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Mixing time in high aspect ratio vessels stirred with multiple impellers

Franco Magelli [a,*], Giuseppina Montante [a], Davide Pinelli [b], Alessandro Paglianti [b]

[a] *Department of Industrial Chemistry, Alma Mater Studiorum—Università di Bologna, via Terracini 28, 40131 Bologna, Italy*
[b] *Department of Civil, Chemical, Environmental and Materials Engineering, Alma Mater Studiorum—Università di Bologna, via Terracini 28, 40131 Bologna, Italy*

HIGHLIGHTS

- We propose a novel mixing time correlation for multiple impeller stirred tanks.
- Mixing time is strongly dependent on the impeller number and spacing.
- The model is tested against a number of literature and original mixing time data.
- Zoning and non-zoning multiple impeller configurations are successful analyzed.

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ABSTRACT

Mixing time is a key parameter for evaluating the blending effectiveness of stirred tanks but, in contrast with the case of single impeller configurations, a general purpose correlation for multiple impeller geometries is not available to date. In this work, a lumped parameter equation for mixing time in the turbulent regime in high aspect ratio tanks stirred with multiple identical impellers is presented. The experimental data are collected by conductivity probes on a variety of stirred tank configurations, dimensions and impeller types with the purpose of identifying the influence of two main geometrical parameters: (i) the impeller number at fixed vessel aspect ratio, and (ii) the vessel aspect ratio at constant impeller distance. The results show that a single equation adding the impeller efficiency, the impeller number and the liquid height to the well-known correlation due to Grenville and Nienow (Grenville, R.K., Nienow, A.W., 2004. Handbook of Industrial Mixing: Science and Practice. In: Paul, E.L., Atiemo-Obeng, V.A., Kresta, S.M. (Eds.), Wiley-Interscience, Hoboken, NJ, USA) properly represents the whole experimental data relevant to axial and mixed-flow impellers collected in this work and in some of previous literature studies. For multiple radial turbines giving rise to compartmentalization of the vessel volume, a modified model based on a simplified fluid dynamic schematization of the vessel as a cascade of ideal stages with backmixing is proposed.

1. Introduction

The mechanically agitated tank is a very common type of equipment used in the chemical, process and specialty industry to realize various elementary processes. Homogenisation is one of these key processes and the so-called mixing time is an empirical parameter largely adopted for defining the time scale of the liquid mixing inside a stirred reactor (Kasat and Pandit, 2004). Mixing time is defined as the time needed for the system to reach a certain degree of mixedness starting from a given state of unmixedness—usually it is determined by the measurement of the dynamic distribution of a small amount of material added almost instantaneously in the vessel.

A single detection position has been used in most investigations; two, three or more detection points have also been employed to get a more representative view of the system behaviour (e.g.: Ruszkowski, 1994; Micheletti et al., 2003; Roussinova and Kresta, 2008); and attempts to use the whole information provided by the vessel contents (with the decolourisation method, Electrical Resistance Tomography, Planar Laser Induced Fluorescence, etc.) have been developed lately (e.g. Cabaret et al., 2007; Bai et al., 2007; Rodgers et al., 2011; Montante et al., 2011; Coroneo et al., 2011).

Attention has been typically focused on vessels stirred by means of a single impeller and characterised by an aspect ratio equal to about one, as reviewed by Nere et al. (2003) and Grenville and Nienow (2004); comparatively, a less extensive number of experimental studies has been carried out on tanks featured by an aspect ratio greater than one and/or stirred by multiple impellers (Jahoda and Machon, 1994; Jahoda et al., 1994; Baudou et al., 1997; John et al., 1998;

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[*] Corresponding author. Tel.: +39 5120 90 425; fax: +39 516 347 788.
E-mail address: franco.magelli@unibo.it (F. Magelli).

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Otomo et al., 1995; Vasconcelos et al., 1995, 1998; Hari-Prajitno et al., 1998; Whitton et al., 1997; Bouaifi et al., 1997; Machon and Jahoda, 2000; Pinelli et al., 2003). The development of a general correlation of mixing time with system geometry and operating conditions based on fluid dynamic reasoning started in the late 80′s and has been carried out until recently (Cooke et al., 1988; van′t Riet and Tramper, 1991; Nienow, 1997; Grenville and Nienow, 2004; Rodgers et al., 2011). For single impellers in vessels characterised by $H/T=1$ there is a general consensus on the following correlation for the turbulent regime (Grenville and Nienow, 2004):

$$N \times t_{95} = 5.2 \times N_P^{-1/3} \times \left(\frac{D}{T}\right)^{-2} \tag{1}$$

that can easily be put in the equivalent form (Nienow, 1997):

$$t_{95} = 5.9 \times \varepsilon^{-1/3} \times \left(\frac{D}{T}\right)^{-1/3} \times T^{2/3} \tag{2}$$

The effect on mixing time of aspect ratios greater than one and of multiple impellers has been touched only rarely and it is still an open issue. In these cases, the above equations are modified by the ratio $(H/T)^a$: van′t Riet and Tramper (1991) suggested $a=1$ (though with a different exponent for the D/T ratio). Most recently Rodgers et al. (2011) have provided the value of a in the range 1.2 to 2.72 for a few impeller types. For multiple Rushton turbines, Cooke et al. (1988) suggested the value $a=2.43$, which gives a dramatic increase in mixing time relative to the $H=T$ case. Zoning produced by these radial turbines, that allows only limited material exchange between the circulating loops pertaining to adjacent turbines, has been invoked as the main cause of this increase. The only consolidated result for other impeller types (axial or mixed-flow) produce (much) lower mixing times at equal energy expenditure (Cronin et al., 1994; Manikowski et al., 1994; Otomo et al., 1995; Hari-Prajitno et al., 1998; Vrabel et al., 2000; Pinelli et al., 2003; Grenville and Nienow, 2004; Rodgers et al., 2011).

