Residence Time Distribution of A Tubular Reactor

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ABSTRACT:
Most flow reactors are neither ideal plug flow nor continuous stirred tank reactors. This makes it difficult in accounting for actual conversion obtained from such reactors thus causing much concern to the industrialists especially Chemical Engineers. The extent of departure from the two ideal limits of flow reactors remained unclear until the concept of residence time distribution (RTD) was developed and applied to real reactors, to assess the extent of non-ideality, plus their effects on reactor performance. To study the empirically generated RTD behavior, a tubular reactor was designed and built with improved features to ensure minimum axial dispersion. It was found that the RTD functions generated were generally of the shapes expected, with long tails beyond the peak concentration exit age, but with mean residence times (\(\bar{\tau}\)), and distribution variance (\(\sigma^2\)) fairly large, and sensitive to flow rates. While a range of experimental conditions were tried, the run with the highest turbulent Reynold Number (Re) revealed \(\bar{\tau} = 46s\), which differed markedly from the expected (i.e., calculated) reactor space time (\(\tau\)) of 17s. This significantly higher empirical \(\bar{\tau}\) was due to transport delay (\(\approx 15s\)) and delay due to actual axial dispersion (31s) as obtained under the peak of the E(t) curve. Furthermore, it was also found that variance (\(\sigma^2\)) of 60s² obtained in this work signified that the axial dispersion was high, despite high Re of \(3.3 \times 10^{-3} \frac{L}{D} = 176\), giving a calculated Peclet Number of 69. Also, when n-CSTR theoretical model was applied to that same run, an n value of 35 was estimated, which was good compared to the theoretical value of n = \(\infty\). However, at lower flow rates and Re, the implied n in the n-CSTR model was too optimistic and high, with n =15. However, \(1 \leq n \leq 3\) would have tallied better with the high observed axial dispersion. But that was a weakness of n-CSTR theory, not of the empirical results. Thus, every reactor is neither a CSTR nor PFR but a continuum exhibiting features of ideality of both reactors. It is recommended that RTD be applied as a tool not only for troubleshooting existing reactors but also in test running new ones as it would give insight into designing future reactors with improved performance.

Keywords: Residence Time Distribution, Plug Flow Reactor, Tubular Reactor, Axial dispersion, Peclet number.

1. INTRODUCTION

Chemical reactors are important pieces of equipment in chemical facilities where chemical transformation takes place. Therefore, the design of a chemical reactor is not a routine matter. Many alternatives can be proposed for a process since every industrial chemical process is designed to economically produce a desired product [1]. In searching for the best; it is not just the cost of the reactor that must be minimized as a particular reactor design may have low reactor cost but the materials leaving the unit (reactor) may be such
that their treatment requires much higher cost than alternative designs hence the economics of the overall process must be considered. In reactor design, the size (volume), the type as well as the mode of operation of the reactor are taken into considerations depending on the job to be done by the proposed reactor [2]. Industrial reactors apart from the ones found in pharmaceutical, food and other industries whose specifications are high, operates continuously and can be classified based on the hydrodynamics of flow pattern. Hence, they are called flow reactors.

Two broad classes of flow reactors emerged, and these are: Continuous Stirred Tank Reactors (CSTR) and Plug Flow Reactors (PFR). The Plug Flow (an ideal tubular) Reactor is an ideal flow reactor in which its feed is assumed to move as a plug from the inlet to the outlet with no mixing or diffusion along the flow path whereas the Continuous Stirred Tank Reactor (an ideal stirred-tank reactor) is based on the assumption that, the flow at the inlet is completely and instantly mixed into the bulk of the reactor; hence, the condition of the effluent is the same as the condition in the reactor - uniform concentration [3].

