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MIXING OF TWO MISCIBLE HIGHLY VISCOUS NEWTONIAN LIQUIDS IN A HELICAL RIBBON AGITATOR

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In a helical ribbon agitator, mixing patterns and mixing times for two miscible, highly viscous Newtonian liquids with different viscosities are investigated. From the observed mixing patterns, empirical correlations for mixing time are obtained as functions of the Reynolds number and a dimensionless number defined by the ratio of gravitational to viscous force. The optimum operational conditions for the mixing process are predicted from these correlations.

Introduction

Mixing of two miscible liquids having different rheological properties is frequently encountered in the chemical and the food industries. Several investigators[3,4,7] have observed mixing patterns and measured mixing times, but most of their experiments were restricted to low-viscosity liquids.

In this work, the two miscible, highly viscous Newtonian liquids with different viscosities and densities are mixed in a helical ribbon agitator. Three distinct mixing patterns are observed according to the agitation speed, the physical properties of the liquids and their feed ratio. The mixing time correlation with the Reynolds number is found to differ for each mixing pattern. A new dimensionless number, the ratio of gravitational to viscous force, is proposed to make a concise formula of mixing time. The optimum operational conditions for the mixing process are also discussed.

1. Experimental

Figure 1 shows the geometrical configuration of the helical ribbon impeller. Newtonian aqueous solutions of corn syrup with various viscosities were used for tests. Mixing patterns and mixing times were observed by the decoloration method, employing the reaction between iodine and sodium thiosulfate in the presence of a starch solution. The optimum equivalent ratio, 1.4-fold sodium thiosulfate to iodine, suggested by several investigators,[2,5] was adopted in all experiments. The sodium thiosulfate solution was mixed well with the more viscous liquid and both the iodine and the starch solutions were mixed with the less viscous one, in advance. An example of the initial locations of the two liquids is also shown in Fig. 1. The mixing times were obtained in the following

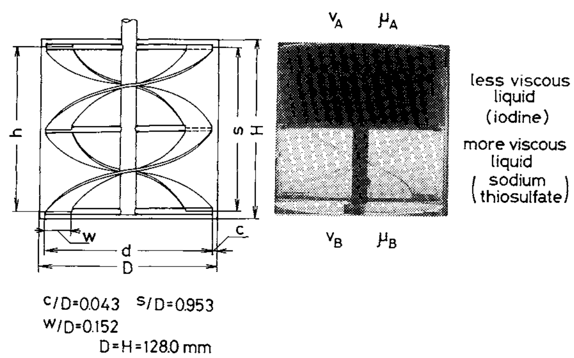

Fig. 1. Geometrical configuration of helical ribbon agitator and initial location of two miscible liquids.

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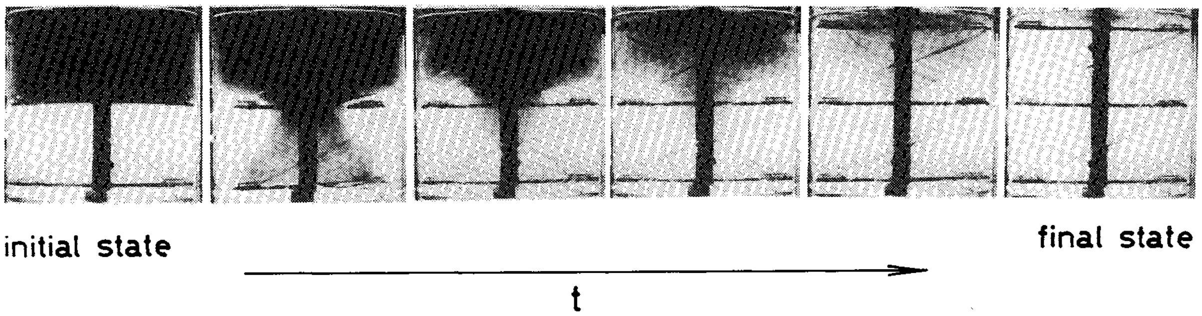

Fig. 2. First mixing pattern ($v_B/v_A=1$, $\mu_B/\mu_A=6.85$, $Re=0.831$, $Nt_m=186$).

