

Effect of drag-reducing additives on mixing and residence times in continuous-flow stirred tanks

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ABSTRACT

Polyethylene oxide (PEO) was used as a drag-reducing additive in a continuous-flow-stirred tank and its influence on mixing and residence times was investigated. It was found that the presence of a small amount of PEO (as low as 40 ppm) caused a noticeable change in the mixing time data as compared to that of pure water. The direction of change was found to be dependent on the liquid flow rate. The average residence time decreased with an increase in PEO concentration. The depression in the mixing time curve, observed at the critical impeller speed by other investigators, disappeared due to the presence of PEO. In agreement with the literature, mixing time was found to be proportional to the Froude number raised to an exponent α , where α is a constant which depends on the type of impeller used.

INTRODUCTION

Mixing of fluids in agitated vessels is one of the most common unit operations in the chemical industry. For the complete design of mixing equipment, it is necessary to predict the power consumption required to operate under a given set of conditions in order to achieve a desired degree of homogeneity. The mixing time is not as precisely defined as the power requirement. It is a subjective measure based on the approach of the vessel contents to an arbitrarily defined level of mixedness. Mixing time measurements are usually based on the analysis of a transient chemical or physical property such as color, temperature or conductivity. The observed mixing time depends on the degree of homogeneity, on the experimental technique used, and on the scale of the mixing process investigated (i.e. micro or macro). Therefore, data reported by different researchers are not readily comparable.

An area which has stimulated research in the past few years is the use of drag-reducing additives (DRA) in agitated vessels for the purpose of impeller torque suppression resulting in power saving. The DRA commonly employed consists of polymers, solid fibers or surfactants in pure form or in combination. Although the reduction in power consumption can certainly be obtained by the addition of DRA (Lumely 1969; Lee *et al.* 1974; Masheklar *et al.* 1975a, b; Al-Ameeri 1987), it is not clear, however, as to whether or not the mass and heat transfer processes will be affected in any significant way. Indeed, since the torque suppression is linked to an

alteration in hydrodynamics of the system, it is natural to anticipate that such changes will probably occur. However, the direction in which such transport processes will be affected is not clear.

In certain industrial processes it is important to maintain good circulation patterns in the agitated vessels. Thus it is highly desirable to find out what influence the drag-reducing additives exercise upon the mixing time required to achieve a certain degree of homogeneity.

Surveying the literature, it was found that relatively little work has been done on the effect of DRA on mixing times and that work has focussed on mixing in batch systems, for example, Kramers *et al.* (1953), Van de Vusse (1955), Norwood & Metzner (1960), Prochazka & Landau (1961), Holmes *et al.* (1964), Brennan & Lehrer (1976) and Quraishi *et al.* (1977). Although continuous-flow stirred tanks are widely used in the chemical industry, they have received almost no attention in these investigations. The main objective of this study is to investigate the effects of DRA on the mixing process in a continuous-flow stirred tank. Such study is important in order to assess the benefits of using DRA in practical applications.

EXPERIMENTAL

Fig. 1 is a schematic diagram of the experimental apparatus used which consisted of a one liter (ID = 11.6 cm) unbaffled cylindrical tank fitted with feed and discharge ports for continuous flow of liquid through the tank. A Fisher steady-speed stirrer motor with a 6.4 cm diameter vertical propeller was used for agitation. A variable speed pump, connected to the feed line, provided a steady flow of liquid to the mixing tank. The mixing times were determined by recording the variation of concentration at a point near the discharge from the tank after a small pulse of a tracer (NaCl solution) was injected into the tank by means of a syringe. A conductivity meter, made by Analytical Control Italia (Model 101), measured the resistance of the conductivity

