Evaluation of Porosity and Liquid Retention Distribution in Cold Flow

Trickle-Bed Pilot Scale Column Using Gamma Ray Based Process Tomography

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Abstract. In the petrochemical industry, many processes are carried out using fixed bed reactors with concurrent upward or downward gas and liquid flows. Random and structured packing are used in process columns to enhance the heat and mass transfer between two phases. The packing used in such columns is meant to obtain a high specific interfacial area. In order to characterize the liquid and gas flow distribution through a mock-up column, data on planar and volume density distribution is very useful. This information can be obtained by employing Gamma-ray tomography or Process Tomography (PT). PT makes use of advanced computational procedure on directly measured data indicating the gamma rays transmitted through a planer section of the column in multiple angular orientations. In this paper a quantitative evaluation of porosity and liquid retention has been carried out in a 600mm diameter cold flow catalytic ($\text{Al}_2\text{O}_3$) fixed bed column using the PT technique. The experimental setup consists of around 300 mCi of collimated Cs-137 radioactive source, detector array of 32 Bismuth Germanium Oxide (BGO) scintillation-PMT collimated detectors and associated Data Acquisition (DAQ) system and a programmable mechanical manipulator. The sub-systems work in synchronous manner to acquire tomography data. This data is later reconstructed and analyzed for any specific parameter of interest like bed porosity and liquid retention behavior in the present case.

Keywords: Process Tomography (PT), Data Acquisition (DAQ) system, tomography data, bed porosity, liquid retention.

1. Introduction
Trickle-bed reactor is a packed column in which gas and liquid flows through a catalytic bed of solid particles while chemical reaction takes place. Such reactors are commonly used in petrochemical industries for hydrosulfurization process (HDS) [1-2]. Gas-liquid flow distribution, void fraction, bed porosity and liquid retention across catalytic bed section are some of the important parameters that control the overall performance of trickle-bed reactors [3-5]. Hence knowledge of these parameters is essential for analysis of fluid dynamics and scale-up of such pilot reactors. Optical methods are not effective to study these columns because of opacity and dense packing. Electrical methods are also unsuitable for electrically non-conducting columns. Non-intrusive techniques that use penetrating radiation such as tomographic imaging methods are suitable to generate 2D map of the steady state flow characteristics and obtain quantitative information about catalytic bed of the columns.

In the present study, void fraction, bed porosity and liquid retention have been evaluated on a pilot scale plant using gamma-ray Process Tomography (PT) technique. The plant is 600mm diameter cold flow catalytic (Al₂O₃) bed column. This work is part of a project to optimize designing and operating conditions of such reactors. For this purpose, a gamma-ray PT set-up has been developed by Isotope Production and Applications Division of BARC in collaboration with Indian Oil Corporation Ltd (IOCL R&D Unit, Faridabad). The experimental setup consists of a Cs-137 radioactive source, detector array, associated Data Acquisition (DAQ) system and mechanical manipulator. The paper is organized as follows. Section 2 describes principle of data acquisition and image reconstruction. In Section 3, the experimental set-up is explained. Experimental results are discussed in Section 4. Finally, a brief conclusion is outlined in Section 5.

2. Principle

Process tomography measurements are based on the detection of attenuated gamma-ray photons. When gamma rays passing through a medium, its intensity will reduce from $I_0$ to $I$ due to the attenuation of ration flux by the medium. The gamma-ray attenuation integrated along the path is measured by detector. The intensity of the radiation received by the detector is related to the attenuation coefficient of the medium by [6]:

$$\mu = \frac{1}{L} \ln \left( \frac{I_0}{I} \right) \quad (1)$$

Where L is the medium thickness crossed by gamma ray.

PT methodology requires attenuation measured along a number of such rays through the column by an array of detectors from different angles. There are two popular data collection modes: parallel-beam geometry and fan-beam geometry. For this study, data was collected using fan-beam...
geometry. Attenuation distribution $\mu(x, y)$ can be reconstructed by using a reconstruction algorithm from measured projection data. In this work, Filtered Back Projection (FBP) has been used for image reconstruction. If the projection angles are evenly spaced in $[0, 2\pi]$ and there are $M$ such projections, then attenuation image in the sampled $(x, y)$ domain can be reconstructed using FBP [7]:

$$\mu(x, y) = \Delta\beta \sum_{i=1}^{M} \frac{1}{L^2(x, y, \beta_i)} Q_{\beta_i}(\gamma')$$

(2)

Where $Q_{\beta_i}(\gamma)$ is the $i$th filtered projection, $\Delta\beta = \frac{2\pi}{M}$, $L$ is the distance from the source to the pixel $(x, y)$ and $\gamma'$ is angle of the fan-beam ray that passing through $(x, y)$ pixel makes with the source-origin line. Obviously, this ray may lie between two other rays in the projection data and suitable interpolation will have to be employed to obtain the interpolated $Q_{\beta_i}(\gamma')$. Gamma-ray PT set-up used to generate experimental data is described in the next section.