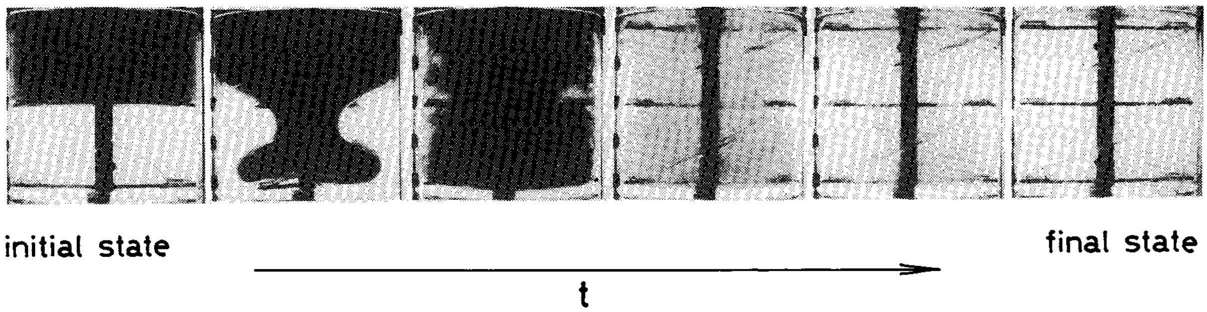

Fig. 3. Second mixing pattern ($v_B/v_A=1$, $\mu_B/\mu_A=6.85$, $Re=6.74$, $Nt_m=41.1$).

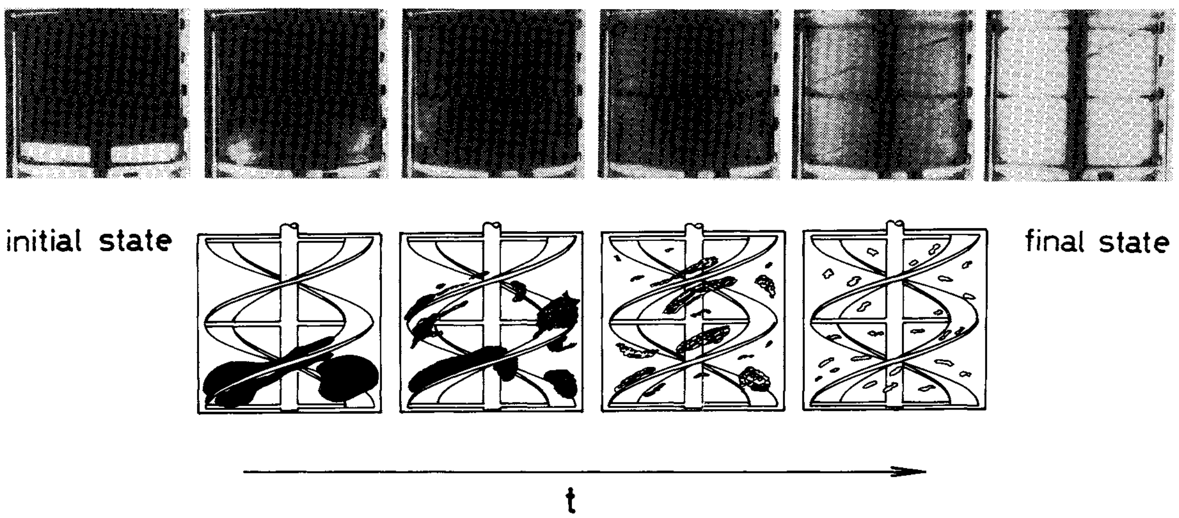

Fig. 4. Third mixing pattern ($v_B/v_A=0.3$, $\mu_B/\mu_A=255$, $Re=5.76$, $Nt_m=189$).

ranges: $1300\ \mathrm{kg \cdot m^{-3}} \leqq \rho_A \leqq \rho_B \leqq 1420\ \mathrm{kg \cdot m^{-3}}$, $0.109\ \mathrm{Pa \cdot s} \leqq \mu_A \leqq \mu_B \leqq 136\ \mathrm{Pa \cdot s}$, $0.3 \leqq v_B/v_A \leqq 3$, $1 \leqq \mu_B/\mu_A \leqq 746$, $0\ \mathrm{kg \cdot m^{-3}} \leqq \Delta\rho \leqq 100\ \mathrm{kg \cdot m^{-3}}$, $0.00710\ \mathrm{s^{-1}} \leqq N \leqq 3.27\ \mathrm{s^{-1}}$, and $0.00747 \leqq Re \leqq 110$, where Re is evaluated by the viscosity and the density of the mixed liquid after an experimental run. The direction of impeller rotation was fixed to create an upward flow at the blade.

