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Tomography for Imaging Large-Scale, Cold-Flow Circulating Fluidized Bed**

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Abstract

A detailed understanding of multiphase flow behavior inside a Circulating Fluidized Bed (CFB) requires a 3-D technique capable of visualizing the flow field in real-time. Electrical Capacitance Volume Tomography (ECVT) is a newly developed technique that can provide such measurements. The attractiveness of the technique is in its low profile sensors, fast imaging speed and scalability to different section sizes, low operating cost, and safety. Moreover, the flexibility of ECVT sensors enable them to be designed around virtually any geometry, rendering them suitable to be used for measurement of solid flows in exit regions of the CFB.

Tech4Imaging LLC has worked under contract with the U.S. Department of Energy's National Energy Technology Laboratory (DOE NETL) to develop an ECVT system for cold flow visualization and install it on a 12 inch ID circulating fluidized bed. The objective of this project was to help advance multi-phase flow science through implementation of an ECVT system on a cold flow model at DOE NETL. This project has responded to multi-phase community and industry needs of developing a tool that can be used to develop flow models, validate computational fluid dynamics simulations, provide detailed real-time feedback of process variables, and provide a comprehensive understating of multi-phase flow behavior.

In this project, a complete ECVT system was successfully developed after considering different potential electronics and sensor designs. The system was tested at various flow conditions and with different materials, yielding real-time images of flow interaction in a gas-solid flow system. The system was installed on a 12 inch ID CFB of the US Department of Energy, Morgantown Labs. Technical and economic assessment of Scale-up and Commercialization of ECVT was also conducted. Experiments conducted with larger sensors in conditions similar to industrial settings are very promising. ECVT has also the potential to be developed for imaging multi-phase flow systems in high temperature and high pressure conditions, typical in many industrial applications.

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Executive Summary

A detailed understanding of multiphase flow behavior inside a Circulating Fluidized Bed (CFB) requires a 3-D technique capable of visualizing the flow field in real-time. Electrical Capacitance Volume Tomography (ECVT) is a newly developed technique that can provide such measurements. In ECVT, a set of non-invasive capacitance sensors are placed around a measurement section of the flow field. Sensors interact with each other collecting real-time measurements that can be related back to phase concentrations in the section. The technique is based on reconstructed volume images from capacitance signals acquired from sensors with inherent 3-D features. The attractiveness of the technique is in its low profile sensors, fast imaging speed and scalability to different section sizes, low operating cost, and safety. Moreover, the flexibility of ECVT sensors enable them to be designed around virtually any geometry, rendering them suitable to be used for measurement of solid flows in exit regions of the CFB.

In the course of this project, a novel ECVT system was developed to study the flow patterns of particles common to pilot scale circulating fluidized beds. The system capability to collect data useful in validating multi-phase flow models was also evaluated. The system is composed of 24 channel data acquisition, reconstruction software, and sensors. An operational ECVT system with three sensors for Developed, Inlet, and Exit regions was developed, delivered, and installed at DOE NETL Morgantown 12 inch circulating fluidized bed unit. The system was successfully tested and capacitance data were used to generate volume images of fluorescent particles flowing inside the CFB at different flow rates.

The developed system has contributed significantly to advancements of multi-phase flow science. This contribution is best illustrated through scientific publications that use the develop system to validate CFD models and explore new flow behaviors. Some of ECVT technology applications include bubble columns, trickle beds, CFB's, bended sections, and irregularly shaped vessels. The technology capability of providing a comprehensive, real-time, 3D images of phase concentrations, average velocities, flow rates, and other flow variables have prompted global interest in its utility. ECVT is currently operating at different countries around the world helping scientist and engineers develop, design, and control multi-phase flow systems.

The introduced system has also the potential of being developed to address scale-up and hot unit applications. To that end, an investigation was conducted to the feasibility of using ECVT in hot unit applications with promising results of operating at high temperatures reported. The system was also tested with various column sizes with the potential of being applied to scale-up applications being validated.

1. Introduction

The use of a circulating fluidized bed (CFB) in industry spans a wide range of applications such as fluid catalytic cracking process and coal combustion. Operating variables for a CFB include both the gas flow rate and the solids flow rate. Flow properties can be determined by different combinations of these two variables (Fan & Zhu, 1998). The riser, inside of which a suspended gas-solid flow takes place, is a key part of a CFB system. Its hydrodynamics have been studied extensively in the literature (Berruti, Pugsley, Godfroy, Chaouki, & Patience, 1972). Computational Fluid Dynamics (CFD) has also been used extensively to study CFB flow (Wang F. , Marashdeh, Wang, & Fan, 2012). Verification of CFD simulations, however, continues to require comprehensive experimental data, particularly the 3-D data and the data from sections of the CFB system other than the riser.

A detailed understanding of multiphase flow behavior inside a CFB requires a 3-D technique capable of visualizing the flow field in real-time. Electrical Capacitance Volume Tomography (ECVT) is a newly developed technology that can provide such measurements (Wang F. , Marashdeh, Fan, & Warsito, 2010) (Wang, Yu, Marashdeh, & Fan, 2010) (Warsito, Marashdeh, & Fan, 2007). In ECVT, a set of non-invasive capacitance sensors are placed around a measurement section of the flow field. Sensors interact with each other collecting real-time measurements that can be related back to phase concentrations in the section. The technique is based on reconstructed volume images from capacitance signals acquired from sensors with inherent 3-D features. The attractiveness of the technique is in its low profile sensors, fast imaging speed and scalability to different section sizes, low operating cost, and safety. Moreover, the flexibility of ECVT sensors enable them to be designed around virtually any geometry, rendering them suitable to be used for measurement of solid flows in exit and inlet regions of the CFB (Wang F. , Marashdeh, Fan, & Warsito, 2010). The feasibility of ECVT technique for volume imaging of multi-phase flows has been demonstrated through its implementation on flow sections of various shapes and sizes (Wang F. ,

Marashdeh, Fan, & Warsito, 2010). ECVT sensors have a wide range of applicability in the shape or size of a process column. The largest known column to which ECVT sensors were applied was 60 inch in diameter, and the smallest was 1 inch in diameter. Sizes outside this range can also be accommodated. As to metal columns, capacitance sensors were placed inside a stainless-steel reactor column and separated by a ceramic layer from the flow in one recent application that involved a chemical looping reactor system. ECVT sensors can be applied to metallic columns following similar arrangements to the example mentioned here.

In this project, an advanced ECVT sensor system is designed and used for imaging gas-solid flows in complex geometries. Sensors are developed for imaging 3-D gas-solid flows in the riser, inlet, and the 90° bend exit region of a 12 inch ID CFB. It is now possible to image and quantitatively analyze the flow structures in the three sections.

In this project, a complete ECVT system was successfully developed and installed on 12 inch ID CFB of the US Department of Energy, Morgantown Labs. In addition, this report also includes technical and economic assessment of Scale-up and Commercialization of ECVT.

