BLENDING LIQUIDS OF DIFFERING VISCOSITIES AND DENSITIES IN STIRRED VESSELS

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Mixing time measurements were carried out in turbulently stirred vessels with miscible liquids of differing viscosities and densities. Depending on the flow characteristics and liquid properties, three mixing regimes can be defined for buoyant additions: the *stirrer controlled regime*, the *gravity controlled regime* and the *intermediate regime*. While in the stirrer controlled regime, the dimensionless mixing times are equal to those for liquids of equal properties (about 30 for the geometry used), the gravity controlled values can be much higher. In the intermediate regime, the dimensionless mixing times can be anywhere in between.

Keywords: stirred vessels; mixing time measurements; density difference; viscosity difference

INTRODUCTION

This study[1] is concerned with the turbulent mixing of miscible liquids in stirred tanks. Insufficient understanding of mixing processes causes the continuous loss of a large amount of money in the chemical process industries[2]. Many processes, for instance in the petrochemical industries, but also in the food industry and in paint manufacturing, hinge on the blending of liquids of differing viscosities and densities. These differences can yield unexpectedly long mixing times, a situation that is undesirable in view of process planning and product quality control.

Traditionally, visualization and mixing time measurements are very important sources of information about the processes involved. The literature on these subjects is vast[3-7], mainly because the number of independent variables is large. Each combination of vessel geometry, stirrer type, liquid properties and liquid addition method can be expected to behave differently.

The literature systematically dealing with the effects of viscosity and density differences is mostly limited to cases where layers of liquid are stratied at the beginning of the process (e.g. Van de Vusse[8], Zlokarnik[9] and Rielly and Pandit[10]). In those situations, the ratio between the added liquid volume and the bulk volume is comparatively large. In the process industries smaller quantities of liquid are often poured into the vessel while stirring is in progress. It is on these systems that the present work focuses. The present work centres on the type of system in which the additions consist of small quantities of liquid with viscosities and densities that differ from those of the bulk.

In the work by Smith and Schoenmakers[11], which was carried out preliminary to this project, experiments were carried out with high viscosity additions in water, because differences in mixing times were expected in that situation. During extended measurements with aqueous additions to viscous bulks, it became clear that density differences are more likely to cause longer mixing times than viscosity

differences[12]. A new series of experiments proved the dependence of mixing time on a combination of viscosity and density differences.

More recently, Burmester[4] described experiments, carried out in vessels of 12.7 and 29 cm diameter vessels, similar to those presented here. The densities of the added liquid were always higher than those of the bulk. The present paper focuses on the behaviour of buoyant additions, and includes experiments in a larger, 64 cm diameter vessel.

The experimental setup is discussed first. The measurements with buoyant additions are then presented, followed by those with settling additions.

EXPERIMENTAL

For the present study, mixing time measurements have been carried out in geometrically identical perspex vessels of 29 cm and 64 cm diameter. The geometry of the vessels is shown in Figure 1. The vessels were fitted with four baffles. There was no gap between the baffles and the vessel wall. The vessels were mounted with a downward pumping 45° pitched 6-blade turbine.

Additions were made using a pipette with a wide mouth, positioned near the impeller, at the surface or in the bulk. The volume of liquid added was always very small compared with that of the bulk liquid: the volume ratio V_a/V was typically of the order of 10^{-5} to 10^{-4}. Rielly and Britter[13] found no significant effect of changing V_a in the range of 5 to 120 cm³ in a 29 cm vessel. In most of the experiments in the present work, the added volume size was 3 cm³ in the 29 cm (19 litre) vessel and 5 cm³ in the 64 cm (206 litre) vessel.

A conductivity method was used to determine mixedness. The period after which the deviations from the final value remain within a fraction of 0.05 of the total conductivity step is termed the mixing time (t_m). The conductivity probe is shown in Figure 2. Several probe positions were tested:
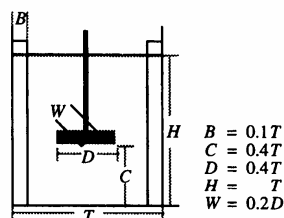
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$B = 0.1T$
$C = 0.4T$
$D = 0.4T$
$H = T$
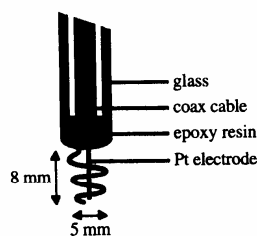$W = 0.2D$

Figure 1. Geometry of the mixing vessels.

