Experimental Study on Liquid Spread and Maldistribution in the Trickle Bed Reactor Using Electrical Resistance Tomography*

Takeshi EDA**, Achyut SAPKOTA**, Jun HARUTA***, Masayuki NISHIO*** and Masahiro TAKEI**

**Division of Artificial Systems Science, Chiba University
1-33 Yayoicho, Inage-ku, Chiba, Japan
E-mail: eda@chiba-u.jp

***Process Technology Research Laboratory, Ube Industries, Ltd.
1978-5 Kogushi, Ube-shi, Yamaguchi, Japan

Abstract

A lab scale trickle bed reactor (TBR) has been employed to investigate the effect of particles and liquid flow rate on the phase distribution in TBR. The TBR module, made up of 100 mm inner diameter acrylic column, was randomly packed with inert porous alumina particles of different average diameters that are used in actual reactor. Water was fed from the top of the column by “point feed” and “homogenous feed” strategies and cross-sectional liquid distributions were captured at several axial positions from the top to the bottom of the column by employing electrical resistance tomography (ERT) technique. ERT is a non-invasive cross-sectional imaging technique that provides the cross-sectional conductivity distribution by injecting current and measuring voltages between the several electrodes (16 electrodes in our case) that are attached around the column. The cross-sectional conductivity thus obtained represents the liquid hold up and degree of maldistribution of the liquid. In the experiment, quicker and more homogenous distribution of liquid was obtained for the particles with smaller diameters. That is due to capillary force that cancels the randomness of packing. Electrical resistance tomography seems to be reliable non-invasive instrumentation technique to optimize the design and operations of the trickle bed reactors.

Key words: Trickle Bed Reactor, Electrical Resistance Tomography, Liquid Holdup, Liquid Maldistribution, Gas Liquid Two Phase Flow

1. Introduction

Trickle bed reactor (TBR) is one of the three-phase reactors that are used in the field of petroleum and chemical engineering. TBRs operate in gas-liquid concurrent down-flow through the packed bed of catalytic particles, and are generally involved in desulfurization, hydrogenation, oxidation and hydrotreating (1). Therefore, three-phase (liquid-gas-solid) contact with each other is the most important part in the operation of these reactors from hydrodynamic point of view. There are several flow conditions that occur in the operation of TBR according to gas-liquid flow rate, fluid properties and packing property such as size, shape and surface, which ultimately has great impact on mass and heat transfer rate (2, 3).

Most commercial reactors operate in trickle flow profile that are generally due to the low liquid and gas feed flow rate (4). Liquid flows down the bed creating liquid films around the particles while gas flows at the remaining gap in the bed. In trickle flow operation,
several problems take place. For example, due to the random nature of packing of the particles and surface tension of liquid, liquid films around particles tend to merge, and flow down through the space between the particles which result in inhomogeneous distribution of flowing down liquid in spite of a perfect homogeneous liquid feed on the top of the packing. Moreover, stagnant liquid is generated among the contact point of particles that amount to 10 ~ 30 % of total liquid holdup. These are serious problems that results in the inefficient use of catalytic particles and interfere with the proper discharge of the reaction heat in some exothermic reactions.

Pulsating flow, where liquid rich zone and gas rich zone alternately flow down, should occur in relatively high gas and liquid feed flow rate. A liquid rich zone flushes down the stagnant liquid and causes complete wetting of catalytic particles. In order to eliminate problems involved in trickle flow operation, few studies suggest operating in natural pulsating flow or periodic gas-liquid feed strategy that induces pseudo pulsating flow at rather low time averaged flow than that of naturally occurred. However, complex equipment and scale-up problems prevent practical applications. Therefore, understanding of the liquid maldistribution in TBR is still a big issue.

In order to investigate the liquid behavior in the packed bed, some theoretical approaches were attempted. They investigated the radial liquid spread from point feed by euler-euler two phase CFD model. Since their studies based on averaged porosity distribution model and particularly focused on liquid spread, they neglected the particle scale dynamics that is closely related to formation of channels and stagnant liquid that results in maldistribution.

