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Mixing times for process vessels with aspect ratios greater than one

T.L. Rodgers[a,*], L. Gangolf[b], C. Vannier[b], M. Parriaud[b], M. Cooke[a]

[a] School of Chemical Engineering and Analytical Science, University of Manchester, M60 1QD, UK
[b] Ecole Nationale Supérieure des Industries Chimiques, BP 20451, 54001 Nancy Cedex, France

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ABSTRACT

Stirred tank reactors are one of the most important and common pieces of equipment used in speciality, pharmaceutical, and agrichemical processes. It is also typical for these to be operated at large aspect ratios; however, there is very little information in the open literature about mixing times in vessels with aspect ratios greater than one. This paper aims to provide new information in this area that will enable the design of better reactors.

Electrical resistance tomography is used to monitor the mixing time of systems with aspect ratios higher than one. The mixing time has been measured on vessels of 0.914 and 0.610 m diameter with Cowles disc, Rushton turbine and mixed flow type impellers to aspect ratios of 2. The current correlation of choice, by Grenville and Nienow (2004), has been compared with the results and found to under predict the mixing time at aspect ratios greater than one. The exponent on the H/T term has been explored and it has been found that this varies with agitator type, this information has never been shown before.

The affect of adding a second impeller on the mixing time and flow pattern is also investigated. Adding a second Rushton turbine creates zoning in the vessel which impedes the mixing; this can be visualised using electrical resistance tomography.

1. Introduction

Stirred tank reactors are one of the most important and common pieces of equipment used in speciality, pharmaceutical, and agrichemical processes (Paul et al., 2004); many of which are operated at aspect ratios (the ratio of the liquid height to the vessel diameter) greater than one. The energy required for these processes forms a significant part of the total energy used. The process of mixing occurs as a result of the motion at three levels: molecular, eddy, and bulk motion.

A large amount of work has been carried out on the mixing of liquids within the turbulent regime for Newtonian fluids (Grenville and Nienow, 2004), and a lot of work has gone into trying to predict the mixing time (the time taken for the system to become homogeneous on addition of material) from knowledge of the agitator and the operating conditions; however, very little of this work has been on aspect ratios greater than one. Currently there are no studies that have tried to correlate the mixing times for vessels with aspect ratios much greater than one, or thoroughly studied different types of agitator under these conditions. Many different methods of determining the mixing time have been used, e.g. dye addition (Mann et al., 1987), pH shift (Singh et al., 1986), tracer monitored by conductivity probes (Cooke, 1988; Khang and Levenspiel, 1976; Ruszkowski, 1994), flow followers (Bryant and Sadeghzadeh, 1979), and electrical resistance tomography (Cooke et al., 2001).

It has been shown that the mixing time depends on the specific power input ($P/\rho V$), the tank geometry and the agitator Reynolds number (Re, this is the ratio of the inertial force supplied by the agitator to the viscous force of the fluid). It has been common place in the literature to correlate the dimensionless mixing time ($\theta_{95}N$) against other dimensionless values which represent the above variations, i.e. the agitator power number (Po), the impeller to tank diameter ratio (D/T), the liquid height to tank diameter ratio (aspect ratio, H/T), and the agitator Reynolds number. For mixing in the turbulent regime the dimensionless mixing time is independent of the Reynolds number and has been correlated to Eq. (1) (Grenville and Nienow, 2004) which has a standard deviation of 10%.

$$\theta_{95}N = 5.2\mathrm{Po}^{-1/3}(D/T)^{-2}\left(\frac{H}{T}\right)^{1/2} \quad (1)$$

It should be commented on here that the data for this correlation was mainly collected on vessels with $H/T \leq 1$ and it is not really applicable to large aspect ratios. In fact, most of the previous work has been predominantly carried out at liquid levels equal to or less than the vessel diameter; of the 25 papers reviewed for mixing time

* Corresponding author. Tel.: +44 161 306 4358.
E-mail addresses: T.Rodgers@postgrad.manchester.ac.uk, mjki3tr2@gmail.com (T.L. Rodgers).

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correlations by Nere et al. (2003) only one looks at values of H/T greater than one and their maximum value is 1.11.

Cooke (1988) has shown that for $H/T \gg 1$ the exponent on H/T can increase considerably due to zoning (zoning refers to the phenomenon where competing mixing loops hinder the exchange of material from one loop to the other). The value of this exponent was found to be 2.43 which is a lot larger than 0.5. However, it is unclear if this dramatic increase in mixing time (over 10 times longer for $H=3T$ compared to $H=T$) was due to just the increase in height or due to zoning effects as three Rushton turbines were used. Zoning has been shown to significantly increase the mixing time in vessels, which is agreed with by Otomo et al. (1995) who have shown that by using a dual axial system, with much less zoning, they can reducing the mixing time at large aspect ratios by up to 50% of that predicted by Cooke (1988). Vrábel et al. (2000) also show long mixing times, $N\theta_{95} \sim 300$, for four Rushton turbines and a significant reduction when replaced with axial impellers.