Figure 2. Conductivity probe.

behind a baffle, in the stirrer discharge stream and in the centre of the circulation loop that is formed by the flow in the vessel. The only significant difference between the measured mixing times occurred in the transition region between turbulent and laminar flow (see next section). For all experiments, the probe was placed in the stirrer plane, halfway between the stirrer and the vessel wall.

The liquids used in all the experiments were water based, so all liquids were mutually miscible. Polyvinylpyrrolidone (PVP), sodium carboxymethyl cellulose (CMC), sugar syrup and glycerol were used to raise both the viscosity and the density. Ethanol and NaCl were used to change the density. NaCl and NaOH were used to raise the conductivity of the addition. In total, densities ranged from 900 to 1500 kg m^{-3}. The density difference $\Delta\rho$, defined here as the density of the added liquid, ρ_a, minus the density of the bulk liquid, ρ_0, ranged from -100 to $+400$ kg m^{-3}. Viscosities (μ) ranged from 1 to 104 mPa s. The power law index of the viscosity of the liquids, measured using a Couette type viscometer, always exceeded 0.9, which for the stirrer speeds used here would give a decrease in viscosity of at most 10%. Therefore, the liquids were regarded to be Newtonian. An overview of the liquids reported on in this paper is given in Table 1.

In the literature on miscible liquids the word 'drop' is frequently used to indicate parts of the added liquid. In that case, as in this paper, the word does not imply either immiscibility or the presence of interfacial tension. When miscible liquids are brought into contact, interfacial tension effects are almost absent[14].

For each condition (combination of viscosities, densitie and stirrer speed), depending on the scatter in the results, five to twenty measurements were carried out consecutively, giving average values and standard deviations for Nt_m (where N is the impeller speed). This 'dimensionless mixing time' represents the number of stirrer revolutions needed for homogenization. As a rule of thumb, differences that are larger than the standard deviation within a series of measurements, σ, will be regarded as significant.

It should be emphasized here that the average of Nt_m was calculated by determining the mixing time for each individual measurement and averaging those values, and not by averaging the conductivity responses and determining a mixing time from the averaged curve. The mixing times arrived at by the last method are too short because the averaged curves are too smooth.

MIXING TIME MEASUREMENTS

Liquid was added near the stirrer, in the bulk and at the surface. The results are presented in that order.

Addition Near the Stirrer

When buoyant liquid is added near the stirrer, the upward forces are not strong enough to transport the addition to the surface. Moreover, in the vicinity of the stirrer the shear stresses and turbulence intensities are high, so that the added liquid is rapidly distorted, which further reduces buoyanc effects. This will be referred to as *stirrer controlled mixing*.

Figure 3 shows the resulting dimensionless mixing times vs. the Reynolds number Re:

$$Re \stackrel{\text{def}}{=} \frac{\rho_0 N D^2}{\mu_0},$$

where D is the impeller diameter and μ_0 the bulk viscosity. The additive was tap water with salt added for the purpose of the conductivity measurements. Data processing was done manually. The standard deviation within the series of ten measurements varies, not systematically, between 10 and 20% of the average. Two probes are used: one is positioned in the stirrer plane, the other close to the bottom of the vessel behind a baffle. The dimensionless mixing

Table 1. Overview of fluids used in the experiments. A bullet (●) indicates a combination of ethanol, glycerol and PVP.

figure	T cm	bulk: water + ...	μ_0 mPa s	addition: water + ...	μ_a mPa s	$\Delta\rho$ kgm^{-3}
3	29	PVP	1...115	—	1	< 0
table 2	29	PVP	10	●	1...100	−100...0
4, 6, 7	29	●	1, 9, 40	●	0.024...125	−100...−5
8	29	●	10	●	2...1000	−50...−5
9	64	—	1	●	5...100	−100...−5
10	64	PVP	8	●	58	−70
table 3	29	●	9	●	≈ 13	≈−20
12	64	PVP	1...8	●	86...1500	−80...−70
table 4	64	—	1	●	54...360	−85...−70
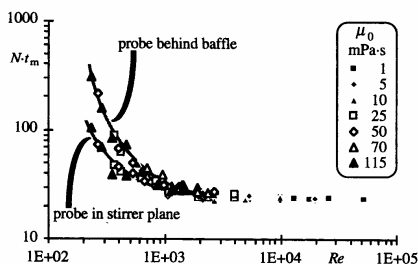
Figure 3. Nt_m vs Re. (T = 29 cm; μ_a = 1 mPa s; addition 3 cm above the stirrer).

