Residence Time Distribution of Three Stirred-Tank Reactors in Series

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Abstract-The need for this study arose from the awareness that 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 ideality was unclear until the concept of residence time distribution (RTD) was developed and applied to chemical reactors, to assess the extent of non-ideality, plus their effects on reactor performance. To study the empirically generated RTD behavior, 3 stirred-tanks in series reactors were designed and built with improved features. The principal findings from the study showed that the empirical mean residence times (\bar{t}) generated were generally larger than the corresponding reactor space times (τ). For the 3 stirred-tank reactors in series tracer experiment \overline{t} = 72s as against $\tau = 45s$, while distribution variance, σ_t^2 = 1994s². Finally, it was observed that the E(t) signature for 3 stirred-tanks in series was not identical with theoretical expectation for ideal 3 CSTRs in series. In fact, it was determined that the 3 stirred-tank reactors in series were theoretically equivalent to 2.6 reflecting imperfect back mixing in each of the stirred-tanks. However, application of the axial dispersion model showed our stirredtanks to be near perfectly mixed with Peclet number of approximately 10⁻⁴ equivalent to infinite axial dispersion coefficient. Thus, every reactor is neither a CSTR nor PFR but a continuum exhibiting features of ideality of both reactors. It is recommended that RTD should be used 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, Continuous Stirred Tank Reactors, Plug Flow Reactor, Axial dispersion, Peclet number.

I. INTRODUCTION

Every industrial chemical process is designed to produce economically, a desired product from a variety of starting raw materials. To transform the raw materials chemically into a desired product, such materials must pass through a reactor (transformer) where chemical reaction for the required transformation can take place. Based on the hydrodynamics of the flow, reactors such as crackers for crude oil refining, polymerization tanks for plastics, paints and fibers manufacturing etc; are designed to approximate the ideal continuous stirred-tank reactor (CSTR) or ideal plug flow reactor (PFR) for optimum conversion of raw materials to products [1]. It was found that most flow reactors are neither ideal plug flow nor continuous stirred tank reactors making it difficult to predict their performance.

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 [2]. Often, 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 [3]. 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 [4].

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 [2]. RTD is a probability distribution that describes the amount of time a fluid element could spend inside the reactor [1]. Although, the concept of RTD has been known for decades [5]; [6]; [7]; [8]; [9]; [10] and [11], 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. This is useful not only for troubleshooting existing reactors, but in estimating the yield of a given reaction and designing future reactors [12]. The aim of the study is to design three stirred-tank reactors in series with improved features and experimentally investigate using a tracer

method, the departure from ideality exhibited by these reactors to know the extent of their departure from the CSTR-end via n-CSTR theoretical flow model and the PFR-end via a dispersion model.

II. LIMITATION OF THE STUDY

This work is limited to the following:

- Even though the results from a single and two stirred-tank reactors in series (bench scale) may have been discussed, this work seeks to examine the behavior of three stirred-tank reactors in series to see how it exhibits Ideal Plug Flow reactor characteristics [2] and [13].
- 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 Gitis, *et al* [14] has been effective and easy to detect even at low concentration. Low concentration of the tracer pulse is expected since once injected, the tracer gets dispersed 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 and/or peakedness respectively) were not evaluated as they were not relevant in this work.

III. MATERIALS AND METHOD

Aim of the Experimental Work

The aim of the study is to design three stirred-tank reactors in series with improved features and experimentally investigate using a tracer method, the departure from ideality exhibited by these reactors to know the extent of their departure from the CSTR-end via n-CSTR theoretical flow model and the PFR-end via a dispersion model.

> **Materials for the Work:** The materials used for this work apart from the general apparatus found in Chemical Engineering Laboratory include:

1. Saturated KCl solution prepared at 29°C as a tracer for the work.

- 2. Distilled water used as the carrier medium
- 3. Electrical conductivity meter whose sensitivity is 0.0001-10.0g/ml
- 4. A pump with 100-1500 cm³/min delivering capacity.
- 5. Battery as source (12 Volt)
- 6. Electric motor for stirrers (12Volt)
- 7. A reservoir (cylindrical tank) for the carrier medium
- 8. Syringe (5ml capacity) coupled with needle for the pulse tracer injections.
- 9. Beakers at reactor exit for sample collection
- 10. Metallic piece for stirrer's shaft, blades and reactor's support.
- 11. Stainless Steel plate for Reactors

Design Strategy: Designing and fabricating three bench-scale stirred-tank reactors in series to obtain adequate RTD profile from these reactors 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 stirred-tank reactors was expected to be of the form shown in Figures 1a and 1b.



