A NONIDEAL FLOW EXPERIMENT

JUAN RAMON GONZALEZ-VELASCO AND
JAVIER BILBAO ELORRIAGA
Universidad del Pais Vasco
Bilbao, Spain

REAL REACTORS NEVER fully satisfy one of two very specific idealized flow patterns: plug flow or backmix flow. Deviation from ideality can be caused by the channeling of fluid through the vessel, by the recycling of fluid within the vessel, or by the existence of stagnant regions or pockets of fluid in the vessel.

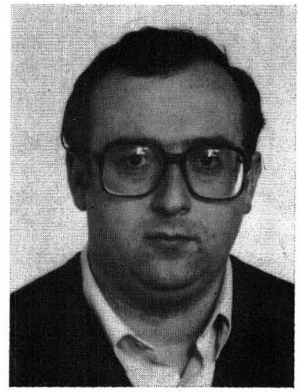
To predict the exact behaviour of a vessel as a chemical reactor we must know what is happening in it. We must at least know how the fluid is passing through the vessel. One way to determine this is to tag and follow each and every molecule as it passes through the vessel. Though fine in principle, the attendant complexities make this method impractical and we must resign ourselves to finding out how long individual molecules stay in the vessel. This information on the distribution of ages of molecules in the exit stream can be found easily and directly by a widely used experimental technique, the stimulus-response technique.

In this work we hope to consider the deviation from the ideal flows of both a backmix tank and a backmix tank followed by a plug flow vessel. From the C curves we calculate the dispersion number and the number of tanks in series that represent the deviation from ideality of the two studied systems.

THEORY

Since extensive treatments of this subject are available in many books on process modeling [1-5], only a concise review will be given here.

The exit age distribution function of fluid leaving a vessel or residence time distribution of fluid in a vessel is called the E curve. This curve

Juan R. Gonzalez-Velasco graduated as a chemist in 1975 and received his PhD in industrial chemistry in 1979 from the Universidad del Pais Vasco, both degrees with extraordinary mention. Since 1975 he has been a professor of technical chemistry and economics at the same university. His research studies have been focused upon heterogeneous catalysis, with special emphasis on design and optimization of fixed bed reactors subject to catalyst deactivation. He has published about thirty papers on these topics. He is presently conducting research on batch distillation optimization. **(L)**

Javier Bilbao Elorriaga obtained his PhD degree in industrial chemistry from the Universidad del Pais Vasco in 1977. Since 1973 he has been working as a professor of chemical reaction engineering at the Universidad del Pais Vasco. He has published about forty articles on heterogeneous kinetics and catalyst deactivation. Presently he works on simulation of deactivating catalyst reactors, especially on reaction-regeneration systems. He arranges his research with the supervision of some doctoral thesis. **(R)**

is normalized in such a way that the area under it is unity

$$\int_0^\infty E\ dt = 1 \tag{1}$$

In stimulus-response experimentation we perturb the system and then see how the system reacts or responds to this stimulus. The analysis of the response gives the desired information about the system. In our problem the stimulus is a tracer input signal to the vessel, the response signal being the recording of tracer leaving the vessel. Any type of tracer input signal may be used: a random signal, a cyclical signal, a step or continuous signal, a pulse or discontinuous signal. The two last modes of injection are the most used. The concentration-time curve at the vessel outlet is called the F curve when the input signal is a step signal and is called the C curve when the input signal is a pulse signal.

Considering steady-state flow of fluid through a closed vessel, it can be easily deduced that

$$C = E \tag{2}$$

The mean age of the exit stream or mean residence time is

$$\tau = \tau_E = \tau_C = \int_0^\infty t\,E\,dt = \Sigma\, t\,E\,\Delta t \tag{3}$$

and the variance of the E or C distribution is

$$\sigma_t^2 = \int_0^\infty t^2\,E\,dt - \tau^2 = \Sigma\, t^2\,E\,\Delta t - \tau^2 \tag{4}$$

The last terms in Eqs. (3) and (4) are used when the continuous distribution function is measured only at a number of equidistant points.