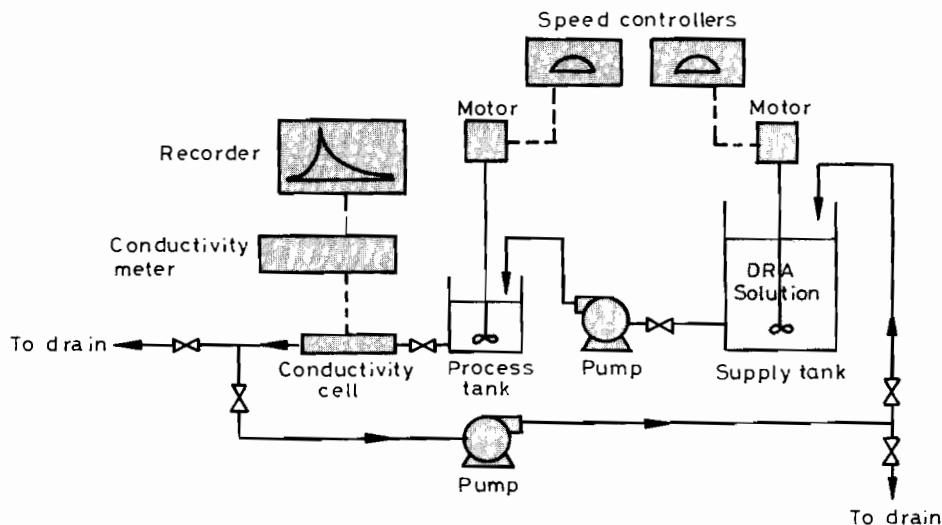


Fig. 1. Experimental apparatus.

probe, and a recorder was used to record the resistance variation of the conductivity probe with time. Since the conductivity of the solution was a linear function of the tracer concentration over the concentration range investigated, the response curve recorded was indicative of the variation of concentration with time at the discharge point. The drag-reducing additive used in this study was polyethylene oxide (PEO) supplied by Ferak of Berlin with an average molecular weight of 190–210 and a density of 1.130 g/cc.

RESULTS AND DISCUSSION

Fig. 2 is a sketch of a typical chart recording representing a response curve for a pulse input. Similarly to the approach of Biggs (1963), three characteristic mixing times, shown on the response curve, are defined as follows:

- t_1 : the time required for the tracer to pass through the dead volume from the discharge point to the conductivity cell.
- t_2 : the time corresponding to the maximum concentration measured, C_M .
- t_3 : the terminal mixing time required for the tracer concentration to approach 5% of C_M .

Over the concentration range investigated, it was established experimentally that vertical distances on the recorder chart were directly proportional to the

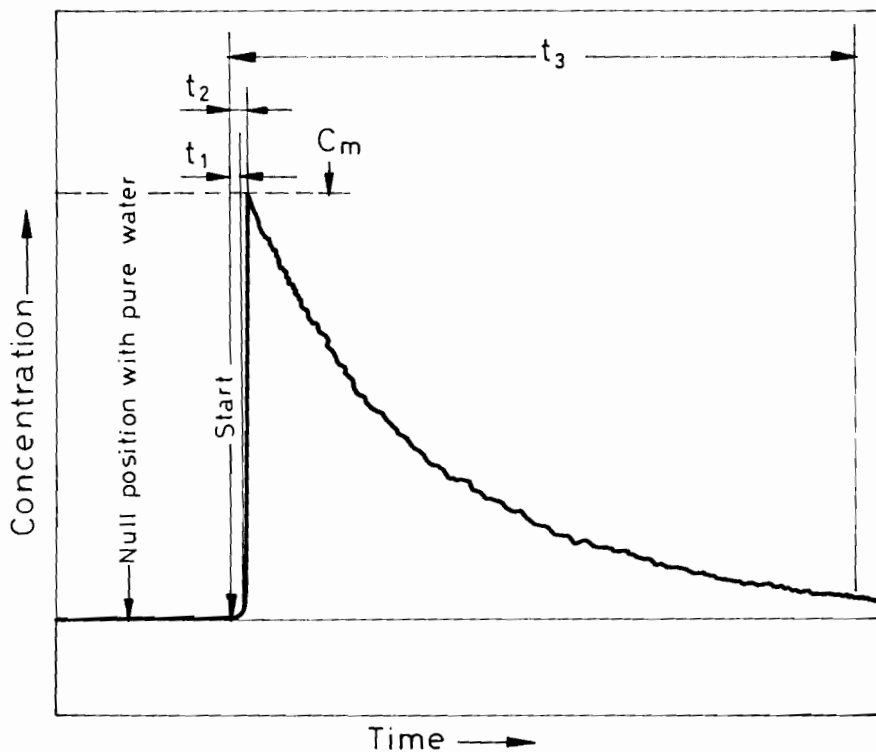


Fig. 2. A typical response curve for a pulse input.