3. Description of the Process Tomography (PT) Set-up

Fig. 1 shows the schematic and actual process tomographic system geometry. Fig. 2 shows the schematic and actual PT set-up. It consists of around 300 mCi of collimated Cs-137 radioactive source, an array of 32 Bismuth Germanium Oxide (BGO) scintillation-PMT collimated detectors. These detectors are separated by spaces of same thickness as their detection width, that is 10mm. So with small lateral movement the projections are sampled over 64 detectors. The system displacement, Data Acquisition (DAQ) system and mechanical manipulator are totally automated by a computer. More details on the whole system can be found in [8,9].
4. Experimental results

This section presents evaluation of void fraction, porosity and liquid retention which provide data for two-dimensional hydrodynamic models.

4.a. Void fraction

Study of void fraction distribution within catalytic fixed bed is essential for analysis of fluid dynamics. Let the attenuation coefficients of a dry alumina bed, an alumina bed flooded by water and a column flooded by water are $\mu_{\text{dry Al}}$, $\mu_{\text{flood Al}}$ and $\mu_{\text{water}}$, respectively. Then void fraction can be estimated by using following equation [10]:

![Fig. 1: (a) Schematic block diagram of fan beam (equiangular) configuration of data acquisition (b) Photograph of process tomographic system geometry](image1)

![Fig. 2: (a) Schematic diagram of the process column (b) Photograph of the process column with catalyst alumina](image2)
\[ \ln \left( \frac{I_{\text{water}}}{I_{\text{floodAl}}} \right) = \ln \left( \frac{I_{\text{dryAl}}}{I_{\text{floodAl}}} \right) = \frac{\mu_{\text{water}} - \mu_{\text{floodAl}}}{\mu_{\text{dryAl}} - \mu_{\text{floodAl}}} \]

where \( I_{\text{water}} \), \( I_{\text{dryAl}} \) and \( I_{\text{floodAl}} \) are the intensities measured with the water flow, dry bed and flooded bed.

Eq. (1) indicates that the gamma-ray intensity, \( I \), received by detector decreases if \( L \) is high for uniform attenuation medium. The central ray of the column travels maximum distance inside bed. Hence, relatively high error is expected in the reconstruction for central region compared to the outer regions. This fact is observed in Fig. 3. The average void fraction value has been evaluated from the image shown in Fig. 4(a). Radial profile is presented in Fig. 5(b). The average void fraction value is lower than 1.1%. It indicates most of the bed filled with catalyst. The error on void fraction remains less than 0.5%, which is satisfactory.

![image](a)

**Fig. 3**: (a) Reconstructed attenuation CT image for bed filled with alumina (image size 128 x 128)

(b) Radial profile along the central horizontal line in the cross-section
4.b. Porosity

Experimental data on bed porosity variation is quite an important since it has a significant effect on the liquid flow distribution within a catalytic bed column and it also describes the volume left to the gas-liquid flow [11-12]. To measure the bed porosity, two measurements are performed. First measurement is performed with the alumina (catalyst) bed totally flooded by liquid and second measurement is carried out with the alumina bed totally drained. The attenuation distribution \( \mu(x, y) \) determined from the log ratio of these measurements. It corresponds to the interstitial liquid distribution. The bed external porosity \( \varepsilon_{\text{ext porous}} \) distribution can be deduced from \( \mu(x, y) \) using the following expression [10]:

\[
\varepsilon_{\text{ext porous}} = \frac{\mu(x, y)}{\mu_{\text{liquid}}} \tag{4}
\]

Where \( \mu_{\text{liquid}} \) is the liquid attenuation distribution.
Fig. 5: (a) Surface map (b) Radial profile of the reconstructed CT image along the central horizontal line in the cross-section

Fig. 6 presents the results of the reconstructed surface map of external bed porosity and its radial profile along the central line. The mean porosity obtained with this alumina bed is close to 23%.

Fig. 6: Catalytic fixed bed external porosity results (in %)  (a) Reconstructed surface map (b) Radial profile along the central line. Dotted line refers average value.

4.c. Liquid retention

After the bed porosity distribution is determined, the important parameter to measure is liquid retention distribution in the liquid flow condition. It allows to check the liquid distribution inside the bed in industrial operating conditions with the industrial liquid inlet distributor. It also provides data for two-dimensional hydrodynamic models for liquid flow distribution. Two measurements are required to determine the liquid retention map for a column cross-section. First measurement is made with the catalyst (alumina) bed drained and second measurement is performed with gas-liquid
flow across the catalyst bed. The attenuation \( \mu(x, y) \) obtained from log ratio of these two measurements. It corresponds to the liquid fraction distribution in the whole column volume. The liquid retention \( \beta_L(x, y) \) in the catalytic fixed bed external porosity is expressed by [10]

\[
\beta_L(x, y) = \frac{\mu(x, y)}{\mu_{\text{liquid}} e_{\text{expansity}}} \quad (5)
\]

Fig. 7 shows liquid retention image and surface map. The mean liquid retention obtained is close to 45% for the inlet liquid velocity 1.6 cm/s. The images show that the flow is almost axial symmetric in several zones. Little irregularity by liquid appeared in the bed.

![Liquid retention image and surface map](image)

5. Conclusions

In this study, porosity and liquid retention have been evaluated using experimental Process Tomography (PT) data. The values of mean porosity and liquid retention for inlet liquid velocity 1.6 cm/s obtained are close to 23% and 45% respectively. These results show that gamma-ray CT system can be very useful in analyzing the steady state condition of the process and to approximately measure liquid retention inside the bed in dynamic conditions. Further studies are necessary to compare the results obtained by the experimental data with hydrodynamic model in the same flow condition.

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