The Study of Bubbly Gas-Water Flow Using Displacement Current Phase Tomography

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ABSTRACT: Displacement Current Phase Tomography (DCPT) is a real-time 3D imaging and measurement technique for the online study of multiphase flow behavior. Here, it is applied for the study of a bubbly, two-phase flow of gas and water. A straight cylindrical column was constructed and an experiment conducted where the air mass flow rate through the column was varied. A DCPT system was used to capture real-time, three-dimensional data about the bubbly flow, and this data was analyzed to determine important factors about the bubbly flow, such as void fraction, bubble size, bubble frequency, and bubble velocity.

Keywords: Bubbly Flow, Bubble Column, Two-Phase, Gas-Liquid, Volume Fraction, Liquid Holdup, Void Fraction, Bubble Size, Bubble Velocity, Bubble Frequency, Bubble Distribution, Displacement Current Phase Tomography, Electrical Capacitance Tomography, Electrical Capacitance Volume Tomography

I. Introduction

Gas-liquid bubble columns serve important roles in numerous chemical and industrial processes. It is critical that these components operate correctly so that reactions taking place within the columns occur at maximum efficiency. Factors that affect bubbly column operation include liquid and gas flow rates, liquid and gas volume fractions, and bubble size, frequency, distribution, and velocity.

Several methods have been utilized for the study of these flows [1]. Computational Fluid Dynamics (CFD) simulations and flow equations provide predictions about how a flow will behave under given conditions. Numerous invasive or bulky measurement techniques, such as optical probes, pressure probes, particle image velocimetry, and radiography, have been used for experimental analysis of bubbly gas-liquid columns. However, a more practical method of flow validation is desired for the online monitoring of these reactions. Displacement Current Phase Tomography (DCPT) is a noninvasive, real-time imaging and measurement method that can be used for the study of gas-liquid bubbly columns.

Other noninvasive global measurement techniques such as Electrical Capacitance Tomography (ECT) have been used for study of such columns. However, ECT has historically proven unsuccessful in the imaging and monitoring of flows where a conductive medium like water is the continuous phase. This is due to the high permittivity contrast between water and other phases in the flow. In response to this issue, Tech4Imaging developed the measurement technique of DCPT, which uses the phase shift information of low-frequency, low-voltage electric fields to analyze a region of interest where a conductive medium like water is the continuous phase [2].

II. Theory

ECVT is a natural extension of Electrical Capacitance Tomography that collects noninvasive capacitance measurements on a 3D space. An ECVT system consists of three major components: a passive sensor comprised of plate electrodes which surround a region to be studied, a data acquisition system that sends and receives electric fields from the sensor, and software to interface with the acquisition system and interpret its data in real time. Figure 1 shows a diagram of these three components.

With this ECVT system, distributions of electric field are measured with the multitude of electrodes on the sensor. The measured fields are related to the dielectric constant distribution within the sensing region via proprietary algorithms within the Tech4Imaging software [3]. Tech4Imaging's ECVT system has been proven for the noninvasive analysis of two phase bubbly columns [4]. Given the scalability and noninvasive nature of ECVT, this measurement technique can be applied to numerous multiphase flow scenarios. Here, such a system is used to analyze the flow of bubbles in a gas-water column.

Tech4Imaging's technology is also capable of utilizing Displacement Current Phase Tomography (DCPT) with the same hardware. This tomography method analyzes the AC phase shifts in electric fields that arise from the loss-tangent of material within the sensing region of DCPT. These displacement current phase shifts depend on both the permittivity and conductivity of the material. This makes DCPT more capable than ECT and ECVT in the measurement of water-based flows [2].

Figure 1: The three major components of an ECVT/DCPT system (from left to right): a sensor surrounding the flow, a data acquisition system, and data analysis software.

