Asian J. Exp. Sci., Vol. 23, No. 1, 2009; 157-164

Energy Efficiency and Mixing Time Calculations in Mechanically Agitated *Liquid Liquid* Contactors

G.M. Madhu, A.J. Girish, Priya Ravi Ganesh, Sagar S. Agarwal, Rohit Kacker and Karanth Akshaya S.
Department of Chemical Engineering,
R.V. College of Engineering,
Bangalore-560 059 (Karnataka); India.

Abstract : The present paper involves the comparison of disc turbine, Rushton turbine and pitched blade turbine in terms of mixing time and energy efficiency for the mixing of miscible liquids with density difference. Comparison is also based on the change in the tracer volume added as well as the effect of change of the impeller diameter. The study has been restricted to the stirrer controlled regime due to lower mixing times as compared to gravity controlled or intermediate regimes. Conductivity meter has been used to ascertain the total mixing time, which being the time required to reach a constant conductivity. Effect of amount of tracer fluid added, density difference with the bulk and also the type and geometry of the impeller on the mixing time has been investigated. The pitched blade turbine with lesser diameter is recommended amongst the different impellers studied in the present work.

Key words : Energy, Efficiency, Time Calculations, Mechanically Agitated, Liquid Contactors

Introduction

The operational success of many industrial processes depends on effective agitation and mixing of liquid. Fluid mixers cut across almost every process industry: minerals, pulp, and paper, waste and water treatment and almost every individual process sector. The main purposes of agitation are:

1. Suspending solid particles,
2. Blending miscible liquids,
3. Dispersing a gas in liquid in the form of small bubbles,
4. Dispersing a second liquid, immiscible with the first,
    a. To form an emulsion or
    b. Suspension of fine drops and
5. Promoting heat transfer between the liquid and a coil or jacket (McCabe and Harriot, 1993).

Homogenous mixing of two miscible liquids with difference in various physical properties such as density and viscosity is a common industrial practice. The equipment used for the physical operation is selected based on the components to be mixed such that mixing takes place in the required time with smallest amount of power consumption.

There are the three classes of mixing namely macro scale mixing, micro scale mixing and molecular scale mixing. Macro Scale mixing refers to blending the feed so that every gallon in a reactor has the same average composition. Mixing on the macro scale is controlled through the use of agitators. Micro Scale mixing refers to interdispersing the feed to give uniform composition to the 10-100 Micrometer scale. Mixing on the micro scale is controlled by eddies and is not much affected by agitation. Molecular scale mixing is complete when every molecule in the reactor is surrounded by exactly the same molecule at

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* **Corresponding author :** A J Girish, Department of Chemical Engineering, R.V. College of Engineering, Bangalore-560 059 (Karnataka); India; Mobile : 918026799032; E-mail : *aj_girish@indiatimes.com*

least on a time-averaged basis. This mixing is almost totally driven by diffusion.

A completely well stirred tank reactor implies good mixing in all these levels. Many agitated vessels are well mixed on the macro scale, however, no commercial reactor is perfectly well mixed or thoroughly plug flow. This incomplete mixing may be unimportant if the reaction is dominant or all reactions are slow. In many applications, the reaction and mixing times are often similar and must be carefully studied.

Impellers agitators are divided into two classes. Those that generate currents parallel with the axis of the impeller shaft are called axial flow impellers; those that generate current in radial or tangential direction are called radial flow impellers. The three types of impeller for low to moderate viscosity liquids are propellers, turbines, and high efficiency impellers. For very viscous fluid the most widely used impellers are helical impellers and anchor agitators.

The simple straight-blade turbine pushes the liquid radially and tangentially with almost no vertical motion at the impeller. The currents it generates travel outwards to the vessel wall and the flow either upward or downward. Such impellers are sometimes called paddles. In process vessels they typically turn at 20 to 150 rpm. The disk turbine, with multiple straight blades mounted on a horizontal disk, like the straight-blade impeller, creates zones of high shear rate; it is especially useful for dispersing a gas in a liquid. A pitched-blade turbine is used when good overall circulation is important (Perry and Green, 1999).

