MIXING TIME ESTIMATION AND ANALYSIS IN A JET MIXER

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ABSTRACT

Mixing of reactants, catalysts, etc. in a chemical reactor may be achieved using jets which offer the advantage of having no moving parts inside the reactor. While there have been many experimental studies and thumb rules for the design of jets, the details of mixing process is not properly understood. An experiment was carried out to study the effects of various parameters such as nozzle diameter, angle of inclination, jet position and jet velocity on mixing time. Results show that, for a given geometric arrangement, the angle of the jet injection is significantly more important in determining the time required for 95% mixing than the length of the jet. The optimum angle was found to be an injection angle of 30º for jet located either at two-third of the volume of the tank or top and bottom of the tank, which gave the shortest mixing time. The optimum angle is not universal and varies with the location of the jet inlet. An increase in the nozzle diameter was found to reduce the mixing time at a given level of power consumption and in turn the energy efficiency can be improved.

Keywords: jet mixer; mixing time; jet velocity.

INTRODUCTION

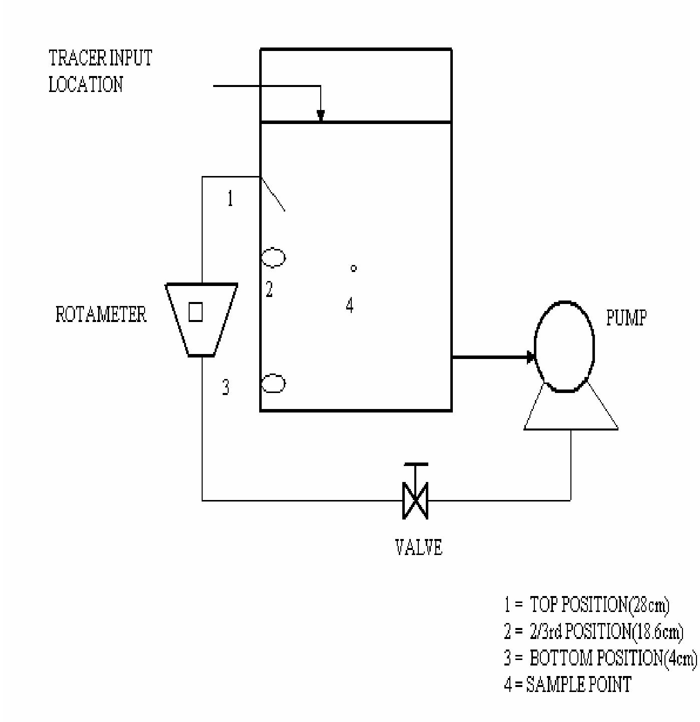
Mixing is an important unit operation in many chemical engineering applications. Mixing is usually carried out in order to produce a uniform mixture and it can be achieved using mechanical mixers, fluid jet mixers, static mixer or pipelines with tees. It can be used for a variety of purposes. e.g, homogenization of physical properties and composition prevention of stratification (or) deposition of suspended particles, for and improved rates of heat, mass transfer and chemical reactions[1]. Examples of mixing operations include dissolution, leaching, gas absorption, crystallization and liquid-liquid extraction. Depending on the specific application and process mixing may be done in batch wise (or) in continuous mode and the content may be stirred either by rotating turbines and propellers (or) by jets of liquid. Jet mixers are one of the simplest devices to achieve mixing. In fact, side entry mixers (or) jet mixers are commonly used to achieve mixing in storage tank. In jet mixing, a part of the liquid in the tank is drawn through a pump and returned as a high-velocity jet through a nozzle into the tank. This jet entrains some of the surrounding liquid and creates a circulation pattern within the vessel thus leading to mixing of the content. In jet mixers, a fast moving jet stream of liquid is injected into a slow moving (or) stationary bulk liquid. The relative velocity between the jet and the bulk liquid creates a turbulent mixing layer at the jet flow, entraining and mixing the jet liquid with the bulk liquid. Based on this concept, it has been assumed that longer jet lengths results in better mixing. The jet length, referred to as the maximum distance a jet travels before it impinges on the opposite wall. This means that for a jet injected at the bottom of a tank, an injection along the diagonal of the liquid mass inside the tank results in the longest jet. Accordingly, for an aspect ratio (tank diameter/liquid height) of 1, an angle of injection of 45° results in the longest jet length. Jet mixers are easy to install; there is no requirement for any structural reinforcement of the tank and they are normally cheaper compared with conventional mixing devices. In large storage tanks the conventional top entry mixer may not be suitable. Usually, small side entry mixers are used, but they require mechanical seals and contain rotating equipment inside the tank. In such situations, mixing induced by a jet of liquid can be advantageous[2]. Jet mixers can be used for sludge suspension processes where the particles are of fairly small size. The issues that need to be addressed are: (i) the effect of nozzle angle over a wide range. (ii) the effect of nozzle diameter and (iii) the effect of nozzle position on mixing time. From a process point of view the various nozzle configurations need to be compared on the basis of equal power input. The various factors that influence the energy efficiency have to be studied. Systematic studies of jet mixing are of fairly recent origin. The early work in this area was done by Prosser (1949)[3] and Fossett (1951)[4] who reported performance figures of free jets for mixing fluids in large circular tanks.