Experience has shown that the ideal reactor approach of the piston (laminar) flow pattern for tubular reactors as in the case of PFR and the perfect mixing pattern for stirred-tank reactors as in the case of CSTR do not exist as real reactors deviate from their ideal flow pattern. It was observed that ideal reactors – CSTR and PFR were mere models which rarely exist, irrespective of configurations and improved features to attain ideal models. Thus there is usually a significant departure in the performance of real reactors when compared to their ideal reactors. Often, in a stirred-tank reactor, complete mixing cannot be approached as stirrer’s blade may be too large or too small to achieve perfect mixing as insufficient micro and/or macro mixing abound. Also fluid elements farther away from the stirrer’s blade and those that are very close to the stirrer’s shaft constitute stagnant regions (dead volume) within the reactor as they could not be thoroughly mixed [4]. In some cases, fluid elements bypass the mixing operation and leave the reactor sooner than others (i.e. short circuiting or channeling of fluid elements inside the reactor). The performance of such reactor is found to be usually below the expectation of the designer and the conversion achieved would be undesirable [5].

There is need to examine the extent of departure from ideal reactor’s model. This requires knowledge of complete velocity distribution map for the fluid flowing through the reactor, thus providing information on what is happening within the reactor (i.e., how long individual molecules or fluid elements stay in the reactor). The tool applied to investigate the actual departure from ideal reactor model or to predict the behavior of a vessel as a reactor is the Residence Time Distribution (RTD) of material flowing through the reactor [3]. RTD is a probability distribution that describes the amount of time a fluid element could spend inside the reactor [6]. Although, the concept of RTD has been known for decades ([7], [8], [9], [10], [11], [12] and [13]), there is the need to apply the RTD concept in modeling the imperfection or departure from ideality exhibited by a given reactor to know how far away such a reactor is from the CSTR-end via n-CSTR theoretical flow model or the PFR-end via a dispersion model.

Thus this study seeks to investigate experimentally non-ideality in a tubular reactor using Residence Time Distribution (RTD) as a tool in order to account for the extent of departure of the reactor from ideal reactor’s model. This requires knowledge of complete velocity distribution map for the fluid flowing through the reactor; this provides information on what is happening within the reactor. A study of this nature will require designing and building a bench scale tubular reactor, with improved characteristics, of mean residence time and flow conditions as to permit a study of empirically generated RTD behavior. The flow condition within the tubular reactor as well as its effluent properties can be monitored using tracer. The idea behind the RTD was to see how a dye (tracer) injected into a reactor is dispersed without distorting the existing flow pattern of the reactor. The exit age of the dye from this reactor reveals what is happening within this reactor [14]. This is useful not only for troubleshooting existing reactors, but in estimating the yield of a given reaction and designing future reactors.
1.1: Limitation Of The Study
This work is limited to the following:
This work seeks to examine the behavior of a tubular reactor to see how it exhibits Ideal Plug Flow reactor characteristics ([3] and [15]).
A pulse tracer injection method is preferred to other input methods such as step input (switching tank) because it is convenient for bench scale work as it requires small amount of saturated tracer solution.
Tracer chosen for this work is saturated Potassium Chloride solution. This tracer as it has been used by other researchers such as [16] has been effective and easy to detect even at low concentration. Low concentration of the tracer pulse is expected since once injected, the tracer may be dispersed (though not expected in ideal system) and becomes diluted by the carrier medium (water) without influencing the carrier fluid viscosity and density.
The empirical parameter s obtained from \( E(t) \) were limited to the first and second moments (mean and variance respectively) as they are required to determine the RTD (n-CSTR Theoretical Flow and Axial Dispersion) models’ parameters. The third and fourth moments (skewness and kurtosis/peakedness respectively) were not evaluated as they were not relevant in this work.