Therefore experimental approach is important to investigate the liquid maldistribution. In the past years, great effort has been spent to visualize the liquid distribution in the packed bed. Liquid collector method is famous technique due to its very simple principle. In this method, liquid dripped from column is collected in the separated cells in the bottom of column. But, it only provides the liquid distribution at the bottom of bed. Hence, major disadvantage of this method is that it cannot provide information on liquid distribution for different depth simultaneously. Dye absorption method discloses the very fine traces of liquid flow in the column but cannot provide temporal variations of liquid distribution. For opaque and complex nature of packed bed, tomographic techniques are suitable for visualization of the liquid distribution. Till date, some medical imaging techniques have been applied to the visualization of liquid distribution in packed bed. X-ray computed tomography (CT), gamma-ray CT and magnetic resonance imaging (MRI) method provide liquid distribution in packed bed with quite high spatial resolution. But, MRI is applicable only to small vessels, and X-ray CT and gamma-ray CT suffer from low temporal resolutions. Further, the common disadvantage of these tomographic techniques is their highest cost for safety monitoring and, most of them are complex equipment. To overcome these limitations, authors believe that electrical resistance tomography (ERT) is quite applicable technique. ERT is very simple and robust non-invasive cross-sectional imaging technique. In this technique, the cross-sectional electrical conductivity distribution is obtained by injecting constant current and measuring voltages between electrodes arranged around the object. Additionally, it can provide fast capture (up to 100 frames per second). Thanks to the quite distinct difference between the resistivity of air and water, ERT can provide more accurate liquid distribution in water-air system without disturbing the flow.

In the present study, the authors have investigated the effect of liquid feed rate, liquid feed technique and particle diameter on the distribution of the liquid in TBR using electrical resistance tomography.
2. Theory of Electrical Resistance Tomography

Electrical resistance tomography is one of the electrical tomographic techniques that provide the cross-sectional electrical conductivity distribution by means of number of voltage measurements via electrodes arranged on target boundary and numerical image reconstruction procedures. The methodology is able to detect the higher and/or lower conductivity objects in the conductive bulk phase by change in measured voltage. ERT has been applied to industrial process monitoring involved in mixing \(^{16}\), hydrocyclone \(^{17}\), chemical reaction \(^{18}\) and so on.

In ERT, to obtain the cross-sectional conductivity distribution, two major processes should be carried out. One is voltage measurements and the other is to construct the tomographic image which represents the conductivity distribution in the cross-section.

Schematic diagram of voltage measurements strategy of ERT is shown in Fig. 1. A constant current is injected at a pair of adjacent electrodes among 16 electrodes arranged on boundary of measurement target. And voltage distribution on boundary of concerned area was measured between all remained pairs of adjacent electrodes. Then the pairs of injecting current were moved to next adjacent pair, and voltage measurements are repeated for all remained combinations except the combination that is replaced in injecting current and voltage measurement pairs from previous combination due to reciprocity theorem. This measurement strategy provides \((16 \times [16 - 3] / 2 =) 104\) voltage measurements set for one image. This type of measurement philosophy is guided by the governing equations of electric field. A conductivity distribution in to which current is injected and corresponding voltage is measured is governed by following Laplace equation:

\[
\nabla \cdot (\sigma \nabla V) = 0.
\]

And, following boundary conditions express current injection on a pair of electrodes and insulation on remaining boundary:

\[
\begin{align*}
\sigma \frac{\partial V}{\partial n} &= i, \quad \text{on source electrode,} \\
\sigma \frac{\partial V}{\partial n} &= -i, \quad \text{on sink electrode,} \\
\sigma \frac{\partial V}{\partial n} &= 0, \quad \text{otherwise.}
\end{align*}
\]

Where \(V\) is voltage distribution, \(\sigma\) is conductivity distribution, \(n\) is normal vector on boundary of cross-section and \(i\) is injecting current density.

Following the voltage measurements, it is necessary to process the voltage data using an appropriate image reconstruction algorithm. Reconstructed image provide cross-sectional electrical conductivity distribution. In our case, spatial resolution of image is 20 pixels \(\times\) 20 pixels (= 400 pixels). However, some of these pixels near the four corners represent the space outside the cylindrical column. Therefore, 316 pixels among the 400 pixels are meaningful. Reconstruction process often refers to ill imposed inverse problem. Therefore forward problem have to be solved in advance. In other words, one must compute the Jacobian matrix called sensitivity matrix \(S\) of 104 measured voltages vector \(U\) and 316 pixel conductivities vector \(C\) expressed as follows:

\[
S = \begin{bmatrix}
\frac{\partial u_1}{\partial c_{11}} & \cdots & \frac{\partial u_{104}}{\partial c_{11}} \\
\vdots & \ddots & \vdots \\
\frac{\partial u_{104}}{\partial c_{315}} & \cdots & \frac{\partial u_{104}}{\partial c_{316}}
\end{bmatrix}
\]

