ECVT Imaging of 3-D Flow Structures and Solids Concentration Distributions in a Riser and a Bend of a Gas-Solid Circulating Fluidized Bed

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ECVT IMAGING OF 3-D FLOW STRUCTURES AND SOLIDS CONCENTRATION DISTRIBUTIONS IN A RISER AND A BEND OF A GAS-SOLID CIRCULATING FLUIDIZED BED

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ABSTRACT

Experimental studies using electrical capacitance volume tomography (ECVT) are conducted to examine gas-solid flows in a riser and a bend of a 0.05 m (2 in) ID gas-solid circulating fluidized bed (CFB) system. The quantitative measurements using ECVT are made that illustrate a three-dimensional symmetric core-annulus structure in the riser and a non-centro-symmetric core-annulus structure in the bend. Results on the volume solids holdup distributions in the riser and in the bend at various operating conditions are also obtained.

INTRODUCTION

Gas-solid flows have been employed extensively in industrial operations (Kunii and Levenspiel (1), Fan and Zhu (2)). Bent vessels are commonly used in solids handling systems such as an exit of a riser in a gas-solid circulating fluidize bed (CFB) and elbows to change the solids transport direction in solids pneumatic conveying. The details of the gas-solid flow behaviors in such bends as well as in straight vessels are of great importance for the design of the CFB reactors and pneumatic conveying systems. Due to the lack of advanced imaging technologies in the past, visualizations of on-line three-dimensional gas-solid flow patterns and measurements of volumetric solids holdup in straight vessels and bends were rarely reported. Currently, there are two main methods of measurement, intrusive and non-intrusive techniques, applied to gas-solid flows. Classification of these methods is predicated by the mechanism by which measurement signals are acquired. For intrusive techniques, the measurement sensor, such as a capacitance probe (Lanneau (3), Geldart and Kelsey (4)), optical fiber probe (Yasui and Johanson (5), Cui and Chaouki (6)), endoscopic probe (Peters et al. (7), Du et al. (8)) or pressure transducer probes (Kang et al. (9), Geldart and Xie (10)), requires direct contact with the flow media to record a measurement. This intrusive nature may potentially disturb the physical flow behavior. Conversely, non-intrusive techniques are based on remote acquisition of the measurement signals from sensors mounted away from the flow and avoiding interference with the internal of a multiphase flow system. Non-intrusive techniques are widely applied for the measurements of gas-solid flows. In this regard, electrical capacitance volume tomography (ECVT) has emerged as a practical technology for realistic measurements without interfering with the flow.
ECVT has provided the means for imaging gas-solid flows in complex geometries due to the flexibility of its sensors (Marashdeh et al. (12), Wang et al. (13, 14, 15)). In this study, an advanced ECVT sensor system is designed for imaging gas-solid flows in complex geometries. Two developed sensors are used for imaging real-time three-dimensional gas-solid flows in a riser and a 90° bend at the exit region of a CFB. The flow structures in the riser and the bend are analyzed based on quantitative ECVT images. The volumetric solids holdup in the riser and the bend in the CFB are obtained for various superficial gas velocities and solids fluxes.

**EXPERIMENTAL SETUP**

Figure 1 is a schematic diagram of the gas-solid circulating fluidized bed. The CFB unit, made of Plexiglas, consists of a 0.05 m ID riser with a height of 2.6 m, a porous distributor, a 90° bend, a cyclone system, a standpipe/downer and an L-shape non-mechanical valve. The FCC particles (Geldart group A) with a mean diameter of 60 µm and a particle density of 1400 kg/m³ and air are used as the fluidized particles and fluidizing gas. A porous plate with a pore size of 20 µm and a fractional free area of 60% is used as the distributor of the CFB riser. The gas flow rate in the riser is controlled by a flowmeter in the main gas line. Another flowmeter is used to control the aeration gas flow rate at the bottom of the downer to provide different solids flux in the CFB. A bend sensor and a cylindrical sensor are mounted at the exit region and in riser in the CFB, respectively. Figure 2 is a photo of the real gas-solid circulating fluidized bed mounted with the ECVT bend sensor and the cylindrical sensor.
In an ECVT, a volume image of different phases in the test domain is reconstructed based on utilizing nonlinear distributions of electric field lines. An ECVT system consists of three basic components: (1) a capacitance sensor, (2) a data acquisition system, and (3) a computer system for reconstruction and viewing. Figure 3 is a schematic diagram of the ECVT system incorporating the three components. The capacitance sensor is made of a number of capacitance electrodes, \( n_e \), distributed around the peripheral of the domain of interest. Additionally, there are \( n_e (n_e - 1)/2 \) combinations of independent capacitance measurements between all pairs of electrode. The ECVT image reconstruction employed here is based on an optimization reconstruction technique called the neural network multi-criterion optimization image reconstruction technique (NN-MOIRT) (Warsito and Fan (16)). The technique has also been extended to reconstruct volume images from 3D capacitance sensors (Warsito et al. (11)). This extension increased the accuracy of reconstructed images.