In addition to the use of mixing time, the description of the homogenisation process has also been effected with fluid dynamic models of different complexity (a short account for multiple-impeller tanks will be given later on in this paper) as well as, lately, with CFD tools (e.g. Jaworski et al., 2000; Bujalski et al., 2002; Montante and Magelli, 2004; Montante et al., 2005; Hartmann et al., 2006; Jahoda et al., 2007). Most recently, liquid homogenization has been detailed predicted by Direct Numerical Simulations (Derksen, 2012).

In principles, a specific analysis of the stirred tank fluid dynamic characteristics should be performed in order to accurately predict the homogenization process and therefore, the mixing time for each particular stirred tanks configuration. Although CFD methods are nowadays available for accomplishing this task, the significant computational requirements for accurately modelling real scale stirred tanks and the complexity of the modelling issues make mixing time correlations still useful for industrial design and rating purposes. For this reason, the development of general purpose correlations has not been abandoned yet, although significant research efforts are nowadays increasingly devoted to more complex and specific predictive tools.

The subject of this paper is an analysis of the influence of multiple impellers of different types on mixing time in tanks of various aspect ratio and size and an attempt to implement the above-mentioned correlation to account for the effect of these unconventional geometrical characteristics. Only the case of single-phase, liquid systems is addressed in this paper. The study is based partly on unpublished data gathered over the years as a fall-out of different fluid dynamic investigations and partly on retreatment of information already published by this research group.

2. Experimental

The investigation was carried out in various cylindrical, flat-bottomed vessels of three sizes (vessel diameter, T, equal to 132, 232 and 480 mm—in shorthand T_{13}, T_{23} and T_{48}, respectively); the experimental set-up and impeller types are reported in Fig. 1. The smallest vessel was completely closed, while the other two had a free surface and the liquid level, H, was varied to get different aspect ratio ($H/T=2, 3, 4$). They had four vertical 10% baffles placed at 90° and a concentric shaft, where the impellers were mounted on. Several types of impellers were used: six-bladed Rushton turbines (*RT*), pitched-blade turbines down-pumping (PBTD), Lightnin A310 and A315, Chemineer BT-6. For each arrangement, the stirrer consisted of a number J of identical, evenly spaced impellers. In the first part of the study, the influence of impeller type and diameter, D, as well as H/T was investigated and the impeller spacing $S=T$ only was adopted. In the second part, the influence of impeller spacing, S, was investigated: this parameter was in the range $T/3$ to T. In all cases, the lowest impeller was placed at a distance above the base and the uppermost one at a distance from the top cover or the liquid surface equal to $S/2$ (C_1 and C_2 in Fig. 1). The various geometrical combinations studied in this work are summarised in Table 1, together with additional literature configurations considered for widening the analysis.

All the experiments were performed in batch conditions at room temperature. The liquids used were water and aqueous solutions of PVP exhibiting Newtonian behaviour (viscosity range: 0.8 to 18 mPa s). The rotational speed was in the range 160 to 2000 rpm for the smallest T_{13} vessel, 200 to 700 rpm for the medium size T_{23} and 120 to 440 rpm for the biggest T_{48}; as a result of the different conditions, the flow regime was either transitional or fully turbulent. Operation in the open vessels was always such as not to cause surface aeration, thus ensuring single phase flow conditions.

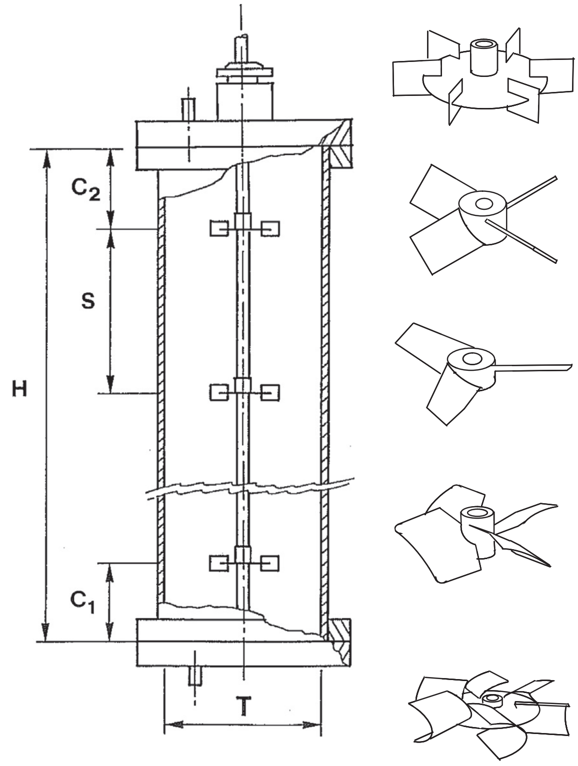

Fig. 1. Experimental set-up of the multiple impeller vessels and impellers types.