2. Objectives

The overall goal of the project was to develop a novel ECVT system to study the flow patterns of particles common to pilot scale circulating fluidized beds and evaluate its capability to collect data useful in validating multi-phase flow models. The proposed project further advances research in multiphase flow and an ECVT system is expected to become an invaluable asset in this field. Toward this end, the following objectives were attained in the proposed project:

- 1- Develop high speed capacitance acquisition hardware with up to 50 imaging frames per second for a 24 channel system.
- 2- Develop a 3D reconstruction software to view 3D images of solid concentrations, volume average velocity profiles, average volume granular temperatures, and other related properties.

- 3- Design 3D capacitance sensors custom to the cold-flow fluidized bed under investigation to image the fully developed, “L-valve” feed, and “elbow” exit regions.
- 4- Conduct through analysis of acquired images.
- 5- Install the capacitance sensors and deliver a fully operating ECVT system.

3. Statement of work

The scope of work consisted of three phases designed to complete the proposed work with cohesiveness and efficiency. In phase I, different capacitance measuring technologies were considered for ECVT hardware. The proper design was identified based on computer simulations of different possible measuring circuits. Sensor designs for the three sections were also investigated to image the three regions of interest (fully developed, feed, and exit). Simulated reconstruction was also performed to confirm integrity of selected designs. In phase II of the project, sensors and acquisition system were fabricated and tested. Phase III involved development and implementation of reconstruction software. In this phase, an ECVT system was demonstrated in integrated and continuous mode. The system was also installed on NETL’s cold flow circulating fluidized bed.

Key tasks of the project were:

- Revise Project Management and Plan
- Design of sensors and acquisition hardware based on Computer Simulations
- Fabrication of one capacitance sensing channel
- Fabrication of 3D capacitance sensors
- Design of user friendly reconstruction software
- Test integrated system performance
- Testing developed system on 12” cold flow CFB unit
- System installation and user training
- Technical and Economic Assessment of Scale-up and Commercialization of ECVT

4. Information required in topical reports that Occur at end of each milestone

An ECVT system is generally composed of three parts: Data acquisition hardware, 3D sensor, and 3D reconstruction algorithm. The three components function together to decode the 3-dimensional spatial information hidden in the capacitance signal acquired from the 3D capacitance sensor. The decoding task for obtaining this spatial information, referred to often as the ECVT inverse problem, requires proper design of the three ECVT components to function together toward a complete operating volume capacitance system.

The 3D sensor design and the reconstruction algorithm are interdependent where a change in one of them would affect the performance of the other. Every 3D sensor design is represented by a sensitivity matrix used by the reconstruction algorithm for acquiring the required spatial mapping. On the other hand, the ECVT hardware imposes a limit on the number of capacitance plates that can be used in the sensor design, thus indirectly affecting the accuracy of reconstructed results.

The acquisition hardware design involves recording small capacitance changes, caused by flow dynamics, in short times. This is a challenging problem as the targeted capacitance change to be recorded is far less than the capacitance inherent in the system itself. Thus, ECVT acquisition hardware would require a design capable of eliminating static capacitances in the system and tracking variations in capacitance level. The hardware design also requires each capacitance acquisition circuit to be immune for electric noise, as a high imaging rate requires acquisition of high number of frames per second. The short time left for each capacitance reading makes it more vulnerable to electric noise. This is due to the fact that electric noise varies over time and is modeled as a natural curve in terms of voltage amplitude with zero mean. Thus, the integration of electric noise over the time of capacitance sensing approaches zero as the capacitance sensing time is increased. From here one can see that as high imaging speed is required, the effect of noise on capacitance sensing channels increases.

Below are the Milestones achieved during this project toward a successful implementation of an operational fully integrated ECVT system:

Selection of capacitance channel design & Selection of sensors designs for various sections of CFB

The ECVT Data Acquisition System (DAS) provides selectivity for driving each sensor plate with an AC signal measuring the current through each of the capacitors formed by pairs of plates. The DAS is also designed to reject parasitic and cable capacitances. This enhances the DAS resolution for measuring small variation in capacitance signal. Data acquired by the DAS is to be delivered to an external reconstruction computer and viewing station by a high speed communications port.

Specifications for the developed DAS system

Number of Channels	24
Number of Independent Measurements	276
Operating Speed	50 frames / second, minimum 72.46 E-6 sec / measurement, max
Resolution	$\leq 1 \text{ E-15 farad}$
Standing Capacitance	1 E-12 farad , typical

The block diagram of the receiver side for the final integrated DAS is provided in Figure 1. In Figure 1, the design depicts the driving side of the electronics where the sending plate is selected and activated with electric voltage. Further details of DAS design were provided in Topical report 3 of phase I of this project.

Using 24 channel sensors produces 276 independent capacitance measurements. For each independent capacitance measurement, two plates are selected to measure the capacitance between them. The FPGA controls which plates are selected for each slot of time that the measurement takes place. The multiplexer is also controlled by the FPGA and it provides enough time for each channel to measure the capacitance between the plate connected to that channel and every other plate. The ADC converts the DC signal from the amplifier to a digital number read by the FPGA. This number is a function of the capacitance between the selected plates and is used to read the capacitance values. The FPGA sends this digital value of capacitance to the computer through a USB link.

Figure 1 Block diagram for the sending side of the acquisition electronics

For ECVT sensors, they were designed custom to the cold-flow fluidized bed sections of developed, feed, and exit regions. The developed section sensor was designed by distributing 23 plates in four layers on the outside wall of the Plexiglas section. The design accommodates a side injection in the developed section and sensitivity distribution along the vertical dimension of the section is depicted in Figure 2-A.

Both the Feed and Exit section are similar in shape as depicted in Figure 2-B. The Feed and Exit sensors were designed to accommodate regions of solid feeding and exiting as well as reinforcement strips along the sections, as depicted in Figure 2-B. The sensors are composed of 24 channels distributed in 6 layers. The sensors have been analyzed using COMSOL finite element analysis program.

ECVT sensor design is based on utilizing shape and distribution of plates to give distinct sensitivity signatures to various regions in the imaging domain. This is achieved by altering sensor plates' shapes and distribution. However, excess variation in electric

field intensity in the imaging domain contributes to an increase in ill-posedness of the inverse problem. A common feature of this ill-posedness is the bias of ECVT imaging toward edges of the column where electric field is at its maximum. Nevertheless, reconstruction of ECVT images can be enhanced by reducing this inherent bias in sensor sensitivity through proper sensor design. Here, sensors are designed to maximize gradient of sensor sensitivity while limiting maximum sensitivity value for each pair of plates to a range comparable with other plate combination. The gradient variation here would provide the distinctive sensitivity feature required for identifying different regions of the imaging domain and the limited range is to reduce ill-posedness of the inverse problem. In Figure 3, sensitivity distributions of the riser sensor along horizontal and vertical axis are depicted. Lines in the images are relative sensitivity values along the x and z direction for all 217 capacitance plate combinations in the left and right images of Figure 3, respectively. It is clear from the left image that relative sensitivity is elevated near the wall of the riser. Other than the walls, sensitivity lines are all within a relatively close maximum/minimum limits. This indicates that the ECVT sensor has a natural tendency to emphasize imaging near the wall. In the right image of Figure 3, sensitivity disruption along the vertical direction also shows maximum/minimum sensitivity of different plate combinations to be close. However, variation in relative sensitivity follows a steeper gradient. This increased steepness reflects the sensor ability to distinguish flows at different lengths along the riser and is a function of plate lengths. One can notice that there are seven peaks corresponding to plates from different layers interacting with each other.