Figure 1a: Pulse tracer input (Pulse disturbance) Figure 1b: Expected output (pulse response) [1].

Ability to capture enough details of the pulse response (RTD profile) as the tracer eluted not just for space time (τ) value, but for τ = + 2 or -2 σ (σ is standard deviation) led to the basis for choice of space time.

Choice of tracer is important as some substances when used as tracers have effect on the hydrodynamics of reactors [15] while others revealed new method for determination of residence time [14]. KCI 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 (Table 1)

Table 1: Fluid's Parameters

Fluid	Parameters	Value		
Tracer	Nature	Saturated concentration		
(KCI)	Volume	2ml		
	Density	Negligible		
Carrier	Density	1000kg/m ³		
(Water)	Flow Rate	480cm ³ /min		

Design Parameter

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

- a. The volumetric flow rate: with the aid of the valve, the pump delivers 480cm³/min (8ml/s).
- b. Reactor's volume: For a single stirred-tank reactor, 120cm^3 was used to avoid splashing and spilling of the fluid during the experiment. Therefore the actual reactor's volume (constant quantity of fluid maintained) was 120cm^3 for a reactor and its diameter (d) = 5.1 cm and depth (h) = 6 cm.
- c. The implied space time (τ) using V_R/ ν_o is (120/480) = 0.25min (15s) for a single reactor. The volume of the 2 stirred-tank reactors in series = (2x120) cm³. Therefore, for 2 stirred-tank reactors in series (V_R) = 240cm³.

The implied space time (τ) = (240/480) cm³ = 0.5min = 30s

For the 3 stirred-tank reactors in series, $V_R = 360 \text{ cm}^3$ Therefore, space time (τ) = 360/480 = 0.75min = 45s The linear velocity of the fluid at the tip of the stirrer's blade is 4m/s (400cm/s).

Estimated energy input (i.e., maximum energy supplied) = 8KJ (8000J) [16].

Reynolds number	$(N_{Re}) = 2.03 \times 10^4$.
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	Table 2: Paramete	ers used for Test	Reactor Design
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Component	Description	Dimension				
Component	Tank Diameter	5.1cm				
	Tank Thickness	N/A				
Reactor	Tank height	6.0 cm				
	Tank volume	120cm ³				
	Stirrer height	4.5cm				
Q.	Blade Length	1.3 cm				
Suiter	Blade Thickness	N/A				
	Space time	45s				
Others	Reynold number	2.03x10 ⁴				
	Pump capacity	100-1500cm ³ /min				
	Tank volume	360cm ³				
Experimental Procedure						

A steady-state flow without reaction and density change of a single/carrier fluid (water) through these reactors with a pulse input of a tracer (KCI) at the upstream. The first reactor must be filled to the required volume before its effluent gets to the second reactor which too will be filled too before its effluent is allowed to the third reactor with the same condition, the flow was regulated (with the aid of a valve and the pump's voltage) until a condition steady-state flow is achieved before the effluent of the third reactor is collected at every 10s to determine the concentration-time information using a conductivity meter (Figure 2).



Figure 2: Schematic of the Experimental set up

The distance (d) is the distance from the injection point to the first reactor as well as the reactor's exit (r) in figure 2 must be carefully chosen otherwise a different model which differs from a 3 stirred-tank reactors in series model will be obtained as this amounted to small PFRs interconnecting CSTRs, with consequent PFR-like tracer exit-age delays enlarging both \bar{t} and σ_t^2 . 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.

In order to obtain the concentration-time information required from the pulse tracer experiments of 3 stirredtank reactors in series, a reasonable quantity of the effluents from these reactors was collected using beakers, and the conductivity meter was used to measure the concentration of the samples collected at a particular time. The raw data (i.e., concentration-time) from these experiments was used to plot graphs of concentration, C(t) versus time to check the trends in the effluent tracer concentrations for each set of conditions (runs). 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 (σ_t^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.

IV. RESULTS AND DISCUSSION

Tracer Responses

The raw data (i.e., concentration-time) from these experiments (Table A.1 to A.3) were used to plot graphs of concentration, C(t), versus time to check the trends in the effluent tracer concentrations for each set of conditions (runs) as shown in Figures 3-5. It should be noted that the area under these curves is equivalent to the quantity of tracer injected.