Flow Patterns

The way a liquid moves in an agitated vessel depends on many things: the type of impeller; the characteristics of the liquid especially its viscosity; and the and proportions of the tank, baffles, and impeller. The liquid velocity at any point in the tank has three components, and the over all flow pattern in the tank depends on the variations in these three velocity components from point to point. The first velocity component is radial and acts in a direction perpendicular to the shaft of the impeller. The second component is longitudinal and acts in a direction parallel with the shaft. The third component is tangential, or rotational, and acts in a direction tangent to a circular path around the shaft. In the usual case of a vertical shaft, the radial and tangential components are in a horizontal plane, and the longitudinal component is vertical. The radial and longitudinal components are useful and provide the flow necessary for the mixing action. When the shaft is vertical and centrally located in the tank, the tangential component is generally disadvantageous. The tangential flow follows a circular path around the shaft and creates a vortex in the liquid. The swirling perpetuates stratification at the various levels without providing longitudinal flow between levels. If solid particles are present, circulatory currents tend to throw the particles to the outside by centrifugal force; from there they move downward and to the centre of the tank at the bottom. Instead of mixing, its reverse-concentration- occurs. Since, in circulatory flow, the liquid flows with the direction of motion of the impeller blades, the relative velocity between the blades and the liquid is reduced, and the power that can be absorbed by the liquid is limited. In an unbaffled vessel, circulatory flow is induced by all types of impellers, whether axial flow or radial flow. If the swirling is strong, the flow pattern in the tank is virtually the same regardless of the design of the impeller. At high impeller speed the vortex may be so deep that it reaches the impeller, and gas from above the liquid is drawn down into the charge. Generally this is undesirable.

Baffled Tanks

For vigorous agitation of thin suspensions, the tank is provided with baffles, which are flat vertical strips set radially along the tank wall. Four baffles are almost always adequate. A common baffle width is one-tenth to one-twelfth of the tank diameter (radial dimension). For agitating slurries, the baffles often are located one-half of their width from the vessel wall to minimize accumulation of solids on or behind them.

For Reynolds numbers greater than 2000, baffles are commonly used with turbine impellers and with on-centerline axial-flow impellers. The use of baffles results in a large top-to-bottom circulation without vortexing or severely unbalanced fluid forces on the impeller shaft. In the transition region (Reynolds numbers from 10 to 10,000), the width of the baffle may be reduced, often to one-half of standard width. If the circulation pattern is satisfactory when the tank is unbaffled but a vortex creates a problem, partial-length baffles may be used. These are standard-width and extend downward from the surface into about one-third of the liquid volume.

The present work involves the comparison of different commonly used impellers, namely disc turbine, pitched blade turbine and Rushton turbine, and recommending a particular impeller based on the study for mixing operation of adding a tracer pulse to the liquid bulk in turbulent conditions.

Materials and Methods

Materials and Reagents

Tachometer was supplied by Dot tech (Digital Photo type Tachometer model - 792) and was used as received. Conductivity meter was supplied by Systronics and was used after initial calibrations as per its user manual. Purified sodium hydroxide pellets were procured from Merck Limited and used without further purification. Impellers were fabricated by Mechtrix Engineers, Bangalore as per our design specifications. Weights of the salt to be taken were measured using Class I digital weighing balance by Essae-Teraoka ltd (model AQ2130/3EO).

Experimental Setup

The experiments have been performed in a mechanically agitated open top cylindrical stainless steel baffled vessel with an inner diameter of 0.197 m and a height of 0.322 m. The vessel is provided with an opening fitted with a drainage valve at the bottom center to flush out its contents. The entire setup is supported on a stand that also holds the conductivity meter used for the measurement of the bulk solution conductance. The impeller is mounted vertically on a stand with its shaft positioned at the center of the tank and padded to minimize oscillations of the shaft tip. All impellers were mounted with a clearance of 0.031 m from the bottom of the tank.

All aqueous solutions were prepared with deionized water. The salt solutions were prepared as molar concentrations by transferring a known amount of material to a volumetric flask and diluting to the specified volume with deionized water.