Figure 4. Nt_m vs Re for six combinations of liquids. The dotted lines are intended to guide the eye. (T = 29 cm; μ_0 = 9 mPa s; V_a = 3 cm³; addition 1 cm below the surface, 5 cm from the shaft).

times in the turbulent regime are constant and both probes measure the same value. For Re lower than 1000, i.e. in the turbulent to laminar transition regime, the mixing times are higher. The ratio between mixing times measured behind baffles and those in the bulk increased with decreasing Re, to a value of about 3 at Re = 250.

In later experiments, the viscosities and densities of both bulk and addition were varied independently. Typical examples of dimensionless mixing times are given in Table 2 for $\mu_0 \approx$ 10 mPa s, all in the turbulent regime. The viscosity ratio μ_a/μ_o is denoted by μ^*. The average value of Nt_m for the data in the table is 26. The standard deviation within each series of six measurements, σ, varies, not systematically, between 11 and 19% of the average. The difference between the lowest value and the highest value in the table is 6, which is only a little more than σ, so again the correlation of Nt_m = constant can be used.

Experiments with μ_0 = 1 mPa s and settling additions ($\Delta\rho \approx$ 60 kg m⁻³) showed that for stirrer controlled mixing Nt_m is independent of μ^* for μ^* up to the tested value of 5000.

Addition in the Bulk

Three regimes

Addition of the liquid at positions far from the stirrer result in different mixing mechanisms. Experiments in the 29 cm vessel, partly reported on by Bouwmans and Van den Akker[12], showed that the mixing time is strongly influenced by viscosity and density differences when 3 cm³ of a tracer liquid is injected about 1 cm below the free surface. Figure 4 shows the dimensionless mixing times versus Re in this situation for six combinations of liquids; μ_0 = 9 mPa s.

For $\Delta\rho$ = −5 kg m⁻³ and μ^* = 0.11 (open squares) the mixing time corresponds to that of addition near the stirrer. The value of Nt_m is about 30 for Re > 10³. For the whole range of Re the stirrer frequency is high enough to produce a
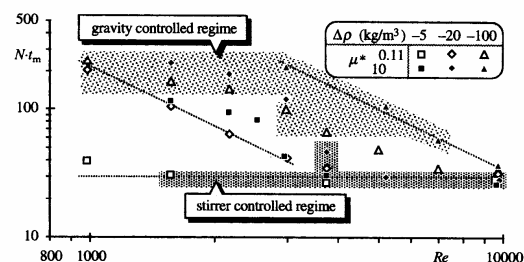
strong large-scale flow that can overcome buoyancy forces, so that the added liquid is transported to the stirrer region, where the drop is broken up. This will be called the *stirrer controlled regime*, by analogy with the case of addition near the stirrer (previous section). Figure 5 (a) shows a typical resulting conductivity response. The probe registers the first two or three passages of saline liquid, but each passage the passing becomes less pronounced. In this example, $Nt_m \approx$ 25. For $Re \approx$ 10³ the mixing time is more than 30% higher than 30 (see Figure 4). This is more than the standard deviation, σ, and the increase is caused by the turbulent to laminar transition, as in Figure 3. All other open squares lie in the turbulent regime: Re is larger than 10³.

