Effect of Specific Gravity Differences on Nonideal Mixing of Continuous Flow Systems

The effect of specific gravity differences as a primary factor of nonideal mixing was investigated and demonstrated by means of a combined M-T (mixed-tubular) reactor in a simple cylindrical flow tank. Specific gravity differences were provided by a temperature gradient created by a strongly exothermic, second-order adiabatic chemical reaction. The results also allow investigation of the effects of the inlet feed rate, agitator diameter, and speed on the agitator fraction of the combined reactor.

MARTIN P. PELLETIER
and LÉONCE CLOUTIER

Département de Génie Chimique
Université Laval
Ste-Foy, Québec 10, Canada

SCOPE

The purpose of this paper is to improve knowledge in two fields of chemical engineering: mixing and reactor design.

For many years, it has been considered doubtful that a density difference, especially when small, could be an important cause of nonideality of agitation in continuous flow systems. However, recent preliminary work having shown that possibility, it has been decided to study systematically that phenomenon.

In particular, the use of a highly exothermic reaction *in a continuous* adiabatic system had a double effect:

It created a temperature difference between the inlet and the outlet, and hence a density difference causing the formation of two zones, one being well mixed, and the other in tubular flow. Thus, nonideality existed and the effect of different parameters on the relative importance of both zones could be studied.

The two zones could be adjusted so as to reproduce the mixed and tubular zones of a combined M-T reactor; this type of combined reactor is known to present marked advantages over the mixed or the tubular reactor alone.

From a practical point of view, the scope of the research then became:

1. the creation of a combined M-T reactor in a single vessel through the use of a highly exothermic reaction, and
2. a study of the effect of different parameters on the agitated fraction of the reactor.

CONCLUSIONS AND SIGNIFICANCE

The results obtained have demonstrated that it is possible to create a combined M-T reactor in a simple cylindrical tank when a specific gravity difference between the inlet and the outlet exists.

The agitated fraction has shown to be very sensitive to the following variables: inlet feed rate, speed and diameter of the agitator, and specific gravity difference between the inlet and the outlet of the reactor.

It has been possible to correlate the experimental results; the obtained equations allow to show the effect of each variable studied on the value of the agitated fraction of the combined M-T reactor.

Industry should be interested in a reactor of this type. Indeed, instead of constructing a combined reactor in two parts, one can use the natural stratification of the fluid by means of the density difference. Moreover, by using a strongly exothermic chemical reaction to obtain the density difference, one uses exactly the type of reaction which is known to present marked advantages in the case of a combined M-T reactor.

However, the authors are well aware of the fact that more studies in the field of scale-up are necessary before practical industrial applications can be obtained.

PREVIOUS WORK

Even if density differences of miscible fluids have been considered often in several publications on stratification phenomena (Gill, et al., 1970), very few articles have been concerned with their effects on mixing. Van de Vusse (1955) and Zlokarni (1970) studied batch systems and measured the time of mixing of two miscible fluids having different densities and viscosities. Chiang (1967) showed visually the importance of density differences in continuous flow systems in the phenomenon of nonideal mixing in the Cholette-Cloutier (1959, 1968) model.

In a previous paper (Pelletier and Cloutier, 1970), the authors used a positive step demand (with a sodium-chloride solution) to create a density difference between the inlet and outlet of a CSTR. In that article, a mechanism which takes into account the initial specific gravity difference between the feed and the initial contents of the tank is presented to describe nonideal mixing.

Since the density difference between the inlet and outlet flows was not constant during the transient period following the step demand, it was decided to use a strongly exothermic chemical reaction under adiabatic conditions. In a CSTR, the temperature difference between the inlet and outlet at steady state determines a corresponding specific gravity difference. This difference is approximately independent of the agitator speed, provided the residence time (controlled by the inlet feed rate), the initial concentrations, and temperatures are chosen properly. This matter will be explained in greater detail shortly in this article.

PROPOSED MODELS

When a strongly exothermic homogeneous chemical reaction (either in gas or liquid phase) takes place in a reactor under adiabatic conditions, there always exists a temperature difference between the inlet and the outlet streams of the reactor. With the exception of very special cases, this means that the incoming fluid is denser than the outgoing fluid. This also means that, if not agitated, the incoming fluid will tend to stratify at the bottom of the reactor. If this phenomenon is considered in the case of a simple cylindrical adiabatic flow tank fed at the

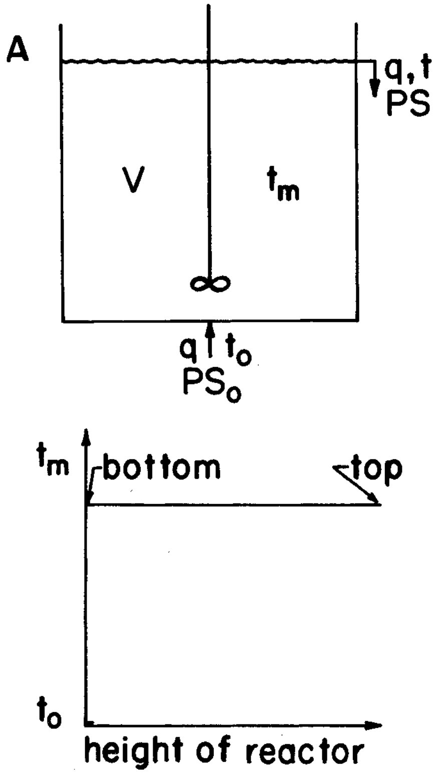

Fig. 1a. Perfect mixing: temperature-height of reactor profile.

