Real-time Imaging and Holdup Measurement of Carbon Dioxide under CCS Conditions Using Electrical Capacitance Tomography

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Abstract- This paper presented a method for real-time cross-sectional imaging and holdup measurement of gas-liquid two-phase carbon dioxide (CO₂) flow using electrical capacitance tomography (ECT). A high-pressure ECT sensor with 12 electrodes was constructed and a dedicated digital ECT system with a data acquisition rate of 757 frames per second was developed for capacitance measurement. Three widely-used image reconstruction algorithms were compared for tomographic imaging and phase holdup measurement. Experiments were carried out on a DN25 laboratory scale CO₂ two-phase flow rig at a pressure of 6 MPa for the gaseous mass flowrates from 0 to 430 kg/h and liquid mass flowrates at 515, 1100 and 1900 kg/h. The experimental results show that the cross-sectional distribution of two-phase CO₂ flow can be monitored using the ECT system, which matches well with the images captured by a high-speed imaging system. Compared with the reference gas holdup obtained by the flowmeters in the single phase gaseous and liquid loops, the absolute accuracy of the gas holdup measurement can reach 6%, indicating that the developed system is promising for real-time monitoring of carbon dioxide in CCS transportation pipelines.

Keywords- Electrical capacitance tomography, Carbon dioxide transport, Image reconstruction, Holdup measurement

I. INTRODUCTION

Carbon dioxide (CO₂) is the most significant long-lived greenhouse gas in the atmosphere [1]. Since the industrial revolution, a large amount of CO₂ has been produced due to the burning of coal, oil and gas. The increasing emission of CO₂ has leading to serious problems, such as global warming and ocean acidification. Carbon Capture and Storage (CCS) technique is a potential means to prevent the release of large quantities of CO₂ into the atmosphere, which has attracted worldwide attentions [2].

CCS is the process of capturing CO₂ from large point sources, such as fossil fuel power plants, transporting it to a suitable storage site, and depositing it where it will not enter the atmosphere, normally an underground geological formation [3], [4]. This paper focuses on the carbon dioxide transport process, most likely through pipelines because of the cheapest cost.

Monitoring and holdup measurement of the CO₂ flow are essential to monitor and accurately account the captured CO₂ across the CCS chain and help prevent leakage during transport [5]. During the pipeline transport, CO₂ is maintained as dense liquid phase under high pressure (>5MPa) to increase the transport efficiency. Due to thermodynamic properties of CO₂, minor variations in temperature and pressure will result in phase change of CO₂ and the CO₂ flow will become a gas-liquid two-phase flow. In this case, it is challenging to monitor the flow condition and provide accurate measurements using traditional flowmeters.

In the literatures, the Orifice flowmeter has been used for the measurement of slugging gas-liquid flow, but the error can reach up to 80% [6]. The Coriolis mass flowmeter can also be applied to measure gas-liquid CO₂ flow [6], [7]. However, the techniques based on these flowmeters cannot provide distribution information of the two phases.

In the last decades, several tomographic techniques have been developed to monitor two-phase flows including ultrasonic [8] and electrical methods [9], [10]. Each technique makes use of differences between physical characteristics of the two phases and is suitable for specific applications [11]. For example, the electrical impedance tomography technique has been applied to monitor solid-liquid and gas-liquid flows [12].

Among these tomographic techniques, electrical capacitance tomography (ECT) is an imaging technique to obtain the permittivity distribution in the interior of the pipe from capacitance measurements at external boundary [13]–[15]. ECT is one of the most promising techniques for multi-phase flow measurement, which has been successfully applied to gas-oil two-phase flows in oil industry [16] and gas-liquid-solid three-phase flows [17]. It has several advantages such as low cost, high speed and non-invasive compared with other tomographic techniques [15], [18], [19].