In the other two cases with μ^* = 0.11 (open diamonds and open triangles) the buoyancy forces are stronger than the forces exerted on the added liquid by the bulk flow, so all or part of the additive rises to the surface. The liquid is then slowly merged with the bulk by turbulent eddies, which results in mixing times that can be ten times longer than in the stirrer controlled regime. The regime where all of the added liquid always rises to the surface will be termed the *gravity controlled regime*. An analogous situation arises when an addition that is denser than the bulk sinks to the bottom of the tank, as studied by Burmester[4]. In this regime the conductivity curve is much smoother (see Figure 5 (c), where $Nt_m \approx$ 150): the break-down of the layer at the surface by the turbulent eddies is a continuous process. The regime between the stirrer controlled regime and the gravity controlled regime will be called the *intermediate regime*. The conductivity response in this case is a combination of the other curves, as can be seen in Figure 5 (b) (where $Nt_m \approx$ 80). Sharp peaks during the first seconds indicate the passage of liquid that has been pulled down into the stirrer.

Table 2. Dimensionless mixing times for various viscosity ratios and density differences; Re = 1.6 × 10³ in all cases. (T = 29 cm; $\mu_0 \approx$ 10 mPa s; addition 3 cm above the stirrer).

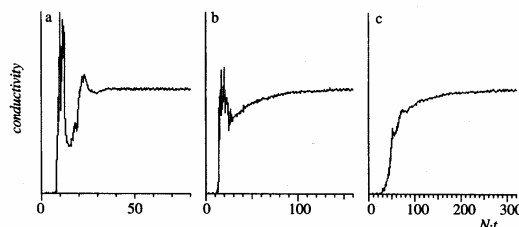| $\Delta\rho$ kg m⁻³	μ^* 0.1	μ^* 1.0...1.8	μ^* 10...14
0	25	26	29
−20	24	28	27
−100	30	25	24

Figure 5. Conductivity (in arbitrary units) as a function of dimensionless time; (a) stirrer controlled regime; (b) intermediate regime; (c) gravity controlled regime.

The smooth second part of the curve is caused by the mixing of the remaining fluid from the surface.

Figure 4 also shows the effect of μ^* on Nt_m for a constant density difference. For $\Delta\rho = -5\,\text{kg m}^{-3}$ (squares) the dimensionless mixing time is higher for $\mu^* = 10$ (solid squares) than for $\mu^* = 0.11$ (open squares). When the viscosity of the added liquid is high, the addition is less deformed by the mean flow. Less deformed drops experience smaller friction forces from the mean flow, resulting in larger upward velocities. In that case the liquid is more likely to reach the surface, which would result in the intermediate or gravity controlled regime.

For more negative values of $\Delta\rho$ (diamonds and triangles) the mixing time is also affected by μ^*: higher values of μ^* (solid markers) result in longer mixing times, because larger portions of the added liquid reach the surface. Moreover, once the addition has reached the surface, higher viscosities more strongly resist mixing by the bulk.

The Richardson number

From Figure 4 it is clear that the three mixing regimes cannot be distinguished on the basis of Re. A dimensionless group that does include the density difference is the Richardson number (see for instance Rielly and Pandit[10]):

$$Ri \equiv \frac{\Delta\rho g H}{\rho_0 N^2 D^2}$$

(with g the gravitational acceleration and H the liquid height in the vessel). For additions at a fixed position, it is a measure for the ratio of the potential energy needed to transport the added liquid to the stirrer and the kinetic energy of the bulk. The dimensionless mixing time as a function of the absolute value of Ri is given in Figure 6 for the same measurements as in Figure 4 and two extra data points. The figure shows that Ri sorts the data better than Re does, because buoyancy effects are taken into account. However, the viscosity ratio is not included in Ri, and two bands can be seen, one for $\mu^* = 0.11$ (open markers) and one for $\mu^* = 10$ (solid markers). The stirrer controlled regime and the gravity controlled regime—both determined by visual observation—are indicated by shading. The boundaries of the regimes are not sharp. Two data points have been added: one for $\mu_0 = 1\,\text{mPa s}$ (solid circle) and one for $\mu_0 = 40\,\text{mPa s}$ (open circle). The regime they belong to is the same as that of the neighbouring data points. However, they fall outside the band of data and the mixing time for the
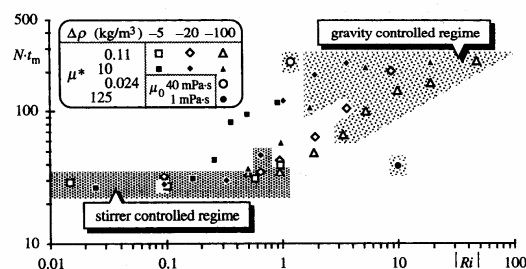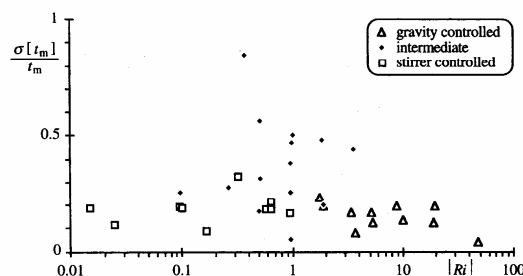

