rho_s = \text{density of the material, kg/m}^3
\end{equation}

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**References**