All the above concepts can be used with time measured in units of mean residence time. This is called reduced time

$$\theta = t/\tau \tag{5}$$

and then

$$\begin{aligned} E_\theta &= \tau E \\ C_\theta &= \tau C \\ \overline{\theta}_E &= 1 \\ \sigma_\theta^2 &= \sigma_t^2/\tau^2 \end{aligned} \tag{6}$$

If the flow were ideal the theoretical curves for the studied systems would be as shown in Fig. 1.

To characterize nonideal flow patterns many types of models can be used. These models are useful in accounting for the deviation of real systems (such as tubular or packed beds) from

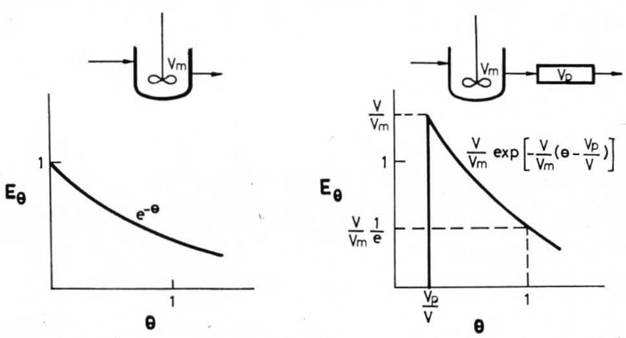


FIGURE 1. Theoretical E_θ-curves for systems studied.

From the C curves we calculate the dispersion number and the number of tanks in series that represent the deviation from ideality of the two studied systems.

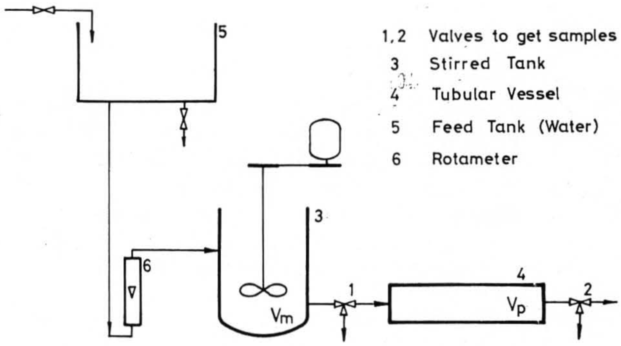


FIGURE 2. Schematic diagram of apparatus.

plug flow; or in describing the deviation of real stirred tanks from the ideal of backmix flow. The most important models are the dispersion model and the tanks in series model.

The dispersed plug flow model (for brevity we simply call it the dispersion model) considers that some degree of backmixing or intermixing is superimposed on the plug flow of the fluid. The magnitude of this deviation of the ideal plug flow is indicated by the dimensionless group D/uL which is called the vessel or reactor dispersion number. It varies from zero for plug flow to infinity for backmix flow and is the reciprocal of the axial Peclet number for mass transfer. For closed vessels we can calculate the dispersion number from the C curve

$$\sigma_\theta^2 = 2\left(\frac{D}{uL}\right) - 2\left(\frac{D}{uL}\right)^2 \left(1 - e^{-uL/D}\right) \tag{7}$$

The tanks-in-series-model is an alternate approach to the dispersion model for dealing with small deviations from plug flow. In this model we assume that the actual reactor can be represented by a series of N equal-sized backmix flow vessels. From experimental variance measurements N can be found

$$\sigma_\theta^2 = 1/N \tag{8}$$

APPARATUS

As is shown in Fig. 2, the experimental equipment consists of a stirred tank and a tubular vessel made of glass. The characteristics and dimensions

In stimulus-response experimentation we perturb the system and then see how the system reacts or responds to this stimulus. The analysis of the response gives the desired information about the system. In our problem the stimulus is a tracer input signal to the vessel, the response signal being the recording of tracer leaving the vessel.

of two vessels are:

STIRRED TANK
Height of fluid = 150 mm
Inside diameter = 143 mm
Volume = 2.409 liters
Agitation: A vertical flat 4-blade turbine impeller with diameter of 6.0 cm and width of 1.0 cm was used. It is connected to a motor of 1/23 HP arranged with a rotation speed governor (335-2500 rpm). Four vertical side-wall baffles projecting 1/10 of the tank diameter into the vessel perform a helpful purpose in controlling vortex action.