2. Mixing of Two Liquids with Same Physical Properties

Several sets of two liquids with the same viscosities and densities were prepared and experiments for different volume ratios, $v_B/v_A=0.3$, 0.5, 1, 2, 3 and 10, were carried out. The mixing patterns were almost the same as observed by previous investigators[1,5,6] by the method using a small amount of tracer. The mixing time measured was almost independent of the volume ratio. For this case, the dimensionless mixing time becomes:

$$Nt_m=40.2 \quad (Re<10) \tag{1}$$

3. Mixing of Two Liquids with Different Viscosities and Densities

3.1 Mixing pattern

Figures 2 to **4** show the three different mixing patterns observed in the mixing of two liquids with different viscosities and densities. Here we call them the first, the second and the third mixing patterns. In Fig. 4, sketches of the third mixing pattern are also shown for a better understanding of the mixing process.

In the first mixing pattern, the upper liquid permeates gradually into the lower liquid and the interface between the two liquids rises slowly. Therefore, mixing proceeds only inside the lower liquid and the permeate flow rate is a controlling step in this mixing process. The mixing time becomes longer than that for the two liquids with the same physical properties.

The second mixing pattern is almost the same as that obtained in mixing of two liquids with the same viscosities and densities. The dimensionless mixing time is nearly equal to that given by Eq. (1).

In the third mixing pattern, it is noted that the blade motion disperses the more viscous liquid into large drops. These drops are transported into the high-shear field by the bulk flow and mixing proceeds by the penetration of the more viscous liquid into the less viscous one through the interfaces of these drops. With the lapse of time, the drop size gradually decreases and mixing finally reaches completion. The mixing time for the third mixing pattern becomes longer than that for the second mixing pattern.

The conditions for each mixing pattern depend on the physical properties of liquids and their feed ratio as well as the agitation speed. Namely, in the range of low Reynolds number, the first mixing pattern appears in all cases, but in the range of high Reynolds number mixing proceeds by the third pattern when the conditions, $v_B/v_A<1$ and $\mu_B/\mu_A>60$, are both satisfied, and under other conditions it proceeds by the second pattern.

3.2 Mixing time

The relationship of the dimensionless mixing time to Reynolds number is shown in **Fig. 5**.

In the first mixing pattern, the permeate flow rate plays an important role in mixing. As the Reynolds number decreases, this permeate flow rate decreases and the mixing time increases. The slopes for the sets of data, which are obtained for the same viscosities and densities of each initial constituent liquid and its initial location, are almost equal.

The mixing times for the second pattern are approximately equal to those for mixing of the two liquids with the same physical properties.

In the case of the third mixing pattern, the mixing time can be controlled by the size of the drop formed at the beginning of mixing. An increase in Reynolds number enlarges the drop size formed, and the mixing time becomes long. Scattering of measured mixing times, as shown in Fig. 5, may be due to the complicated formation of the various sizes of drops.

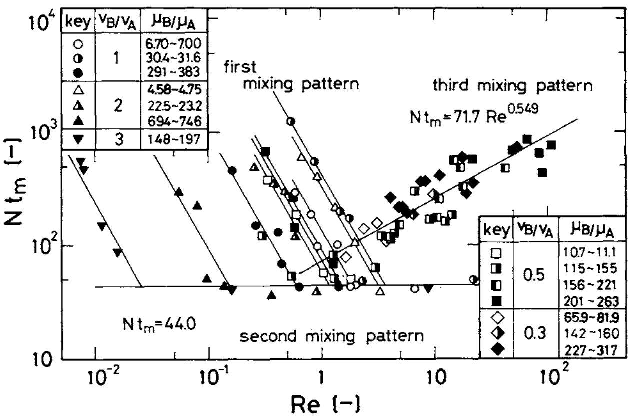

Fig. 5. Measured mixing time of two miscible liquids with different physical properties.

1) Correlation of mixing time As shown in Fig. 5, the mixing times for the second and the third mixing patterns are expressed by the following equations.

For the second mixing pattern:

$$Nt_m=44.0 \tag{2}$$

For the third mixing pattern:

$$Nt_m=71.7Re^{0.549} \tag{3}$$

In the first mixing pattern, it can be considered that the difference in densities between the two liquids has a significant influence on the mixing time. Therefore, we proposed a new correlation based on a dimensionless number as $N_M=\Delta\rho L_B g/\mu_M N$, which is the ratio of gravitational to viscous force. The mixing time for the first mixing pattern is represented by the following equation.