Where \(u\) and \(c\) are component of measured voltage vector and pixel conductivity vector respectively. Each component of \(S\) expresses the change in measured voltage for change in conductivity for one pixel. These are obtained by solving Eqs. (1) and (2) on \(V\) for given \(\sigma\). By using the obtained Jacobian matrix, the relationship between measured voltages and
unknown conductivity is expressed as follows:

\[ U = SC. \]  

(4)

The inverse problem is to solve Eq. (4) to obtain unknown \( C \) as follows:

\[ C = S^T U. \]  

(5)

Since the sensitivity matrix is not regular and Eq. (4) has no unique solution. It is necessary to obtain an approximate solution. Linear back projection method was used to find the approximate solutions of unknown conductivity. Finally, obtained \( C \) provides the cross-sectional discretized conductivity distribution.

Figure 1. Schematic diagram of sensor geometry and measurement strategy.

3. Experimental setup

3.1 TBR setup

Schematic representation of experimental apparatus is shown in Fig. 2. Packed column is made of transparent acrylic pipe of 100 mm inner diameter. Liquid distributor is installed at the top of column. In present study, two types of liquid distributors are employed. One is named as “Single Point”, in which only one hole was drilled at central axis to observe the radial spread of fed liquid. And, the other is named as “Square Array”, in which 0.5 mm capillary holes are arranged in 10 mm interval forming a square array. Each of the holes is so small that liquid get hold by capillary force when pump is stopped and liquid start dripping from each hole at the same flow rate when pump is started. Hence, homogeneous liquid feed is achieved. A mesh made of stainless steel is inserted to support packing at 600 mm from the top of column. Bottom part of column acts as a reservoir where liquid dripped through the bed is accumulated. Liquid is pumped from reservoir to liquid distributor at constant flow rate by roller pump. In present study, experiments were conducted under no gas flow. However, two air holes were placed on the wall of column above and below the packing in order to maintain the atmospheric pressure throughout column. Two types of particles with different average diameters (3, 5 mm) were employed for packing. For densely packing, the column was filled with particles little by little while pipe wall was being tapped. The particles are made of inert porous alumina used in actual reactor for catalyst support. Water, mixed with 0.5 % Sodium chloride (NaCl) to provide enough conductivity for ERT detection, was used as liquid.

3.2 ERT system set-up

Each ERT sensor consists of 16 measurement electrodes and 2 reference electrodes made of stainless steel. The electrodes are attached in the wall of the column as shown in
Fig. 3. Measurement electrodes have geometry of 5 mm width and 20 mm height and arranged 22.5° split from central axis of column. Reference electrodes, that are grounded to stabilize the voltage measurements, have cylindrical shape of 100 mm diameter and 5 mm height, and are arranged on above and below the measurement electrodes with 5 mm clearance. 4 ERT sensors are located at different bed depth (z = 60, 180, 300 and 420 mm, named P1, P2, P3 and P4 respectively) to capture the changes in liquid distribution as it flows down. Each sensor is connected to data acquisition unit (*Industrial Tomography Systems P2000*) by co-axial cable.

3.3 Experimental procedure

Before conducting an actual experiment, experimental system was calibrated for the minimum and maximum wetness. To set the maximum wetness, TBR column was flooded with liquid so as to ensure the soaking of porous packing. In the other hand, drain valve was kept opened for 5 minutes to produce pre-wetted condition. The ERT systems’ conductivity value was set as 0 for pre-wetted condition (minimum wetness) and 1 for flooded condition (maximum wetness).

For the actual experiment, at first, the liquid flow rate was set to 100 cm³/min for 10 minutes. The cross-sectional ERT images were captured throughout the experiment by averaging the conductivity distribution obtained in every 10 seconds at each of the four measurement planes at a rate of 5 frames per second. Then, the procedure was repeated for the liquid flow rates of 300, 700 and 1100 cm³/min. The whole procedures were repeated to particles of different sizes (3, 5 mm) and liquid inlets (single point and square array). Furthermore above procedure was repeated for four times for reliability and reproducitively. Volumetric liquid flow rate in this experiment is equivalent to 0.064, 0.149 and 0.233 cm/s in superficial velocity respectively. Table 1 summarizes the key points of the experimental condition.