Figure 7. The relative standard deviation within the measurement series against $|Ri|$. ($T = 29\,\text{cm}$; $\mu_0 = 9\,\text{mPa s}$; $V_a = 3\,\text{cm}^3$; addition 1 cm below the surface, 5 cm from the shaft).

solid circle is almost that of the stirrer controlled regime. This shows that the bulk viscosity is an essential factor in the eventual gravity controlled mixing time.

In the intermediate region, where only part of the added liquid rises to the surface, the standard deviation within a series of repeat measurements is high. Figure 7 gives the relative standard deviation $\sigma[t_m]/t_m$ as a function of $|Ri|$. For $0.2 < |Ri| < 4$ the standard deviation reaches values of up to 80%, whereas outside that region the deviation remains below 30%.

The unpredictability of the mixing time in the intermediate regime is caused by the unpredictability of turbulent motion. In this regime the forces exerted on the addition by the bulk flow are of the same order as the buoyancy forces. Therefore, the turbulent part of the local velocity at the moment of addition determines the fate of the injected liquid. Moreover, the liquid contained in one drop does not always follow one path: very often part of the drop rises to the surface while the rest of the drop is transported to the stirrer where it is broken up. The amount of liquid that reaches the surface determines the mixing time, as will be shown in the next section. Due to this effect, the resulting mixing times can have any value from the stirrer controlled mixing time on the low side to the gravity controlled mixing time on the high side. This results in a large standard deviation in the mixing times.

The combined effect of density and viscosity differences

A characteristic of the Nt_m vs. $|Ri|$ graphs is the bend between the stirrer controlled regime and the intermediate regime. Above this bend, the mixing times depend on the amount of liquid rising to the surface, whereas for lower values of $|Ri|$ the mixing time is constant. As may be expected from the results discussed earlier, the location of the bend depends on the properties of the liquids being blended.

In Figure 8, the stirrer rotational speed where this transition occurs, N_t, is given as a function of the density difference and the viscosity of the added liquid. The bulk viscosity is about 10 mPa s. Drops were added 10 cm below the surface at a radial distance of 10 cm, 5° behind a baffle.

The figure shows that for $\mu_a < 200\,\text{mPa s}$ the value of N_t depends on μ_a as well as on $\Delta\rho$. For higher values of μ_a the dependence on μ_a is much lower: above a given value of μ_a the deformation after injection is so low that a further increase in μ_a does not change the chance of surfacing

Figure 6. Nt_m versus the absolute value of Ri for eight combinations of liquids; regimes are indicated by shading; $\mu_0 = 9\,\text{mPa s}$, except in those cases indicated by circles. ($T = 29\,\text{cm}$; $V_a = 3\,\text{cm}^3$; addition 1 cm below the surface, 5 cm from the shaft).
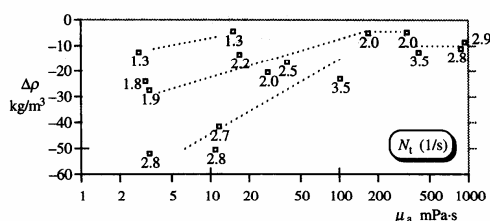
Figure 8. Stirrer rotational speed (N_t, s^{-1}) at the transition between the intermediate regime and the stirrer controlled regime, as a function of μ_a and $\Delta\rho$. The dotted lines are intended to guide the eye. ($T = 29$ cm; $\mu_0 \approx 10$ mPa s; $V_a = 3$ cm^3; addition 10 cm below the surface, 10 cm from the shaft).

Figure 10. Nt_m at three injection positions, 5 cm below the surface. Relative standard deviations are also given below the mixing times. ($T = 64$ cm; $\mu_0 = 8$ mPa s; $\mu_a = 60$ mPa s; $\Delta\rho = -70$ kg m^{-3}; $V_a = 5$ cm^3).

whereas relatively small changes in the density difference cause large changes in the value of N_t.