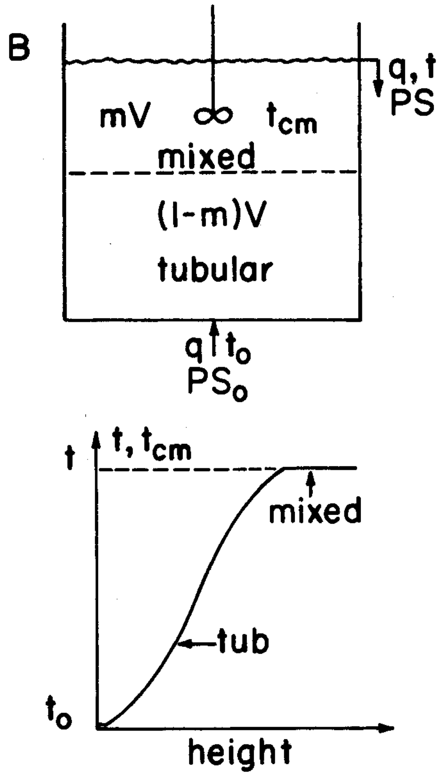

Fig. 1b. Perfect plug flow: temperature-height of reactor profile.

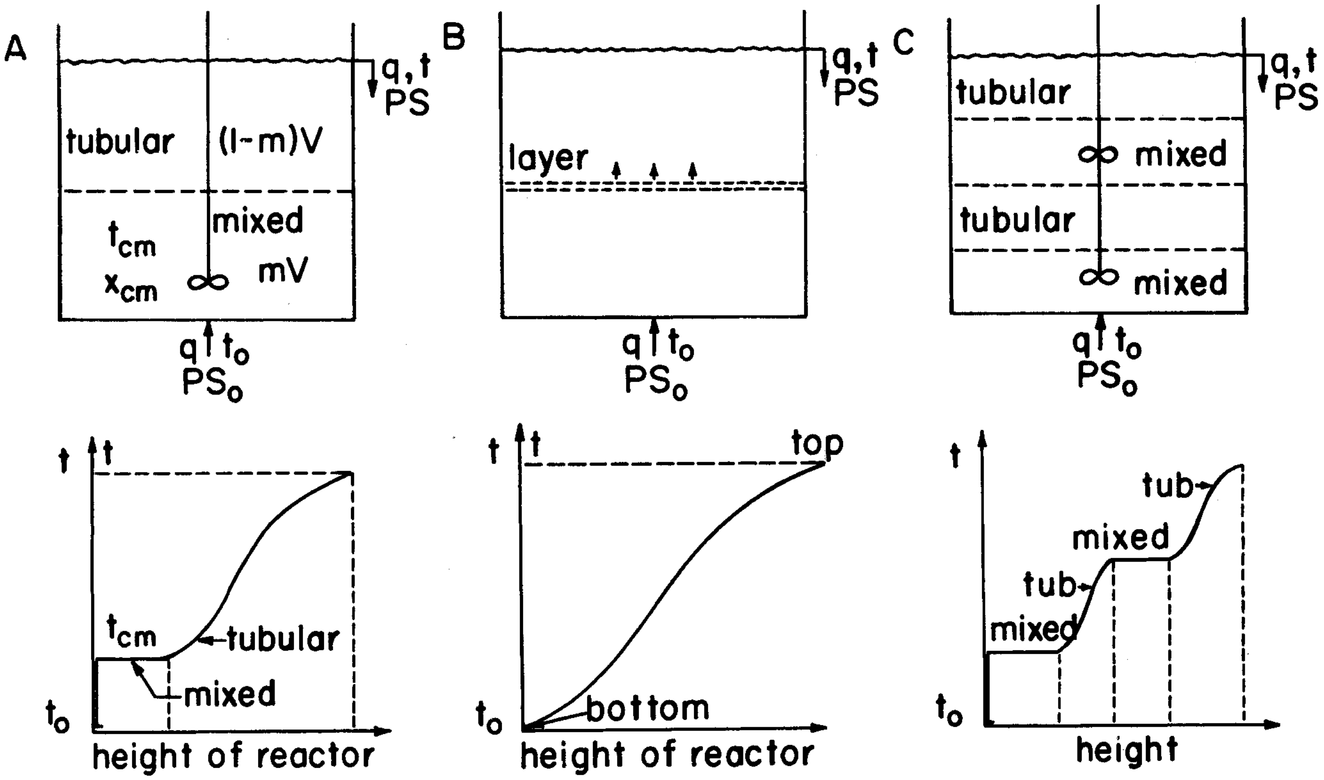

Fig. 2. Proposed models: A—combined mixed-tubular reactor; B—combined tubular-mixed reactor; and C—series of mixed-tubular reactors.

bottom with an inlet jet velocity close to zero, one may think that, at steady state, the stratification will result in a behavior of the tank similar to that of a tubular reactor standing upright. Figure 1 shows this possibility as well as the case of perfect mixing. The temperature-height of reactor profiles are also illustrated.

If this reasoning holds, let us now imagine three other possibilities:

1. If an agitator is placed near the bottom of the tank, it can happen that for small speeds, only a part of the tank is agitated and the other part is still in plug flow, creating then a combined M-T (mixed-tubular) reactor. Figure 2a illustrates this case.
2. On the other hand, if the agitator is located at a higher level, it may produce a combined T-M (tubular-mixed) reactor. (See Figure 2b.)
3. Finally if two or more agitators are used, a series of alternatively mixed and tubular reactors can be achieved. These three cases as well as their temperature-height of reactor profiles are illustrated on Figure 2.

COMBINED M-T REACTOR

Among these models, the M-T reactor is very attractive since it presents an optimal combination when a strongly exothermic adiabatic chemical reaction is performed in it (Cholette and Blanchet, 1961; Lo, 1972; Lo and Cholette, 1972).