Procedure

The baffled vessel was cleaned completely and fitted with the stirrer having the first impeller to be studied. 6 litres of water were filled in it to have the liquid holding volume as per the standard specifications (Perry and Green, 1999). The electrode of the conductivity meter was kept in place near one of the baffles in a fixed position for all readings. Care was taken that the electrode was never exposed to air to keep it from drying. The agitator was switched on and the speed of rotation of the impeller was found by using the tachometer. The rpm of the agitator was controlled at the desired rate and maintained during the course

Table 1 : Range of variables covered in the study

Variable	Range of values covered
Impeller type	Rushton turbine, pitched blade turbine, disc turbine
Impeller diameter (Pitched blade turbine)	0.055 m and 0.0695 m
Tracer concentration	30 – 120 gm NaOH in 500 ml solution
Tracer volume	2 – 8% of bulk volume
Position of tracer input	Along stirrer rod axis, Along baffle

of the experiment. The measured volume of the tracer (NaOH solution that was prepared of calculated concentration) was added along the stirrer rod axis as a pulse input and the stopwatch was switched on. The time was noted when the conductivity meter reading showed a constant steady value. This was recorded as the mixing time for that reading. The parameters that were varied were the position of tracer input, tracer concentration, tracer volume, impeller type and impeller speed to perform the analysis for the present study. Range of variables covered is listed below in Table 1.

Results and Discussions

Effect of amount of tracer added

The mixing time is found to be dependent on the amount of tracer fluid added to the system, which is in contradiction with related available literature (Burmester *et al*., 1991; Bakker adn Akker, 1997 and Rielly and Britter, 1985). All the previous literature dealing with the effect of volume of tracer fluid on mixing time is restricted to tracer volume of maximum of 1% of the bulk. Such low volume does not retain its identity even after one circulation in the stirrer-controlled regime due to the impeller turbulence and the buoyancy forces generated due to the density difference that are easily overcome. The mixing times are thus found to be small in these cases.

The volumes added in the present study (2 to 8% of the total bulk volume) are such that the tracer pocket has sufficient volume to retain the identity even after 3-4 circulations and hence if the volume is increased further, larger mixing times are expected. Thus our study reveals the dependency of mixing time on the amount of tracer added to the system. Similar observations were made on varying the density difference between the tracer input and the bulk liquid (Gogate and Pandit, 1999).

The effects of tracer volume on mixing times were studied at different pulse injection points in the tank for two concentrations of the tracer (for consistency check of trend) and the results are plotted below in Fig. 1 and Fig. 2.

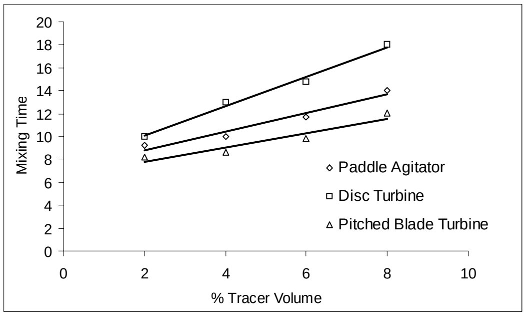

Fig. 1 : Mixing time versus tracer volume% in tank for various impellers at 492 rpm and tracer concentration of 150g/1500 ml water *input along the stirrer rod.*

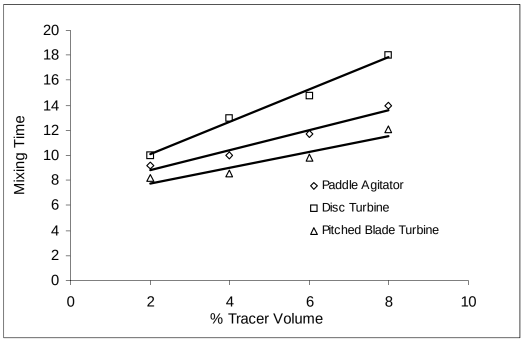

Fig. 2 : Mixing time versus tracer volume% in tank for various impellers at 492 rpm and tracer concentration of 150g/1500 ml water *input along the baffle*

The effect of tracer volume on the mixing time was found by taking two concentrations of the tracer to check for consistency of result trend (150g and 250 g in 1500 ml water). The mixing time was found to increase as more amount of the tracer pulse was added to the bulk liquid. This is indeed true as more tracer is added to the system, it takes a longer time to get completely mixed as it retains its identity after many more circulations than minute quantities of tracer take. As the tracer concentration increased, the mixing time was more for the same volume of tracer added.