Recent developments have focused on the ECVT sensor design with 3D features for detecting capacitance variations due to permittivity perturbations in the imaging volume. For imaging complex geometries using ECVT, sensor design is the main element of the imaging system to define the volume under interrogation. In this work, two ECVT sensors are designed to image flows in the riser and the transition region in the right-angle bend. The design of the cylindrical sensor is aimed at establishing an electrically varied field around the riser by arranging 12 electrodes in three layers as depicted in Figure 4 (a). The capacitance measurements are obtained between the plates at each layer and between plates in different layers of the cylindrical sensor to image the flow in the riser. The design of the bend sensor is also aimed at establishing an electrically varied field at and around the corner of the bend by arranging 12 electrodes in two layers perpendicular to each other as depicted in Figure 4 (b). While the plates at each layer image the flow entering and exiting the bend, it is the interaction between plates in both layers that most reveals the flow dynamics in the region where the flow changes direction. The ECVT sensor design is developed intuitively and confirmed by computer simulation (Marashdeh et al., 2008). Simulations in this case confirmed the sensitivity distribution is focused at and around the bend corner. The acquisition frequency is 80 Hz and the reconstruction resolution is \( 20 \times 20 \times 20 \) for the three-dimensional reconstructed images of all tests.
Volume fraction as measured by ECVT is in the range of 2-5% of total volume. The accuracy varies within this range depending on the flow structure and particles used in flow. The assessment for the accuracy of ECVT images of a flow in a bend is based on previous assessments of ECVT imaging accuracy in straight sections.

![Schematic diagram of the ECVT system](image)

Figure 3. Schematic diagram of the ECVT system.

![Configuration of the ECVT sensors](image)

Figure 4. Configuration of the ECVT sensors: (a) cylindrical sensor; (b) bend sensor.

RESULTS AND DISCUSSION

Solids Holdup Distribution in the Riser

The cylindrical sensor is used for imaging real-time three-dimensional gas-solid flows in the riser of the CFB. The volumetric solids holdup distribution in the sensor section of the riser at varying superficial gas velocity and solids flux is obtained. The instantaneous three-dimensional dynamic gas-solid flow structures in the riser are analyzed based on quantitative ECVT images. Figure 5 shows the time-averaged solids holdup distribution in the test region of the riser with superficial gas velocity, $U_g$, from 0.97 m/s to 1.94 m/s and a solids flux, $G_s$, of 21.6 kg/m²s within 10 seconds. The sub-image on the left in each image is the solids concentration distribution in the X-Z (X, Y: two horizontal directions; Z: direction of the axis of the riser) whereas the right sub-image represents the solids concentration distribution at the top, middle, and bottom cross-sectional planes of the test region of the riser. Figure 6 shows the time-averaged volume solids holdup in the riser at $G_s=21.6$ kg/m²s. The experimental results indicate that the averaged volume solids holdup decreases with $U_g$. A symmetric core-annulus structure with a low solids holdup in the core area and a high solids holdup in the annulus area in the riser is observed. The thickness of the annulus and solids holdup in the annulus near the wall decrease with $U_g$. 
Figure 5. Time-averaged solids holdup distribution in the riser at $G_s=21.6$ kg/m²s: (a) $U_g=0.97$ m/s; (b) $U_g=1.16$ m/s; (c) $U_g=1.36$ m/s; (d) $U_g=1.55$ m/s; (e) $U_g=1.75$ m/s; (f) $U_g=1.94$ m/s.

Figure 6. Time-averaged solids volume holdup in the riser at $G_s=21.6$ kg/m²s.

