EVALUATION OF GASEOUS FLUID DISPERSION THROUGH PACKED BED USING RADIOTRACERS TECHNIQUE

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ABSTRACT

In this study, it was developed a methodology for the determination of the dispersion of a gaseous tracer in porous media using the radiotracer technique. In order to evaluate several porous media, a cylindrical filter was constructed in PVC and connected to a system with constant flow. Inside this unit silica crystals (16-20) mesh was used as porous media and CH₃Br (Methyl Bromide) marked with §²Br was used as radiotracer. An instantaneous pulse of tracer was applied in the system entrance and registered by two NaI (3x3)" scintillation detectors located one before and the other after the filter. The curves produced by the radioactive cloud and recorded by the detector were analyzed statistically using the weighted moment method. The mathematical model one considered as great dispersion of tracer was used to evaluate the flow conditions inside the filter system. The results show us that the weight moment method associated with radiotracer techniques is useful to evaluated an industrial filter and allows to measure the residence time distribution, τ, and the axial dispersion, Dₐₑ, gas in a porous medium.

1. INTRODUCTION

There are many types of equipment used in industry that possess porous media, for example: distilling equipment, ion exchangers, catalytic converters, fluidized bed reactors, general filtration, i.e. numerous studies of packed bed. Residence time distribution and dispersion are important factors of fluid flow mechanics for application in industrial projects; thus, it is necessary to survey these data through previous experiments which should also be considered in periodic maintenance planning.

Many are the researchers who study porous media to find the dispersion and residence time distribution in packed bed. Those highlighted as being among the first are: Iwasaki, 1937 [1], Stein, 1940 [2], Shekhtman, 1961 [3].

In order to evaluate the behavior of porous media the technique of radioactive tracers was used due to the following advantages: high gamma radiation penetrability (permitting non-invasive measures), large number of isotopes (allowing to choose a tracer with the same physical/chemical characteristics as the system’s), high sensitivity
of radiation detectors (use low activity, around 370 KBq), low memory effect (radiotracers of short half-life are used, allowing consecutive measurements).

The objective of this work was to study a methodology to determine the dispersion of a gaseous radiotracer in porous media, as well as the Residence-Time Distribution (RTD), based on mass balance equation. For this, it was necessary to design a test bed that consisted of a PVC (polyvinyl chloride) cylinder, through which the air flowed and treated silica as filtering medium.

## 2. THEORETICAL FUNDAMENTS

The basic principle for the construction of a model that describes a real process is based on the transport of mass flux that enters and exits a certain unit, reacting or not with it, as represented in the flowchart in figure 1.

![Figure 1 – Flowchart of the transport equation.](image-url)

The transport of fluids can be represented by differential equations. In this way, the detailed knowledge is generalized by a fraction of the fluid, point by point, as occurs to diverse variables associated to fluid flow such as velocity and pressure. The phenomenological representation is an approximation of the system due to the continuum hypothesis, where applying boundary conditions (geometric) and initial conditions (temporal) is essential for finding an analytical solution.

The mass balance of component A interacting in a determinate element of the volume is represented by equation 1. [4]

\[
\frac{\partial \rho_A}{\partial t} + \frac{\partial}{\partial x} [\rho_A v_x] + \frac{\partial}{\partial y} [\rho_A v_y] + \frac{\partial}{\partial z} [\rho_A v_z] = -\frac{\partial}{\partial x} [J_A^x] - \frac{\partial}{\partial y} [J_A^y] - \frac{\partial}{\partial z} [J_A^z] \pm R_A
\]

where:
- \( \rho_A \) = mass density of component A (g/cm\(^3\));
- \( J^x \) = mass flux of component A by diffusion (g/s.cm\(^2\));
- \( v \) = fluid mass average velocity with respect to stationary coordinates (cm/s);
- \( t \) = time (s);
- \( R_A \) = reactions of component A in the volume element;