III. Experimental Setup

The column used was an acrylic tube with an outer diameter of 4.5 inches (11.43 cm), an inner diameter of 4.0 inches (10.16 cm), and a length of 2 feet (60.96 cm). A rubber stopper was placed on one end of the tube, with a 1/8 inch diameter (0.3175 cm) hole in the center of the stopper. A one-way check valve was inserted into the hole. This valve was connected to an air compressor. The compressor was used to control the volumetric flow rate of air into the column.

The sensor used was 3D-printed from nylon and fabricated with conductive nickel paint. The sensor had an inner diameter of 4.5 inches (11.43 cm), and a height of 7.0 inches (17.78 cm). The ECVT sensor consisted of 36 plate-shaped electrodes, in three axial layers of 12 plates each. This sensor was attached to the exterior of the acrylic tube, with the sensor's bottom end 5 inches (12.70 cm) above the rubber stopper at the end of acrylic tube.

The experimental setup of the system and bubble column can be seen as a diagram in Figure 2 and as a picture in Figure 3.

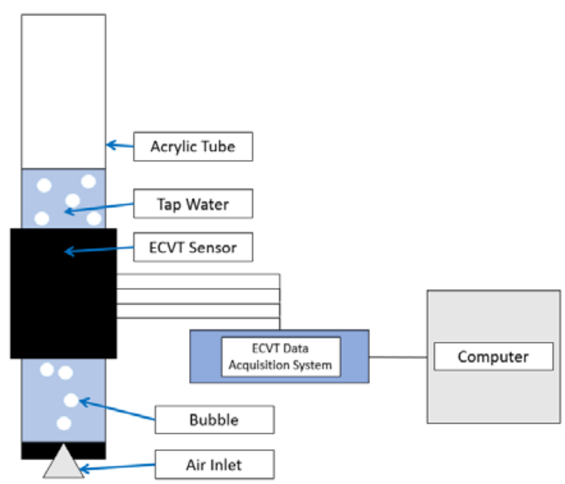


Figure 2: Experimental Setup

The sensor was connected with coaxial cables to Tech4Imaging's patented system. This system was used to collect real-time data about the bubbly column. The system sequentially excites the sensor plates with an AC voltage and receives readings from the other plates. The plates were excited with a 2-Megahertz wave at a 5 V peak amplitude. The system collected an average of 60 measurements a second. The excitation frequency, voltage, and data acquisition speed were all selected based on the flow being studied. The Tech4Imaging system operating conditions are adjustable to fit into a wide variety of measurement scenarios.

The system was connected to a PC with a USB 2.0 connection, and the system was controlled with Tech4Imaging's 4Sight software. This software was used to interface and operate the system, as well as analyze the system data in real-time and in post-processing.