2. MATERIALS AND METHOD
2.1 Aim of the Experimental Work
The aim of the study is to design a tubular reactor with improved features and experimentally investigate using a tracer method to monitor the departure from ideality exhibited by the reactor to know the extent of deviation from the PFR-end via a dispersion model and the CSTR-end via n-CSTR theoretical flow model.
2.2 Materials for the Work
The materials used for this work apart from the general apparatus found in Chemical Engineering Laboratory include:
Saturated KCl solution prepared at 29°C as a tracer for the work.
Distilled water - used as the carrier medium
Electrical conductivity meter whose sensitivity is 0.0001-10.0g/ml
A pump with 100-1500 cm³/min delivering capacity.
Battery as source (12 Volt)
Electric motor for stirrers (12Volt)
A reservoir (cylindrical tank) for the carrier medium
Syringe (5ml capacity) coupled with needle for the pulse tracer injections.
Beakers at reactor exit for sample collection
Metallic piece for reactor’s support.
Stainless Steel tube for Reactors
2.3 Design Strategy
Designing and fabricating a tubular reactor to obtain adequate RTD profile from it via selected number of runs was the main objective of this work. The expected (pulse) response (RTD profile) from the pulse tracer input (disturbance) of this experiment using a tubular reactor was expected to be of the form shown in Figures 1a and 1b.
Choice of tracer is important as some substances when used as tracers have effect on the hydrodynamics of reactors [17], while others revealed new method for determination of residence time [16]. KCl was chosen as a tracer because it exhibits good sensitivity appropriate for the electrical conductivity meter. It is cheap, effective, less corrosive, and does not have effect on the hydrodynamics of reactors (see Table 1).

Table 1: Fluid’s Parameters

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracer (KCl)</td>
<td>Nature</td>
<td>Saturated concentration</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>2ml</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>Negligible</td>
</tr>
<tr>
<td>Carrier medium (Water)</td>
<td>Density</td>
<td>1000kg/m³</td>
</tr>
<tr>
<td></td>
<td>Flow Rate</td>
<td>480cm³/min</td>
</tr>
</tbody>
</table>

### 2.4: Design Parameter

Although earnest effort was put to achieve the proposed design parameters, some of the parameters as discussed were subject to change (see Table 2), and these include:

**Space time (τ):** To capture enough details from the reactor, 3 minutes was proposed. Since a spike may not be expected (as it is common in a real reactor) but a distribution as the time is not too short to miss the detail though convenience for bench – scale work and not too long such that it would require large tank, longer reactor and a bigger tank as this would be economically disadvantaged.

**The volumetric flow rate (v):** with the aid of valve, the pump can deliver 1000cm³/min to achieve turbulence.

**Reactor’s volume (V_R):** Generally, \( V_R = \tau \cdot v = 360 \text{ cm}^3 \). For a cylindrical PFR, \( V_R = \left( \frac{\pi D^2}{4} \right) L \), the criterion for minimum axial dispersion is \( \frac{L}{D} > 100 \) [18], where L and D are reactor’s Length and Diameter respectively. These have been evaluated and their values are presented in Table 2.

**Reynold Number (Re):** This is a very important parameter in a flow system, \( Re = \frac{vD}{\mu} \), where \( v \) and \( \mu \) are velocity and viscosity of the fluid. Reynolds number \( (N_{Re}) = 2.03 \times 10^4 \) (see Table 1 for the fluid parameters) Estimated energy input (i.e., maximum energy supplied) = 8KJ (8000J)