In this paper, the ECT technique is introduced to flow...
process monitoring and holdup measurement of CO\textsubscript{2} two-phase flow because of the following two reasons: 1) Compared with sensors of other electrical tomography modalities, such as electrical resistance tomography (ERT) [20], ECT sensors are not required to directly contact with the high-pressure CO\textsubscript{2} fluid. Compared with optical and ultrasonic sensors, ECT sensors have simpler configuration [21]; 2) The permittivities of gaseous CO\textsubscript{2} and liquid CO\textsubscript{2} are 1 and 1.6, respectively, which are both non-conducting. In this application scenario, ECT can be applied while ERT cannot.

However, it is still a challenging task to accurately account and monitor the CO\textsubscript{2} flow using ECT. Firstly, the structure of the ECT sensor should be carefully designed for high-pressure conditions to prevent CO\textsubscript{2} leakage. Secondly, the permittivities of gas CO\textsubscript{2} and liquid CO\textsubscript{2} are close to each other and the two phases change rapidly, which requires an accurate and fast capacitance measurement system and an anti-noise image reconstruction algorithm.

In this research, a high-pressure ECT sensor was constructed and a high-performance digital ECT system was developed. Three typical algorithms were evaluated regarding image reconstruction and holdup calculation. Experiments were performed on a two-phase CO\textsubscript{2} flow rig to verify the feasibility of the proposed technique.

II. DESIGN OF THE ECT SYSTEM

A. High-pressure ECT sensor

The ECT technique is used to obtain the permittivity distribution of the two-phase CO\textsubscript{2} flow inside the conveying pipeline. A typical ECT sensor consists of a number of electrodes, which are placed around the periphery of the pipeline.

A high-pressure ECT sensor is designed in this paper, which can withstand the pressure of 10 MPa. The cross-sectional view of the sensor is shown in [Fig. 1]. The ECT sensor consists of 12 brass electrodes of 40 mm in length, which are symmetrically placed around the periphery of a polytef pipe. The inner diameter of the pipe is 25 mm, while the outer diameter is 31 mm. A piece of brass foil is wrapped around the electrodes for shielding.

To withstand the high pressure inside the pipe, a stainless steel pipe section is placed outside the polytef pipe. Sufficient epoxy resin and curing agent are injected into the space between the two pipe sections. When the epoxy resin is completely cured, the two pipes are fixed tightly with bolts and nuts. The design sketch of the ECT sensor is shown in [Fig. 2]. The spool piece is installed on the pipeline using flanges.

![Fig. 2. Design sketch of the ECT sensor.](image)

B. Capacitance measurement unit

A capacitance measurement unit is developed to measure the capacitances between every two electrodes of the ECT sensor, including one capacitance measurement circuit and several multiple CMOS switches. The schematic configuration is shown in [Fig. 3].

![Fig. 3. Schematic diagram of the capacitance measurement unit.](image)

The capacitance measurement circuit consists of a Complex Programmable Logic Device (CPLD), a Digital-to-Analog Converter (DAC), an Analog-to-Digital Converter (ADC), a capacitance-to-voltage (C-V) converter, a Low-pass filter (LPF) and an internet interface device. The CPLD is used for channel selection, signal demodulation and logic control. A sine-wave excitation signal is generated by CPLD, DAC, and LPF based on the Direct Digital Synthesize (DDS) technique. The capacitance is measured with the C-V converter using AC-based method [15], [19]. The internet device is used for data communication between the capacitance measurement unit and the host PC.

The excitation frequency is 100 kHz and the duration of each capacitance measurement is 10 μs. By using the CMOS switches, the capacitance between every two electrodes can be measured one after another. A time interval of 10 μs is
added between two adjacent measurements to reduce the influences of switching oscillations. The data acquisition rate of the proposed measurement unit is 757 frames per second.

III. IMAGE RECONSTRUCTION AND HOLDUP CALCULATION

A. Image reconstruction

The permittivity distribution can be reconstructed by measuring the capacitance values between every two electrodes and using a suitable reconstruction algorithm. A number of reconstruction algorithms have been developed in recent years, which can be divided into two types, i.e., non-iterative algorithm and iterative algorithm. In this paper, three widely-used algorithms are introduced and used for image reconstruction.