Figure 3 shows the variation of conversion with residence time for the completely mixed and the tubular reactor. The curve *ABC* also represents one example of the combined reactor behavior. Segment *AB* holds for the agitated part and segment *BC* (which is parallel with *B'C'*) holds for the tubular part of the combined reactor. The dotted lines display typical conversions for a given overall residence time. This figure has been constructed from the kinetic data summarized in Table 1 for the chemical reaction between H_2O_2 and $Na_2S_2O_3$:

$$\alpha\, H_2O_2 + Na_2S_2O_3 \rightarrow \text{products} \qquad (1)$$

For a second-order reaction [which is the case of Equation (1)], the design equations have been developed by Cholette and Blanchet (1961) for the different types of reactors involved here. Defining the conversion, the mean residence time, the initial concentration of the limiting reactant, and the ratio of inlet concentrations by x, θ, C_t^0 and R_F, those equations are

1—CSTR

$$\theta_m = \frac{x_m}{C_t^0\, k(1 - x_m)\,(R_F - \alpha x_m)} \qquad (2)$$

2—Tubular reactor

$$\theta_t = \frac{1}{C_t^0} \int_0^{x_t} \frac{dx}{k(1 - x)\,(R_F - \alpha x)} \qquad (3)$$

where

$$k = k_0 \exp\left[\left(\frac{E}{RT_0} \right) \left(\frac{1}{1 + (T_0/bx)} \right) \right] \qquad (4)$$

$$k_0 = A \exp\,(-E/RT_0) \qquad (5)$$

$$b = \frac{C_t^0(-\Delta H)}{\rho c} \qquad (6)$$

3—M-T Reactor

If one lets m and x_{cm} be the mixed fraction of the tank and the conversion in it, since the inlet conversion in the tubular part of the combined reactor is x_{cm}, the design equations are

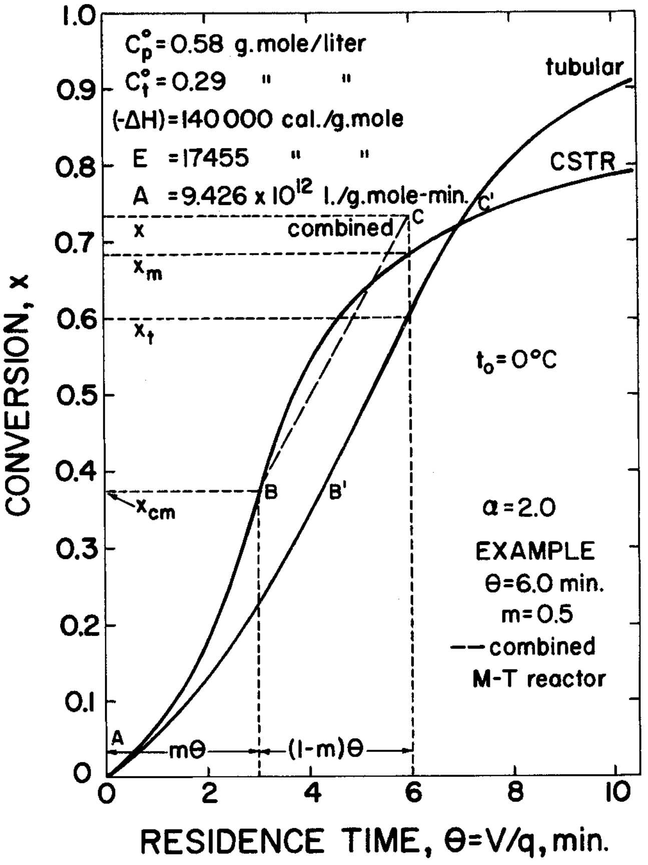

Fig. 3. Variation of conversion as a function of residence time for a strongly exothermic second order adiabatic chemical reaction.

Table 1. Kinetic Data for the Chemical Reaction between Hydrogen Peroxide and Sodium Thiosulfate (Pelletier, 1971)

$\alpha = 2.0$ moles H_2O_2/mole $Na_2S_2O_3$
$(-\Delta H) = 140{,}000$ cal/g mole
$E = 17{,}455$ cal/g mole
$A = 9.426 \times 10^{12}$ liter/g mole-min
$R_F = 2.0$

$$\theta_{cm} = m\theta = \frac{x_{cm}}{C_t^0 k(1 - x_{cm})\,(R_F - \alpha x_{cm})} \qquad (7)$$

$$\theta_{ct} = (1 - m)\theta = \frac{1}{C_t^0} \int_{x_{cm}}^{x} \frac{dx}{k(1 - x)\,(R_F - \alpha x)} \qquad (8)$$

Equations (7) and (8) result in the M-T curve (curve *ABC* on Figure 3).

CHOICE OF EXPERIMENTAL CONDITIONS

The aim of this project was first to verify that a combined reactor could be designed with the help of a density gradient between the inlet and the outlet of the reactor and secondly, if so, to study the effect of different mixing parameters, including the density difference, on the agitated fraction of the tank. As Figure 2a shows, when the agitator speed is increased, if the model holds the reactor behavior changes from piston flow to combined M-T reactor and finally to perfect mixing. In order to allow comparisons, it is imperative that the density difference between the inlet and the outlet stays constant or approximately constant while the reactor behavior changes through the three situations.

As can be seen in Figure 3, this can be realized if the operating conditions are chosen at the meeting point of the CSTR and tubular curves; the outlet conversion will then be identical for the well mixed and tubular reactor and in the same region for the combined M-T reactor. In fact, when the reactor is in the M-T situation, the outlet conversion is greater than in both piston flow or perfect mixing situations; but reactants concentrations can also be chosen to minimize this effect. The residence time selected for this criterion determines a feed rate for the given volume of the reactor. Since the conversion will not vary much, the temperature difference between the inlet and the outlet will remain relatively constant, since it is related to conversion by

$$x = \frac{(t - t_0)\rho c}{C_t^0(-\Delta H)} \qquad (9)$$

To the temperature difference, there also corresponds a specific gravity difference between the same points, which will also be approximately constant. It is then possible to study the variation of the agitated fraction of the tank m at steady state as a function of the speed of rotation, the specific gravity difference, the feed rate, and the agitator diameter.