Another way to analyze and view sensitivity distribution of sensor designs is through iso-surface plots of sensitivity volumes covered by each plate combination in the sensor, as depicted in Figure 4 and Figure 5 for plate combination covering top and bottom portions of sensing volume, respectively. The volume covered by iso-surface in each image reflects volume in which a change in flow concentration would trigger a change in measured capacitance for that particular plate combination. The reconstruction algorithm uses the collective sensitivity maps of all plate combinations to reconstruct a volume image where a change in flow concentration took place. It is clear from Figure 4 and Figure 5 that increasing the number of plates covering the same

volume would make each iso-surface narrower, as the plate area is reduced. This in effect provides higher resolution imaging as iso-surfaces can be viewed here as beams with more focus.

Similar sensitivity analysis was conducted for the Inlet/Exit sensors as depicted in Figure 6, Figure 7, and Figure 8. One can notice in Figure 6 that Inlet/Exit sensor has less variation in the horizontal direction and more variation in the vertical direction when compared to the Riser sensor. This is a direct effect of increasing the number of planes, and thus decreasing the number of plates in each plane. This type of design emphasizes vertical sensitivity of the sensors and limits axial sensitivity. The right image in Figure 6 shows 11 peaks corresponding to plates in six planes interacting with each other. The axial sensitivity in the left image of Figure 6 can be improved by positioning the plates in each plane shifted to each other. However, due to design of the Inlet/Exit, sections where vertical strips of Plexiglas are mounted (see Figure 2), this enhancement was not implemented.

Volume sensitivity analysis of the Inlet/Exit sensors depicted in Figure 7 and Figure 8 shows the iso-surface covering thinner volume along the vertical axis of the section. This is also a result of the increase number of layers here. A close examination of the images in the Figures would also reveal that the iso-surface is wider in the Inlet/Exit

images compared to Riser volume sensitivity maps. This is also a result of the Riser section having more plates in each plane. Both Figure 4 and Figure 7 show volume sensitivities of plate pairs covering the top regions of the sensing volume. Whereas Figure 5 and Figure 8 are for plate pairs covering bottom regions of the sensing volume.

Figure 4 Volume Sensitivity for each plate combination of riser sensor. Number on top of each image represents order of plate combination. Numbers of plate combination selected here are related to coverage toward top of the sensing region.

Figure 5 Volume Sensitivity for plate combination of riser sensor. Number on top of each image represents order of plate combination. Numbers of plate combination selected here are related to coverage toward bottom of the sensing region.

Figure 8 Volume Sensitivity for each plate combination of Inlet/Exit sensor. Number on top of each image represents order of plate combination. Numbers of plate combination selected here are related to coverage toward bottom of the sensing region.

Successful fabrication of one capacitance channel & Verification of imaging speed

In this stage, Rice, Carolina brand Enriched Jasmine Rice (product of Thailand), and vegetable oil were used as the material for testing. Rice and Oil were used here to assess the system performance with gas-solid and gas-liquid systems. Rice and vegetable oil have dielectric constants close to most particles and liquids commonly used in circulating fluidized beds, respectively. Their use presents a safer alternative to using FCC particles or hydrocarbon liquids. The DAS system was connected to two plate sensor test units using a 10 ft coaxial cable. A computer equipped with Matlab software was used to acquire capacitance data from the 24 channel DAS system. The

test cells were normalized in the full and empty modes. The data acquired from the DAS system includes raw capacitance data, standard deviation of variation, signal to noise ratio, and contrast ratio. The signal to noise ratio was defined as the log of dividing the signal level over the standard deviation of variation in the signal. The contrast ratio is the difference between the signals for the full and empty modes divided by the signal for the full mode. The contrast ratio gives an indication to the dynamic range which measures the increment in capacitance from the minimum empty signal to the maximum full signal.

Measurement Method

Testing was conducted according to the following procedure:

- 1- Empty the test cell and initiate calibration through software.
- 2- When step 1 is finished, fill the test unit with oil or granules and initiate calibration in the full mode to identify dynamic range.
- 3- Empty the test cell again to measure capacitance in empty mode. This step eliminates parasitic capacitance inherent in the system and in the test cell.
- 4- Acquire 200 frames of capacitance of data.
- 5- Acquire one capacitance frame in empty mode.
- 6- Acquire one capacitance frame of data in full mode.
- 7- Import the data frames into Microsoft Excel and compute the standard deviation of signal, signal to noise ratio, and contrast ratio.
- 8- Plot the signal to noise ratio and contrast ratio for each pair of capacitance channels.

Test Results:

A 12 and 24 channel test cells were used for acquiring the test results reported here. The 12 channels test cell is designed with 12 plates distributed in three layers. For the 24 channel cell, the sensor is composed of 24 plates distributed in four layers. Each test cell was normalized according to the steps reported above. For the 12 channels cell, 66 independent capacitance measurements are available. On the other hand, 276

independent measurements are acquired from the 24 channels cell. The DAS is programmed to acquire each capacitance reading based on a predefined sequence.

Figure 9 SNR for the (A) 66 measurements acquired from the 12 channels sensors and (B) 276 measurements acquired from the 24 channels sensors.

Figure 9-A depicts the signal to noise ratio (SNR) for each independent measurement of the 12 channel test cell. All SNR are above 45 db. A 45 dB accounts for a difference of more than 2 orders of magnitude between the signal level and the noise level. The time required to capture each independent capacitance value is 72 micro-second. At this rate, the system can acquire the full 66 and 276 measurements when using all of the 12 and 24 channels at a rate of 200 and 50 frames per second, respectively.

In Figure 9-B, the SNR for each independent measurement of the 24 channels sensor is depicted. From the Figure, it is clear that the least SNR is found for measurements between the first and forth layers of the sensor. In the 24 channels sensors, the plates are distributed in 4 layers with 6 in each layer. As the distance between plates increases, the SNR decreases.

Based on the results recorded by the 12 and 24 channels experiments, the DAS basic operation on various sensors with different number of channels has been validated. From testing results, the DAS has been consistent in providing measurements in terms of imaging speed and SNR. Further details on DAS operation and performance are available in the 7th topical report.