1) Linear back projection (LBP) algorithm

In the LBP algorithm, the relationship between the measured capacitances and permittivity distribution is simplified to a linear form [22].

\[ \Delta C = J \Delta \varepsilon, \]

where \( \Delta C \) is the capacitance change, \( \Delta \varepsilon \) is the permittivity change and \( J \) is the sensitivity matrix of the capacitance versus permittivity distribution. In general, equation (1) is written in a normalized form

\[ \lambda = Sg, \]

where \( \lambda \) is the normalized capacitance vector, \( S \) is the sensitivity matrix of normalized capacitance with respect to normalized permittivity vector, and \( g \) is the normalized permittivity vector, i.e. the pixel values to be imaged. An approximated solution of \( g \) is given as

\[ g_{LBP} = (S^T \lambda)/(S^T f_x), \]

where \( f_x = [1,1,\ldots,1] \) and \( g_{LBP} \) is the reconstructed permittivity vector. The LBP algorithm is simple and suitable for online image reconstruction. However, it provides poor-quality images.

2) Landweber algorithm

Iterative algorithms are developed to improve the reconstructed image quality. The projected Landweber algorithm is the most widely used iterative algorithm [23, 24].

\[ g_{k+1} = P \left[ g_k - \alpha S^T (Sg_k - \lambda) \right], \]

where \( \alpha \) is a relaxation factor, \( P \) is a projection operator and

\[ P[f(x)] = \begin{cases} 
0 & f(x) < 0 \\
 f(x) & 0 \leq f(x) < 1 \\
1 & f(x) > 1 
\end{cases}, \]

The main drawbacks of the iterative algorithm are that it is time-consuming and a suitable relaxation factor and stop criteria for the iterations need to be pre-determined.

3) Calderon algorithm

Unlike the sensitivity-matrix-based algorithms described above, the Calderon algorithm can independently provide the gray value at any pixel of the reconstructed image using a direct approach. The Calderon algorithm is time-saving as no matrix inversion or iterative process is involved and it is suitable for imaging of low contrast dielectrics [25].

For ECT, the governing equation of the sensing field, denoted by \( \Omega \), is

\[ \nabla \cdot e(z) \nabla \varphi(z) = 0, \]

where \( z = x+iy \) represents the point with coordinates \( (x, y) \), \( e(z) \) and \( \varphi(z) \) are the permittivity and electrical potential at \( z \).

According to the divergence theorem, the relationship between the integrals of the spatially varying permittivity and voltage and current measurements on the boundary is

\[ \int_{\partial \Omega} e(z) \nabla \varphi(z) \, dl = \int_{\partial \Omega} \nabla e(z) \varphi(z) \, dz = 0, \]

where \( e(z) \) is an arbitrary continuous function in L2-space and \( dl \) is the measured arc length on the boundary \( \partial \Omega \).

Denote the voltage-to-current density map, i.e., the Dirichlet-Neumann map, as

\[ A_\varepsilon : \varphi(z) |_{\partial \Omega} \rightarrow \frac{\partial \varphi(z)}{\partial n} |_{\partial \Omega}, \]

where \( A_\varepsilon \) denotes the voltage-to-current density map when \( \Omega \) contains \( e(z) \). Equation (7) can be rewritten as

\[ \int_{\partial \Omega} e(z) \nabla \varphi(z) \, dl = \int_{\partial \Omega} \nabla e(z) A_\varepsilon(\varphi(z)) \, dl \]

For a disturbed permittivity \( e(z) = 1 + \delta e(z) \) and if this change only exists in \( \Omega \), we obtain

\[ \delta e(x, y) = \delta e(z) \approx \frac{1}{2\pi} \int_{\mathbb{R}^2} t(k + ik) e^{ik(x,y)} \, dk \]

and the scattering transform \( t(k) \) is

\[ t(k) \approx -2(k^2 + k^2) \int_{\Omega} \delta e(x, y) e^{ik(x,y)} \, dx \, dy, \]

where \( k = k_1 + ik_2 \). Then the distorted permittivity can be obtained from (10). In the polar coordinates of parameters \( r \) and \( \theta \), equation (10) can be rewritten as

\[ \delta e(x, y) \approx \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} t(r, \theta) e^{i(k_1 \theta - k_2 r)} \, dk_1 \, dk_2, \]

where \( R_0 \) is the radius of the region used for the numerical integration.