Table 2: Parameters used for Test Reactor Design

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of Reactor</td>
<td></td>
<td>0.0635cm (1/4” nominal ID)</td>
</tr>
<tr>
<td>Thickness of Reactor</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Length of Reactor</td>
<td></td>
<td>11.2m (36.7 ft)</td>
</tr>
<tr>
<td>Volume of Reactor</td>
<td></td>
<td>355cm³ (≈ 360cm³)</td>
</tr>
<tr>
<td>Tank Volume (capacity)</td>
<td></td>
<td>≥ 720cm³</td>
</tr>
<tr>
<td>Tank Diameter</td>
<td></td>
<td>9.1 cm (= 3.6”)</td>
</tr>
<tr>
<td>Tank Height (depth)</td>
<td></td>
<td>10.9 cm (Maximum)</td>
</tr>
<tr>
<td>Space time</td>
<td></td>
<td>180s (3 minutes)</td>
</tr>
<tr>
<td>Reynolds number</td>
<td></td>
<td>2.03x10⁴</td>
</tr>
<tr>
<td>Pump capacity</td>
<td></td>
<td>100-1500cm³/min</td>
</tr>
<tr>
<td>Flow line</td>
<td></td>
<td>1/8” nominal ID</td>
</tr>
<tr>
<td>Volumetric flow rate</td>
<td></td>
<td>1000 cm³/min</td>
</tr>
</tbody>
</table>
2.5: Experimental Procedure
Distilled water was pumped through the reactor. A steady-state flow without reaction and density change of a single/carrier fluid (water) through the reactor with a pulse input of a tracer (KCl) at the upstream. The flow was regulated (with the aid of a valve and the pump’s voltage) until a steady-state flow condition was achieved before the effluent of the reactor was collected at every 5 s to determine the concentration-time information using a conductivity meter. The schematic of the experimental set up is shown in Figure 2. However, to get the best (optimum) process condition and as well observe the effects of flow rates on the performance of the reactor, three runs of the experiments were conducted. In each of the runs, flow parameters were varied as shown in Table 3. The progress of the tracer’s effluent concentrations with time was monitored via conductivity probe (i.e. querying tracer molecules on their exit from the reactor) until the KCl injected was fully eluted. These data were converted into RTD profiles that show how much time each fraction of charge spent in the reactor.

![Figure 2: Schematic of the Experimental set up](image)

In order to obtain the concentration-time information required from the pulse tracer experiments of the tubular reactor, a reasonable quantity of the effluents from this reactor was collected using beakers, and the conductivity meter was used to measure the concentration of the samples collected at a particular time.

<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>REYNOLD NUMBER</th>
<th>SPACE TIME (s)</th>
<th>FLOW RATE (cm³/minute)</th>
<th>REACTOR’S VOLUME (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>340.0</td>
<td>213</td>
<td>100.3</td>
<td>355.0</td>
</tr>
<tr>
<td>2</td>
<td>2000.0</td>
<td>35.5</td>
<td>600.00</td>
<td>355.0</td>
</tr>
<tr>
<td>3</td>
<td>3300.0</td>
<td>17.0</td>
<td>1000.0</td>
<td>355.0</td>
</tr>
</tbody>
</table>

The raw data (i.e., concentration-time) from these experiments were used to plot graphs of concentration, C(t) versus time to check the trends in the effluent tracer concentrations. The data were then reduced to RTD function, E(t).

The characteristic parameters of the distribution function, E(t) such as mean residence time (\(\bar{t}\)), variance of the distribution (\(\sigma^2\)) were deduced. Furthermore, with the empirical E(t) parameter determined, theoretical RTD model formula was applied to assess the corresponding theoretical RTD parameters such as equivalent ‘n’ via n-CSTR theoretical flow model, the Peclet number and the axial dispersion coefficient using axial dispersion model.

3. RESULTS AND DISCUSSION
3.1: Tracer Responses
The raw data (i.e., concentration-time) from this experiment was used to plot a graph of concentration, C(t), versus time to check the trends in the effluent tracer concentrations. This is shown in Figure 1 - 3. It should be noted that the area under this curve is equivalent to the quantity of tracer injected.
The graph shows the time-lag as expected for a tubular reactor in each of the runs. Run Number 3 (Figure 3) with approximately 25s indicating minimal dispersion is considered the best. The spike (though not perfect) as shown from the curve of Figure 3 has minimal width indicating that there is a distribution but very poor for other Runs (see Figure 1 and 2). Thus, condition for Run 3 is considered the best as it shows a behavior similar to a PFR and will be discussed in this work.