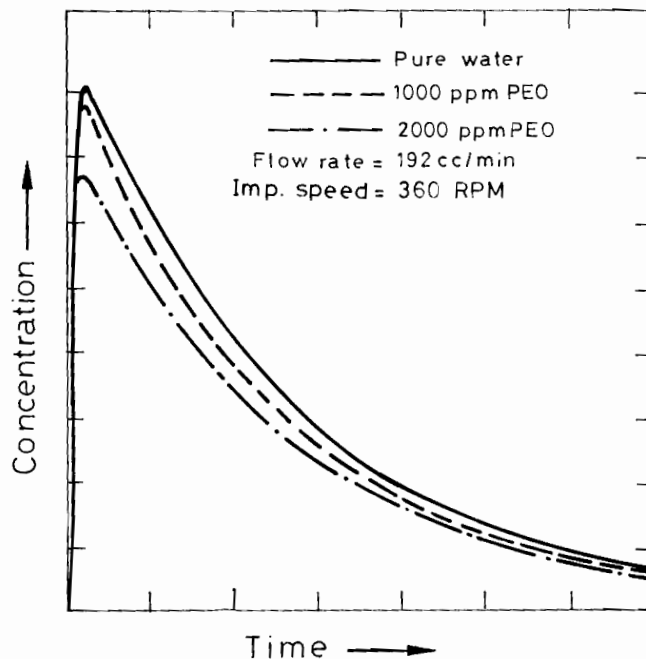


Fig. 3. Comparison of response curves for pure water and PEO solutions of different concentrations.

concentration: therefore, the 5% deviation required to measure t_3 was obtained by direct measurement on the chart.

Fig. 3 illustrates three response curves, at a fixed flow rate of 192 cc/min and a fixed rpm of 360, for pure water, 1000 ppm and 2000 ppm PEO solutions respectively. The curves are superimposed in such a way as to eliminate the small shift in baseline due to the difference in conductivity between pure water and polymer solutions. Thus the difference in the three curves is attributed to the change in the circulation and flow patterns in the tank due to the presence of the DRA.

For a continuous-flow stirred tank, the response curve of a pulse input can be represented by an equation of the form

$$C = C_0 e^{-t/\bar{t}} \quad (1)$$

where

C = tracer concentration at time t

C_0 = initial tracer concentration

\bar{t} = average residence time

As clearly explained by Westertrep *et al.* (1984), the average residence time (\bar{t}) can differ from the holding time ($\tau = V/q$) which is also often called average residence time. For example in the case of adsorption on a catalyst or on the reactor walls, the average residence time is larger than the holding time.

Fig. 4 is a semi-log plot of concentration *v.* time as derived from the response curves of three different PEO concentrations at three different flow rates. As seen from this figure, the slopes of these lines ($-1/\bar{t}$) are dependent on both flow rate and PEO

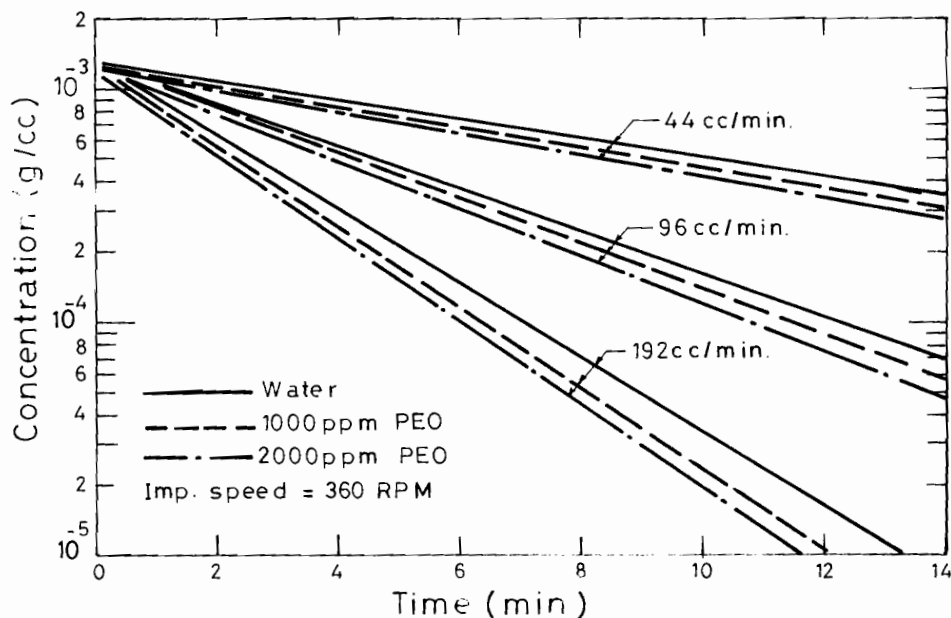


Fig. 4. Concentration *v.* time derived from response curves.

concentration. The effect of PEO concentration on the average residence time (\bar{t}) is illustrated in Fig. 5. At a fixed flow rate (q), the average residence time decreases with increase in DRA concentration. This can be attributed to the decrease in friction forces and/or a change in the mixing pattern due to the presence of the long chain polymer molecules which may hinder spreading of the tracer and cause channeling and short circuiting in the flow stream lines. The role played by the drag-reducing additives in the boundary layer near the solid surface is not yet clear. It is possible that these additives make mixing in this region less efficient, thus excluding a certain volume from the mixing process and as a result reduce the average residence time.