EXPERIMENTAL APPARATUS

Figure 4 shows the flow diagram and a schematic representation of the different pieces of equipment. Essentially it is composed of three main parts: feed tanks, experimental reactor, and cooling system. The cooling system was necessary because, at room temperature the rate of reaction was much too high. All the equipment was insulated with 3-in. glass wool covered by an aluminium sheet and the lines with Armaflex. All the equipment and lines were in stainless steel or polyethylene.

Figure 5 shows the experimental reactor. It was a 12-in. inside diameter flat-bottomed cylindrical flow tank made of stainless steel to avoid corrosion. The inlet was located at the bottom in the center of the tank and the outlet was on the side at 11½ in. from the bottom. The only difference of this reactor with respect to a conventional one lies in the presence of a deflector plate which is placed in front of the inlet to keep the feed at the bottom. (Preliminary experiments have shown that piston flow could not be achieved without this deflector plate.) Preliminary work has also shown that the best location for the agitator was 2 in. above the bottom, in which case even at low speeds of rotation the agitated part of the tank starts at its bottom. The speed of rotation could be varied from 0 to 1,200 rev./min. Flat blade turbines have been found satisfactory. Five different six blade turbines were used, the diameters being 1, 1½, 2, 2½ and 3 in. During an experiment, for a given agitator speed temperatures were taken periodically at the inlet, (with a precision glass thermometer) at 1, 6 and 11 in. from the bottom, (with YSI Telethermometers) and was registered continuously at the outlet until steady state was reached. (See Figure 6.) When the system was at steady state, a special device allowed to measure the temperature profile in the tank. Essentially, it consisted of a probe with a time constant of only 0.5 second (YSI #421) mounted on a toothed rack that could be lowered at constant speed into the tank and whose reading was registered. (See Figure 7.) The same procedure was repeated for 10 to 13 agitator speeds during an experiment.

EXPERIMENTAL EVIDENCE OF THE COMBINED M-T REACTOR

Figure 7 shows the temperature profiles in the reactor for two different speeds of rotation and Figure 6 shows the recording of the outlet temperature as a function of time for the same experimental conditions. From Figure 6 it is obvious that a steady state can be obtained and from Figure 7 that a combined M-T reactor does exist. One can also notice that temperature fluctuations occur about the equilibrium point, but one must keep in mind that this M-T reactor is stabilized by a density gradient resulting from a temperature gradient. A study of these fluctuations (Pelletier, 1971) has shown that the larger the density difference the more stable the M-T reactor is, whatever the experimental conditions are.

CALCULATION OF THE AGITATED FRACTION

The agitated fraction of the M-T reactor can be calculated by three different methods.

The first one consisted in evaluating graphically the agitated fraction from temperature profiles (see Figure 7). Since the probe was displaced vertically at a constant

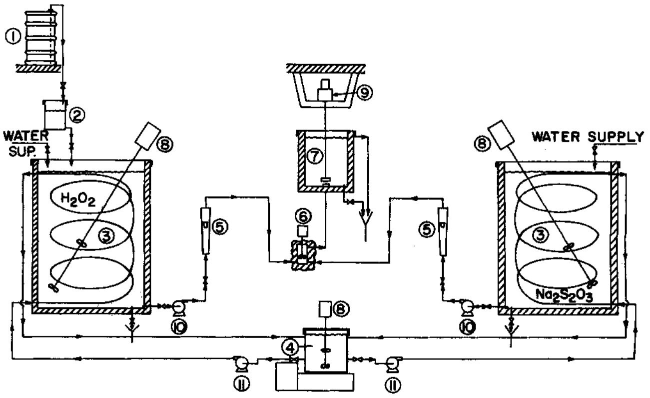

Fig. 4. Flow diagram and schematic representation of equipment: 1—concentrated peroxide supply; 2—small calibrated plastic tank; 3—feed tanks (600 liters each); 4—cooling system; 5—rotameters; 6—mixing chamber (small); 7—experimental reactor; 8—mixers; 9—variable speed agitator; 10—feed pumps; 11—cooling pumps.

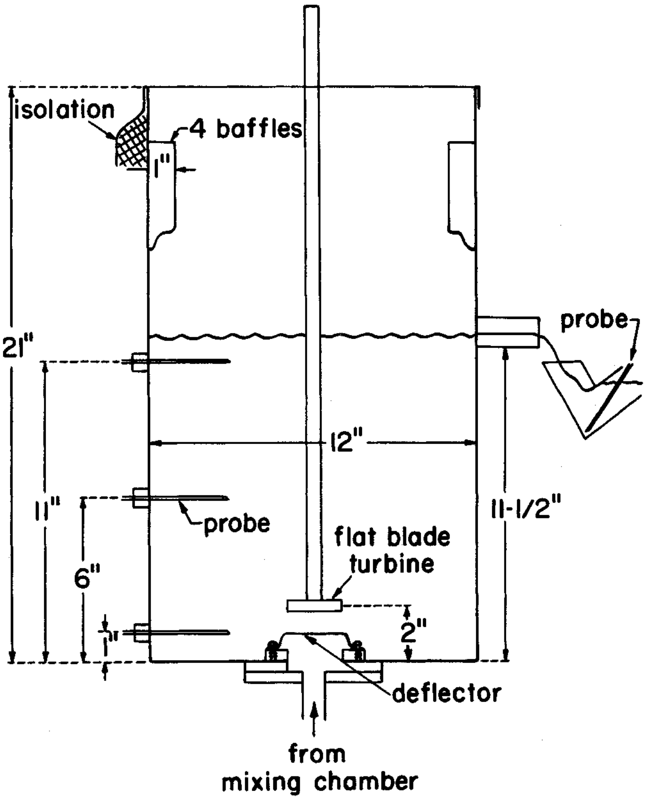

Fig. 5. Experimental reactor.

velocity, the evaluation of the agitated fraction, after having determined the position of the mixed part on the graph, is simply equal to the ratio of lengths on the graph.