MATERIALS AND METHODS

Experimental setup

The experimental set up used in the present study is shown schematically in Figure-1. It consists of a metallic tank of diameter 28cm and height 45cm. The liquid level in all the experiments was kept constant at 28cm from the bottom. The outlet of the tank was located at 4cm from bottom. A centrifugal pump of 0.5hp was used to recycle part of the liquid from the tank and return it to the tank with a high velocity through a nozzle. Nozzles of different diameters and angles were tested. These are listed in Table-1.

The tank was provided with two positions at which the conductivity probe could be located. Initial trials were done to identify the locations, where minimum mixing were possible and based on which the location of the conductivity probes were decided. These positions are shown in Figure-1. The conductivity probe was connected to a conductivity meter. Tap water was used as the working fluid and a small amount of sodium chloride solution is added as the tracer pulse at the centre of the vessel at the top liquid surface. The jet could be oriented at various angles (15, 30, 45 and 60 degrees) to the horizontal with the help of specially fabricated nozzles. Mixing time was considered as the time required attaining 95% of the fully mixed concentration. Each mixing time experiment was repeated at least three times (initial runs were repeated more times) and average mixing times were taken.



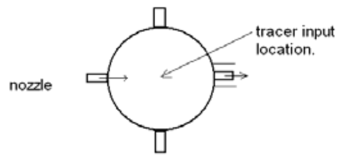


Figure-1. Experimental setup.

Table-1. Dimensional details of the nozzles.

Diameter of nozzle (mm)	**Angle of nozzle** (Degrees)			
5	15	30	45	60
10	15	30	45	60
15	15	30	45	60

RESULTS AND DISCUSSION

Experiments results on mixing time obtained for various nozzle sizes (5 mm, 10 mm and 15 mm), nozzle locations (top, 2/3rd and bottom positions) and nozzle angles (15, 30, 45 and 60 degrees of inclination) have been analyzed and discussed under different and suitable heading.

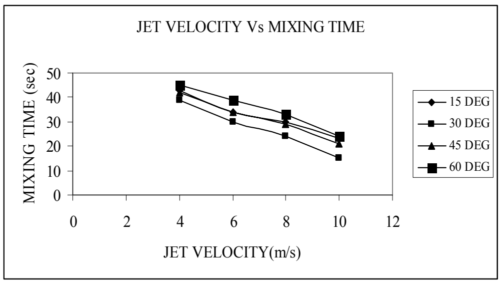
Effect of nozzle position on mixing time

The jet was placed at three different position i.e. at the top (28cm from the top), two-third (18.6 from the top) and at the bottom (3cm from the bottom of the tank). When the jet was placed at the top position, the flow field formed was not good, hence it resulted in larger mixing time. When the jet was placed at two- third position, the flow field was good, but there were some irregularities in the flow, which leads to improper mixing. Jet placed at the bottom gave shortest mixing time compared to others. The flow field formation was regular and uniform. Hence it was found that when the jet placed at the bottom position gave optimum mixing time for this geometry of the tank. However this optimum position is not universal and varies with the geometry of the tank.