According to Fick’s first law, particle current density is proportional to the unidirectional concentration gradient, as represented by equation 2.

\[
J = -D \frac{\partial n}{\partial x}
\]
Taking into account a tubular flux with axial dispersion in the “x” direction applying Fick’s first law, registering the entrance as start-time and the exit as end-time, and with no reactions occurring in the system (the initial concentration is equal to the final concentration, \( R_A = 0 \)), the equation is reduced to the simplified equation 3.

\[
\frac{\partial C_A}{\partial t} + v_x \frac{\partial C_A}{\partial x} = D_{AB} \frac{\partial^2 C_A}{\partial x^2}
\]  

where:

\( D_{AB} \) = coefficient of axial diffusion (\( \text{cm}^2/\text{s} \));
\( C_A = \rho_A/M_A \), \( M_A \) = molecular weight of component A.

From the definition of the N-order momentum associated to a statistical distribution function, we can use the relations for \( M_N \), the N-order momentum centered in origin and \( \overline{M}_N \), the N-order momentum centered in mean, as shown in equations 4 and 5.

\[
M_N = \int_0^\infty t^N \cdot C(t) \, dt  
\]  

\[
\overline{M}_N = \int_0^\infty (t - \bar{t})^N \cdot C(t) \, dt
\]  

The first momentum around the origin, equation 4, represents the mean of a statistical distribution and the second order momentum around the mean, equation 5, represents its variance.

When evaluating porous media, there is a considerable tail effect associated to the curves at the exit of the unit, and to minimize RTD error, the weighted momentum technique is applied, \( w(t) = t^N e^{-st} \), and the new momentum is designated the weighted statistical momentum by equation 6. \[5\]

\[
M_N = \int_0^\infty t^N \cdot e^{-st} \cdot C(t) \, dt 
\]  

The Laplace Transform of a function \( C(t) \) is defined according to equation 7.

\[
L[C(t)] = \int_0^\infty e^{-st} \cdot C(t) \, dt = C(S)
\]  

It can be noted that, deriving equation 7, in function of \( S \), equation 6 is found. In this way, the generalization in equation 8 may be deduced.

\[
M_N = (-1)^N \frac{d^N}{ds^N} C(S)
\]  

Therefore, the momentum of the first order and the momentum of the second order can be defined by equations 9 and 10.

\[
M_1 = C(S)
\]
Now considering that a unit where a tracer is injected according to function \( A(t) \), as shown in figure 2. Two detectors are positioned registering the entry and exit signals, \( X(t) \) as the normalized response at entry and \( Y(t) \) as the normalized response at exit.[6,7]

![Figure 2 – Injection of tracer in a unit, registered by two detectors: one at entry and the other at exit.](image)

Applying the stimulus and response technique shown in figure 2, \( Y(t) \) is the convolution between the functions \( H(t) \) (system) and \( X(t) \) (entry), according to equation 11. [6]

\[
Y(t) = H(t) \ast X(t) = \int_{0}^{\infty} X(\tau) \cdot H(t-\tau) \, d\tau
\]

(11)

When using Laplace Transformation in the input and output functions, the result of the convolution is a simple algebraic equation, as it is represented in equation 12

\[
Y(S) = H(S) \cdot X(S) \quad \rightarrow \quad H(S) = \frac{Y(S)}{X(S)}
\]

(12)

Deriving equation 12, in relation to \( S \), and dividing by the same function, we have equation 13. [5]:

\[
\frac{H'(S)}{H(S)} = \left[ \frac{C'(S)}{C(S)} \right]_{\text{OUT}} - \left[ \frac{C'(S)}{C(S)} \right]_{\text{IN}}
\]

(13)

where: \( X(S) = C_{\text{IN}}(S) \)  
\( Y(S) = C_{\text{OUT}}(S) \)

Associating the statistical moment’s methodology and Laplace transformations we can use the experimental results to adjust a model to the system as shown in equation 14.