Figure 3: Effluent Tracer Concentration versus Time for a Single Stirred-Tank Reactor



Figure 4: Effluent Tracer Concentration versus Time for 2 Stirred-Tank Reactors in Series



Figure 5: Effluent Tracer Concentration versus Time for 3 Stirred-Tank Reactors in Series

Overall, the trends show that the time-lag in 3-stirredtank reactors is longer compare to others. The peak decreases as the number of stirred-tank reactors increases for same quantity of tracer injected (Figure 6).



Figure 6: Effluent Tracer Concentration versus Time for All Runs

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 (equation 1a - b respectively).

$$E(t) = \frac{dC(t)}{dt} \dots \dots \dots 1a \quad E(t) = \frac{C(t) - C(t=0)}{\int_0^\infty [C(t) - C(t=0)] dt} \dots \dots \dots 1b \quad [17]$$

Equation 1(b) was used to determine E(t) and the RTD curve for the 3 stirred-tank in series system is shown in Figure 7.



Figure 7: RTD Curve for 3 Stirred-Tank Reactors in Series

Determination of Mean Residence Time and RTD Variance

Determination of Mean Residence Time

The mean residence time (t) was calculated by integrating the RTD as follows

$$\bar{\mathbf{t}} = \int_{0}^{\infty} tE(t)dt = \frac{\int_{0}^{\infty} t.C(t)dt}{\int_{0}^{\infty} c(t)dt} \dots \dots 2 \text{ [17]}$$

Table 3 summarizes the parameters require for the calculation of mean residence time distribution for 3stirred-tank reactors in series.

Table 3: Parameters of Mean Residence Time for 3 Stirred-Tank Reactors in Series.

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S/N	1	2	3	4	5	6	7	8	9	10	11	12
t{s}	0	10	20	30	40	50	60	70	80	90	100	110
c(t) {g/ml}	0	0.76	2.07	2.93	3.26	3.23	2.99	2.57	2.17	1.78	1.45	0.9
t.c(t)s. g/ml)	0	7.6	41.4	87.9	130.4	161.5	179.4	179.9	173.6	160.2	145	126.5
yn	0	7.6	41.4	87.9	130.4	161.5	179.4	179.9	173.6	160.2	145	126.5
S/N	13	14	15	16	17	18	19	20	21	22	23	24
t{s}	120	130	140	150	160	170	180	190	200	210	220	230
c(t) {g/ml}	0.68	0.51	0.39	0.3	0.23	0.17	0.13	0.1	0.08	0.06	0.05	0.04
t.c(t)s. g/ml)	108	88.4	71.4	58.5	48	39.1	30.6	24.7	20	16.8	13.2	11.5
yn	108	88.4	71.4	58.5	48	39.1	30.6	24.7	20	16.8	13.2	11.5
S/N	25	26	27	28	29	30	31	32	33	34	35	
t{s}	240	250	260	270	280	290	300	310	320	330	340	
c(t) {g/ml}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0	
t.c(t)s. g/ml)	9.6	7.5	7.8	8.1	8.4	8.7	9	6.2	6.4	6.6	0	
y _n	9.6	7.5	7.8	8.1	8.4	8.7	9	6.2	6.4	6.6	0	

Applying Simpson's rule [18], using column yn of the Table 3

 $\int_0^\infty t. C(t) dt = \frac{10}{3} [5983.4] = 19944.7 \text{g/ml.s}^2.$ But $\bar{t} = \frac{\int_0^\infty t.C(t) dt}{\int_0^\infty C(t) dt}$ Where $\int_0^\infty C(t) dt = 272 \text{g/ml.s}$ (evaluated

using Simpson's rule). Thus, $\bar{t} = 19944.7/272 = 72.2$ s

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 [13]. The variance or square of the standard deviation of the RTD can be evaluated using equation 3.

$$\boldsymbol{\sigma}_{t}^{2} = \int_{0}^{\infty} (t-\bar{t})^{2} E(t) dt \qquad 3$$

Table 4 shows the parameters for calculating variance of the residence time distribution for 3 stirred-tank reactors in series.