It should be emphasized that Equation (1) refers to a fixed DRA concentration. The straight lines shown in Fig. 4 were obtained directly from the response curves (Fig. 3 and similar curves). The linear behavior of the concentration *v.* time on a semi-log plot indicates that Equation (1) provides a relatively good representation of the experimental data.

Research is continued in our laboratories to collect data under various conditions and for different drag-reducing additives. The objective is to develop a general model that incorporates the DRA concentration effects in a single equation. Cooper & Jeffreys (1971) discussed different stirred-tank models which account for short circuiting, partial plug flow and partial stagnation in various combinations. It is possible that this combined effect approach may provide a good base for the general model sought.

Fig. 6 is a log-log plot of dimensionless mixing time (Nt_3) against impeller speed (N) for pure water and a dilute PEO solution at two different flow rates. It is observed that the presence of a small amount of PEO as low as 40 ppm has caused a noticeable shift in the data as compared to that of pure water. At a flow rate of 192 cc/min and a

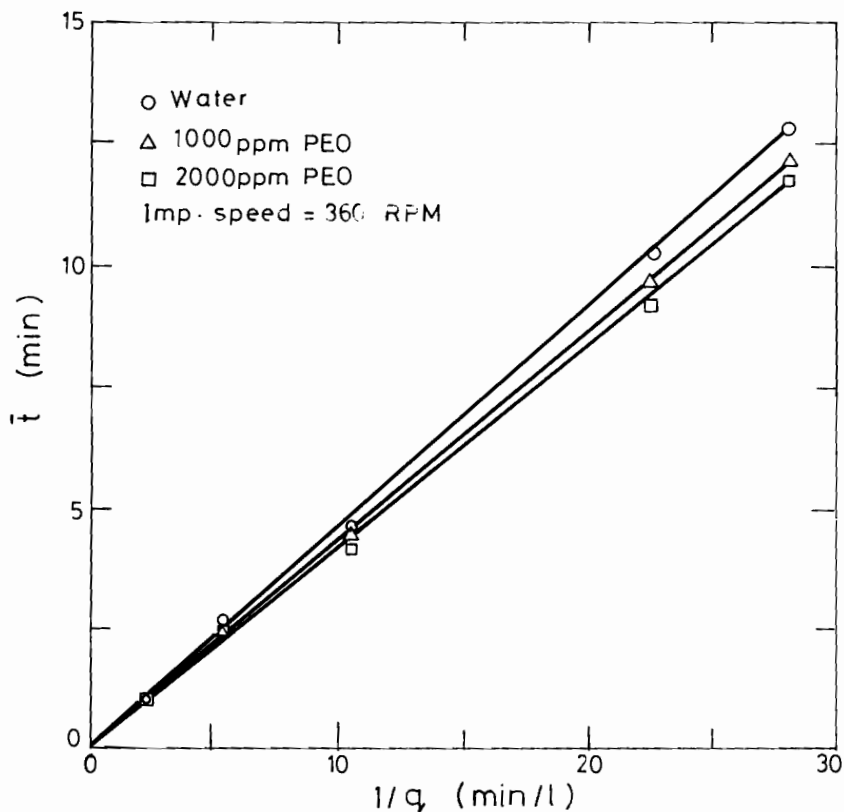


Fig. 5. Effect of PEO concentration on the average residence time.

fixed impeller speed, the dimensionless mixing time is slightly higher for PEO solution than that of pure water. At the higher flow rate (435 cc/min) the trend seems to be the opposite. The reversal of the trend at higher flow rate may be due to alterations in the boundary layer resulting in enhanced mixing. This observation is rather complex and difficult to explain, since the definition of t_3 involves the value of C_M which is affected by the additives in addition to the effect of the impeller speed which is also included in the dimensionless mixing time (Nt_3). Experiments under different conditions are being conducted in an attempt to isolate the effects of these factors which will perhaps lead to a better understanding of this phenomenon.

The mixing times t_1 and t_2 were found to be practically independent of PEO concentration even at a concentration as high as 2000 ppm. This can be easily observed in Fig. 3.