TUBULAR VESSEL
Length = 2370 mm
Inside diameter = 20 mm
Volume = 0.744 liters

The fluid flows by gravity and a rotameter indicates the flow rate. Valves 1 and 2 let us remove the samples for analysis.

EXPERIMENTAL PROCEDURE

The experimental procedure can be divided into the following steps:

a. We calibrated the rotameter. The fluid used is water. The volumetric feed rate selected was 142 cm^3/ min.
b. We obtained steady state flow (no accumulation in the stirred tank).
c. We inputed into the system an H_2SO_4 injection (tracer input pulse signal).
d. Every five minutes we removed samples at points 1 and 2 (as indicated in Fig. 1) until practically all tracer had left the vessels.
e. We analyzed these samples with 0.4N Na_2CO_3.

The concentration values obtained are shown in Table 1.

TABLE 1
Experimental results

Time, min	Concentration, moles/l	
	Point 1	Point 2
0	0.00	0.00
5	0.32	0.09
10	0.27	0.30
15	0.20	0.25
20	0.16	0.21
25	0.12	0.16
30	0.10	0.12
35	0.07	0.09
40	0.05	0.06
45	0.03	0.04
50	0.01	0.02
55	0.01	0.01
60	0.003	0.000

TABLE 2
Values calculated for the stirred tank

t, min	$E=\frac{c_1}{\Sigma c_1 \Delta t}$, min^{-1}	$\theta = \frac{t}{\tau}$	$E_\theta = \tau E$
0	0.0000	0.000	0.0000
5	0.0476	0.286	0.8333
10	0.0402	0.571	0.7038
15	0.0298	0.857	0.5217
20	0.0238	1.142	0.4170
25	0.0179	1.428	0.3134
30	0.0149	1.713	0.2609
35	0.0104	1.999	0.1821
40	0.0074	2.285	0.1296
45	0.0045	2.570	0.0788
50	0.0015	2.856	0.0263
55	0.0015	3.141	0.0263
60	0.0004	3.427	0.0070

RESULTS AND DISCUSSION

We now calculate the E curve, the dispersion number, and the number of tanks in series for these systems: 1) the stirred tank and 2) the stirred tank followed by the tubular vessel.

Stirred tank: The area under the concentration versus time curve

$$\Sigma c_1 \Delta t = 5 \Sigma c_1 = 6.715 \text{ mol min/l}$$

gives the total amount of tracer added in the pulse input. To find E this area must be unity; hence the concentrations must each be divided by $\Sigma c_1 \Delta t$, giving

$$E = \frac{c_1}{\Sigma c_1 \Delta t}$$

To obtain E_θ, t must be changed to θ and E to E_θ. But to do this we first need the mean residence time in the vessel which is given by Eq. (3) as

$$\tau = \Sigma t E \Delta t = 5 \Sigma t E = 17.51 \text{ min}$$

Hence from Eqs. (5) and (6) the necessary conversions are

$$\theta = \frac{t}{\tau} = \frac{t}{17.51}$$

$$E_\theta = \tau E = 17.51 E$$

The values are tabulated in Table 2.

Fig. 3 is a plot of the distribution where we have also drawn the curve corresponding to the ideal backmix flow, $E_\theta = e^{-\theta}$. In this figure we see a small deviation of the ideal E curve from the real one.