\[
-\frac{H'(S)}{H(S)} = \left[ \frac{M_4}{M_2} \right]_{\text{OUT}} - \left[ \frac{M_4}{M_2} \right]_{\text{IN}}
\]

(14)

Now considering a model of axial dispersion flux, the solution for the initial and boundary conditions, using Laplace techniques, is represented in equation 15. [8]
\[\frac{H'(S)}{H(S)} = -\tau (1 + 4N_d \tau s)^{-1/2}\] 

where:

\[\tau = \frac{L}{v}\] (15a)

\[N_d = \frac{D_L}{L} v = 1/Pe\] (15b)

In this way, the ratio between function \(H(S)\) derivative and the same function can be calculated, resulting in equation 16.

\[H'(S) = \frac{H(S)}{H(S)} = -\tau (1 + 4N_d \tau s)^{-1/2}\] (16)

Thus, using the equations 14 and 16, obtaining equation 17 will be used to adjust parameters to the system.

\[\left[\frac{M}{M_0}\right]_{DUF} - \left[\frac{M}{M_0}\right]_{EN} = \tau (1 + 4N_d \tau s)^{-1/2}\] (17)

Pecklet’s number, \(Pe\), is a dimensionless number that relates to the dispersive flux diffusion velocity and characterizes the type of mixture. When it has a value close to 1, a perfect mixture is characterized; when it presents a value greater than 100, it behaves as piston-type flux; when the value is intermediate (1 – 100) the flow is characterized as non-ideal (turbulent). [9]

3. EQUIPMENT AND METHODOLOGY

The measurements were simulated in an experimental prototype with ducts mounted in a laboratory, where a centrifuge exhaust (150 l/s) proportions a constant flow-rate to the system, sucks the air from the environment, passes it through a filter, having its exit directed to a hood. The exhaust fan can be seen in figure 3.

![Photograph of a Centrifugal exhaust fan.](image)

The test bed (filter) shown in figure 4 was manufactured of PVC in a cylindrical shape (height of 100 mm and inside diameter of 100 mm). Silica was studied as filtering medium (amounts of 250 g and 500 g) and particle sized distribution (16 – 20) mesh.
The tracer pulse use was a CH$_3$Br [10] marked with $^{82}$Br, half-life of 36 h, energy of (0.55 – 1.31) MeV and activity for used in the experiment was 638 KBq.

Through the stimulus-response technique, at every instantaneous injection of the gaseous tracer, realized 5 m before the first detector, the passage of a radioactive cloud is registered by the scintillator detectors. The normalized generated curves were analyzed by the relations of the statistical moments (experimental), where a function for some values of “S” (0 – 0.01) is adjusted. The dispersion number and RTD are found for each experiment through the calculated adjustment, using the least squares method, according to equation 17.

4. RESULTS

Six experiments were conducted, three related to the filter medium containing 500 g of silica and three containing 250 g of silica, Figure 5(a) represents the response of detectors A and B, with 500 g of silica for one of the experiments. In figure 5(b), the curve is adjusted using the least squares method for some values of “S”.

![Figure 4 – Test bed.](image)

![Figure 5 – Response of experiment 1, using filter medium with 500 g of silica: a) response curve of detectors A and B; b) adjusted curve for some values of S.](image)
Figure 6(a) represents the response of detectors A and B with 250 g of silica for one of the experiments. In figure 6(b), the curve is adjusted for some values of “S”.

![Graph showing experimental and theoretical responses](image)

**Figure 6 – Response of experiment 1, using filter medium with 250 g of silica: a) curve response of detectors A and B; b) curve adjusted for some values of S.**

In the experiments realized, it was observed that:

1) Adjusting the S values, in Figure 5(b) and 6(b), the correlation coefficients, r, of the curve adjustments are greater than 0.99, confirming the existence of a mathematical adjustment correlation between the experimental model and the theoretical model.