Successful fabrication of 3D capacitance sensors

Three acrylic sections were manufactured to be installed on the 12" ID circulating fluidized bed with ½" wall thickness. Previously designed ECVT sensors were mounted on the sections prior to installation. Tests have been conducted on a 4" ID and 3/8" wall thickness with particles similar to those currently used in the 12" CFB. Tests have also been conducted on the three 12" sections with FCC particles and yielded satisfactory results. Tests on the three sections using DOE florescent particles were not possible due to shortage of available particles at Tech4Imaging site. However, considering the similarities between FCC and florescent in electrical properties, the sensors were verified to perform well when shipped to DOE site for testing. This has been also confirmed at a later stage when the system was delivered and actually tested on the 12" CFB. The designed DAS was able to detect a reliable capacitance signal from the test sensors. More details on this milestone are available in Topical report number 8.

Design and program of operator user friendly reconstruction software

The 3D-NN-MOIRT (Warsito, Marashdeh, & Fan, 2007) was implemented here to reconstruct capacitance data acquired from sensors into volume images of concentration distribution. The algorithm is based on optimizing a set of objective functions for yielding the most likely volume image. Software with a user friendly interface was also developed for acquiring data from sensors. Snapshots of the reconstruction viewing results are depicted in Figure 10. The reconstruction result in Figure 10 is obtained from a 4 inch gas-solid test system (Justin Weber, 2012).

Demonstration of successful integrated system performance

Testing of integrated system involved evaluating the performance of data acquisition system, ECVT sensors, and reconstruction software when operated together. The ECVT sensors were fabricated following a design of 24 capacitive plates distributed in 6 layers. Plates in each layer are rotated 45 degrees with respect to plates in adjacent

planes. The sensitivity matrix for each sensor was developed and integrated into the reconstruction software programmed as part of this project. Measured capacitance data were recorded and used to reconstruct a volume image, with fluorescent particles as the solid phase and air the gas phase. Figure 11 depict the experimental setup and volume concentration image from the reconstruction software (Justin Weber, 2012). The tests confirmed integrated operation of developed ECVT system.

In Figure 11-B, light colors represent low solid concentration and darker colors are for higher solids concentrations, with dark red representing voxels packed with solids.

Testing on Cold Flow CFB unit

ECVT for cold flow systems delivers detailed quantitative information of solid concentrations at each voxel location. The reconstructed real-time data also enables bubble tracking and mapping of average velocities in the sensing domain. In this task,

ECVT results were validated by studying ECVT images closely and comparing them to other measurement techniques. Here, a 24 channel ECVT sensor of six layers and 24 plates was designed and mounted on the outside wall of a 4 inch ID fluidized bed column, as depicted in Figure 12-A. ECVT results are depicted in Figure 12-B where lighter and darker colors represent lower and higher solid concentration, respectively.

Quantitative validation of bubble frequency and diameter was conducted by applying a thresholding filter of ECVT images captured over a time interval. Figure 13 depicts the process of applying the filter and quantifying bubble size and location. Figure 14 presents average bubble frequency as a function of distance from distributor, and for various gas velocities. A porous media filter was used for gas injection here. Results of bubble frequency show an increase in bubble frequency near the distributor as gas velocity increases. The number of bubbles also decreases away from the distributor as a result of bubble coalescence. Those observations are confirmed by models reported in literature of bubble behavior in gas-solid fluidized bed systems.

In Figure 15, average bubble diameter as a function of distance from distributor is presented for various gas velocities. The figure shows clearly that average bubble size increases proportional to distance from the distributor and increases as gas velocity increases. Both observations are confirmed by conventional knowledge of gas-solid bubbling systems.

The ability of ECVT sensors to provide quantitative volume images of solids concentration enables various kinds of measurements that are essential for understandings of multi-phase flow systems. In Figure 16, bubble velocities were calculated by tracking center of gravity for each bubble extracted using the method in Figure 13. This technique enabled quantification of bubble velocity along the column length. This technique can also be extended to measuring bubble velocities in the axial direction as it moves upwards in the column. Direct measurement of bubble size, frequency, and 3D velocity provides unique insight into gas-solid systems.

The technique developed to calculate velocities, as in Figure 16, was also used to track bubbles as depicted in Figure 17. Here, each bubble is assigned a tracer line through which its evolution in the column can be tracked and analyzed.

Figure 16 Bubble velocity in a 4 inch ID column of gas-solid bubbling bed (Courtesy of DOE NETL)

Figure 17 Bubble Tracking in 4 inch Column (Courtesy of DOE NETL)

In Figure 18, two ECVT sensors were used to image solid concentration in a gas-solid CLC Demo unit. The sensors at the top and bottom are for 2 inch and 4 inch ID sections, respectively. Flow passes through a tapered section from the 4 inch to the 2 inch section. Both sensors were designed with 24 plates distributed in 6 layers. The images in Figure 18 show instantaneous snapshots of 2D sections at each sensor location. The images show clearly transition from a bubbling flow in the 4 inch section to a slug flow in the 2 inch sensor due to increased gas velocity in the smaller section.

In Figure 19, bubble diameter as a function of distance from distributor is compared to models published in scientific literature. ECVT results here are found to be consistent with model predictions. Further details on those findings were published in a Journal paper (Weber & Mei, 2013).

In Figure 20, ECVT results were validated by comparison to CT images of static Ping-Pong balls in a bed of 185um glass beads. Diameters of the balls were 40% of the 4 inch column used for testing. ECVT here detected clearly location of each ball, with artifacts in recovered shape. Further validation of ECVT imaging was also conducted by comparing it to CFD simulations using Barracuda software, as depicted in Figure 21.

Here, also, ECVT detects bubbles and flow concentrations consistent with CFD simulations. Further details about this comparison are available in (Weber, Layfield, VanEssendelft, & Mei, Submitted).

Delivery and successful testing of ECVT system on NETL CFB

The ECVT system developed for the 12 inch ID CFB was delivered to DOE NETL site at Morgantown on schedule. The system was also tested with fluorescent particles at various flow rates. Figure 22 depicts the three sections (Riser, Inlet, and Exit) with ECVT sensors installed on the CFB. A diagram of the CFB is also included in the Figure. The three sections were tested while the unit was in operation and solids circulating. An inner conductive and grounded layer was placed on the inner wall, below and above the sensing region. The conductive grounded layers are aimed at diffusing excess electrostatic charge buildup in the flow particles. The sensors were also grounded to the building to protect users from arcs that are often generated. Figure 23 shows the developed region section (Riser) filled with particles and under operation. Part B of the figure is a snap-shot of a real-time data capture and image reconstruction. The sensors were also modified to discharge excess electrostatic buildup from circulating the particles at high flow rates.