**Figure 2.** Schematic representation of experimental apparatus.

**Figure 3.** Appearance of the ERT sensor.
4. Results and discussion

Figure 4 shows the typical result of 50 times averaged voltage measurements and their standard deviations for an instance of current injection (50mA, on electrodes 16-1). Measured voltages vary according to the distance between injecting pair and measuring pair. Since trickle flow is a kind of steady flow, standard deviation shown in Fig. 4 almost expresses the electrical measurement noise caused by external factors as well as falling particle-scale droplet, which has almost no effect on reactor scale performance. And, these are small enough (about 0.5% of average value) to be cancelled by averaging the multiple results in given period.

However, despite the same operating condition (gas-liquid flow rate, particle diameter, liquid inlet), another attempt gave the quite different results of voltage measurement because random nature of packing induces different liquid flow path at a start of liquid flow. However, in four different but identical experiments, measured voltage values had standard deviation of about 22%. That difference in measured voltages was not cancelled by averaging before reconstructing, because it was provided by the liquid maldistribution in trickle bed caused by random nature of irregular packing which was under study. This resulted to the 10% standard deviation in the conductivity values of corresponding reconstructed tomograms.

Figure 5 shows the results of tomographic visualizations for each condition. In each
image, color represents the corresponding normalized conductivity. Blue color (normalized conductivity = 0) represents the minimum wetness and red color (normalized conductivity = 0.2) represents the moderately wet condition. Since, there was no fully flooded condition (normalized condition = 1.0) in the real experiment blue to red gradation corresponds normalized conductivity 0 to 0.2.

For the supplement of visual observation of Fig. 5, two numerical parameters were extracted from each picture. Cross-sectional averaged conductivity was calculated by taking arithmetic average of each pixel value. That indicates the cross-sectional liquid hold up. And, liquid maldistribution was quantified by maldistribution factor $M_f$ that is standard deviation of each pixel value divided by cross-sectional averaged conductivity shown as follows:

$$M_f = \sqrt{\frac{1}{16} \sum_{i=1}^{16} (c_i - c^*)^2}$$

Where $c^*$ is component of normalized conductivity vector. Figures 6 and 7 show the averaged values with their standard deviation in the four different but identical attempts.

4.1 Point feed

In case of point feed, radial liquid spread with axial down flow is shown in Figs. 5 (a) and (b). In the case of small particles (particle diameter = 3 mm), the liquid, represented by higher conductivity, is concentrated in center zone, and then quickly spread to entire cross-section and results in almost homogeneous distribution. Radial spread seems to be almost completed at P2 (bed depth = 180 mm). Moreover, no dry zone (low conductivity zone) exists in bottom section regardless of liquid flow rate. In the other hand, for large particles, the liquid is concentrated in center zone at P1 (bed depth = 60 mm) same as small particles, however mainstream split in two with slight spread and wall flow at P2 (bed depth = 300 mm). The progress in the spread of the liquid continued gradually resulting the shrinking dry zone in the downward sections. The dry to wet zone ratio decreased with the increase in the liquid flow rate. But, in contrast to the case of smaller particles, small dry zones still existed in the bottommost section of the measurement (P4, bed depth = 420 mm).

Figures 6 (a) and (b) shows the trend that conductivity increases with increasing liquid feed rate. It is simply due to the quantity of water in the column. Furthermore, conductivity increases in downward direction despite the constant volumetric flux of liquid. This indicates that decreasing average axial velocity of liquid in the downward section results in more liquid holdup. In upper zone, lower holdup is caused because liquid flows faster due to liquid jet at center zone. As liquid flows downwards along the bed, liquid clusters change into smaller channels by branching effect.