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S/N	t/e)	C(t)	C(t).(t-	Уn	
3/11	ເຽ	{g/ml}	\overline{t}) ² (g/ml.s ²)		
1	0	0	0	0	
2	10	0.76	5792.7	5792.7	
3	20	2.07	5392.4	5392.4	
4	30	2.93	3528.6	3528.6	
5	40	3.26	1693.8	1693.8	
6	50	3.23	497.5	497.5	
7	60	2.99	21.6	21.6	
8	70	2.57	109.3	109.3	
9	80	2.17	520.4	520.4	
10	90	1.78	1064.8	1064.8	
11	100	1.45	1582.8	1582.8	
12	110	0.15	1996.5	1996.5	
13	120	0.9	2217.0	2217.0	
14	130	0.68	2296.2	2296.2	
15	140	0.51	2318.3	2318.3	
16	150	0.39	2275.9	2275.9	
17	160	0.3	2168.5	2168.5	
18	170	0.23	1949.9	1949.9	
19	180	0.17	1782.6	1782.6	
20	190	0.13	1615.4	1615.4	
21	200	0.01	1503.7	1503.7	
22	210	0.08	1298.3	1298.3	
23	220	0.06	1234.0	1234.0	
24	230	0.05	1116.8	1116.8	
25	240	0.04	940.9	940.9	
26	250	0.03	1050.1	1050.1	
27	260	0.03	1165.4	1165.4	
28	270	0.03	1286.7	1286.7	
29	280	0.03	1413.9	1413.9	
30	290	0.03	1547.2	1547.2	
31	300	0.03	1124.3	1124.3	
32	310	0.02	1221.1	1221.1	
33	320	0.02	1322.0	1322.0	
34	330	0.02	1405.0	1405.0	
35	340 0		0	0	

Table 4: Parameters of RTD Variance for 3 Stirred-

Tank Reactors in Series

Applying Simpson's rule [18], using column y_n of the Table4.Therefore, variance of the RTD is approximately 1994.4s^{2.}

The mean residence time and the variance of distribution which are RTD characterizing parameters for a stirred-tank reactor and 2 stirred-tank reactors in series were also evaluated empirically and tabulated in Table 6. 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 [19]. However, theoretical RTD (N-CSTR Theoretical Flow and Axial Dispersion) model parameters can as well be determined through E(t). This is discussed next.

Fitting Experimental Data into N-CSTR Theoretical Flow Model and Axial Dispersion Model

(a). 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 [2]. The model parameter 'n' can be estimated via equation 5b

(5a)

$$\sigma_t^2 = \frac{\overline{t}^2}{n}$$

It follows that:

$$n = \frac{t^2}{\sigma_t^2}$$
(5b)

Where n = number of ideal reactors required.

In the case of 3 stirred-tank reactors in series, the equivalent number of ideal reactors required for the given task can be $n = (72.2)^2/1994.9 = 2.61$. This implies that about 2.6 ideal CSTR is required to accomplish the given task performed by 3 stirred-tank reactors in series. Therefore, the departure from ideality reduces the efficiency of the reactor. Similar calculations are done to get equivalent 'n' in the case of a stirred-tank reactor as well as that of 2 stirred-tank reactors in series and tabulated in Table 6.

From the foregoing, there is a difference between nstirred-tank reactors in series as in the experimental work (i.e., non-ideal reactor) and n-CSTR in series (i.e., ideal reactor). The departure from ideality reduces the efficiency, the conversion as well as the selectivity of the real reactor. Thus, it takes less ideal CSTR to accomplish the work (task) performed by the real (stirred-tank) reactors as summarized in the Table 6

(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 [20] and [21] is as shown in equation 6

Equation 6 can be solved using method of residuals (equation 7). Rearranging equation 6 to have equation 7, one can guess for Pe_{I} in order to get $f(Pe_{I})$.

$$\frac{\sigma_t^2}{t^2} - \frac{2}{Pe_L} \left\{ 1 - \frac{1}{Pe_L} (1 - e^{-Pe_L}) \right\} = f(Pe_L) \dots .7$$

First guess can be estimated using equation 8: $\frac{\sigma_t^2}{t^2} = \frac{2}{Pe_t} \dots \dots 8$

For 3 stirred-tank reactors in series, the first guess for $\mathsf{P}_{\mathsf{e},\mathsf{L}}$ is given by:

 $Pe_{L} = \frac{2\overline{t^{2}}}{\sigma_{t}^{2}} = \frac{2 \times (70.6)^{2}}{1985.25} = 5.02$

With the first estimate for $P_{e,L}$ = 5.02 one gets:

$$\frac{1985.25}{70.6^2} - \frac{2}{5.02} \left\{ 1 - \frac{1}{5.02} \left(1 - e^{-5.02} \right) \right\} = -0.08136$$

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

 Table 5: Peclet Number for 3 Stirred-Tank Reactors

 in Series

S/N	P _{e,L}	f(_{PeL})
1.	5.02	-0.08136
2	4	-0.03016
3	3.865x10 ⁻⁴	9.92x10 ⁻⁴
4	3.864x10 ⁻³	2.18x10 ⁻⁴
5	3.866x10 ⁻⁴	1.3x10 ⁻⁴

Peclet numbers for a single stirred-tank reactor and 2 stirred-tank reactors in series are presented in Table 6.