With buoyant additions of very high viscosity ($\mu_a = 10$ Pa s), mixing can be even less predictable than for lower added liquid viscosities, for then there are three possibilities:

• When the liquid rises to the surface it may remain there while it is slowly blended into the bulk. It may also form a long thread extending from the surface to the stirrer where it is mixed. Eventually, the thread is totally pulled down into the stirrer and mixed.

• The addition may also go to the stirrer. In that case the mixing is fast and usually Nt_m does not significantly differ from 30.

• When the liquid goes neither to the surface nor to the stirrer, it floats in the bulk liquid, the buoyancy forces about equalling the downward forces exerted by the mean flow. The shear forces and pressure forces in the bulk may then be too weak to blend the high viscosity liquid quickly. Longer mixing times will result in this case. When by chance the addition is transported to the stirrer the mixing will be fast from then on.

Scaling up

In the stirrer controlled regime, dimensionless mixing times in the 64 cm vessel are about equal to those in the 29 cm vessel. Characteristic stirrer controlled mixing times for the larger vessel are given in Figure 9. On the left, the representation is the same as in Figure 8; on the right, the density differences and added liquid viscosities are indicated. In these experiments the stirrer speed was 2 s^{-1},
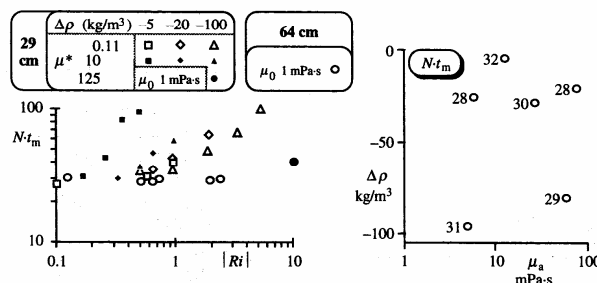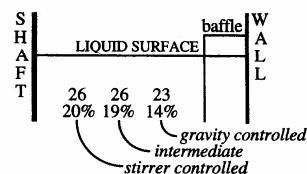
and 5 cm^3 of a saline liquid was injected 3 cm below the liquid surface near the shaft. The bulk was tap water. The figure shows there is no systematic influence of either μ_a or $\Delta\rho$ on the dimensionless mixing time. The standard deviations are low, ranging from 10% to 23%, again not systematically.

Mixing times were also measured with $\mu_0 = 8$ mPa s and $\rho_0 = 1003$ kg m^{-3}. The stirrer speed was 3 s^{-1}. The added liquid properties were $\mu_a = 60$ mPa s and $\rho_a = 933$ kg m^{-3}, so $\Delta\rho = -70$ kg m^{-3}. The added liquid volume was 5 cm^3, injected as a cylinder with a diameter of about 6 mm. The dimensionless mixing times are given at three positions in Figure 10. The positions were between the shaft and a baffle, 5 cm below the liquid surface at radial distances of 0.2, 0.4 and 0.6 times the vessel radius. Here, again, Nt_m is low. The corresponding relative standard deviations, given in the same figure, are low as well.

These mixing times seem to suggest stirrer controlled mixing. However, visual observation showed that at the middle position the mixing is in the intermediate regime, while at the position closest to the baffle the mixing is gravity controlled. The mixing times were low even in the gravity controlled regime, because the volume of added liquid for Figure 10 was only small. As will be shown in the section on addition at the surface, the mixing time increases for larger added liquid volumes.

The mixing times in the stirrer controlled regime (Figures 9, and 10, left position) are longer than those in the gravity controlled regime (Figure 10, right position), but the difference is about equal to the standard deviation σ. Because there is no significant difference between the stirrer controlled mixing time and the gravity controlled mixing time for $V_a = 5$ cm^3, the standard deviation for the middle position in Figure 10 is not higher than that of the other two positions, contrary to the situation in the 29 cm vessel.