The other two methods are based upon temperature measurements at the outlet and at 1 inch above the bottom of the tank. The outlet temperature can be expressed in terms of conversion by means of Equation (9) and then, by trial and error, using Equations (4), (7), and (8), one can find the two corresponding residence times for the agitated part of the combined M-T reactor which yields the calculated outlet conversion. Finally, because there was experimental evidence that the probe positioned at 1 inch from the bottom was always in the agitated part of the combined reactor, (even when the rotational speed of the agitator was zero), its reading can be used to define the temperature and conversion in the mixed part of the reactor. This method requires only Equations (4) and (7) to determine the agitated fraction of the tank, called m_1, because of its way of calculation.

Only this last method has been utilized to calculate the agitated fraction, because it was the only one which could yield good results at any speed of rotation. Indeed, the graphical method is not adequate when the reactor behavior approaches perfect mixing because the temperature profile becomes too flat to be clearly cut into two sections. Moreover, since experimental initial concentrations of the reactants have been chosen so as to keep the outlet temperature approximately constant, the calculation of the agitated fraction by the combined reactor theory was not precise. This is the case because the outlet temperature variations on which the calculation is based were small and also because the exact outlet temperature itself was difficult to measure due to fluctuations (see Figure 6).

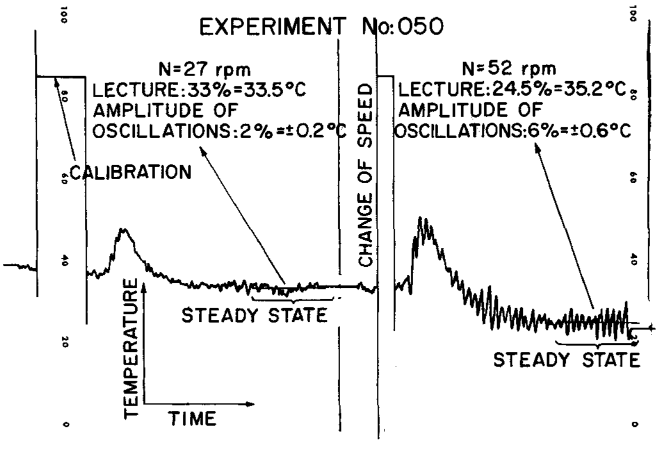

Fig. 6. Recording of outlet temperature versus time.

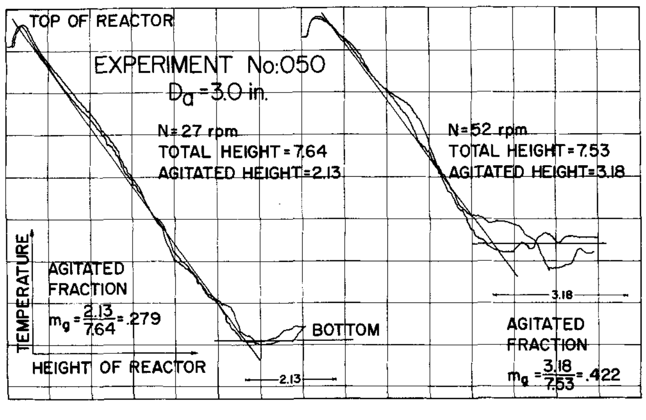

Fig. 7. Recording of two experimental temperature profiles in the reactor.

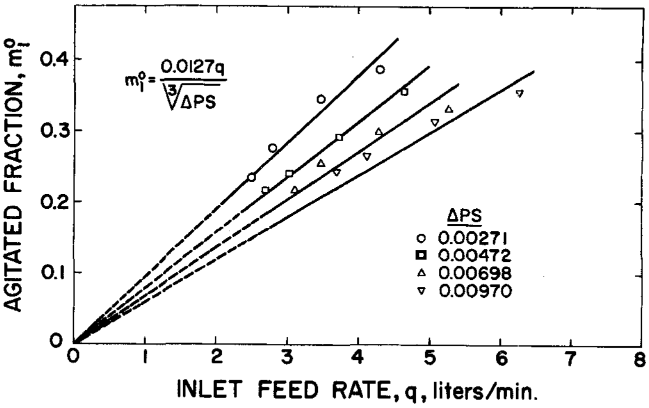

Fig. 8. Effect of specific gravity difference on the variation of the initial agitated fraction (speed = 0) as a function of the inlet feed rate.

RESULTS AND DISCUSSION

Agitator Stopped

Even when the agitator was stopped, one could notice that a fraction of the tank contents was agitated. Obviously in this case, the value of the agitated part m_1^0 is then a function of only two parameters, the inlet feed rate and the specific gravity difference.

Figure 8 shows the variation of the initial value (speed equal to zero) of the agitated fraction of the tank as a function of the inlet feed rate. The experimental points have been evaluated by averaging the initial values corresponding to the same feed and initial specific gravity difference.

Apparently experimental points fall on different curves whose shapes are a function of the specific gravity differences. However, careful analysis of results has shown that due to the nonlinearity of the specific gravity with temperature, the specific gravity difference was increasing slightly with the flow rate of the feed stream. (The inlet temperature determines the meeting points of the CSTR and tubular curves for given concentrations of reactants, and consequently it specifies the feed.) This can explain the apparent curvature. One may expect however, that, taking into account the slight increase in density difference, this relationship can be approximated by straight lines whose slopes are function of the specific gravity differences.

Obviously, if there exists an agitated fraction in the tank when the agitator is stopped, this is due to the feed stream. One can expect that if the rate of flow of the feed stream is decreased, the agitated part of the tank contents will be also diminished. At the limit, one could by extrapolation assume that the agitated fraction should be zero when the feed is zero. This reasoning allows to include the origin in each curve shown in Figure 8.