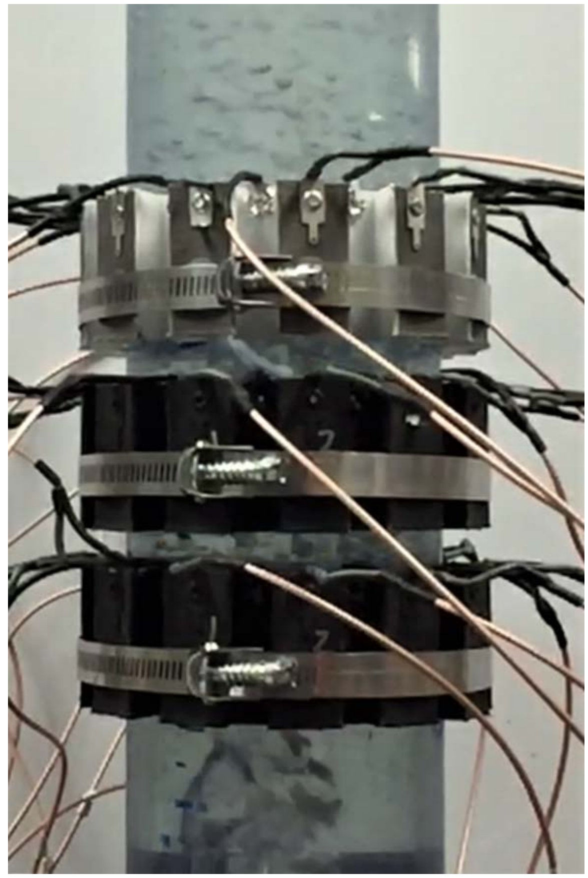


Figure 3: Sensor on Bubble Column

The acrylic tube was filled with tap water to a height of 17.125 inches (43.50 cm), with the water level rising 5.125 inches (13.02 cm) above the top of the ECVT sensor. The air flow rate was raised from 0 to 50 standard cubic feet per hour (0 to 1416 liters per hour) in increments of 10 SCFH (283.2 LPH), and system data was captured at each of these steady air flow rates for 3.33 seconds (or 200 measurements at 60 measurements per second).

The experiments were conducted at standard temperature and pressure. The water temperature was 20˚C.

IV. Experimental Results

Several metrics about the movement of air bubbles in the column were calculated from the collected data. A summary of these metrics are presented in Table 1.

Table 1: Summary of Experimental Results

Air Flow Rate (SCFH) [LPH]	Average Void Fraction	Average Bubble Radius (in), [cm]	Average Bubble Velocity (in/s), [cm/s]	Average Bubble Frequency (Hz)
0	0	0	0	0
10 [283.2]	0.0217	0.770 [1.96]	18.75 [47.63]	2.7
20 [566.4]	0.0358	0.909 [2.31]	21.43 [54.43]	3.9
30 [849.6]	0.0429	0.966 [2.45]	25.00 [63.50]	3.6
40 [1132.8]	0.0627	1.096 [2.78]	30.00 [76.20]	3.3
50 [1416]	0.0712	1.143 [2.90]	37.50 [95.25]	3.9

The real-time water volume fraction and void fraction inside the sensing region were calculated by an equation that relates the measurements to volumetric void fraction. The average void fraction at each flow rate is shown in the second column of Table 1.

To verify this metric, the bubbly column was filmed at each air flow rate. The changing height of the water column was observed and compared with the static water column height of 17.125 inches (43.50 cm). The average column height was measured and used to determine the average void fraction in the bubbly column using the following equation:

$$Void\ Fraction = \frac{Column\ Height - Static\ Column\ Height}{Column\ Height} \quad (1)$$