Figure 9. Left: Nt_m versus the absolute value of Ri; the open circles correspond to the 64 cm vessel, the other symbols are the same as in Figure 6 (29 cm vessel); ($V_a = 5$ cm^3; addition 5 cm from the shaft: 1 cm below the surface in the 29 cm vessel, 3 cm in the 64 cm vessel). Right: Nt_m as a function of μ_a and $\Delta\rho$ for the same measurements ($T = 64$ cm; $\mu_0 = 1$ mPa s; $V_a = 5$ cm^3; addition 3 cm below the surface).

Table 3. Nt_m for surface addition halfway between shaft and wall. ($T =$ 29 cm; $\mu_0 = 9$ mPa s).

V_a cm^3	$\Delta\rho$ kg m^{-3}	μ^*	N s^{-1}	Nt_m
3	−18	1.6	1.45	114
30	−22	1.3	1.75	164

Table 4. The effect of added liquid volume on Nt_m; N = 0.5 s^{-1}. ($T = 64$ cm; $\mu_0 = 1$ mPa s; surface addition halfway between shaft and wall).

$\Delta\rho$ kg m^{-3}	μ^*	Nt_m $V_a = 5$ ml	$V_a = 5$ ml
−81	54	34	40
−68	360	46	64

Addition at the Surface

For some series of measurements, liquid was deliberately added at the surface. As will be shown here, in those cases the mixing time depends on the amount of liquid added.

For the 29 cm vessel, addition at the surface was done with $\mu_0 = 9$ mPa s. The result is given in Table 3. The dimensionless mixing time increases as more liquid is added.

The results for an addition of 20 cm^3 in the 64 cm vessel are shown in Figure 11. The circles are data for a bulk of 8 mPa s. The mixing times increase with increasing |Ri|, which corresponds to decreasing N. For |Ri| ≈ 6 ($N = 1$ s^{-1}) the dimensionless mixing time is also given for a bulk viscosity of 1 mPa s (squares). These times are all much shorter than those for the more viscous bulk, even though the viscosities of the added liquids are much higher. The viscosity of the bulk plays a crucial part in this type of mixing.

Table 4 shows the effect of added liquid volume on mixing times in the 64 cm vessel. The duration of the addition was always shorter than 5 s. The stirrer speed in these examples is 0.5 s^{-1}, $\mu_0 = 1$ mPa s ($Re = 3.3 \times 10^4$). As mentioned before, the mixing times for small amounts of added liquid equal those of the stirrer controlled regime. The table shows that for $\mu^* \approx 55$, Nt_m increases by 18%— about one standard deviation σ—when V_a is quadrupled. For $\mu_a = 360$ mPa s the increase amounts to 39%, which is more than σ. This shows that the relative increase in mixing time does not only depend on the amount of liquid added, but also on its viscosity: more viscous liquids are less successfully attacked by the eddies in the bulk.

PRACTICAL IMPLICATIONS

The effect of density differences on mixing times is stronger than that of viscosity differences. For the geometry used here, mixing times for liquids of similar densities can be predicted with reasonable accuracy by $Nt_m \approx 30$. This corresponds well with the findings of Ruszkowski[7], who
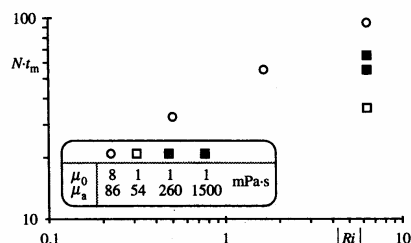

Figure 11. Dimensionless mixing times versus |Ri| ($T = 64$ cm; $\Delta\rho = -70$ to -80 kg m^{-3}; $V_a = 20$ cm^3; surface addition, halfway between shaft and vessel wall, halfway between baffles).

found $Nt_m = 42$ for $D/T = 0.33$, and $Nt_m = 20$ for $D/T = 0.5$ for mixing of turbulently stirred liquids with no significant difference in density and viscosity. In the present study, $D/T = 0.4$. Ruszkowski's correlation predicts $Nt_m = 28$ for the current set-up, which is within 7% of our measured value.

This rule of thumb is valid for added liquid viscosities well into the region where in industry the addition would be premixed anyway. For liquids of similar viscosities, however, even negative density differences as small as -20 kg m^{-3} can result in mixing in the gravity controlled regime. Depending on the liquids' properties and on the process conditions the mixing times can then be very long.