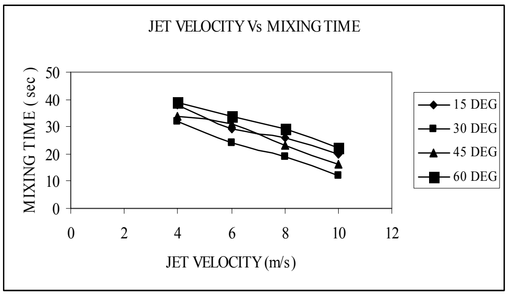
Effect of nozzle angle on mixing time

The effect of nozzle angle was studied by measuring the mixing time with the nozzles having angle of 15°, 30°, 45°and 60° by keeping the nozzles at all the three locations (top, 2/3rd and bottom position) and this was repeated for all three nozzle diameters (5mm, 10mm and 15mm). Data was collected, analysed and compared (Figure-2).

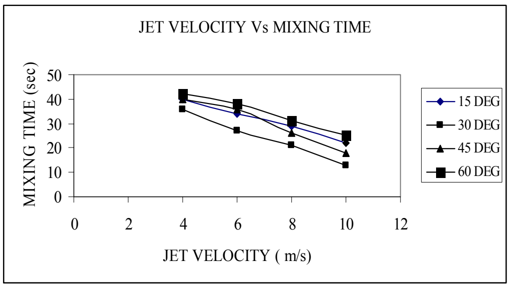
Nozzle at top position



(2.a) Effect of jet velocity on mixing time (5mm)

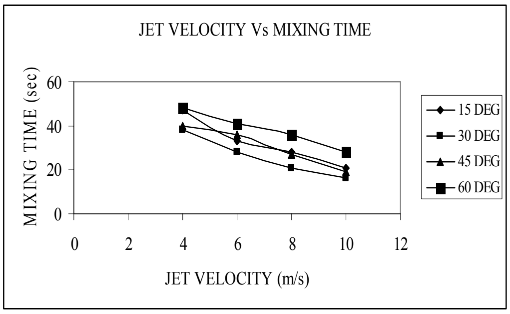


(2.b) Effect of jet velocity on mixing time (10mm)

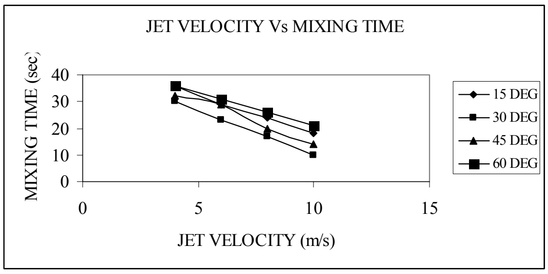


(2.c)Effect of jet velocity on mixing time (15mm)

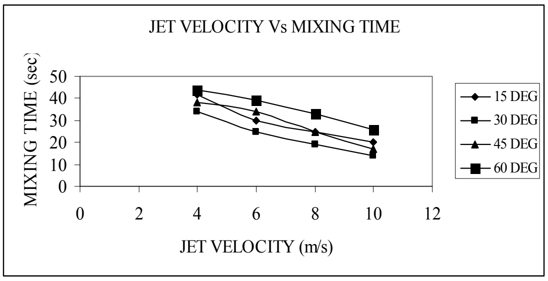
Nozzle at 2/3rd position



(2.d) Effect of jet velocity on mixing time (5mm)

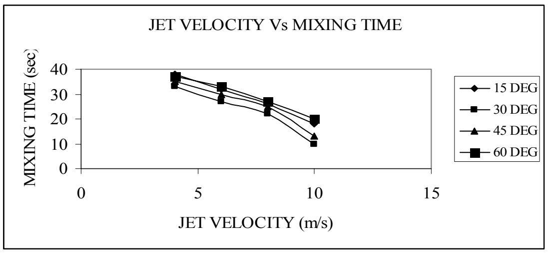


(2.e)Effect of jet velocity on mixing time (10mm)

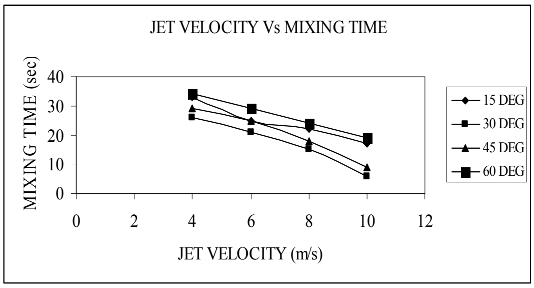


(2.f) Effect of jet velocity on mixing time (15mm)

Nozzle at Bottom Position



(2.g) Effect of jet velocity on mixing time (5mm)



(2.h) Effect of jet velocity on mixing time (10mm)

Figure-2. Effect of jet velocity on mixing time using different nozzle angles and positions.