The equation for these curves has been found to be

$$m_1^0 = \frac{0.0127 \times q}{\sqrt[3]{\Delta PS}} \tag{10}$$

for which the correlation coefficient is 0.9939.

Agitator Rotating

When the agitator is rotating, two other variables must be considered: agitator diameter and speed of rotation.

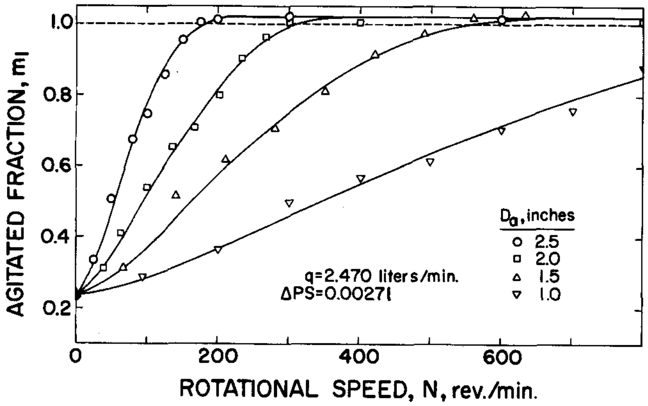

Fig. 9. Effect of the agitator diameter on the variation of the agitated fraction as a function of the speed of the agitator.

Table 2. Values of A_3 and C_3 of Equation (13)

ΔPS	A_3	C_3	CR	ES
0.00271	0.266	−0.0354	0.99727	0.00259
0.00472	0.283	−0.0349	0.97920	0.00765
0.00698	0.294	−0.0311	0.99049	0.00531
0.00970	0.276	−0.0245	0.99627	0.00300

Effect of the Agitator Diameter on the Variation of the Agitated Fraction with Respect to the Speed of Rotation

Figure 9 shows the effect of the agitator diameter on the variation of the agitated fraction with respect to the speed of rotation. As it could be expected, when the speed is increased, the agitated fraction also increases to the maximum value at high speeds. The larger the agitator diameter, the faster the increase of the agitated fraction.

One can notice that for large speeds of rotation, the value of the calculated agitated fraction falls slightly over 1.0, which is theoretically impossible. However, this deviation stays within experimental error.

Figure 9 shows the variation for one feed rate and one specific gravity difference. However, the shape of the family of curves is characteristic of the reactor behavior and is similar for other values of feed rates and specific gravity differences.

Variation of the Agitated Fraction as a Function of Power Consumption

Power consumption has been calculated from Rushton's equations (Rushton and Oldshue, 1953) for a six flat-blade turbine used in a baffled tank. Figure 10 is a logarithmic plot of agitated fraction versus power consumption of the agitator in the reacting mixture.

It is interesting to notice that the agitator diameter has little effect on this variation. In exponential form, the equation representing the variation can be written as

$$m_1 = A_2 P^{B_2} \tag{11}$$

The value of A_2 has been found to be independent of the specific gravity difference and is well defined by a second-order polynomial

$$A_2 = 1.83 - 0.269q + 0.0173q^2 \tag{12}$$

The variation of B_2 as a function of the inlet feed rate can be represented by a straight line of the form

$$B_2 = A_3 + C_3 q \tag{13}$$

Table 2 summarizes the values of A_3 and C_3 with respect to specific gravity differences.

Variation of the Agitated Fraction as a Function of the Modified Reynolds Number

Figure 11 shows the effect of the modified Reynolds number on the agitated fraction of the tank contents. Here again, the agitator diameter has no effect. The best equation representing this variation is

$$m_1 = 1 - (1 - m_1^0)(1 + N_{Re}/C_4)\exp(-N_{Re}/C_4) \tag{14}$$

where C_4 is a function of the specific gravity difference and the inlet feed rate.

Figure 12 presents the variation of C_4 as a function of feed rate. The points fall approximately into straight lines,

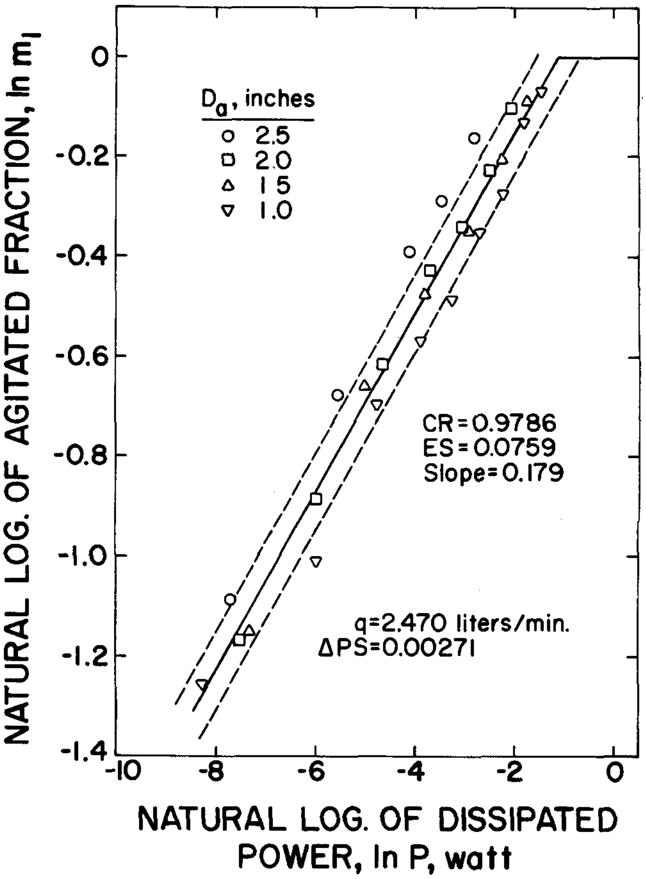

Fig. 10. Variation of the agitated fraction as a function of the dissipated power for given inlet feed rate and specific gravity difference.