B. Holdup calculation

Based on the above-mentioned ECT hardware and image reconstruction algorithms, the flow pattern of the two-phase CO\(_2\) flow can be identified and the gas holdup can be calculated.

Firstly, the capacitances between every two electrodes when the pipe is full of gaseous CO\(_2\) or liquid phase CO\(_2\) are measured for calibration.

Secondly, the permittivity distribution \( e \) is reconstructed using an image reconstruction algorithm. The normalized permittivity distribution is calculated by

\[ e_{\text{norm}} = \frac{e_m - e_{\text{low}}}{e_{\text{high}} - e_{\text{low}}}, \]

where \( e_m \), \( e_{\text{low}} \) and \( e_{\text{high}} \) are the reconstructed permittivity distribution of the CO\(_2\) flow, gaseous CO\(_2\) and liquid phase CO\(_2\).
CO₂.
Thirdly, a series of ECT images of normalized permittivity distribution is obtained within a short time period to identify the flow pattern.
Finally, the gas holdup can be calculated by
\[ h = 1 - \frac{\sum_{t=1}^{L} \varepsilon^{\text{Norm}}(i)}{L} , \]  
where \( L \) is the number of pixels in the reconstructed image and \( \varepsilon^{\text{Norm}}(i) \) is the \( i \)-th pixel of normalized permittivity value. In this paper, as the sensor electrodes are rectangle and 40 mm long, the cross-sectional images reconstructed by ECT represent the averaged permittivity distribution within the axial coverage of the electrodes. In the cross-sectional area, the flow velocity profile is not uniform. If we want to obtain a more accurate volume holdup, the velocity information should be considered. However, the velocity information cannot be obtained using the present structure of ECT sensor, which needs to be further studied.

IV. EXPERIMENTAL RESULTS
A. Experimental setup
The schematic diagram and photo of the DN25 experimental setup are shown in Fig. 4 and Fig. 5 including three main pipelines for gaseous phase, liquid phase and gas-liquid two-phase CO₂ flow. Coriolis mass flowmeters are installed in gas and liquid phase loops to obtain the mass flow rates, temperatures and densities of the gas and liquid single-phase flows, respectively. A sight window and the ECT sensor were mounted next to the mixer. A high speed imaging system was used to capture the image of the CO₂ flow through the sight window.

B. Experiment
The experiment was performed under laboratorial conditions at 22 °C and 101 kPa ambient. In the experiment, by setting the liquid CO₂ flowrates at 515, 1100 and 1900 kg/h and increasing the gaseous CO₂ flowrate stepwise from 0 to 430 kg/h, the gas-liquid two-phase CO₂ flow with different gas holdups can be generated through a mixer. The sight window and the ECT sensor are mounted next to the mixer and the pressure in the pipelines is 6 Mpa and kept stable. Therefore, the phase change of the CO₂ flow is small between the sight window and the ECT sensor.