In all cases it was observed that mixing time for the nozzle angle 30^0 were found to be minimum. At a nozzle angle of 45^0, the jet length is the longest, as it directly hits the opposite corner of the tank before getting diverted by its impact on the wall as shown in Figure-3. However the mixing time is not very low as expected as the jet velocity following impact seems to be very weak and the jet have dispersed significantly especially after impacting somewhere near the angle near opposite to the injection point. When the angle of nozzle was lowered from 45^0, more of the fluid volume comes within the upper more agitated zone. The re-circulated jet is much stronger than before. As a result, the mixing time is a strong function of

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the volume fraction under strong agitation, goes on decreasing progressively with the decrease in nozzle angle, until an optimum is observed for an angle of 30°. The observation has been well explained with flow fields produced at different configuration (Figure-3). When the jet is further lowered below this nozzle angle say at 15°, the wall effects due to the base of the tank come into effect, which reduces the effectiveness of the jet as a mixer. For nozzle angle more than 45°, that is 60° there is a rollover of the jet after it hits the top of the tank. After rollover, a liquid motion driven by the jet flow moves the fluid along the tank wall and agitates the bulk fluid[4].

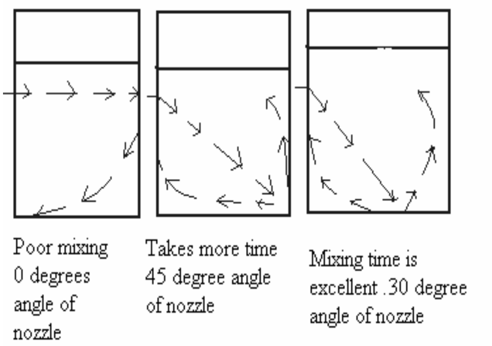

Figure-3. Schematic representation of the flow field produced by nozzles of different angles.

From the Figure-3, it is observed that when the nozzle angle was horizontal, the jet was horizontal and mainly confined to the bottom of the tank. The tracer pulse was introduced at the top liquid surface was found to mix very slowly with the liquid near the bottom and hence resulting in poor mixing. When the nozzle angle was higher say 30° the jet was free from wall. It also had large path length; as a result, it entrained the surrounding liquid to a large extent, which resulted in better mixing (lower mixing time). In addition, the tracer pulse was put at the top; poorly mixed liquid at the tank bottom was circulated through the pump and the nozzle and reached the top due to the inclination of the nozzle. Thus, making the nozzle inclined at 30^0 had a two-fold effect. It enables the jet to spread and entrain more of the surrounding liquids. The liquid from the poorly mixed bottom region was circulated through the pump and the nozzle to the top. As the results of both of these, the mixing time is better. These results are in accordance with the general recommendation made by Jayanthi (2001)[5] that the jet should be oriented so that its path length is largest and recycling of liquid should be from the region, which is not well mixed. From the same set of graphs shown in Figure-2, it is observed that increase in jet velocity has decreased the mixing time in all the cases, due to the higher turbulence created at higher jet velocity.

Effect of nozzle diameter on mixing time

In order to analysis the effect of nozzle diameter on mixing time, the same data set was plotted (Figure-4) for the nozzles positioned at bottom and top positions whereas the plots corresponding to the nozzles positioned at other locations are also available elsewhere[6]. Analysis the graphs (in Figure-4) drawn between jet velocity versus mixing time for different nozzle diameters show that, for any angle, an increase in the nozzle diameter leads to reduction in the mixing time at the same level of power consumption. For example, graph corresponding to 30° nozzle and 5mm of diameter, at the bottom position (Figure-4), shows that the mixing time would be about 10 seconds, and the mixing time for 10mm nozzle would be about 6 seconds. Thus, an increase in the nozzle diameter leads to better mixing at the same level of power consumption. When the diameter was increased, the flow rate through the nozzle increases for the same level of velocity. This would mean that for a given power, the liquid is circulated faster through the bigger nozzle, which leads to reduction in the mixing time.