3.2: RTD Function E(t) versus Time

The residence time distribution function, E(t) can be obtained from the plots of tracer concentration by differentiating the curve with respect to time or from the concentration-time data (see equation 1a –b respectively).

\[ E(t) = \frac{dC(t)}{dt} \quad \text{…….1a} \]
\[ E(t) = \frac{C(t) - C(t=0)}{\int_{0}^{t}[C(t') - C(t=0)]dt'} \quad \text{…….1b} \] [19]

Equation 1(b) was used to determine E(t) and the RTD curve for Run No. 3 is shown in Figure 4.
3.3: Determination of Mean Residence Time and RTD Variance (Run No. 3)

(a) Determination of Mean Residence Time

The mean residence time ($\bar{t}$) was calculated by integrating the RTD function (see equation 2).

$$\bar{t} = \int_0^\infty t E(t) dt = \int_0^\infty \frac{t.C(t)}{C(t)} dt \quad \ldots \ldots \ldots \ldots \ldots [19]$$

Table 3 summarizes the parameters require for the calculation of mean residence time distribution for a tubular reactor.

<table>
<thead>
<tr>
<th>S/N</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time, t (s)</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>C(t) g/ml</td>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.08</td>
<td>0.14</td>
<td>0.3</td>
<td>0.92</td>
<td>0.11</td>
<td>0.03</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>t.C(t) s.g/ml</td>
<td>0</td>
<td>0</td>
<td>13.468</td>
<td>10.048</td>
<td>7.128</td>
<td>4.708</td>
<td>8.367</td>
<td>10.9</td>
<td>6.28</td>
<td>0.086</td>
<td>10.018</td>
<td>7.577</td>
<td>5.30</td>
<td>6.69</td>
<td>0</td>
</tr>
<tr>
<td>$\gamma_n$</td>
<td>0</td>
<td>0</td>
<td>13.45</td>
<td>10.05</td>
<td>7.13</td>
<td>4.70</td>
<td>8.37</td>
<td>10.9</td>
<td>6.28</td>
<td>0.087</td>
<td>10.02</td>
<td>7.58</td>
<td>5.30</td>
<td>6.69</td>
<td>0</td>
</tr>
</tbody>
</table>

Applying Simpson’s rule [20], using column $\gamma_n$ of the Table 3

$$A = \int_0^\infty t.C(t)dt = \frac{2}{3}[202.16] = 336.93g/ml.s^2.$$  

But $\bar{t} = \int_0^\infty \frac{t.C(t)}{C(t)} dt$

Where $\int_0^\infty C(t)dt = 7.33g/ml.s$ (evaluated using Simpson’s rule).

Thus, $\bar{t} = 336.93/7.33 = 46$ s

(b) Determination of RTD Variance

The $E(t)$ or the RTD function is a weighting function through which empirical RTD parameters use to estimate departure from ideality of chemical reactors can be determined. The magnitude of this second moment is an indication of the spread of the RTD [15]. The variance or square of the standard deviation of the RTD can be evaluated using equation 3.

$$\sigma_t^2 = \int_0^\infty (t - \bar{t})^2 E(t) dt \quad \ldots \ldots \ldots \ldots \ldots [3]$$

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Table 4 shows the parameters for calculating variance of the residence time distribution for a tubular reactor.