ECVT images for the developed region here were acquired and compared to pressure measurements as depicted in Figure 24. The left image in the Figure compares ECVT solid fraction estimations along different lines across the sensing domain to pressure measurements. Two lines of $\pm 10\%$ range are included to gauge accuracy of ECVT estimations. The right image in the Figure is a depiction of solid fraction over a cross section of the imaging domain. It is evident from Figure 24 that ECVT imaging has higher accuracy of solid fraction estimation away from the edges compared to the center of the column. This observation confirms sensitivity analysis of the Riser sensor in Figure 6 where sensitivity was higher near the Riser walls. Average solid fraction near the wall is over emphasized here and it is deemphasized toward the center of the column where sensitivity is at its minimal.

Based on the sensitivity analysis, a model can be developed to take this bias into account during image reconstruction for yielding better distributed images. It is also important to note that the Riser section had a side injection that enables solids to flow

through. This opening is not covered by an ECVT sensor and solid concentration there are estimated based on readings from other plates that partially cover that region of the Riser (see Figure 2 for section and ECVT sensor design of developed region). This opening in the Riser is a possible explanation for the abnormality in Figure 24 where two solid fraction estimation points have higher error than points near the wall.

Figure 23 Integrated system testing (A) Experimental setup using developed DAS and (B) Reconstruction result acquired by DOE NETL (Courtesy of DOE NETL)

Figure 24 12 Inch Riser sensor (Courtesy of DOE NETL)

Inlet and Exit sensors were also utilized for acquiring capacitance data at various flow conditions. In Figure 25, a snapshot of gas-solid flow at the entrance region is depicted. The image shows clearly solid distribution as gas from below interacts with the inlet side injection of gas and solid. In Figure 26, a time average of 100 frames (equivalent to duration of 2 seconds) is provided. It shows clearly a gas jet at the center of the inlet section that gets narrower toward the top. The result here matches what one would expect in such a system. Quantitative analysis of average solid distributions at various lines along the vertical direction is also provided in Figure 27. The center line in the figure shows gradual increase in average solid holdup as solids mix with gas from the bottom. Along the line from the inlet side, solids are concentrated the bottom of the side injection as they are introduced to the CFB inlet region. As solids are introduced into the flow, they are picked up vertically, thus explain the increase of solids concentration right above the inlet opening. As for along the line opposite to the inlet opening, solids increase gradually from bottom to top. Initially, gas-solid jet momentum would increase the solid concentration at the opposite side of the inlet opening. However, solid concentration at that region is also affected by gas flow rate from the bottom. Here, as the flow rate increases, the jet penetration depth decreases, thus limiting solid concentration at the wall opposite to the inlet opening.

In Figure 28, a snapshot of solid concentration at the exit region is provided. A time averaged result of 100 frames is also depicted in Figure 29. Quantitative data of solid concentration along three different lines in the exit region are provided in Figure 30. The Figures here show an increase of solid concentration in the center and away from the side exit. This indicates that solids are entrained at the top of the CFB and above the exit region. As for solids concentration along the line passing through the exit side, Figure 30 indicates an increase in solid concentration at the top and bottom corners of the exit sides (marked by two peaks at 5 and 10 inches from the bottom of the exit sensors region). The solids concentration then decreases and increases again where particles are entrained.

In Figure 31, 3D time averaged solid concentration on the walls of the Riser, Inlet, and Exit sections are provided. Of interest in this Figure are solid concentrations at the inlet and exit locations of the Inlet and Exit sensors where average solid concentrations

seem to be lower compared to other locations. Instantaneous 2D snapshot of each section is provided in Figure 32. Here, again, inlet and exit regions in the Inlet and Exit sections depict lower solid concentrations.

Figure 31 3D time averaged solid concentration of JP 455 particles (Courtesy of DOE NETL)

System Installation and Training

ECVT sensors were installed and tested for operation on the 12 inch ID CFB of NETL, B22. A manual was also developed (Appendix I: Manual , page 53) to serve as a future reference for later use of the system.

5. Task Results and their impact on overall goal of project:

Technical Success

Overall, the project achieved technical success by delivering an operational ECVT system meeting or exceeding specifications outlined in Statement of Project Objectives. In Phase I of the project, design for data acquisition and capacitance sensors was devised based on computer simulation. Integrity of data acquisition design was

assessed at this stage by adding noise to the system and assessing its SNR. For the sensors design, it was based on a sensitivity distribution inside the imaging domain that balances amplitude and gradient of sensitivity variation.

In phase II of the project, Data Acquisition System was fabricated per the design developed in phase I. The fabricated system was tested in continuous mode operation and for assessment of SNR and imaging speed. The system was also examined with test sensors using different materials of solids (Rice and FCC) and liquids (Water and vegetable Oil) to assess its performance. A successful implementation of functional data acquisition was achieved in this phase.

In Phase III of the project, capacitance sensors were fabricated and tested, in an integrated manner, with data acquisition and reconstruction software. The system performed well and volume images of solid concentration in the 12 inch ID CFB were acquired. Initial tests revealed Electrostatic buildup at significant levels, which interfered with acquired capacitance signal. This problem was solved by providing dissipation paths of electrostatic charge at the sensors location of the ECVT system. With this modification, the integrated system performance was successfully demonstrated and an operational ECVT system was delivered and installed to NETL at Morgantown.

Recommended development:

The successful implementation and development of ECVT system in this project is a significant step in the advancement of multi-phase flow research. However, areas of further development recommended for better visualization of multiphase systems are listed below:

- 1- Resolution: The main drawback of ECVT technology at its current status is the limited spatial resolution that the system can provide. It is estimated that the system can accurately visualize phase concentrations with 2~3% resolutions. Due to the soft field nature of capacitance tomography, resolution varies at different regions of the imaging domain and depends on phase distributions. Developments in enhancing spatial resolution would bring ECVT technology closer to emulating computational fluid dynamics simulations, thus providing an invaluable validation tool. Advancements in ECVT resolution are related to all

elements of the system (Data acquisition, reconstruction algorithm, and sensor design).

- 2- Hot Unit: The developed system was targeted at addressing multi-phase flow imaging of cold flow units. However, potential applications of ECVT in the energy industry often involve flows of high temperatures and pressures. Here, it is recommended to develop ECVT for applications that involve hot flows toward its industrial adoption. Testing of particles at high temperatures has revealed a change in electric properties with increasing temperatures. This observation needs to be taken under consideration for development of ECVT for hot unit applications. Moreover, this change in electric properties can also be used for temperature mapping of hot flows.
- 3- Real-time imaging: ECVT, in its current form, is based on off-line image reconstruction of capacitance measurements acquired in real-time. This separation between data acquisition and image reconstruction is due to the time required to acquire each image from a capacitance frame. Typically, 2-4 seconds are required for processing each frame of data. However, for some applications that require real-time feedback of reconstructed images for process control, performing real-time image reconstruction is of value. Development of real-time ECVT would involve research in image reconstruction and implementation of developed algorithm in the data acquisition FPGA.