For mixing time determinations in agitated vessels, Brennan & Lehrer (1976) observed the presence of a critical impeller speed (N_{crit}), beyond which air bubbles were entrained by the impeller and dispersed in the liquid as a result of the formation of a deep vortex. Brennan & Lehrer (1976) reported that plots of mixing time *v.* impeller speed exhibited minima at critical impeller speeds. Fig. 7 illustrates a plot of mixing time (t_3) *v.* impeller speed for pure water and 40 ppm PEO solution. At a flow rate of 192 cc/min, N_{crit} is observed for pure water data but not for PEO solution data which

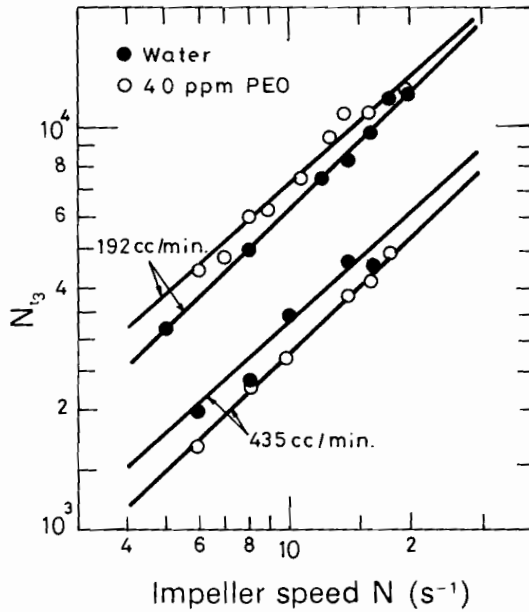


Fig. 6. Dimensionless mixing time *v.* impeller speed.

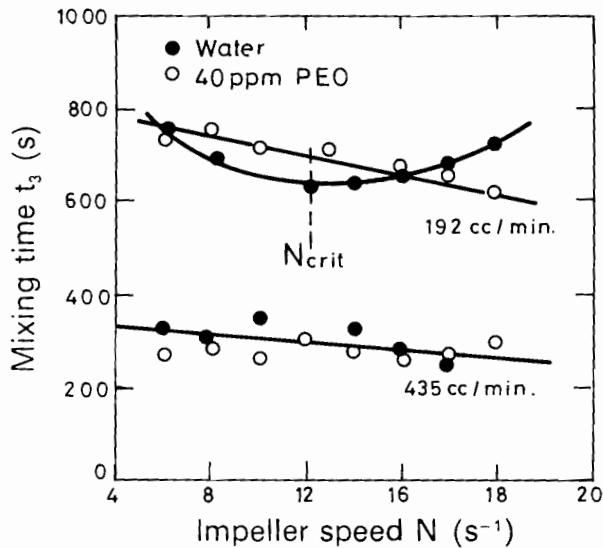


Fig. 7. Disappearance of critical impeller speed due to presence of PEO.

lie on a straight line. The presence of a DRA in an agitated vessel is known to inhibit vortex formation as discussed in detail by Gordon & Balakrishnan (1972). This explains the disappearance of N_{crit} in the case of PEO solution. At the higher flow rate (435 cc/min), the mixing time data of pure water do not seem to exhibit any distinct minimum, perhaps due to the disturbance of the vortex by the high rate of liquid flow.

Most workers have correlated their mixing time data using the dimensionless groups $Nd^2\rho/\mu$ (Reynolds) and N^2d/g (Froude). Comparisons of data taken by different researchers are usually difficult because of wide variations in experimental techniques and equipment.

For unbaffled vessels, Van de Vusse (1955) and Kafarov *et al.* (1971), reported that Nt_3 was proportional to F_r^α , where the exponent α is a constant which depends on the type of impeller used. In Table 1 an attempt is made to compare the values of α reported in the literature with that obtained in this study. As seen from this table, different values of α were reported from different impellers ranging from -0.30 to 0.80 . In this work, an average of $\alpha = 0.46$ was obtained which falls in the middle range between the values of disc turbine and flat-blade impellers reported by Kafarov *et al.* (1971).