The reference gas holdup is calculated using the measured flow rates, temperatures and densities of the two single-phase flows. Assume that \( m_g \) and \( m_l \) be the mass flowrates of the gaseous and liquid CO₂ flow, \( \rho_g \) and \( \rho_l \) be the densities of the gaseous and liquid CO₂ flows, respectively. Then superficial gas velocity and superficial liquid velocity of the CO₂ flow can be calculated by
\[ \begin{align*}
  u_g &= \frac{m_g}{\rho_g \pi r^2}, \\
  u_l &= \frac{m_l}{\rho_l \pi r^2}
\end{align*} \]  
The reference gas holdup of the gas-liquid two-phase CO₂ flow is
\[ h = \frac{m_g / \rho_g}{m_g / \rho_g + m_l / \rho_l}, \]  
C. Results
1) Liquid flowrate at 515 kg/h
Firstly, the liquid flowrate is set to be 515 kg/h and the gas flowrate ranges from 0 to 430 kg/h, resulting in a reference gas holdup ranging from 0 to 77%. When the gas-liquid two-phase CO₂ flow becomes stable, images were captured by the high-speed imaging system, as shown in Fig. 6.
The images reconstructed by the ECT system are shown in Fig. 7. For the Landweber algorithm, it is crucial to select a suitable relaxation factor and number of iterations, which greatly affect the reconstruction result. According to Tian et al. [24], the relaxation factor is chosen to be 0.5 and the number of iterations is 8. For the Calderon method, the radius of the region used for the numerical integration is set to be 1.8. In the ECT images, the blue and red colors represent low and high permittivities, respectively. The blue outer ring in each image represents the wall of the polytetrafluoroethylene pipe. For the ECT images from left to right, the corresponding gas holdups change from 0 to 77%. The last image at each row is reconstructed when the ECT sensor is filled with gaseous CO$_2$.

From Fig. 6 and Fig. 7, it can be seen that the gaseous CO$_2$ and liquid CO$_2$ can be distinguished via ECT imaging of permittivity distributions. The flow pattern of the CO$_2$ flow at lower liquid flowrate is obviously stratified flow, which can be recognized via image reconstruction using the three algorithms. The boundary between the gaseous CO$_2$ and liquid CO$_2$ obtained using the LBP and Landweber algorithms is more obvious than that using the Calderon algorithm. When the gas flowrate increases, the gas holdup increases and the area of blue region increases in the ECT images.

The reconstructed permittivity distributions are then used to calculate the gas holdup. To evaluate the measurement accuracy, the absolute error is defined as

$$e_i = h_m - h_r,$$  \hspace{1cm} (17)

where $h_m$ is the gas holdup measured by ECT and $h_r$ is the reference gas holdup. The standard deviation is defined as

$$\sigma = \sqrt{\frac{\sum_{i=1}^{M} (h(i) - \bar{h})^2}{M-1}},$$  \hspace{1cm} (18)

where $h(i)$ is the i-th gas holdup value measured by ECT, and $\bar{h}$ and $M$ are the average gas holdup value and the total number of measurements by ECT, respectively.

The absolute errors and standard deviations of the gas holdup measurement by ECT at lower liquid flowrate are shown in Fig. 8. The upper triangular blocks, square blocks and plus signs represent the gas holdups calculated using the LBP, Landweber and Calderon algorithms, respectively.

In general, we expect that the relationship between the measured gas holdup and reference gas holdup is linear. However, the relationship is determined by a polynomial. Here, a third order polynomial is used to fit the curve. Then the fitted gas holdup curve can be described by

$$h = p_1h_m^1 + p_2h_m^2 + p_3h_m^3 + p_4,$$ \hspace{1cm} (19)

The coefficients of the polynomial are calculated using the least squares method. Then the calculated $p_1$, $p_2$, $p_3$ and $p_4$ are -2.66, 3.46, 0.22 and -0.02 for the LBP algorithm, -3.11, 4.07, 0.06 and -0.03 for the Landweber algorithm, and -2.25, 2.84, 0.44 and -0.03 for the Calderon algorithm, respectively.

In Fig. 8, the lower triangular blocks, diamond blocks and multiple signs represent the fitted gas holdups for the LBP, Landweber and Calderon algorithms, respectively. As seen from the fitted results, the maximum absolute errors are 6.0%,
6.8% and 6.0%, and the maximum standard deviations are 6.2%, 4.4% and 6.0% for the LBP, Landweber and Calderon algorithms, respectively. Overall, the three algorithms provide similar absolute errors. The Landweber algorithm provides lower standard deviation because the iteration process acts as a filter and reduces the noises. The standard deviation can be reduced by averaging more measurements at an expense of measurement speed.