But when 15mm diameter was used the mixing time was found to be to more than 10mm and less that 5mm nozzle diameter. The reason for this is the flow field was not uniform in 15mm diameter and the flow was disturbed by the walls of the tank. The diameter of 10mm was found to be optimum for this geometry of the tank and this optimum diameter is not universal and varies with the geometry of the tank.

When two nozzle of different diameter (d_1 and d_2) are operated at velocities Uj_1 and Uj_2, respectively, in such a way that the power input by both is the same, the ratio of the velocity through the two nozzles would have to be in the following manner:

$$Uj_2/Uj_1 = (d_2/d_1)^{2/3} \qquad (1)$$

As a result, the ratio of flow rates $(Q = \pi/4 * d\ ^{2} * Uj)^4$ through the nozzle having different diameter being operated at equal power consumption would be:

$$Q_2/Q_1 = (d_2/d_1) \qquad (2)$$

This equation indicates that, as the nozzle diameter increases, the flow rate through the nozzle increases for the same level of velocity. This would mean that for a given power, the liquid is circulated faster through the bigger nozzle, which leads to reduction in the mixing time. The ratio of the momentum flux entering the tank ($J = \pi/4\rho dj\ ^2\ Uj\ ^2$) through the nozzles having different diameter being operated at equal power consumption is:

$$J_2/J_1 = (d_2/d_1)^{2/3} \qquad (3)$$

The above equation also shows that, as the nozzle diameter increases, the momentum flux entering the tank through the nozzle increases for the same level of power consumption. An increase in the momentum flux implies that the mixing is more vigorous with a large diameter nozzle at the same level of power consumption[4]. The increase in the momentum flux and the flow rate thus explains the reduction in the mixing time with an increase in the diameter. Thus larger diameter nozzle is more energy efficient than the smaller diameter Nozzles as hypothesized by Fox and Gex (1956)[7].

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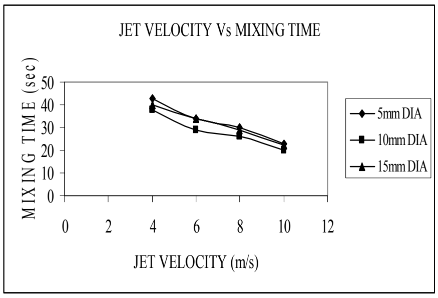
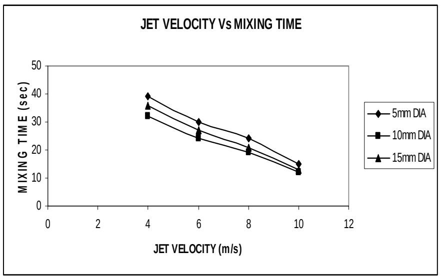
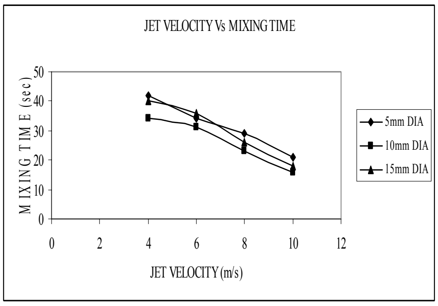
Nozzle at top position



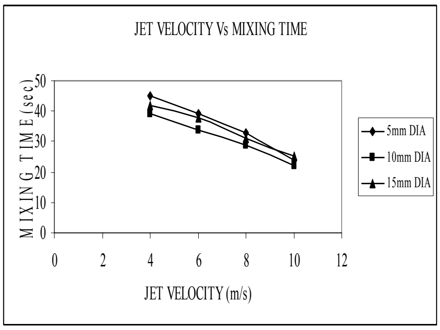
(4.a) Effect of jet velocity on mixing time (15deg)