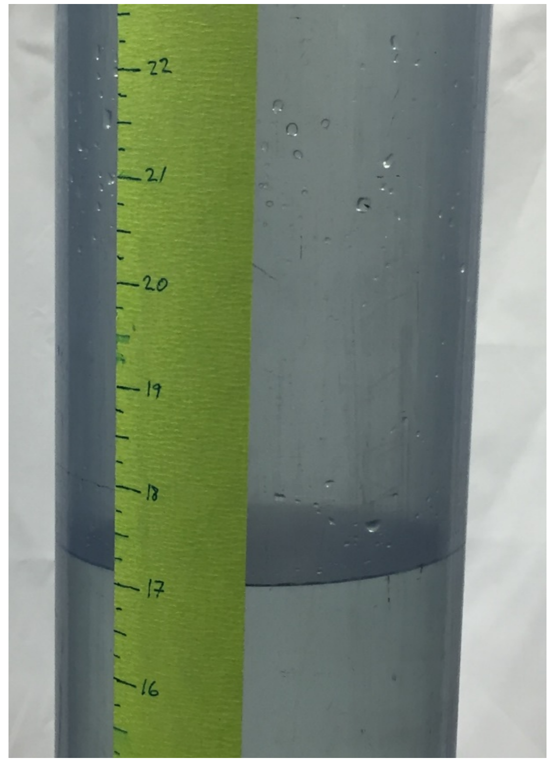


Figure 4: Static Water Surface Height

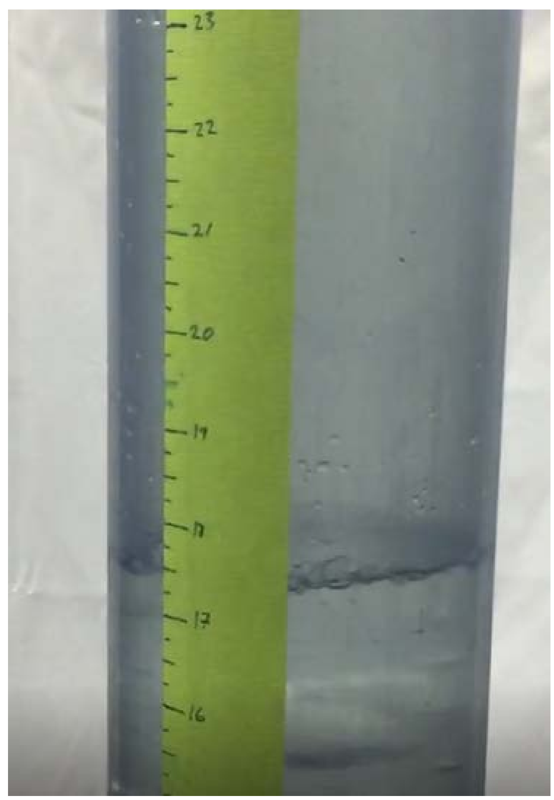


Figure 5: Water Surface Height at 10 SCFH Air Flow Rate

This method of measuring void fraction is prone to some errors. The water surface of a bubbly column is constantly fluctuating, and visually measuring the surface level has its own amount of error. Furthermore, this method of determining void fraction only determines the total void fraction of the entire gas-water bubble column, and it is assumed that this is representative of the average void fraction in the ECVT sensing region. Table 2 shows the visual estimation of column void fraction, compared with the void fraction as measured by the system. Figures 4 and 5 show the water column surface height at air flow rates of 0 and 10 SCFH (0 to 283.2 LPH), respectively.

Table 2: Void Fraction as Determined Visually and by DCPT

Air Flow Rate (SCFH), [LPH}	Average Column Height (in), [cm]	Average Void Fraction (Visual)	Average Void Fraction (DCPT)
0	17.125 [43.50]	0	0
10 [283.2]	17.500 [44.45]	0.0214	0.0217
20 [566.4]	17.750 [45.09]	0.0352	0.0358
30 [849.6]	18.000 [45.72]	0.0486	0.0429
40 [1132.8]	18.250 [46.36]	0.0616	0.0627
50 [1416]	18.500 [46.99]	0.0743	0.0712

As can be seen in Figure 6, at larger air flow rates, the average water volume fraction decreases and fluctuates more aggressively. It can be inferred that a large bubble is crossing directly through the sensing region of the device when the water volume fraction is minimum. The size of this bubble can be found by taking the water volume fraction at this local minimum and determining the void fraction by taking the difference between the water fraction and 1:

$$Void\ Fraction = 1 - Water\ Volume\ Fraction \quad (2)$$

Then, the radius of the bubble can be found with the following relationship:

$$Radius_{Bubble} = \sqrt[3]{\frac{3}{4}(Void\ Fraction)hR^2} \quad (3)$$

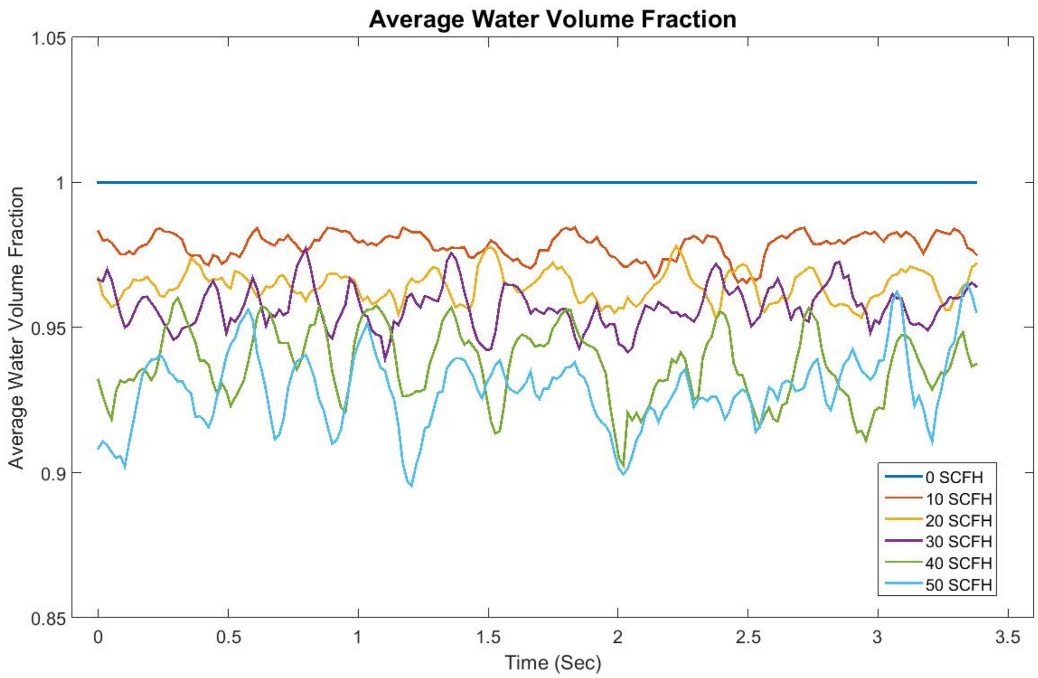
Here, h is the overall height of the sensor (7 inches, or 17.78 cm) and R is the radius of the sensor's active sensing region (2 inches, or 5.08 cm). This calculation was used to produce the third column of Table 1.

Similarly, the average bubble frequency within the column was found by determining the average time between local minima. This was used to produce the fifth column of Table 1.

Like the average void fraction of the entire sensing volume, the temporal average water volume fraction as a function of space was also captured by the DCPT measurements. This metric was calculated by taking the average 3D spatial reconstruction over a length of time (in this case, the time was the entire length of the data capture, or 3.33 seconds).

The result of this calculation is a single image showing the average water volume fraction at each point in the sensing region. Various cross sections and lines may be studied from these images. In particular, average water volume fractions across the diameter of the column and along its axial length are of interest. These metrics are displayed in Figures 7 and 8, respectively.

It can be seen that void fraction was largest near the center of the bubbling column, logically, and that void fraction increased vertically along the bubbling column as bubbles spread wider throughout the column cross section. This occurred due to the single-point gas inlet design of the experiment. Bubbles formed at the inlet and expanded as they moved away from the inlet point.