### Table 4: Parameters of RTD Variance for a Tubular Reactor

<table>
<thead>
<tr>
<th>S/N</th>
<th>t[s]</th>
<th>C(t) [g/ml]</th>
<th>C(t).( (t-\bar{t})^2 ) [g/ml.s^2]</th>
<th>( y_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.01</td>
<td>13.4689</td>
<td>13.47</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>0.01</td>
<td>10.0489</td>
<td>10.05</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>0.01</td>
<td>7.1289</td>
<td>7.13</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>0.01</td>
<td>4.7089</td>
<td>4.70</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>0.03</td>
<td>8.3667</td>
<td>8.37</td>
</tr>
<tr>
<td>8</td>
<td>35</td>
<td>0.08</td>
<td>10.9512</td>
<td>10.95</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>0.14</td>
<td>6.2846</td>
<td>6.28</td>
</tr>
<tr>
<td>10</td>
<td>45</td>
<td>0.3</td>
<td>0.0867</td>
<td>0.097</td>
</tr>
<tr>
<td>11</td>
<td>50</td>
<td>0.92</td>
<td>10.0188</td>
<td>10.02</td>
</tr>
<tr>
<td>12</td>
<td>55</td>
<td>0.11</td>
<td>7.5779</td>
<td>7.67</td>
</tr>
<tr>
<td>13</td>
<td>60</td>
<td>0.03</td>
<td>5.3067</td>
<td>5.30</td>
</tr>
<tr>
<td>14</td>
<td>65</td>
<td>0.02</td>
<td>6.6978</td>
<td>6.69</td>
</tr>
<tr>
<td>15</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Applying Simpson’s rule [20], using column \( y_n \) of the Table 4. Therefore, variance of the RTD is approximately 60.15 s^2.

However, skewness and kurtosis (peakedness) of residence time distribution (i.e., third moment and fourth moment in that order though, not considered in this work) are also empirical parameters obtained from E(t). The choice of RTD characterizing parameters is a matter of balancing complexity against the required degree of precision [21]. However, theoretical RTD (N-CSTR Theoretical Flow and Axial Dispersion) model parameters can as well be determined through E(t). This is discussed next.

### 3.4: Fitting Experimental Data Into N-Cstr Theoretical Flow Model And Axial Dispersion Model

#### Application of E(t) in N-CSTR Theoretical Flow Model

As discussed earlier, application of RTD empirical parameters obtained from E(t) in n-CSTR theoretical flow model can be used to predict the equivalent number of CSTR, \( n \), required for a particular task. The model is simple (see equation 5a), and can be conveniently used to predict CSTR performance irrespective of the reaction kinetics [3]. The model parameter ‘\( n \)’ can be estimated via equation 5b

\[
\sigma_t^2 = \frac{\bar{t}^2}{n} \quad (5a)
\]

It follows that:

\[
n = \frac{\bar{t}^2}{\sigma_t^2} \quad (5b)
\]

Where \( n \) = number of ideal reactors required.

In the case of the tubular reactor, the equivalent number of ideal (CSTR) reactors required for the given task can be \( n = \frac{(46)^2}{60.15} = 35 \). This implies that 35 ideal CSTR is required to accomplish the given task performed by the tubular reactor.

#### (b) Application of E(t) in Axial Dispersion Flow Model

For completeness, empirical/derived RTD parameters such as the mean residence times and the variance of the residence time distribution can also be used in relation with the dispersion model to determine Peclet number (Pe_L) and then Axial Dispersion coefficient (D_L).

The dispersion model ([22] and [23]) is as shown in equation 6

\[
\frac{\sigma_t^2}{\bar{t}^2} = \frac{2}{Pe_L} \left\{ 1 - \frac{1}{Pe_L} (1 - e^{-Pe_L}) \right\} \quad (6)
\]
Equation 6 can be solved using method of residuals (see equation 7). Rearranging equation 6 to have equation 7, one can guess for \( P_{e,L} \) in order to get \( f(P_{e,L}) \).

\[
\frac{\sigma_t^2}{\bar{t}^2} = \frac{2}{P_{e,L}} \left\{ 1 - \frac{1}{P_{e,L}} (1 - e^{-P_{e,L}}) \right\} = f(P_{e,L}) \ldots .7
\]

First guess can be estimated using equation 8:

\[
\frac{\sigma_t^2}{\bar{t}^2} = \frac{2}{P_{e,L}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .8
\]

For Run No. 3, the first guess for \( P_{e,L} \) is given by:

\[
P_{e,L} = \frac{2 \bar{t}^2}{\sigma_t^2} = \frac{2 \times (46)^2}{60.15} = 70.4
\]