Also, the mixing time was lesser when the tracer pulse was input along the stirrer rod axis. This is because input along the baffle makes the tracer pocket take a longer time to come into contact with the circulation pattern created by the impeller and thus mixing take longer time as it first travel all the way down to the bottom of the vessel atleast before the turbulence in the bulk causes mixing to occur. The pitched blade turbine gives the least mixing times as observed from the graphs above (Fig.1 and Fig.2). However, the Rushton turbine gives comparably low mixing times too. Depending on the process the impeller must be chosen (Van de Vusse, 1955; Rohatgi *et al.*, 1979; Ahmad. *et al.*, 1985).

Effect of Tracer Concentration (density difference)

The mixing times are observed to increase with increasing density difference between the tracer input and the bulk liquid, as shown in fig 3, which can be explained along the lines of reasoning of effect of tracer volume discussed above. This is in accordance with literature that proposes that heavier liquids take longer time to get completely mixed in a given system (Bakker and Akker, 1997)

Among the impellers used, the Rushton turbine is found to result in the least mixing times for varying density differences between the tracer added and bulk. The pitched blade turbine resulted in around 30% lesser mixing time than the disc turbine while the Rushton turbine gave 70% lesser mixing times. The mixing times of the Rushton and the pitched blade turbine vary only by few seconds as observed.

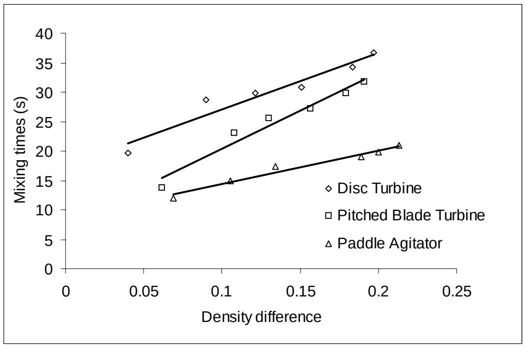

Fig. 3 : Effect of density difference between tracer pulse and bulk at 492 rpm and tracer volume of 300 ml.

On observing the results based on only mixing times the Rushton turbine may be decided the best option for the system under study. However the energy efficiency analysis show it to consume much higher power than the pitched blade turbine that is later found to be the optimal option. This is because the pitched blade turbine assisted in the downward motion of the heavier liquid due to gravity and

Table 2 : R^2 values for the linearisation of the mixing time dependencies on the tracer volume and concentration for the different impellers used.

Impeller type	R^2 values for Fig .1	R^2 values for Fig. 2	R^2 values for Fig. 3
Rushton turbine	0.9581	0.9962	0.9653
Pitched blade turbine	0.9055	0.9902	0.9602
Disc turbine	0.9897	0.9657	0.9318

thus helped in early breakage of the tracer pocket resulting in comparatively low mixing times. From the Table 2 it can be concluded that the mixing time dependencies varies linearly with increase in tracer volume and concentration which is referred in Fig. 1, Fig. 2 and Fig. 3. with the R^2 values being above 0.95.

Table 2. R^2 values for the linearisation of the mixing time dependencies on the tracer volume and concentration for the different impellers used.

Effect of impeller diameter

The effect of change in the impeller diameter was studied and the results are illustrated below in Fig. 4. It is found that there is a marginal increase in the mixing times as the impeller is larger for the range of volume% of the tracer fluid considered.

Thus the pitched blade turbine with the smaller diameter is found to give lesser mixing times when the amount of tracer added to the bulk is varied for the given range of volume%. The impeller with the larger diameter also consumes more power than the smaller one and hence it can be concluded that the pitched blade turbine with the smaller diameter (0.055 m) is preferred. From the Table 2 it can be concluded that the mixing time dependencies varies linearly with increase in tracer volume and concentration which is referred in Fig 1, Fi.2 and fig.3. with the R^2 values being above 0.95.