Taking Eq. (1) but having an unknown exponent on H/T, a, gives

$$\theta_{95}N = 5.2\mathrm{Po}^{-1/3}(D/T)^{-2}\left(\frac{H}{T}\right)^{a} \quad (2)$$

Eq. (2) can be rearranged using the definition of the power number to give Eq. (3), where ρ is the liquid density, V is the liquid volume in the tank given by Eq. (4), where α is the ratio of a dished base height to the tank diameter for a half-ellipsoid base (this is very similar to a torispherical base but simpler to consider, 0 for a flat base to 0.5 for a hemispherical base).

$$\theta_{95} = 5.64\left(\frac{P}{\rho V}\right)^{-1/3}(D/T)^{-1/3}T^{2/3}\left(\frac{H}{T}\right)^{a}\left(\frac{H}{T}-\frac{\alpha}{3}\right)^{-1/3} \quad (3)$$

$$V = \frac{\pi}{4}T^3\left(\frac{H}{T}-\frac{\alpha}{3}\right) \quad (4)$$

Eq. (3), which only applies to the turbulent regime, reveals that:

- Maintaining constant tank dimensions, agitators of the same diameter have the same mixing time if they have the same power input.
- Increasing the agitator diameter will decrease the mixing time at constant power input.
- Increasing the fluid height will increase the mixing time (so long as a is greater than 1/3).
- The mixing time is independent of the fluid viscosity at a constant power input.
- At a constant power per unit mass the mixing time is slightly longer in a dished base tank compared to a flat bottom vessel.
- When scaling-up at constant power per unit mass and geometry the mixing time will increase with the tank diameter.

The flow patterns generated by radial and axial impellers are shown schematically in Fig. 1. For a radial impeller the flow travels radially out from the impeller towards the vessel wall, where it splits and approximately half the flow moves up the vessel and the rest moves down the vessel. These flows then move around the vessel back towards the agitator, Fig. 1(a). For an axial impeller, if down-pumping, the flow travels axially down the middle of the vessel towards the vessel base, where it moves along the base and back up the outside wall of the vessel. This flow then moves towards the top of the vessel where it loops over back to the agitator, Fig. 1(b). For an up-pumping impeller the flow pattern is the same but just in the opposite direction. For a higher liquid height it has been reported that there can be zoning and secondary flow loops towards the top of the vessel both for radial impellers, Fig. 2(a), and axial impellers, Fig. 2(b). This zoning can cause the mixing time to significantly increase, especially with a second impeller reinforcing this zoning (Cooke, 1988).

van't Riet and Tramper (1991) use a bulk flow model analysis based on turn over times in the vessel. A modification of this method can be given by Eq. (5), where the volume of the vessel is given by Eq. (6).

$$N\theta_{95} \propto \mathrm{Po}^{-1/3}(D/T)^{-3}\left(\frac{H}{T}\right) \quad (5)$$

$$V = \frac{\pi}{4}T^3\left(\frac{H}{T}\right) \quad (6)$$

This model produces the same dependence on power as Eq. (1) (Grenville and Nienow, 2004) but has different dependence on both D/T and H/T. The reason for this is most likely that the actual flow in the vessel is not like this ideal flow, and the constrained flow of the vessel means that there is a smaller dependence on the agitator size.

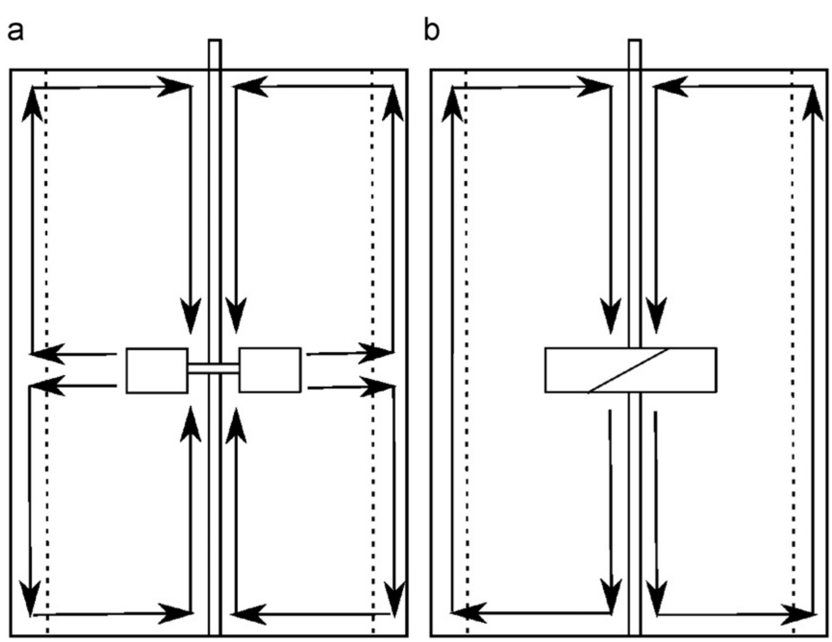

Fig. 1. Schematic flow patterns for (a) radial type agitators and (b) axial type agitators.