For the first mixing pattern:

$$Nt_m=0.0176{N_M}^{1.56} \tag{4}$$

This correlation method differs from that proposed by Zlokarnik[7] for two miscible low-viscosity liquids. The validity of Eq. (4) is confirmed by more experimental data, as shown in **Fig. 6**.

2) Optimum operational conditions **Figure 7(a)** shows the relation between Nt_m and Re in the case, $v_B/v_A<1$ and $\mu_B/\mu_A>60$, in which mixing proceeds by the first or the third mixing pattern. Figure **7(b)** shows the relation in the other cases of the first or the second mixing pattern. In these figures, the arrows indicate the optimum operational conditions for the smallest Nt_m, which represents the lowest power to obtain a certain degree of mixing. From Eqs. (2), (3) and (4), the optimum conditions can be expressed by the following equations.

$$N_M Re^{-0.352}=206 \tag{5}$$

$$\text{for} \quad v_B/v_A<1 \quad \text{and} \quad \mu_B/\mu_A>60$$

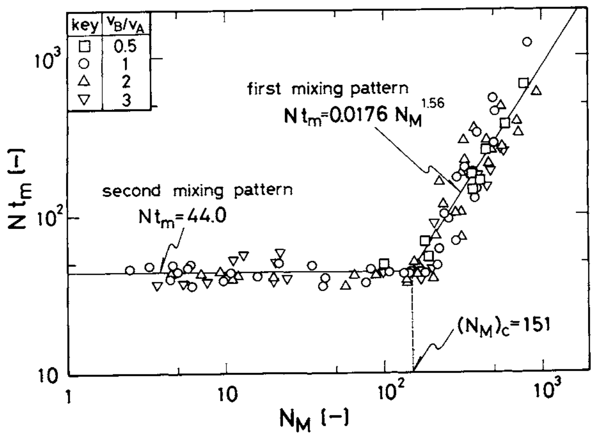

Fig. 6. Correlation of mixing time for first and second mixing patterns with N_M.

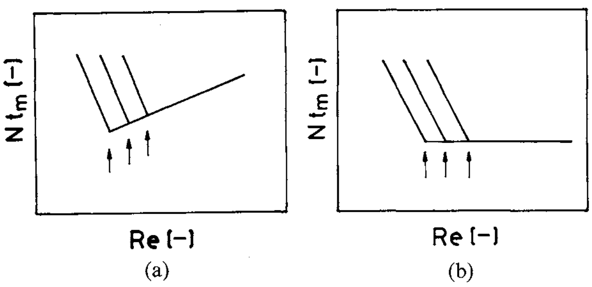

Fig. 7. Diagram of relation between mixing time and Reynolds number. (a) for $v_B/v_A<1$ and $\mu_B/\mu_A>60$; (b) otherwise.

$$N_M=151 \tag{6}$$

$$\text{for} \quad v_B/v_A \geqq 1 \quad \text{or} \quad \mu_B/\mu_A \leqq 60$$

Conclusion

For the system of two miscible, highly viscous Newtonian liquids with different viscosities and densities, mixing pattern and mixing time are investigated in a helical ribbon agitator. Three types of mixing patterns are observed according to the experimental conditions. The correlations based on Reynolds number or a new dimensionless number N_M are proposed to estimate the mixing time in each pattern. The optimum operational conditions for the mixing process are predicted from these correlations.

Nomenclature

c	= clearance between blades and wall	[m]
D	= diameter of vessel	[m]
d	= diameter of impeller	[m]
g	= gravitational acceleration	[$m \cdot s^{-2}$]
H	= height of vessel	[m]
h	= height of impeller	[m]
L_B	= height of more viscous liquid	[m]
N	= rotational speed of impeller	[s^{-1}]
N_M	= dimensionless number ($=\Delta\rho L_B g/\mu_M N$)	[—]
Re	= Reynolds number ($=d^2 N\rho_M/\mu_M$)	[—]
s	= impeller pitch	[m]
t	= time	[s]
t_m	= mixing time	[s]
v_A, v_B	= volume of less or more viscous liquid	[m^3]
w	= blade width	[m]
μ_A, μ_B	= viscosity of less or more viscous liquid	[Pa·s]
μ_M	= viscosity of mixed liquid	[Pa·s]
ρ_A, ρ_B	= density of less or more viscous liquid	[$kg \cdot m^{-3}$]
ρ_M	= density of mixed liquid	[$kg \cdot m^{-3}$]
$\Delta\rho$	= difference in density between more and less viscous liquids ($=\rho_B-\rho_A$)	[$kg \cdot m^{-3}$]

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