(4.b)Effect of jet velocity on mixing time (30deg)

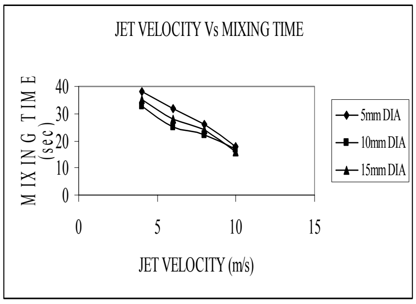


(4.c)Effect of jet velocity on mixing time (45deg)

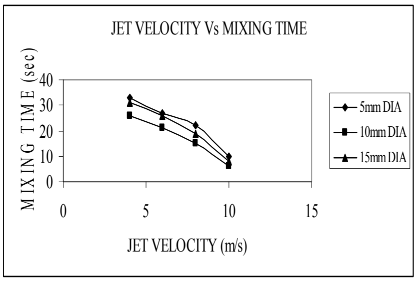


(4.d)Effect of jet velocity on mixing time (60 deg)

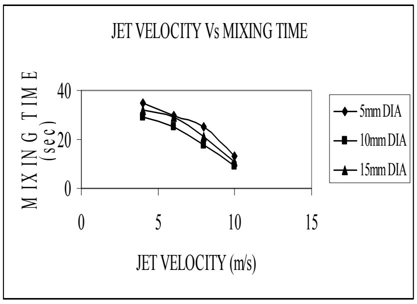
Nozzle at bottom position



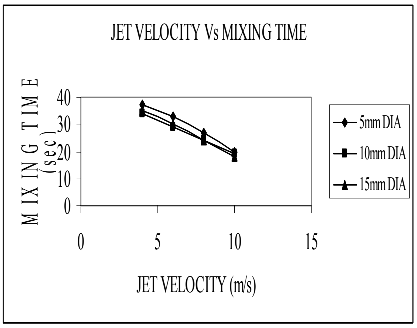
(4.e) Effect of jet velocity on mixing time (15 deg)



(4.f) Effect of jet velocity on mixing time (30 deg)



(4.g) Effect of jet velocity on mixing time (45 deg)



(4.h) Effect of jet velocity on mixing time (60 deg)

Figure-4. Effect of nozzle diameter on mixing time.

Effect of power on mixing time

This section deals with energy efficiency of jet mixer. Previous researchers[4] have shown that the jet mixers are less energy efficient as compared with the top entry agitators, but are economically attractive (lower capital cost as compared with top entry mixers). Grenville and Tilton (1966)[8] investigated the mixing process by giving a pulse of tracer (electrolyte) through the jet nozzle and by monitoring the conductivity at three locations within the tank. They have proposed that the mixing process was controlled by the turbulent kinetic energy dissipation rate in the region far away from the jet entrance. They have taken the energy dissipation rates in the region far way from the nozzle to be proportional to jet velocity and the jet diameter at the location.

The power consumed in mixing process (the power input through the nozzle) was calculated using the kinetic energy of the jet as follows:

$$P_j = (\pi/8)*(\rho*d_j^2*U_j^{\,3}) \ldots \qquad (4)$$

Various correlations available in literature (Fossett and Prosser, 1949[3]; Okita and Oyama, 1963[9]; Grenville and Tilton, 1996[8], 1997[10]) used to predict the mixing time, show that the mixing time is inversely proportional to the jet velocity and the nozzle diameter. The correlation reported by Grenville and Tilton (1996[8], 1997[10]) are valid over a very wide range of the tank diameters and therefore can be considered to be dependable for scale-up. Thus, the mixing time can be considered to be inversely proportional to the product of jet velocity and diameter. That is,

$T_m \alpha$ (1/ Uj*dj) or in other words:
$(T_{m2}/T_{m1}) = (Uj_1*dj_1)/ (Uj_2*dj_2)$…………….... (5)

At equal power, the jet velocity and diameter are related through equation (1). Substituting for Uj_2 /Uj_1 from equation (1) in equation (5) gives

$T_{m2}/T_{m1} = (dj_1/dj_2)^{1/3}$ or in other words:
$Tm *dj^{1/3}$ = constant………………...……….. (6)

The above equation also shows that the product of mixing time and nozzle diameter raised to the power 1/3 would be constant (and independent of the diameter) for a given level of power consumption[8]. To test this hypothesis, the data for different nozzle diameter were re-plotted (figures available elsewhere[6]). From the figure it can be seen that, for a particular nozzle angle, the data for various nozzle diameters (from 5 to 10mm – 3 – folds variation) fall along a single straight line. Thus for a given level of power consumption, an increase in the nozzle diameter would reduce the mixing time. This result is very important for scale-up or for retrofitting jet mixers to improve the mixing efficiency.