To evaluate the degree of deviation we calculate a) the dispersion number and b) the number of tanks in series that represents the stirred tank. To do so we first need the variance of the distribution; this is given by Eqs. (4) and (6) as

$$\sigma_\theta^2 = \Sigma\, \theta^2 E_\theta \Delta\theta - 1 = 0.4592$$

Now for a closed vessel we have from Eq. (7)

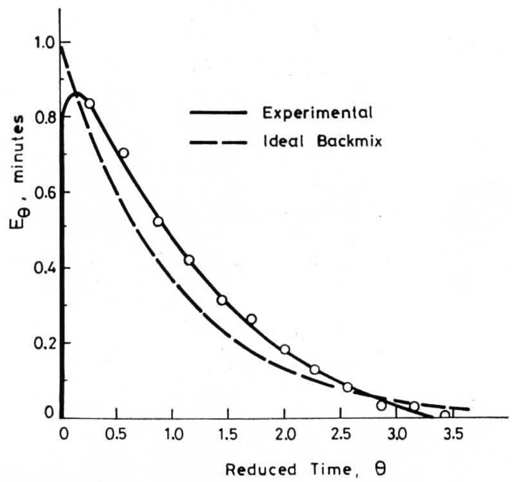


FIGURE 3. Theoretical and experimental E_θ-curves for the stirred tank.

that the dispersion number = D/uL = 0.338 and from Eq. (8) the number of tanks in series = 2.18.

Both numbers indicate to us that there is a large amount of dispersion from plug flow.

Since we work with a volumetric feed rate of 142 cm^3/min, the mean residence time in the tank should theoretically be

$$\tau_t = \frac{V_m}{Q} = \frac{2409}{142} = 16.95 \text{ min}$$

This time is below the experimental mean residence time, 17.51 min, i.e., the fluid leaves the tank after the time predicted theoretically, although both are practically concurrent.

TABLE 3
Values calculated for the stirred tank and the tubular vessel in series

t, min	$E = \frac{c_2}{\Sigma c_2 \Delta t}$, min^{-1}	$\theta = \frac{t}{\tau}$	$E_\theta = \tau E$
0	0.0000	0.000	0.0000
5	0.0133	0.242	0.2749
10	0.0440	0.484	0.9177
15	0.0370	0.726	0.7648
20	0.0311	0.968	0.6428
25	0.0237	1.209	0.4899
30	0.0178	1.451	0.3679
35	0.0133	1.693	0.2749
40	0.0089	1.935	0.1840
45	0.0059	2.177	0.1220
50	0.0030	2.419	0.0620
55	0.0015	2.661	0.0310
60	0.0000	2.903	0.0000

Stirred tank followed by a tubular vessel: Table 3 shows calculated values of E, θ and E_θ. The mean residence time in the system is τ = 20.67 min.

Fig. 4 is a plot of this distribution where we have also drawn the curve corresponding to the ideal backmix and plug flow in series, E_θ = 1.308 exp[-1.308 (θ - 0.236)] (Fig. 1). In this figure we can see a smaller amount of dispersion from ideal plug flow than when there was only the stirred tank. Both curves, the ideal and the ex-

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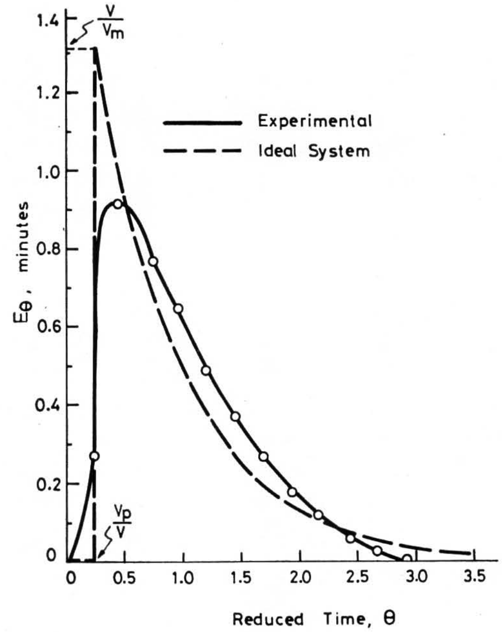

FIGURE 4. Theoretical and experimental E_θ-curves for the stirred tank followed by the tubular vessel.

to treat automotive exhausts and other more conventional oxidation and partial oxidation catalysts to hydrogenation/dehydrogenation catalysts and Ziegler-Natta polymerization catalysts.