2) The detectors’ response represented in Figures 5(a) and 6(a) should be normalized for each injection. The entry and exit responses should present the same area under the curve, since no reactions occur on the test bed. Therefore, the system should always be carefully calibrated, always remembering that any change in the solid angle between the detectors would generate a difference in this area.

3) As the quantity of porous medium was increased, it was observed an increase in signal noise in the second detector generated by micro-canalization. This is more evident in case of low flow-rate.

4) For the filter system, the axial dispersion model is quite representative and it could be use for characterization of porous medium. Furthermore, this technique adjusts the theoretical model to the experimental one without approximation.

Tables 1 and 2 indicate the values for: residence time distribution, RTD, dispersion number, $N_d$, and Peclet number, $P_e$, which were adjusted from the axial dispersion model for filter.
Table 1 – Values of RTD, dispersion coefficient, \( N_d \), and Peclet number, \( P_e \), for the experiments with the filter with total mass of 500 g and superficial velocity of 35 cm/s.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>RTD (s)</th>
<th>( N_d \left(10^{-2}\right) )</th>
<th>( P_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.71</td>
<td>9.91</td>
<td>10.09</td>
</tr>
<tr>
<td>B</td>
<td>1.82</td>
<td>9.72</td>
<td>10.29</td>
</tr>
<tr>
<td>C</td>
<td>1.95</td>
<td>8.88</td>
<td>11.26</td>
</tr>
<tr>
<td>Mean Values</td>
<td>1.83 ± 0.30</td>
<td>9.50 ± 1.36</td>
<td>10.55 ± 1.55</td>
</tr>
</tbody>
</table>

Table 2 – Values of RTD, dispersion coefficient, \( N_d \), and Peclet number, \( P_e \), for the experiments with the filter with total mass of 250 g and superficial velocity of 64 cm/s.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>RTD (s)</th>
<th>( N_d \left(10^{-2}\right) )</th>
<th>( P_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>0.83</td>
<td>8.64</td>
<td>11.58</td>
</tr>
<tr>
<td>E</td>
<td>0.87</td>
<td>8.67</td>
<td>11.53</td>
</tr>
<tr>
<td>F</td>
<td>0.87</td>
<td>8.87</td>
<td>11.27</td>
</tr>
<tr>
<td>Mean Values</td>
<td>0.85 ± 0.06</td>
<td>8.73 ± 0.31</td>
<td>11.46 ± 0.41</td>
</tr>
</tbody>
</table>

The mean error was represented by t-Student of 95%.

It can be noted that as the quantity of silica increases, the superficial velocity decreases consequently, the residence time distribution (RTD) will be greater. The gas dispersion coefficient in the filter is very small comparing with liquids fluids in the same conditions. [11]

The Peclet number characterizes the type of flux. In the experiments the Peclet number was around 11 and according the literature [9] if the Peclet number is between 1 and 100 the flux can be considered as turbulent flow. This agrees with the experimental data, in the filter, there is a large mixture generated inside the porous medium, which is typical of packed bed.

5. CONCLUSIONS

The results referring to porous medium containing silica crystals demonstrated that the method of weighted moments is the one indicated to evaluate the characteristics of the filters, obtaining results reproducible within the error. Therefore, through the general equation of dispersion, the residence time distribution as well as the dispersion for the corresponding geometry can be found.
The flow-rate will depend on the silica mass in the test bed. For a mass of 500 g, the mean time was $(1.83 \pm 0.30)$ seconds to pass through the filter, generating a mean dispersion of $(9.50 \pm 1.36) \times 10^{-2}$; while for a mass of 250 g, the mean time was $(0.85 \pm 0.06)$ seconds and the mean dispersion of $(8.73 \pm 0.31) \times 10^{-2}$ for the tracer used.

The experiments demonstrated that the methodology that was used could be added to periodic maintenance plans to prevent possible problems in industries, such as load loss due to inadequate functioning of the equipment.

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REFERENCES