**Solids Holdup Distribution in the Bend**

The bend-sensor is used for imaging real-time three-dimensional gas-solid flows at the exit region of the CFB riser. The volumetric solids holdup distribution in the exit region of the CFB riser at varying superficial gas velocity and solids flux is probed. The three-dimensional solids holdup distributions in the bend of the riser are illustrated by slices in the volume image cut through the bend vertically and horizontally. The configurations of the vertical and horizontal slices are given in Figure 7. Figure 8 shows the solids holdup distribution in the bend of the riser with $U_g$ of 1.36 m/s and $G_s$ of 21.2 kg/m²s. The images indicate that a core-annulus flow structure is formed both in the vertical and horizontal parts of the bend. The solids holdup in the core region is relatively low compared to that in the annulus region. The annulus structure is non-centro-symmetric in the horizontal part of the bend (Grace, et al. (17)). The asymmetry of the solids volume fraction in the bend is due to the exit at one side and the tortuosity of the flow path at entrance of the cyclone. The solids holdup in the annulus near the top wall area in the bend is higher than that in other
locations of the annulus. The asymmetry is due to the following reasons: (1) back mixing and reflection of solids from the upper wall of the horizontal duct; (2) solids in the bend are difficult to entrain with the gas flow due to an abrupt turn of the gas stream in the bend; (3) a zone with low gas velocities at the upper corner of the bend is formed. The images also indicate that a solids “dune” is formed, at the bottom of the horizontal section of the bend. The sedimentation of solids in the horizontal duct is due to: (1) the velocity of the main gas stream is not high enough to carry all the solids horizontally to the cyclone, and thus the sedimentation of solids occurs; (2) after an abrupt turn in the bend, the gas moves towards the top of the horizontal duct in the bend, which forms a zone with relatively low gas flow rate at the bottom of the horizontal duct. Figure 9 shows the solids holdup distribution in the bend of the riser with \( U_g \) of 1.16 m/s and \( G_s \) of 21.2 kg/m²s. The comparison between Figures 8 and 9 indicates that the solids holdup near the top wall area in the bend increases with the superficial gas velocity. More solids move to the outside wall area from the main stream in the bend due to high solids velocity at high superficial gas velocity. Figure 10 shows the time-averaged volume solids holdup in the bend at a superficial gas velocity of 1.16 m/s. The experimental results indicate that the time-averaged volume solids holdup near the top wall area increases with solids flux. More solids are separated to the outside of the bend from the main stream of the gas-solid flow at high solids flux in the CFB.

![Figure 7](image1)

Figure 7. Configuration of the slices for the plots of the tomographic images in the bend: (a) vertical slices; (b) horizontal slices.

![Figure 8](image2)

Figure 8. Solids holdup distribution in the bend of the CFB riser at \( U_g = 1.36 \) m/s and \( G_s = 21.2 \) kg/m²s: (a) vertical slices; (b) horizontal slices.

![Figure 9](image3)

Figure 9. Solids holdup distribution in the bend of the CFB riser at \( U_g = 1.16 \) m/s and \( G_s = 21.2 \) kg/m²s: (a) vertical slices; (b) horizontal slices.
CONCLUSIONS

An advanced ECVT sensor system is designed for real-time, three-dimensional imaging of gas-solid flows in a riser and a 90° bend at the exit region of a CFB. The instantaneous 3-D dynamic gas-solid flow structures in the riser and the bend are analyzed based on quantitative ECVT images. A symmetric core-annulus structure in the riser is observed. It is found that the thickness of the annulus and solids holdup in the annulus near the wall of the riser decrease with $U_g$. A core-annulus flow structure is formed both in the vertical and horizontal parts of the bend. The annulus structure is non-centro-symmetric in the horizontal part of the bend. The solids holdup in the annulus near the top wall area in the bend is higher than that in other locations of the annulus. A solids “dune” is observed by ECVT at the bottom of the horizontal duct of the bend. The solids holdup at the top wall region in the bend increases with the superficial gas velocity. The time-averaged volume solids holdup near the top wall area increases with the solids flux.

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NOTATION

$G_s$ solids flux (kg/m$^2$s)
$n_e$ number of capacitance electrodes
$U_g$ superficial gas velocity (m/s)

Greek letters

$\varepsilon_s$ solids holdup
REFERENCES