In Fig. 6, it is shown that at a lower liquid flowrate, the flow pattern is stratified flow and the boundary between the two-phases fluctuates sharply, leading to a wavy flow and a larger measurement uncertainty. In Fig. 8 (b), when the gas holdup becomes close to 50%, the boundary area of the two phases becomes larger, resulting in a larger standard deviation and measurement uncertainty. Compared with a calm stratified flow, more measurements are required for averaging to reduce the measurement uncertainty in this case.

2) Liquid flowrate at 1100 kg/h

The medium liquid flowrate is set to be 1100 kg/h and the gas flowrate ranges from 0 to 430 kg/h, resulting in a reference gas holdup ranging from 0 to 60%. The images of the CO₂ flow captured by the camera and reconstructed by ECT are shown in Fig. 9 and Fig. 10 respectively. For the Landweber algorithm, the relaxation factor is chosen to be 0.5 and the number of iterations is 70. For the Calderon method, the radius of the region used for the numerical integration is set to be 1.8.

![Image](a) reference gas holdup-12%

![Image](b) reference gas holdup-21%

![Image](c) reference gas holdup-39%

Fig. 9. Images captured by the high-speed imaging system for different gas holdups when the liquid flowrate is 1100 kg/h.

![Image](a) LBP

![Image](b) Landweber

![Image](c) Calderon

![Image](d) LBP-fitting

![Image](e) Landweber-fitting

![Image](f) Calderon-fitting

Fig. 10. Variation of cross-sectional images reconstructed by ECT with gas holdup obtained by using (a) LBP algorithm, (b) Landweber algorithm and (c) Calderon algorithm when the liquid flowrate is 1100 kg/h.

When the liquid flowrate is 1100 kg/h, the flow pattern of the CO₂ flow is bubble flow. The gas holdup in the upper area is larger than that in the lower area. The ECT images show the rising tendency of the gas holdup.

The absolute errors of the gas holdups measured by ECT and corresponding standard deviations are shown in Fig. 11. After fitted using the least squares method, the maximum absolute errors are 3.9%, 5.2% and 3.2%, and the maximum standard deviations are 5.9%, 3.5% and 5.1% for the LBP, Landweber and Calderon algorithms, respectively.

![Image](a) Absolute error

![Image](b) Standard deviation

Fig. 11. (a) Absolute errors and (b) standard deviations of gas holdups measured by ECT when liquid flowrate is 1100 kg/h.

3) Liquid flowrate at 1900 kg/h

The high liquid flowrate is set to be 1900 kg/h and the gas flowrate ranges from 0 to 430 kg/h, resulting in a reference gas holdup ranging from 0 to 40%. The images of the CO₂ flow captured by the camera and reconstructed by ECT are shown in Fig. 12 and Fig. 13 respectively. For the Landweber algorithm, the relaxation factor is chosen to be 1 and the number of iterations is 100. For the Calderon method, the radius of the region used for the numerical integration is set to be 1.8.

![Image](a) LBP

![Image](b) Landweber

![Image](c) Calderon

![Image](d) LBP-fitting

![Image](e) Landweber-fitting

![Image](f) Calderon-fitting

Fig. 12. In Fig. 12 it is shown that the gaseous CO₂ and liquid CO₂ are evenly mixed when the liquid flowrate is 1900 kg/h. From Fig. 13 the images reconstructed using the Calderon algorithm agree well with the camera images. The small bubbles cannot be distinguished due to the low resolution of the ECT images. The images reconstructed using the LBP and

![Image](a) Reference gas holdup-12%

![Image](b) Reference gas holdup-21%

![Image](c) Reference gas holdup-39%

Fig. 13. Images captured by the high-speed imaging system for different gas holdups when the liquid flowrate is 1900 kg/h.
Landweber algorithms show some inhomogeneity of the two-phase flow but are of distortion.

Fig. 12. Images captured by the high-speed imaging system for different gas holdups when the liquid flowrate is 1900 kg/h.