It follows that Actual Pe,L= 3.866x10⁻⁴

Table 6: Summary of Results

	Empirical Parameters				Theoretical RTD Model Parameters		
N*	$\int_{0}^{\infty} \sigma_{t} = \bar{t} + \sigma_{t}^{2}$		σ_t^2	Inferred 'n' for N-CSTRs PeL			
	$\int_{0}^{C(t)dt}$	(s)	(S)	(s ²)		-,-	
	(g/ml.s)						
1.	90.8	18.3	15	343.1	0.98	6.35x10 ⁻⁸	
2.	202.02	38.45	30	747.04	1.98	2.34x10 ⁻⁶	
3.	272.2	72.2	45	1994.4	2.61	3.86x10 ⁻⁴	

*N= number of identical stirred tanks in series for that run.

Thus, the experimental data collated show that $\bar{t} \neq \tau$ this is because, \bar{t} takes account of actual delays, shortcircuiting and dead zones which exist in real reactors, while τ takes account of the ratio of reactor volume to volumetric flow rate regardless of the complexity (nonideality) of the existing flow pattern of the reactor. Therefore τ is a wrong average \bar{t} is a better estimate, as shown, P_{e,L}< 100 (as expected for CSTR). Equivalent n is less than the actual number of stirredtank reactors in series. \bar{t} as well as σ_t^2 increases as the number of reactors increase, resulting in decrease in the peak for higher n-CSTR. It must be rigorously noted that there is a difference between n-stirred-tank reactor in series (as in our experimental work) and n-CSTR in series. 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-stirredtank (non-ideal) reactors in series were used to generate. That is why, for example, inferred n= 2.6, where the E(t) was generated by 3 stirred-tank reactors in series. One reason why \bar{t} was significantly greater than τ , and σ_t^2 was so large, was the effect of the long tail of E(t) on t and σ_t^2 calculations, since $\bar{t} = \int_0^\infty t E(t) dt$

and
$$\sigma_t^2 = \int_0^\infty (t-\bar{t})^2 E(t) dt$$
.

However, the predominant reason for large σ_t^2 was that high back mixing in stirred tanks always enlarges the tracer exit-age distribution time-span.

V. CONCLUSION

Based on the work, the following conclusions are drawn:

- 1. Even a well-stirred 3 stirred-tank reactors in series experimental configuration as was used in this study exhibits an exit-age RTD function, E(t), profile that is not identical with what theory projects for 3 ideal CSTR in series. In fact, the empirical E(t) obtained was assessed to correspond to approximately 2.6-CSTR in series. This suggests that each stirred-tank reactor in the series was not perfectly mixed, despite double-impeller design and high speed of impeller rotation (about 1500rpm). This imperfect mixing is traceable to the likelihood that while good macro mixing is achieved via good impeller design, adequate micro mixing is not assured.
- 2. The empirical mean residence time of tracer (as calculated from $\bar{t} = \int_0^\infty t \cdot E(t) dt$ is very sensitive to the distance of injection point to the first reactor in the series as well as to the length of the tubes draining the effluent from one to the next. If these tubes were even, 3-in.long each, severe distortion of E(t) as well as \bar{t} and σ^2 would be observed. This is explained in term of the reactor's set up not being simply 3 stirred-tank reactors in series. but rather $PFR \rightarrow CSTR \rightarrow PFR \rightarrow CSTR \rightarrow PFR$. Thus, there is no sharp classification of flow reactors rather a continuous spectrum exists as our reactors exhibit both CSTR and PFR behavior.

3. Though imperfect, the extent of back mixing achieved was very high. This contribution arises from the fact that application of axial dispersion theoretical model to the empirically generated E(t) via \bar{t} and σ_t^2 , gives the corresponding axial dispersion coefficient (D_L) which was nearly infinite as Peclet number is of the order of 10⁻⁴ which is the theoretical limit for perfect back mixing obtained.

4. 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.

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