Similarly, degree of maldistribution ($M_f$) is shown in Figs. 7 (a) and (b). $M_f$ decreases with flow along the column that indicates progress of the liquid spread. For the small particles, value decreases between P1 and P2, then change to the plateau. For the large particles, values decreases between P1 and P2, then steep rise which may be attributed to wall flow. $M_f$ generally lacks the clarity of its trend than that of Fig. 5, but it reflects the trend of liquid maldistribution in agreement with visual observation on Fig. 5 (a) and (b). Larger specific surface area of branched channels results in decrease in ratio of gravity force and frictional force between liquid and another phase. That’s the reason why maldistribution factor decreases with increase in liquid holdup. In the case of small particles, small pores which produce stronger capillary force and flow resistance help liquid spread and deceleration. For the large particles, relatively weak capillary force and randomness prevent the liquid from being homogenously spread, and likely to induce the wall flow that is agreeable with past study (9).
Figure 5. Cross-sectional conductivity distribution of TBR in case of constant liquid feed.
Figure 6. Comparisons of cross-sectional averaged conductivity: ±SD, \( Q = 300 \), \( Q = 700 \), \( Q = 1100 \).

Figure 7. Comparisons of maldistribution factor: ±SD, \( Q = 300 \), \( Q = 700 \), \( Q = 1100 \).
4.2 Homogenous feed

In case of homogeneous feed for small particles, liquid distribution seems to be perfectly homogeneous owing to homogeneous feed at P1 (see Fig. 5 (c)). And Fig. 7 (c) shows almost plateau value maldistribution factor. Between P2 to P4, there is almost no change in the pattern of liquid distribution in homogenous and point feed. For the larger particles, liquid distribution at P1 is a little better than point feed. And then slightly rise. This is due to the relatively weak capillary force and randomness in the case of larger particles, as mentioned above, which prevent the liquid from being homogenously spread and likely to induce the wall flow.

Overall results show that too fine distributor (like homogenous feed) doesn’t produce significantly different results from the point feed distributor indicating that there is no relative advantage in the additional cost of more power used in pump and complex structure for homogenous feeder. Distinct difference of liquid distributors (one hole and 10 mm spread square array) appears only at P1 which is equivalent to the bed depth of less than 200 mm. The trend of the result of present experiment was well agreed with that of experiment on pre-wetted porous alumina bed by dye absorption method (11). However, their result was based upon visual observation on partially colored dismantled bed. In present study, authors visualize the liquid distribution using ERT in real time and quantitatively analyzed the liquid maldistribution. Electrical resistance tomography seems to be reliable non-invasive technique which can aid to the effective design and real time monitoring of the trickle bed reactors.

5. Conclusions

In present study, authors successfully visualized the liquid distribution in the lab scale TBR operated in trickle flow regime by using non-invasive technique ERT. It was found that particles of small diameter (3 mm) results better liquid spread and homogeneous distribution than particles of large diameter (5 mm) due to stronger capillary force and weaker influence of packing randomness. Homogeneous liquid feed has limited effect on liquid distribution compared to point feed. For the effective design of liquid distributor of TBR, packing diameter and bed depth are should be carefully considered.

In present study, authors neglect the effect of gas flow. Hence in actual reactor operation was affected by gas flow in terms of pressure drop and so on. Investigations on combined effect using ERT will be carried out in the near future.

Acknowledgement

This work was supported by Ube Industries, Ltd.

Notation

- \( c \) component of conductivity distribution vector, S/m
- \( c^* \) component of normalized conductivity distribution vector, dimension less
- \( C \) conductivity distribution vector, S/m
- \( n \) normal vector
- \( Q \) volumetric flow rate of liquid, cm\(^3\)/min
- \( S \) Jacobian matrix
- \( u \) component of measured voltage vector, V
- \( U \) measured voltage vector, V
- \( V \) voltage distribution, V
- \( z \) bed depth, mm
Greek letters

\( \sigma \) conductivity distribution, S/m

References

(1) Al-Dahhan, M.H., Larachi, F., Dudukovic, M.P. and Laurent, A., High-Pressure Trickle-Bed Reactors: A Review, *Industrial & Engineering Chemistry Research*, Vol. 36 (1997), pp. 3292-3314.

(2) Larachi, F., Cassanello, M. and Laurent, A., Gas-Liquid Interfacial Mass Transfer in Trickle-Bed Reactors at Elevated Pressures, *Industrial & Engineering Chemistry Research*, Vol. 37 (1998), pp. 718-733.

(3) Boelhouwer, J.G., Piepers, H.W. and Drinkenburg, A.A.H., Particle-Liquid Heat Transfer in Trickle-Bed Reactors, *Chemical Engineering Science*, Vol. 56 (2001), pp.1181-1187.