Development cost

As each recommended development suggested above involve both hardware and software advancements, it is estimated that development for each stage would cost around \$1.5 M.

6. Project Results of ECVT and its relation to advancing Multi-Phase Flow Science

As detailed understanding of multiphase flow behavior inside a CFB requires a 3-D technique capable of visualizing the flow field in real-time, project results are directly related to advancing multi-phase flow science. The attractiveness of ECVT is in its low

profile sensors, fast imaging speed and scalability to different section sizes, low operating cost, suitability for hot unit applications, and safety. Moreover, the flexibility of ECVT sensors enable them to be designed around virtually any geometry, rendering them suitable to be used for measurement of solid flows in irregularly shaped regions of a CFB (Wang F. , Marashdeh, Fan, & Warsito, 2010). The feasibility of ECVT technique for volume imaging of multi-phase flows has been demonstrated through its implementation on flow sections of various shapes and sizes (Wang F. , Marashdeh, Fan, & Warsito, 2010). ECVT sensors have a wide range of applicability in the shape or size of a process column. The largest known column to which ECVT sensors were applied was 60 inch in diameter, and the smallest was 1 inch in diameter. Sizes outside this range can also be accommodated. As to metal columns, capacitance sensors were placed inside a stainless-steel reactor column and separated by a ceramic layer from the flow in one recent application that involved a chemical looping reactor system. ECVT sensors can be applied to metallic columns following similar arrangements to the example mentioned here.

The ECVT system that was developed in the course of this project is already being used to advance Multi-phase flow science (Essendelft, Weber, & Li, 2012) (Justin Weber, 2012) (Wang, Marashdeh, & Fan, 2012). The system was utilized here to validate computational fluid dynamics simulations (Essendelft, Weber, & Li, 2012) and for flow characterization of gas-solids fluidized beds (Justin Weber, 2012). Insights provided by ECVT sensors were also highlighted in a recent press release by DOE NETL newsletter.

7. Cost and Technical issues involved with scale-up and commercialization of ECVT

ECVT has been gaining increased attention as an instrumentation to visualize multi-phase flow systems toward their understanding and optimization. The system developed here has attracted commercial interest and was acquired, and is currently in operation, in three continents (North America, Asia, and Australia). As the system moved into the commercial phase, key technical issues were addressed for a better user experience and enhanced system performance that are summarized as below:

- 1- Standardization: As presented in this report, different sensor designs exhibit different features and sensitivity distributions for various applications. To simplify, better understand, and enhance system performance, a sensor design for straight columns was standardized. This standardization process allows for the same sensitivity models to be used by different customer and for various column diameters. Thus, an update for reconstruction software can be sent for all users without personalized customizations.
- 2- ECVT sensors are flexible and applications to irregularly shaped columns are common. The cost of such systems is increased due to customization involved and support is provided for annual fees to cover extra effort of customized service.
- 3- ECVT sensors were also further developed to fit inside ruggedized compartments that can withstand handling typical in industrial settings. A method was also developed for dismantling the sensor and placing it at different locations, along the column, by the user.
- 4- Scale-up of the system was conducted successfully for one major energy Company. The involved system was designed to image a gas-liquid contact phase of 60 inch ID column. Scalability is one attractive feature of ECVT that makes it a viable instrumentation for industrial use.
- 5- Standardization of image reconstruction program is also required so the software can work with different sensor designs without the requirement of customization. Each sensor design exhibits different features that are represented in the sensitivity model. A standardization of a reconstruction program involves the system being to extract those features and integrate them into the algorithm, automatically.

Scale-up and commercialization of ECVT also involves adapting the technology to addressing and withstanding challenges and harsh environments of industrial settings, respectively. Below are some issues that require attention toward that end:

Ability to reconstruct images in real-time at high resolution

Spatial and time resolutions are two factors that are essential toward commercialization of ECVT to multi-phase flow industries. The former is important to visualize and understand turbulent and high moving flows encountered commonly in the energy industry. As for the later, it is essential to providing an accurate assessment of flow dynamics and distribution. ECVT has the potential of being developed for real-time imaging and with higher spatial resolution. Such a development would involve updating the sensor with advanced designs and increased number of channels, adapting the hardware to acquire frames at higher rates, and developing the reconstruction algorithm to extracting more information from acquired data.

Feasibility (cost estimator and risk factor) of use in industrial scale

Whereas the successful demonstration of ECVT for cold flow units provides significant confidence in scale-up applications, it is worth to mention some risk factors involved.

Large units with same resolutions proposed

ECVT resolution is depicted as a percentage of total volume under interrogation. This has been confirmed through achieving similar range of percentage resolution with various column sizes. Theoretically, resolution for scale-up units can be preserved as the increased distance between plates is balanced by the increase in plate area. However, a risk exists in which the electric field in scale-up units would degrade toward the center of the column to a level that would diminish resolution there. This risk has to be accounted for in designing ECVT systems for scale-up applications.

Electrostatic interference & EM compatibility

Electromagnetic Compatibility (EMC) and electrostatic interference are two risk factors that also have to be accounted for in commercial application of ECVT. EMC is related to the ECVT system receiving electromagnetic signals; that would interfere in its operation; or emitting electromagnetic signals; that would interrupt other instrumentation used in commercial scale units. Mitigating this risk can be achieved by testing electromagnetic emissions of current ECVT system and enhance its electric shield to the desired level of

EMC. As for electrostatic interference, it is related to electrostatic buildup due to flow motion inside the process vessel. The level of this interference depends on many factors; most notable are composition of flow particles, material of process vessel, and velocity of moving flow. Mitigating the electrostatic interference risk is approached by designing the ECVT sensor with routes for dissipating accumulated electrostatic charges.

Testing Multiple Materials

Capacitance sensors in tomography applications operate by detecting change in electrical capacitance caused by change in flow distribution. Here, a change in flow distribution changes equivalent dielectric constant at sub-volumes of the imaging domain, causing the capacitance signal to change. For this process to take effect, change in electric capacitance has to be measureable. Several particles were studied for applying ECVT sensors (FCC, iron oxide, glass beads, Ash, Sand, etc.) and it was observed that ECVT sensors were able to detect meaningful signals of different particles, with an exception to particles with high conductivity. The level of conductivity that an ECVT sensor can tolerate is related to its sensor size. Conductivity in flow particles attenuates electric fields as they pass from the sender to the receiver plates. As the distance in larger columns is greater, electric field is further attenuated. Thus, the upper limit on maximum conductivity for ECVT reconstruction is reduced as sensors grow larger in size.