With the first estimate for \( P_{e,L} = 70.4 \) one gets: - 0.000047

The rest of the iteration is summarized as shown in Table 5

**Table 5: Peclet Number for a Tubular reactor**

<table>
<thead>
<tr>
<th>S/N</th>
<th>( P_{e,L} )</th>
<th>( f(P_{e,L}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.4</td>
<td>-0.000047</td>
</tr>
<tr>
<td>2</td>
<td>71.0</td>
<td>-0.00065</td>
</tr>
<tr>
<td>3</td>
<td>70.6</td>
<td>5.0 x10-4</td>
</tr>
<tr>
<td>4</td>
<td>67</td>
<td>9.79 x10-4</td>
</tr>
<tr>
<td>5</td>
<td>68.7</td>
<td>1.0x10-4</td>
</tr>
<tr>
<td>6</td>
<td>69.4</td>
<td>0</td>
</tr>
</tbody>
</table>

It follows that Actual \( P_{e,L} = 69.4 \)

Axial dispersion coefficient \( (D_L) \) can be evaluated using equation 9.

\[
P_{e,L} = \frac{2 \bar{t}^2}{\sigma_t^2} = \frac{2 \times (46)^2}{60.15} = 70.4
\]

**Table 6: Summary of Results**

<table>
<thead>
<tr>
<th>Empirical Parameters</th>
<th>Theoretical RTD Model Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \int_{(g/ml.s)} )</td>
<td>( \bar{t} ) (s) ( \tau ) (s) ( \sigma^2 ) (s^2) Inferred ‘n’ for N-CSTRs ( P_{e,L} )</td>
</tr>
<tr>
<td>( \int_{(g/ml.s)} )</td>
<td>7.33</td>
</tr>
</tbody>
</table>

Thus, the experimental data collated show that \( \bar{t} \neq \tau \) this is because, \( \bar{t} \) takes account of actual delays, (time lag and axial dispersion) while \( \tau \) takes account of the ratio of reactor volume to volumetric flow rate regardless of the complexity (non-ideality) of the existing flow pattern of the reactor. Therefore \( \tau \) is a wrong average \( \bar{t} \) is a better estimate, as shown, \( P_{e,L} < 100 \). \( \bar{t} \) as well as \( \sigma^2 \) were fairly large and sensitive to flow rates.. It must be rigorously noted that there is a difference between tubular reactor (as in our experimental work) and PFR. So the n-CSTR theory of RTD seeks to estimate the equivalent number of ideal CSTRs in series that produces the empirically observed E(t) that n-stirred-tank (non-ideal tubular reactor) reactor was used to generate. One reason why \( \bar{t} \) was significantly greater than \( \tau \), and \( \sigma^2 \) was so large, was because of the effect of the long tail of E(t) on \( t \) and \( \sigma^2 \) calculations, since \( \bar{t} = \int_0^\infty t E(t)dt \) and \( \sigma^2 = \int_0^\infty (t-i)^2 E(t)dt \).
However, the predominant reason for large $\sigma_t^2$ was that high back mixing in the reactor enlarges the tracer exit-age distribution time-span.

4. CONCLUSION

Based on the work, the following conclusions are drawn:
The fact that no ideal reactor exists is verified by the experiments carried out in this work, in that, empirical $E(t)$ was always a distribution as opposed to a dirac-delta function, $\delta(t - \tau)$ expected for PFR.
The empirical spread-out of $E(t)$ distribution as opposed to the theoretical spike or delta function confirmed the existence of measurable back mixing effect in the reactor irrespective of the improved features.
For flow reactors, when comparing empirical $E(t)$ against theoretical RTD models like n-CSTR and the axial dispersion model, it was found that the axial dispersion offered a better fit with experimental data, in that high or low Peclet numbers were found where expected.
RTD should be used not only for troubleshooting existing reactors but in estimating the effluent properties of a given reactor and designing future reactors with improved performance.

5. REFERENCES