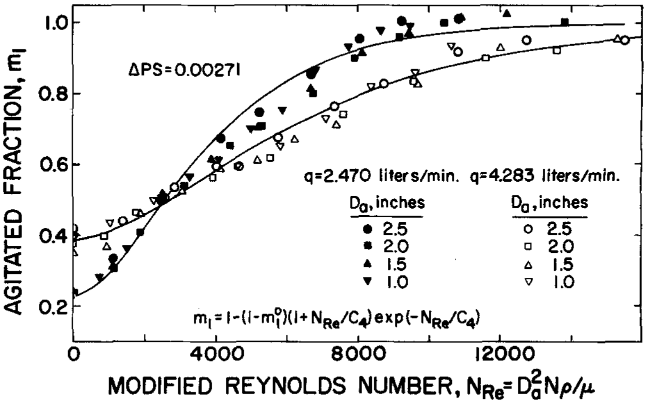

Fig. 11. Effect of inlet feed rate on the variation of the agitated fraction as a function of the modified Reynolds number for a constant specific gravity difference.

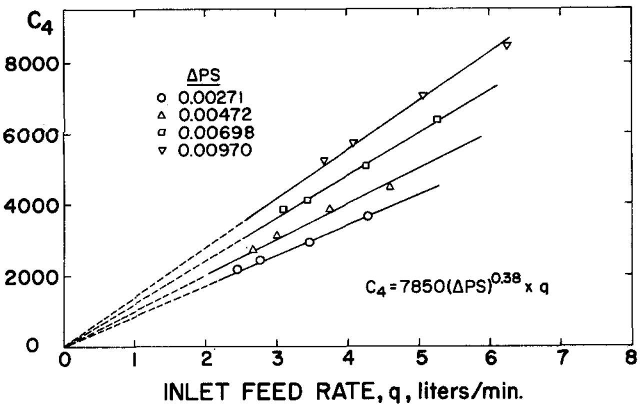

Fig. 12. Effect of the inlet feed rate on the constant C_4 of Equation (14) for the specific gravity differences used.

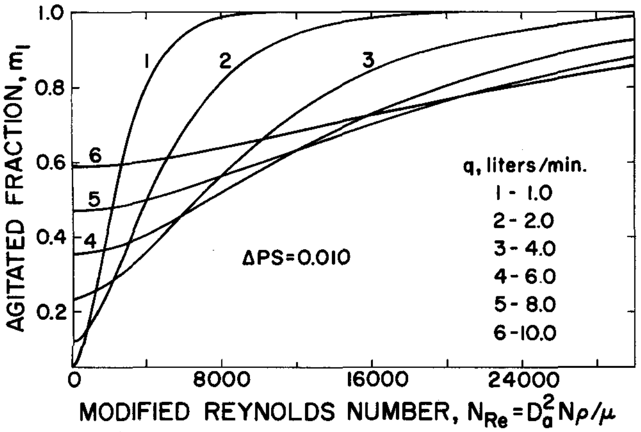

Fig. 13. Variation of the agitated fraction as a function of the modified Reynolds number for different inlet feed rates and a constant specific gravity difference.

whose slopes are functions of the specific gravity differences. The origin has been added to the data of Figure 12 because when C_4 is equal to zero (that is, $q = 0$), Equation (14) yields $m_1 = 1.0$. This is obvious since the power dissipated in a given volume going through the reactor becomes infinity when the feed rate approaches zero.

The equation representing the variation of C_4 is

$$C_4 = 7850 \times (\Delta PS)^{0.38} \times q\,. \qquad (15)$$

Equations (10), (14), and (15) have been used to draw the curves of Figures 11 and 13 to 15. The average error between experimental data and calculated values of the agitated fraction was found to be 0.03.

Effect of Feed Rate. Figures 13 and 14 illustrate the effect of the feed rate on the variation of the agitated fraction of the tank contents. Figure 13 confirms that an increase of the Reynolds number causes an increase of the agitated fraction for a given feed rate. However, this figure shows also an interesting phenomenon: for a given Reynolds number, when the feed is increased, the agitated fraction is lowered, passes through a minimum, and finally increases. That pattern is more evident on Figure 14. No quantitative explanation has yet been found to describe adequately this phenomenon, but a qualitative mechanism is proposed next. Remembering that the system is continuous, one should expect that the agitated volume is also a function of the total energy received by unit volume or unit mass flowing through the vessel. Then for a given power consumption (which also corresponds to a specified Reynolds number), the unit volume flowing through the reactor receives more energy when the feed rate is small since the average residence time is large. As a consequence, the agitated fraction approaches unity. When the feed rate increases, one must also consider the kinetic energy brought into the reactor by the feed itself. Since the mechanical energy by unit volume (or mass) varies inversely with the feed rate whereas the kinetic energy by unit volume varies directly with the square of the feed rate, it follows that the total energy dissipated in a unit volume flowing through the reactor passes through a minimum as the feed is increased and so does the agitated fraction.

Effect of Specific Gravity Difference. Figure 15 demonstrates the important effect of specific gravity differences in continuous flow mixing systems. Indeed, one can notice that, regardless of the value of the Reynolds number, the agitated fraction decreases with an increase in specific gravity difference. It is assumed that nonideal mixing in this system is mainly due to specific gravity difference when one notices that the agitated fraction approaches unity as the specific gravity difference approaches zero, regardless of the value of the Reynolds number.

CONCLUSIONS

The results obtained demonstrate that

1. It is possible to create a combined M-T reactor in a simple cylindrical flow tank when a specific gravity difference between the inlet and the outlet of the reactor exists.