Mixing time data have also been correlated using a dimensionless group called the pumping coefficient ($N_q = q/Nd^3$). In this study, it was found that the correlation could be represented by an equation of the form

$$Nt_3 = a(q/Nd^3)^b \tag{2}$$

Fig. 8 is a log-log plot of Nt_3 versus N_q . As seen from this figure, the correlation is

Table 1. Values of Froude number exponent (α) reported by different authors

Author	Type of impeller	α	Re range
Kafarov <i>et al.</i> (1971)	Disc turbine	0.80	$2.0 \times 10^3 - 3.0 \times 10^5$
	Flat blade turbine	0.12	$2.0 \times 10^3 - 3.0 \times 10^5$
Van de Vusse (1955)	Hydro-turbine	-0.30	$10^2 - 10^5$
Brennan & Lehrer (1976)	Flat blade turbine	0.10	$10^4 - 2.0 \times 10^5$
This work	Propeller	0.46	$2.0 \times 10^4 - 8.0 \times 10^4$

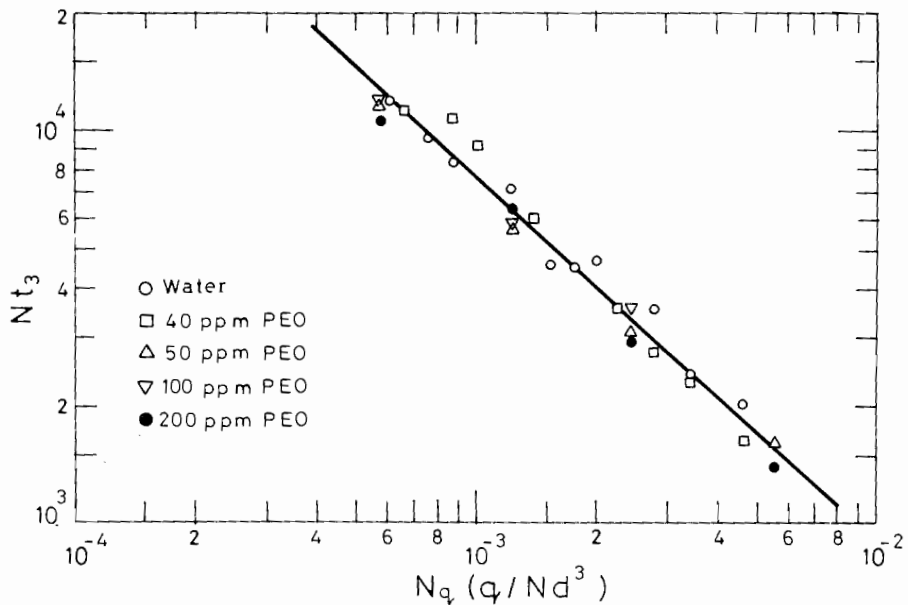


Fig. 8. Dimensionless mixing time t_3 , pumping coefficient.

linear. A least squares fit of the data gave a value of $a = 12.73$ and $b = -0.928$. The average deviation of the PEO data, up to a concentration of 200 ppm, is close to that of pure water indicating that in this concentration range and for this particular correlation, the effect of PEO seems to be insignificant.

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NOMENCLATURE

- C tracer concentration at time t , g/cc
 C_0 initial tracer concentration, g/cc
 Fr Froude number, dimensionless

N	impeller speed, s^{-1}
N_q	pumping coefficient, dimensionless
q	liquid flow rate, cc/min
Re	Reynolds number, dimensionless
t_1, t_2, t_3	characteristic mixing times defined in Fig. 2, s
\bar{t}	average residence time, min
V	tank volume, cc
τ	holding time = V/q , min

أثر المواد المضافة المقللة لقوى الاحتكاك في درجة
الخلط وزمن المكوث في آنية المزج ذات السريان
المستمر

رشيد سالم العميري ونعيمة علي عيسى أحمد
قسم الهندسة الكيميائية بجامعة الكويت ، ص . ب ٥٩٦٩ ،
الصفحة ١٣٠٦٠ ، الكويت

خلاصة

تمت دراسة أثر أوكسيد البولي اثلين ، كعامل مقلل لقوى الاحتكاك ، في درجة المزج وزمن المكوث في الآنية ذات السريان المستمر .
وقد تبين من الدراسة أن وجود كمية صغيرة من أوكسيد البولي اثلين بما يقارب ٤٠ جزءا في المليون له تأثير مباشر على زمن المزج ، كما تبين أن اتجاه التأثير يعتمد على معدل سريان السائل ، وان معدل زمن المكوث يتناقض مع تزايد تركيز أوكسيد البولي اثلين . ومن نتائج الدراسة وجد أن زمن المزج يتناسب تناسباً طردياً مع رقم فراود مرفوعاً للأس ∞ ، حيث ∞ ثابت يعتمد على شكل وحجم مروحة جهاز المزج .