The chance of the added liquid surfacing or reaching the bottom also depends on the feed location. Addition near the stirrer shaft is preferable. If at all possible the liquid should be introduced near the stirrer. Adding the liquid in smaller portions or as an elongated stream is also advantageous.

For the stirrer controlled regime, scale-up is equal to that of the blending of liquids of equal physical properties. On the basis of the experiments no decision can be made about the position of the boundaries of the mixing regimes after scale-up. Furthermore, the gravity controlled mixing time has its own scaling rules that are, as yet, also unknown.

The added liquid volumes used in this study were small. In industrial situations this volume can be much larger so that gravity controlled mixing is more likely to occur. Therefore, in practice, the mixing problems can be larger than those found in this study. Additions with strong adhesive properties that tend to stick to the vessel walls can also be expected to yield mixing problems.

Increasing the stirrer rotational speed reduces not only the stirrer controlled mixing time, but also the chance of gravity controlled mixing. The ideal impeller would provide the right balance between flow and turbulence, so that the chances of surfacing or clinging to the vessel walls are minimized, while the turbulence is strong enough to break up the addition.

CONCLUSIONS

The observations can be summarized as follows.

1. In the *stirrer controlled regime*—when liquid is added near the stirrer or when the bulk flow succeeds in transporting all of the added liquid to the stirrer:
a. the mixing time is practically independent of the viscosity ratio for 1 mPa s $\le \mu_a \le 5$ Pa s;
b. the mixing time does not depend on the location of injection;
c. in the turbulent regime the probe position does not affect the mixing time measurement;
d. for small V_a/V, the mixing time is independent of the added volume;

2. The probability for the added liquid to surface or to reach the bottom is affected by
a. the position of addition;
b. the density difference between the two liquids;
c. the viscosity ratio;
d. the stirrer speed.
This probability is negligible in the *stirrer controlled regime*, and about 1 in the *gravity controlled regime*.
3. In the *gravity controlled regime*—when the added liquid surfaces or is added at the surface:
a. very long mixing times can result;
b. the viscosities of both phases as well as the density difference determine the mixing time;
4. In the *intermediate regime*—when only part of the added liquid is transported to the stirrer—the mixing time is unpredictable and can be anywhere between the stirrer controlled mixing time and the gravity controlled mixing time, and strongly depends on the amount of liquid that surfaces.
5. It is not possible to pronounce upon the position of the boundaries of the mixing regimes after scale-up on the basis of the available data. The scaling rules of the gravity controlled mixing time are, as yet, also unknown.

The absence of an influence of μ^* on the dimensionless mixing time in the stirrer controlled regime implies that the deformation of the added liquid is not the limiting factor in these blending processes. This is confirmed by visualization using photographs, which showed that the deformation is very fast. This, combined with Nt_m being constant, shows that the large-scale flow determines the mixing time, even for added liquid viscosities of up to 5 Pa s. It can be concluded that when all of the added liquid is transported to the stirrer, the homogenization time depends on the rate of distribution of the added liquid over the vessel.

These conclusions are based on studies with one impeller and tank geometry only. Although they are expected to be more generally valid, experimental validation for other systems will be useful.

NOMENCLATURE

B	baffle width, m
C	stirrer to bottom clearance, m
D	stirrer diameter, m
g	gravitational acceleration, ms^{-2}
H	liquid height in the vessel, m
N	stirrer rotational speed, s^{-1}
N_t	N where transition occurs, s^{-1}
Re	$\overset{\text{def}}{=} \dfrac{\rho_0 ND^2}{\mu_0}$, Reynolds number, —
Ri	$\overset{\text{def}}{=} \dfrac{\Delta\rho gH}{\rho_0 N^2 D^2}$, Richardson number, —
T	vessel diameter, m
t_m	mixing time, s
V	vessel volume, m^3
V_a	added liquid volume, m^3
W	impeller blade width, m
μ	viscosity, Pa s
μ	$\overset{\text{def}}{=} \mu_a/\mu_0$, viscosity ratio, —

ρ	density, kg m^{-3}
$\Delta\rho$	$\overset{\text{def}}{=} \rho_a - \rho_0$, density difference, kg m^{-3}
σ	standard deviation within series of measurements

Subscripts
a	added liquid
0	bulk

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