Hot unit and commercial plant (cost estimators and risk factors)

Application of ECVT sensors to hot units is crucial for its adoption in many industrial settings. Below are key points that have to be addressed toward that end:

High temperatures

ECVT sensors have to be adopted to withstand extreme temperatures that can reach above 1000°C. ECVT capacitance plates and their connections to data acquisition would be fabricated from special alloys that are electrically conductive and can withstand high temperatures. Moreover, special attention needs to be given to plate expansion and material composition change of plate. Typically, applications that involve

high temperatures operate with a temperature range through which a flow is interacting. This temperature variation has an effect on plate area, due to expansion, and material properties of the flow itself. The data acquisition and reconstruction algorithm need to be updated to address this issue.

High pressures

ECVT sensors for hot units are usually isolated from the flow being imaged by a separation layer. The separation layer here would be required to withstand pressure inside the process vessel. Quality of ECVT images may be affected by thickness of pressure layer. However, this is a manageable risk as Capacitance sensors were used before in high pressure vessels.

Multiple compositions (ash, slag, refractory, catalyst FCC)

As multiple components are often involved in flow systems of energy applications, an ECVT system developed for hot units would be required to operate with the existence of such compositions. Here, an investigation was conducted to study properties of Ash, Slag, refractory material, and FCC catalyst. For Ash and FCC, experiments were conducted with the developed ECVT system to image bubbles in a gas-solid bubbling bed at room temperature. Volume images were successfully reconstructed of flows in both Ash and FCC beds. As for refractory material, an experiment was conducted by separating capacitance sensors from a 600°C hot flow by a ceramic layer. The ceramic layer here resembles refractory material used in furnaces and combustors. Here, capacitance sensors were able to measure a signal that represents changes in hot flow distribution of iron-oxide particles. Slag electrical properties were also investigated, and according to one study (READE), its conductivity at 230°C is less than 25 micro Siemens.cm. ECVT was tested with flow materials at similar conductivity levels and a volume image was successfully reconstructed.

8. Findings/Conclusion

In the course of this project, a novel Electrical Capacitance Volume Tomography (ECVT) system was developed to study the flow patterns of particles common to pilot scale circulating fluidized beds. The system capability to collect data useful in validating multi-phase flow models was also evaluated. The system is composed of 24 channel data acquisition, reconstruction software, and sensors. An operational ECVT system with three sensors for developed, inlet, and exit regions was developed, delivered, and installed at DOE NETL Morgantown 12 inch circulating fluidized bed. The system was successfully tested and acquired capacitance data were used to generate volume images of fluorescent particles flow at different flow rates.

The developed system has contributed significantly to advancements of multi-phase flow science. This contribution is best illustrated through scientific publications that use the developed system to validate CFD models and explore new flow behaviors. The developed system has also the potential of being developed to address scale-up and hot unit applications. To that end, an investigation was conducted to the feasibility of using ECVT in hot unit applications with promising results of operating at high temperatures reported. The system was also tested with various column sizes with potential of being applied to scale-up applications being validated.

Some of ECVT technology applications include bubble columns, trickle beds, CFB's, bended sections, and irregularly shaped vessels. The technology capability of providing a comprehensive, real-time, 3D images of phase concentrations, average velocities, flow rates, and other flow variables have prompted global interest in its utility.

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ECVT System Manual

Disclaimers:

User should ensure that each sensor is grounded to an external ground near the point at the sensor labeled GRD

When using liquids in ECVT sensors, user should make sure to cover sensors with liquid proof cover. An electric short circuit and damage to sensor may happen if liquids leak into sensors.

This system is intended primarily for cold-flow multi-phase flow systems. For other uses, user should check with customer support before proceeding.

This Manual will be updated with answers to questions from user as they develop. Most recent version of Manual will be sent to user after questions are addressed.

Due to elevated electrostatic build up that sometimes occur in large system when fluidizing or transporting dry particles, electrostatic discharge may appear in capacitance data as spikes in some frames.

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Hardware

Figure 33 DAS of ECVT system

The Data Acquisition System (DAS) serves as an intermediate stage between the sensors and Computer for imaging reconstruction and viewing. It is designed to be fully automated by commands programmed into its FPGA, and through communication from the Data Capture software. Below are details of ECVT DAS operation:

Front view:

Front of DAS enclosure has five lights. Noted for user are the first light from left corner (which indicates DAS is powered), and light before last (which turns on when an error occurs).

Lights are mounted on front box to guide user to better diagnose a problem and report back to customer support. User should report to customer support when error light turns on.

Rear View:

Rear of DAS has 24 coaxial cable connectors. Coaxial cables are provided with the system to connect to sensors by matching numbers on DAS coaxial connectors and ECVT sensors.

Rear of DAS also has the power cord connection, on/off switch, and USB cable connector.

Operation Procedure

Before opening Data Capture Software, user shall ensure the following:

- 1-** ECVT sensors for 12 inch ID are grounded to the CFB grounding system

- 2- The coaxial cables are connected between DAS and ECVT sensor being tested, with numbers on sensor and DAS matched through connecting cables.
- 3- USB cable is connected between DAS and Computer with Data Capture software.
- 4- The power switch on DAS system is turned on.

Data Capture Software

After following the procedure for connecting and turning the DAS on described in the Hardware section, start the Data Capture Software. The software might take up to 20 seconds to start and user interface depicted in Figure 34 will appear afterwards.

Figure 34 Interface for Data Capture Software

User Interface Description

Below is a description of User Interface buttons activated immediately after the software starts:

- 1- **INIT:** This button initiates the system once pressed by flushing previous data recorded in EPROM stored in the DAS system. User usually does not need to press this button. It

is provided for flushing the system when a new calibration is attempted, without turning off and restarting the DAS and Data Capture Software.

- 2- **EPROM-LUTS:** This button reloads calibration stored in EPROM and Lookup table. It provides temporary storage of calibration and normalization variable so they can be reloaded while the system is operating.
- 3- **Reload Calibration:** This button, when pressed, open a new window through which the user can chose a calibration and normalization files stored before for reloading.
- 4- **New Calibration:** Pressing this button triggers the DAS system to start the calibration process. User would need to follow instructions from User Interface to finish calibration process.
- 5- **Cap. Measuring Time:** A default value is specified here of 64 micro seconds. This reflects the time that the DAS averages the signal over to capture a single capacitance value. Decreasing this value would increase systems speed. However, it also reduces averaging time, thus reducing the SNR of the measured data. This value has to be changed, if required, before the calibration is conducted.
- 6- **Driver Amplitude:** This value reflects the percentage of driver amplitude value that each plate is excited with. For plates of larger areas or signals of high strength (due to high dielectric constant of flow), an overflow can happen by the analog signal being the range of the Digital-to-Analog (DA) converter range. When this problem occurs, it is solved by reducing the driver amplitude value until it is within the range of DA converter. This value has to be changed, if required, before the calibration is conducted.

Calibration Procedure

The first step, after following the procedure for hardware connections, in preparing the system for reading frames of data is to start a new calibration procedure or reload a previously saved one. To start a new calibration procedure, follow the steps below.