(4) Boelhouwer, J.G., Piepers, H.W. and Drinkenburg, A.A.H., Nature and Characteristics of Pulsing Flow in Trickle-Bed Reactors, *Chemical Engineering Science*, Vol. 57 (2002), pp.4865-4876.

(5) Colombo, A.J., Baldi, G. and Sicard, S., Solid-Liquid Contacting Effectiveness in Trickle Bed Reactors, *Chemical Engineering Science*, Vol. 31 (1976), pp. 1101-1108.

(6) Boelhouwer, J.G., Piepers, H.W. and Drinkenburg, A.A.H., Enlargement of the Pulsing Flow Regime by Periodic Operation of a Trickle-Bed Reactor, *Chemical Engineering Science*, Vol. 54 (1999), pp. 4661-4667.

(7) Liu, G., Lan, J., Cao, Y., Huang, Z., Cheng, Z. and Mi, Z., New Insights into Transient Behaviors of Local Liquid-Holdup in Periodically Operated Trickle-Bed Reactors Using Electrical Capacitance Tomography (ECT), *Chemical Engineering Science*, Vol. 64 (2009), pp. 3329-3343.

(8) Hamidipour, M., Larachi, F. and Ring, Z., Cyclic Operation Strategies in Trickle Beds and Electrical Capacitance Tomography Imaging of Filtration Dynamics, *Industrial & Engineering Chemistry Research*, Vol. 49 (2010), pp. 934-952.

(9) Lappalainen, K., Manninen, M. and Alopaeus, V., CFD Modeling of Radial Spreading of Flow in Trickle-bed Reactors Due to Mechanical and Capillary Dispersion, *Chemical Engineering Science*, Vol. 64 (2009), pp. 207-218.

(10) Boyer, C., Koudil, A., Chen, P. and Dudukovic, M.P., Study of Liquid Spreading from a Point Source in a Trickle Bed via Gamma-Ray Tomography and CFD Simulation, *Chemical Engineering Science*, Vol. 60 (2005), pp. 6279-6288.

(11) Ravindra, P.V., Rao, D.P. and Sao, M.S., Liquid Flow Texture in Trickle-Bed Reactors: An Experimental Study, *Industrial & Engineering Chemistry Research*, Vol. 36 (1997), pp. 5133-5145.

(12) Pierre, G.I., Ka, M.N. and Edward, P.D., Liquid Distribution in Trickle Beds. An Experimental Study Using Computer-Assisted Tomography, *Industrial & Engineering Chemistry Research*, Vol. 30 (1991), pp. 1270-1280.

(13) Gladden, L.F., Lim, M.H.M., Mantle, M.D., Sederman, A.J. and Stitt, E.H., MRI Visualisation of Two-Phase Flow in Structured Supports and Trickle-Bed Reactors, *Catalysis Today*, Vol. 79-80 (2003), pp. 203-210.

(14) Tapp, H.S., Peyton, A.J., Kemley, E.K. and Wilson, R.H., Chemical Engineering Applications of Electrical Process Tomography, *Sensors and Actuators B*, Vol. 92 (2003), pp. 17-24.

(15) Xie, C.G., Reinecke, N., Beck, M.S., Mewes, D. and Williams, R.A., Electrical Tomography Techniques for Process Engineering Applications, *The Chemical Engineering Journal*, Vol. 56 (1995), pp. 127-133.
(16) Hosseini, S., Patel, D., Mozaffari, F.E. and Mehrvar, M., Study of Solid-Liquid Mixing in Agitated Tanks Through Electrical Resistance Tomography, Chemical Engineering Science, Vol. 65 (2010), pp. 1374-1384.

(17) Williams, R.A., Jia, X., West, R.M., Wang, M., Cullivan, J.C., Bond, J., Faulks, I., Dyakowski, T., Wang, S.J., Climpson, N., Kostuch, J.A. and Payton, D., Industrial Monitoring of Hydrocyclone Operation Using Electrical Resistance Tomography, Minerals Engineering, Vol. 12, No. 10 (1999), pp. 1245-1252.

(18) Fransolet, E., Crine, M., Marchot, P. and Toye, D., Analysis of Gas Holdup in Bubble Columns with non-Newtonian Fluid Using Electrical Resistance Tomography and Dynamic Gas Disengagement Technique, Chemical Engineering Science, Vol. 60 (2005), pp. 6118-6123.