While much useful information is conveyed in the book, this reviewer would be remiss in his obligations to the profession if he did not point out that the book would have benefited significantly if additional effort had been focused on the editing and proofreading aspects of its production. It contains a large number of grammatical errors. The lack of subject-verb agreement was evident numerous times in the second half of the book. Nonetheless I regard the book as a welcome addition to my bookshelf. □

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perimental one, however, are very close.

To evaluate the degree of deviation from the ideal flows we calculate the variance of the distribution, the dispersion number and the number of tanks in series that represents the system. These values are

$$\sigma_\theta^2 = 0.1105$$

$$D/uL = 0.059$$

$$N = 9 \text{ tanks}$$

Again, these values indicate to us that there is a smaller amount of dispersion from plug flow than in the above case.

The theoretical mean residence time is in this case

$$\tau_t = \frac{V}{Q} = \frac{3153}{142} = 22.20 \text{ min}$$

This is above the experimental mean residence time, 20.67 min. In this case the fluid leaves the system before the time predicted theoretically. □

NOTATION

C	dimensionless tracer response curve to an idealized pulse input
c	concentration, mol/l
D	dispersion or axial dispersion coefficient, m^2/s
D/uL	dimensionless dispersion number
E	exit age distribution function, dimensionless
L	length of vessel, m
N	number of equal-sized backmixed flow tanks
Q	volumetric flow, cm^3/min
t	time, min
τ	equals V/Q, reactor holding time or mean residence time of fluid in a flow vessel, min
τ_t	theoretical mean residence time, min
u	velocity, m/s
V_m	volume of the stirred tank, l
V_p	volume of the tubular vessel, l
θ	equals t/τ, reduced time, dimensionless
σ^2	equals σ_t^2/τ^2, variance of a tracer curve or distribution function in θ units, dimensionless
σ_t^2	variance in time units, min^2

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3. Wen, C. Y. and L. T. Fan, *Models for Flow Systems and Chemical Reactors*, Marcel Dekker, New York, 1975.
4. Froment, G. F. and K. B. Bischoff, *Chemical Reactor Analysis and Design*, John Wiley and Sons, Inc., New York, 1979.

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ChE books received

Introduction to Polymer Viscoelasticity, Second Edition, John J. Aklonis, William J. MacKnight; John Wiley & Sons, Somerset, NJ 08873; 295 pages, $39.95 (1983)

Modeling and Identification of Dynamic Systems, N. K. Sinha, B. Kuszta; Van Nostrand Reinhold Co., Inc., New York 10020; 334 pages, $32.50 (1983)

Laser Processing and Analysis of Materials, W. W. Duley; Plenum Publishing Corp., New York 10013; 463 pages, $59.50 (1983)

Phosphates and Phosphoric Acid, Pierre Becker; Marcel Dekker, Inc., New York 10016; 608 pages, $95.00 (1983)

Hydraulic Pumps and Motors, Raymond P. Lambeck; Marcel Dekker, Inc. New York 10016; 176 pages, $24.95 (1983)

Advances in Drying, Volume 2, Arun S. Mujumdar; Hemisphere Publishing Corp., New York 10036; 301 pages, $55.00 (1983)

Physicochemical Aspects of Polymer Surfaces, K. L. Mittal; Plenum Publishing Corp., New York 10013; Vol. 1, 580 pages, $75.00; Vol. 2, to page 1250, $85.00 (1983)