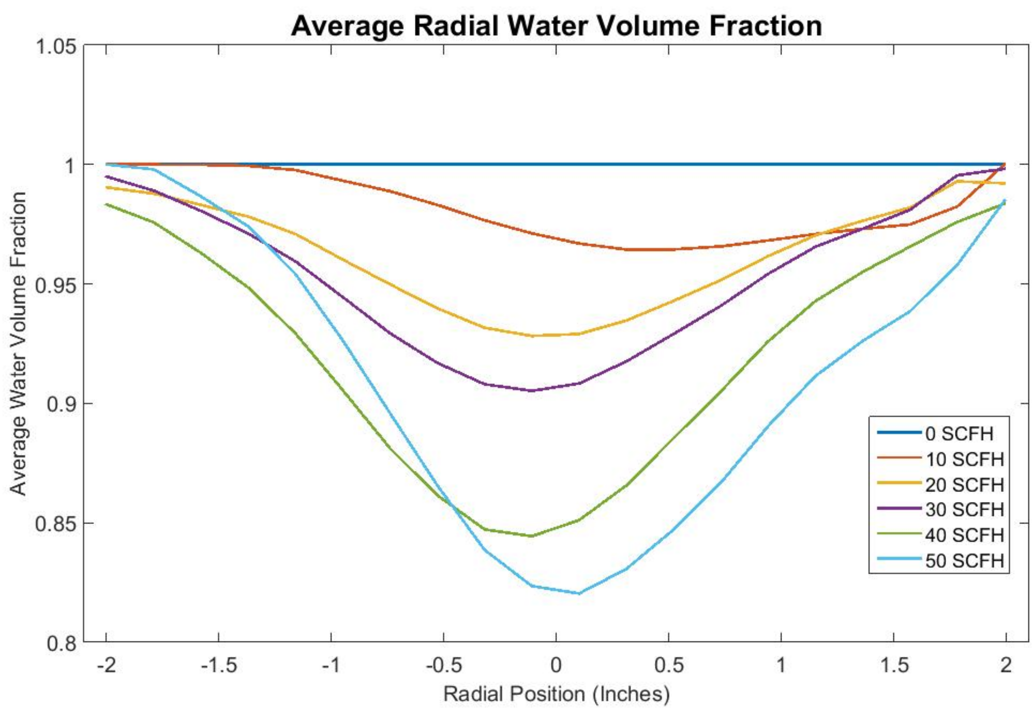
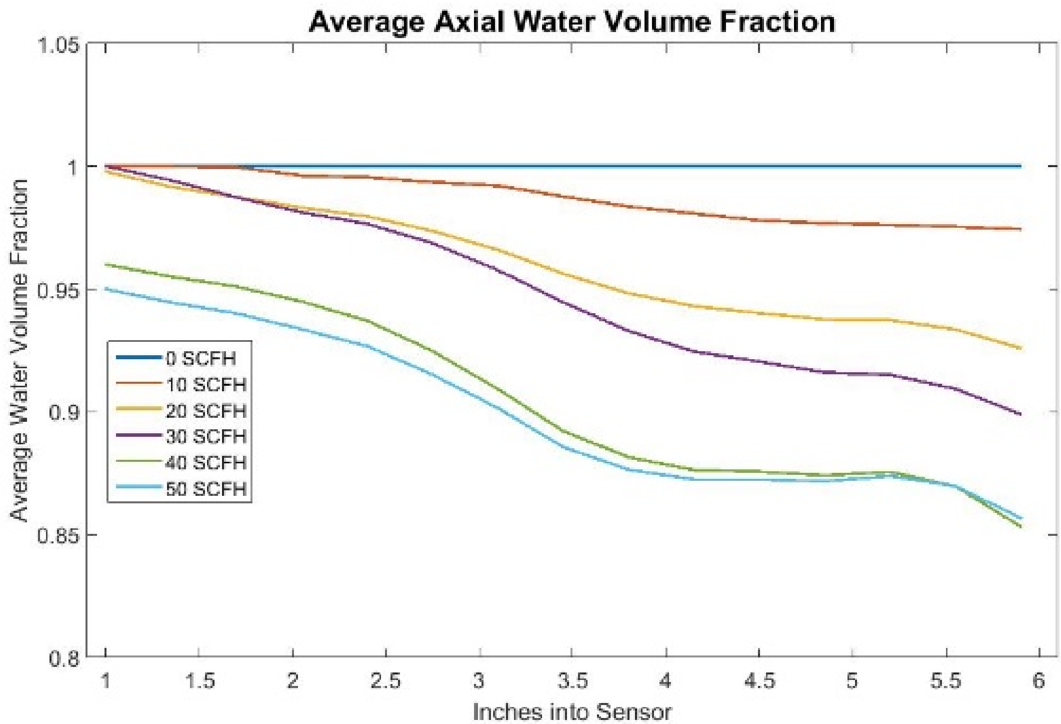


Figure 7: Average Radial Water Volume Fraction of Bubbly Column



In addition to total volume fraction of the space, the real-time phase distribution of gas and water within the column can be analyzed by utilizing 3D spatial reconstructions of the sensing volume.