- 1- **Press the New Calibration button and follow the steps prompted by the software as described below:**
 - a. The software will ask for the number of plates that the user wants to use. The maximum number to enter here is 24. The user shall enter the number of channels on the sensor being tested.
 - b. The software will ask the user to empty the column to start the calibration process. The user shall press enter on the pop-up window after he/she ensures the column is empty. After pressing enter, it will take up to 10 minutes until the system finishes the empty calibration stage. The time required for this step is proportional the number of channels chosen.

- c. After the system finishes this step, the pop-up window will ask the user to fill the column with testing material and press enter. Here, the user shall fill the column, till above the sensor region, with the being tested or fluidized. When a mixture of materials is used, the material with highest dielectric constant shall be used. This step takes up to 5 minutes to conclude.
- d. After calibration with the full state is finishes, the system will ask the user if he/she wants to store the calibration. If the user presses yes, the system will open a window to choose a location for storage. This process takes a few minutes to conclude too.
- e. At this stage, the New Normalization button will be activated. The user shall press this button to start the normalization process. When pressing the button, the system will ask the user to fill the column with test material. IF this step is conducted immediately after calibration, the sensor would be full already after calibration is conducted. This process takes a few second.
- f. The system will then ask the user to empty the column and press enter. This process also takes a few seconds. Normalization after this step is completed and the system will ask the user if he/she would like to save normalization files. If yes, the system will prompt a window for the user to choose a location for saving normalization file.

Data Capture

After Calibration and Normalization are conducted, the system is now ready to capture and store data of capacitance frames.

- 1- After normalization is finished, the column will be empty and it can be tested by capturing data in this state. The user shall enter the number of frames he/she wants to read. If the user prefers to time the frame reading process, then the number of frames to enter based on required time is calculated from the following equation:

$$= \frac{2 \times 10^6}{n(n-1) \times 76} T$$
, where N is the number of frames required to enter in the Number of Frames text box, n is the number of channels entered by the user at the beginning of the calibration process., and T is set by the user (in seconds) over which data will be acquired.
- 2- When the column is empty, data viewed should be around the 0 value.
- 3- To view data without normalization, toggle the Data Normalized Radio button.
- 4- To save capture data, toggle the Log to File radio button. This process is required for data to be used later in image reconstruction. When toggling this button, the software will prompt a window to save the buffered data. THIS IS NOT THE DATA TO BE SAVE.

THE SAVING PROCESS TAKES PLACE AFTER THE SYSTEMS FINISHES CAPTURING THE NUMBER OF FRAMES SET BY THE USER. Then, the system will prompt a window for the user to choose a location to save captured data.

Sensors

Sensor details provided here are for referencing purposes, and for proper analysis of reconstructed results. Figure 35 and Figure 36 provide dimensions of ECVT sensors used in Riser and Exit/Inlet section, respectively.

Figure 37 provides a digitization map of volume being reconstructed. It also shows borders of sensing region inside the digitization map. The volume encapsulated by Riser and Exit/Inlet sensors is divided into 20 voxels in the X and Y directions, and 40 voxels in the Z direction.

Reconstruction Software

Matlab software is used here to perform image reconstruction on captured capacitance data. The use of Matlab is a conscious choice here as it serves as a platform through which users can manipulate reconstructed images and perform various kinds of analysis. In The reconstruction folder, only two m-files require the user's attention to perform reconstruction and view resulting image.

- 1- "StartReconstruction" m-file: The user needs to open this file in Matlab environment and follow the steps below for performing reconstruction on selected capacitance data sets:
 - a. First, the user needs to make sure that the files containing capacitance data for reconstruction are located in the same folder that contains reconstruction files.
 - b. The user shall change the name in the fname1 variable to the name of the capacitance file to be reconstructed. If more than one file are set for reconstruction, the user can enter the file names by separating them with a

semicolon (e.g.: `fname1=['Test1'; 'Test2'; 'Test3' ];`). For files to be reconstructed simultaneously, all file names shall have the same number of characters.

- c. The user shall enter a value for the variable `nm` equal to the number of the last frame to be reconstructed. For example, if the capacitance file has 10,000 capacitance frames, and the user wants to reconstruct up to frame 5,000, then `nm` shall bear the value of 5,000.
 - d. The user shall change the value of variable `nstep` to the increment of capacitance frames he/she wants to reach the last frame for reconstruction. For the above example of 5,000 frames to reconstruct, if the user wants to reconstruct capacitance frame rate in increments of 10, then the value of `nstep` shall be set to 10. The maximum number of frames for reconstruction is achieved by setting this value to 1.
 - e. The user shall set the value of the `n1` variable to the first frame number from where the software will start reconstruction. It is recommended that this value is set for not less than 150, as it takes this number of frames for the DAS to be completely in steady state status.
 - f. The alpha value controls the sharpness of the resulting image. It is set by default to 10. Increasing it will yield sharper images and decreasing it will provide smoother images.
 - g. After setting the parameters above, the user shall run the `mfile`. The software will show the number of frame being reconstructed and the time it takes to reconstruct each frame. After the software finishes the reconstruction process, it will save the set of 3D matrices containing quantitative information of reconstructed volume images in a Matlab data file carrying the same name of capacitance data file, and with `.res` added to its extension.
- 2- “ViewResults” m-file: This m-file views the volume images reconstructed and stored in the Matlab data file. The user needs to open this file in Matlab environment and follow the steps below for performing viewing process on selected reconstruction data sets:
- a. First, the user needs to make sure that the files containing reconstruction data for viewing are located in the same folder that contains the “ViewResults” file.
 - b. The user shall change the name in the `fname1` variable to the name of the reconstruction file to be viewed.
 - c. User shall change the value in `SH` variable to the solid packing ration for viewing solid hold-up. It is set to 0.63 by default.
 - d. The user shall enter the first image in the reconstruction data set to view in the variable `n1`. The reconstruction file will contain a number of volume images

equal to $(nm-n1)/nstep+1$. For the example of $nm = 5,000$, $n1=150$, and $nstep =10$, the total number of reconstructed volume images will be 486.

- e. The user shall enter the last image number to view in the variable $n2$. $N2$ shall not be greater than the maximum number of image in the result data file.
 - f. The user shall enter the increment in which data files will be viewed in the variable $nstep$. This number shall be no less than 1.
 - g. The view angles provided in this m-file are for a certain angle of viewing the 3D volume images. User shall change the angles for different views of the same images.
 - h. The variables $cx0$ and $cx1$ are the minimum and maximum for the color bar associated with viewing the images. For viewing the full range, $cx0$ shall be set to 0 and $cx1$ shall be set to 1. User shall note here that if the SH value of solid holdup is set to a number other than 1, then this number will become the new maximum, and thus $c1$ has to be updated accordingly.
 - i. After setting the above parameters, user shall run the “ViewResults” m-file and volume images with different cross-sections will be viewed.
- 3- User can also write independent m-files to manipulate volume images stored in result data file. To access reconstruction results, user need to use the command load in Matlab.