(a) reference gas holdup-2%
(b) reference gas holdup-10%
(c) reference gas holdup-24%

Fig. 13. Variation of cross-sectional images reconstructed by ECT with gas holdup obtained by using (a) LBP algorithm, (b) Landweber algorithm and (c) Calderon algorithm when the liquid flowrate is 1900 kg/h.

The absolute errors of the gas holdups measured by ECT and corresponding standard deviations are shown in Fig. 14. After fitted, the maximum absolute errors are 1.3%, 1.3% and 1.6%, and the maximum standard deviations are 3.1%, 2.5% and 3.1% for the LBP, Landweber and Calderon algorithms, respectively.

When the gaseous CO\(_2\) and liquid CO\(_2\) are evenly mixed, the two-phase flow becomes symmetrical in geometry. Compared with the results at lower liquid flowrate, the standard deviation becomes lower and hence a lower measurement uncertainty can be obtained.

Fig. 14. (a) Absolute errors and (b) standard deviations of the gas holdups measured by ECT when liquid flowrate is 1900 kg/h.

4) Dynamic process monitoring

A dynamic process of the two-phase CO\(_2\) flow was monitored by the proposed ECT system. The pipe was firstly filled with gaseous CO\(_2\). Then the pump in the liquid phase loop was started and liquid phase CO\(_2\) was ejected into the pipe until all the pipe was filled with liquid phase CO\(_2\). The variation in the liquid holdup against the measurement time was shown in Fig. 15.

Fig. 15. Variation in liquid holdup against measurement time.

Totally, 757 measurements of liquid holdup can be obtained using ECT and the dynamic process can be clearly reflected from those results. The images captured by the camera at the three typical time points of (a), (b) and (c) in Fig. 15 are shown in Fig. 16.
From Fig. 16, the flow pattern in the dynamic process is liquid slug-stratified-bubbly flow. The liquid holdup measured by ECT changes with the increasing transferred liquid CO$_2$. The liquid holdup dramatically increases in the period from 4 to 5 second in Fig. 15, which can be clearly identified by the ECT system.

D. Discussions

The flow patterns of the two-phase flow are relative simple in the CCS chain, i.e. stratified and homogenous. In this case, when the three algorithms in this paper are used to calculate the gas holdup, the absolute errors have no obvious difference. Compared with the LBP and Calderon algorithms, the Landweber algorithm can provide lower standard deviation in an iterative way. However, the parameter selection is crucial and the computing time is long if more iteration times are required in the Landweber algorithm. The single-step algorithms, i.e. the LBP and Calderon algorithms, can significantly shorten the computing time. Compared with the LBP algorithm, the Calderon algorithm is more applicable for complex flow patterns [25]. In consideration of the requirements of real-time and applicability, the Calderon algorithm is suggested in this paper.

The reconstruction method used in this paper is based on a 2D model. In the future, a 3D reconstruction method can be used to provide axial resolution along the pipe. However, it may affect the real-time performance of the system.

V. CONCLUSIONS

This paper presented the potential of ECT for monitoring of carbon dioxide transport in pipelines. Experimental results have shown that

1) The stratified and homogeneous flow patterns of the two-phase CO$_2$ flow can be identified using the proposed method, which matches well with the images captured by the high-speed imaging system. The dynamic process of the CO$_2$ two-phase flow can be captured by the proposed ECT system with a high time resolution.

2) When the liquid flowrate rate is low, the flow pattern of the CO$_2$ flow is a stratified flow and the absolute errors and standard deviations of gas holdup measurements are relatively high. When the liquid flowrate rate is higher, the gaseous CO$_2$ and liquid CO$_2$ are mixed more evenly and the standard deviation is lower.

3) The maximum absolute errors of gas holdup measurements are 6.0% at the lower liquid flowrate, 3.2% at the medium liquid flowrate and 1.6% at the higher liquid flowrate, respectively, when using the Calderon algorithm.

REFERENCES


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