Two of these images are shown in Figures 9 and 10 as 2D cross-sectional views of the volume. Figure 11 shows a 3D volumetric view of a bubble rising through the column. These reconstructions can be used to analyze real-time bubble location and size. By time-stepping these images, the average velocity of bubbles can be determined by observing how long it takes a bubble to travel a known distance. This is done by taking two images of a bubble, taken at different times, and measuring the distance the bubble traveled. This method was used to produce the fourth column of Table 1. It was seen that average bubble velocity increases with air flow rate.

V. Conclusions

Displacement Current Phase Tomography (DCPT) can be used for the real-time, noninvasive study of bubbly two-phase flows of water and gas. This measurement technique allows important metrics such as volumetric and cross-sectional void fractions, volumetric phase distributions, and bubble velocity to be captured without disturbing the flow. In addition, further analysis on the bubble imaging allows metrics about bubble size and frequency throughout the sensing region to be calculated. DCPT provides numerous benefits to the study of two-phase flows, including three-dimensional measurements, non-disruptive sensor design, and real-time data capturing and analysis.

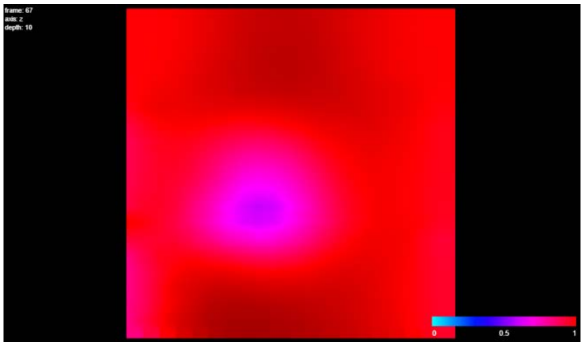


Figure 9: Cross-section of bubble column at 1.12 seconds (50 SCFH air flow rate). Color gradient corresponds with spatial water volume fraction (blue = air, red = water).

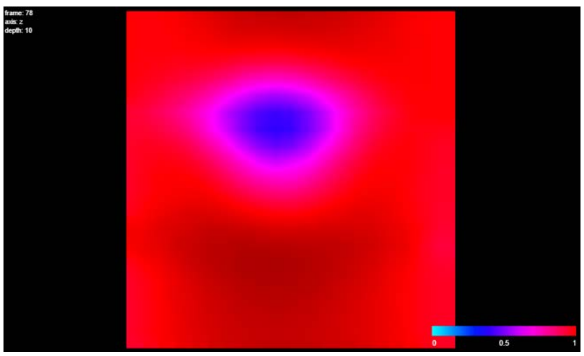


Figure 10: Cross-section of bubble column at 1.30 seconds (50 SCFH air flow rate).

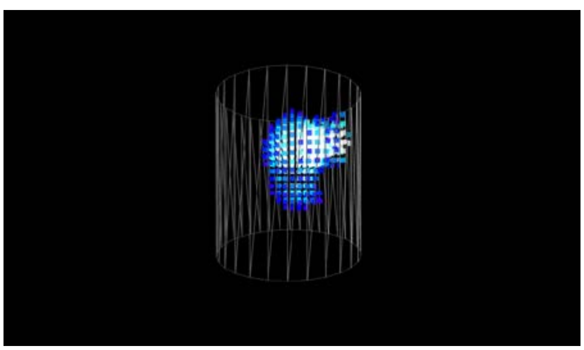


Figure 11: 3D reconstruction of bubble column at 0.221 seconds (50 SCFH air flow rate).

VI. References

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