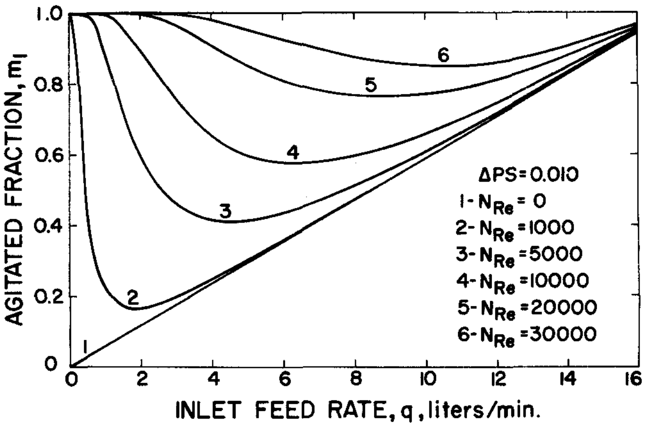

Fig. 14. Variation of the agitated fraction as a function of the inlet feed rate for different Reynolds numbers and a constant specific gravity difference.

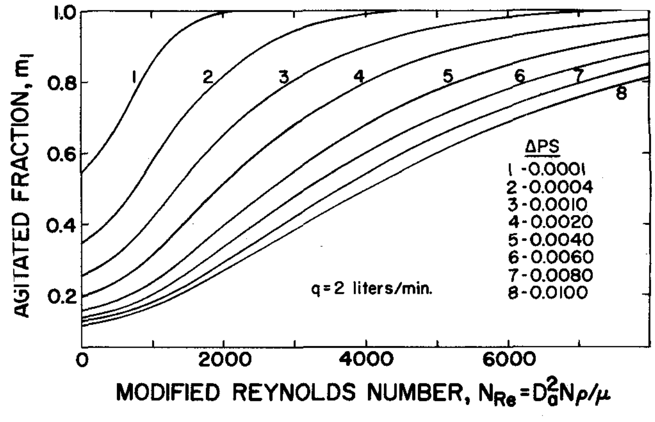

Fig. 15. Effect of the specific gravity difference on the variation of the agitated fraction as a function of the modified Reynolds number at constant inlet feed rate.

2. Even when the agitator is stopped, there exists an agitated fraction in the reactor which is approximately proportional to the volumetric feed rate and inversely proportional to the cubic root of the specific gravity difference.

3. The agitated fraction increases more rapidly with the agitator speed when the agitator diameter is large.

4. The agitator diameter has little effect upon the variation of the agitated fraction as a function of the power consumption or the modified Reynolds number.

5. The variation of the agitated fraction as a function of the power consumption can be represented by Equation (11) when the power input is not zero and when the agitated fraction is smaller than 1.0.

6. Equations (10), (14), and (15) represent the variation of the agitated fraction as a function of the Reynolds number for the system studied.

7. For any given Reynolds number and specific gravity difference, the value of the agitated fraction decreases, passes through a minimum, and increases again as the inlet feed rate increases.

8. The agitated fraction decreases with an increase in specific gravity difference, whatever the feed rate or the agitator speed.

It appears evident that industry should be interested in a reactor of this type. Indeed, in the case of second-order strongly exothermic adiabatic chemical reactions, the M-T reactor presents an optimum condition that can be expressed by a higher outlet concentration or a shorter residence time. Since this applies only to strongly exothermic adiabatic chemical reactions, the density gradient which stabilizes the M-T reactor will always be present, whether the reactor is in gas or liquid phase.

Further work on scale-up of similar systems will be necessary before practical industrial applications of this investigation can be achieved.

ACKNOWLEDGMENT

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NOTATION

A = Arrhenius constant: 9.426×10^{12} liter/g mole-min
A_2, A_3 = constants
b = $C_t^0 (-\Delta H)/\rho c$
B_2 = constant
c = heat capacity: cal/g
C = concentration: g mole/liter
    C_p^0: of hydrogen peroxide at the inlet
    C_p: of hydrogen peroxide in the reactor
    C_t^0: of sodium thiosulfate at the inlet
    C_t: of sodium thiosulfate in the reactor
C_3, C_4 = constants
CR = correlation coefficient
D_a = agitator diameter: in.
E = activation energy: 17,455 cal/g mole
ES = standard error
k = reaction rate constant
k_0 = initial reaction rate constant
m = agitated fraction of the tank contents
    m_1: evaluated with the temperature taken at 1 inch from the tank bottom
    m_1^0: m_1 when the agitator is at rest
N = agitator speed: rev./min.
N_{Re} = modified Reynolds number: $N D_a^2 \rho/\mu$
P = power consumption: watt
PS = specific gravity
    PS: at the outlet
    PS_0: at the inlet
q = inlet feed rate: liters/min.
R = perfect gas constant: 1.987 cal/g mole-K
R_F = C_p^0/C_t^0
t = temp., °C
    t: at the outlet
    t_0: at the inlet
    t_1: at 1 in. from the bottom of the tank
    t_{cm}: in the agitated volume of a combined reactor
T = absolute temp., K
    T: at the outlet
    T_0: at the inlet
V = volume of solution in the reactor: liters
x = conversion based on limiting reactant: $(C_t^0 - C_t)/C_t^0$
    x: at the outlet
    x_m: at the outlet of a CSTR
    x_t: at the outlet of a tubular reactor
    x_{cm}: in the agitated part of a combined reactor
    x_{ct}: at the outlet of the tubular part of a combined reactor
α = stoichiometric ratio: moles H_2O_2/mole $Na_2S_2O_3$ = 2.0
$(-\Delta H)$ = heat of reaction: 140,000 cal/g-mole
ΔPS = specific gravity difference: $PS_0 - PS$
θ = residence time: V/q (min.)
    θ: of a reactor
    θ_m: of a mixed reactor
    θ_t: of a tubular reactor
    θ_{cm}: of the agitated part of a combined reactor
    θ_{ct}: of the tubular part of a combined reactor
μ = viscosity
ρ = density: g/cm^3

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