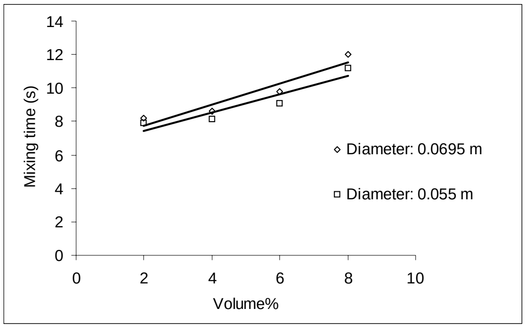

Fig. 4 : Effect of impeller diameter with varying volume% of the tracer of concentration 150g in 1500 ml water added at speed of 495 rpm.

Energy Efficiency Analysis of Different Impellers

Energy efficiency analysis is an important step that must be performed before setting the operating parameters for mixing in a particular system.

The total power consumption is characterized by the impeller power number, N_p, defined as given below

$$N_p = N_P = \frac{Actual\ Power\ Consumption}{\rho N^3 d^5} \quad \ldots\ldots (1)$$

The impeller power number was found from literature to be 5 for Rushton turbine, 2.5 for disc turbine and 1.86 for a pitched blade turbine (1).

Depending on the volume of addition of heavier fluid to the agitated bulk, there would be a change in the center of mass and hence a change in the potential energy of the system. This change is given as (8,9) :

$$E_t = \tfrac{1}{2}*\Psi*(1-\Psi)*V*(\Delta\rho)*g \quad \ldots\ldots (2)$$

The value of Ψ is taken as 0.5 (The E_t value will be maximum for Ψ=0.5 and hence energy efficiency is defined for this value. Ahmad *et al*[10], have also used similar approach.) For a particular mixing process, energy efficiency can be defined as the ratio of E_t to the actual measured energy required (given by actual power consumption * mixing time) for the completion of the mixing process.

$$\eta = E_t/E \qquad \ldots\ldots(3)$$

From Table 3 it can be easily seen from the results that pitched blade turbine is highly energy efficient as compared to other impellers. The values of energy efficiency obtained in the work are quite similar to those obtained in the work of Ahmad *et al*. (1985) and Rohatgi *et al*. (1979) who have also obtained the values of energy efficiency in the same range of 0.3 to 1.1%. The values of energy efficiency are inversely proportional to the speed of rotation and hence operation at lower speeds would be preferred but care should be taken that the operation does not fall into gravity regime or the intermediate regime due to lower speeds as mixing times increase about 10 folds in these regimes. Energy efficiency analysis gave the energy efficiency of the various impellers used in the following range of values that were found to be in accordance with the available literature.

Table 3 : Energy efficiency range for different impellers studied

Impeller type	Energy efficiency values
Pitched blade turbine	0.427 %– 1.187%
Rushton turbine	0 .178% – 0.394%
Disc turbine	0.373% – 0.893%

Conclusions

Mixing time is found to be dependent on the location of addition of the tracer pulse with about 30% reduction in the mixing time when the tracer addition is in the stirrer plane. However, addition of the tracer in the stirrer plane will be associated with additional pumping cost as extra energy will be required to release the fluid against the head of the turbulent bulk. This dependency of mixing time on the location of tracer addition is expected to be stronger in larger vessels with higher reduction in mixing time on addition in the stirrer plane. Selection of the optimum impeller must be done on the basis the total energy consumption and its efficiency rather than on the basis of mixing times alone. From the energy efficiency analysis done in our experiments, the pitched blade turbine with lower diameter (0.055 m) is found to give the maximum energy efficiency and hence the least operating costs would be involved. The speed of rotation must be kept at a minimum with proper care taken to not allow the regime of operation to go out of the boundary of the stirrer-controlled regime (Oldshue, 1966). The mixing time for the addition of the tracer pulse (NaOH) into the agitated bulk liquid is found to be dependent on the amount of tracer added and the density difference between the tracer input and the bulk. This dependence has been found to be a function of the type of impeller used. Thus for the flow protocol of our work, the best impeller was found to be the pitched blade turbine as it gives comparably similar mixing times on the lower range along with providing the maximum energy efficiency among the impellers studied.

Nomenclature

P = Actual power consumption
g = gravitational acceleration.
Da = impeller diameter
N = impeller rotational speed
D = tank diameter
ì= viscosity of stirred liquid
ñ= density of stirred mixture
V = Bulk liquid volume in vessel

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