Optimum conditions for tank geometry

The optimum angle was also confirmed by plotting graphs between the angle and power with constant mixing time. The mixing time was taken as 20, 25 and 30 seconds. From all the graphs (Figure-5 a-h), it was observed that an angle of 30 was optimum, irrespective of position of nozzle and nozzle diameter. The power consumption was less for 30 degree nozzle with 5mm diameter. The bottom position again gave a better result.

The power consumption was found to be shortest for a mixing time of 30 seconds in all the cases. From the Figure-5g, the power consumption for 10mm diameter at bottom position for 30 degree nozzle angle for 20 second of mixing time is 10 watts, while for 25 seconds it is 6.2 watts and for 30 seconds it is 2 watts, whereas from the Figure-5b, the power consumption for 10mm diameter at top position for 30 degree nozzle angle for 20 second of mixing time is 18 watts, while for 25 seconds it is 7 watts and for 30 seconds it is 4 watts. The optimum angle for this geometry with minimum power consumption was found to be 30 degrees. The optimum diameter for less power consumption is 5mm, but 10mm diameter gives shortest mixing time compared to 5mm. This optimum diameter, angle and position are not universal and vary with the geometry of the tank.

Optimum geometry ratio

The optimum nozzle position, angle and diameter with respective to the geometry of the tank used in the study was determined by plotting the ratio of diameter of nozzle to the diameter of the tank with the mixing time for all position and angle with constant diameter and these graphs are shown in Figure-6. It was found form the graphical analysis that the optimum angle was 30 degrees at bottom position for all diameters of the nozzle as visualized and detailed in earlier sections. The optimum diameter with respective to the geometry and mixing time was 10mm.

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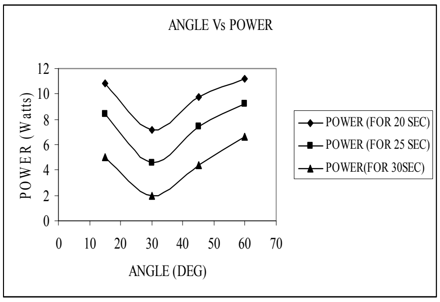
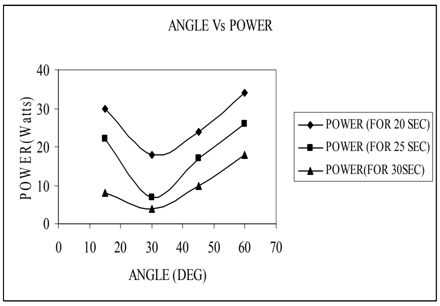
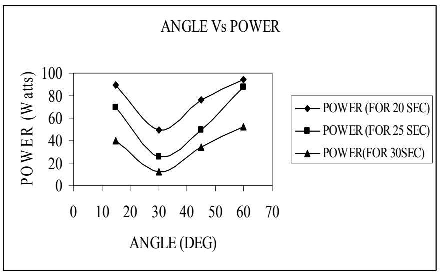
Nozzle at top position



(5.a) Effect of nozzle angle on power requirement (for 5mm)

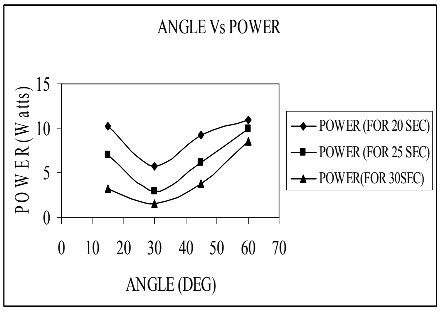


(5.b) Effect of nozzle angle on power requirement (for 10mm)

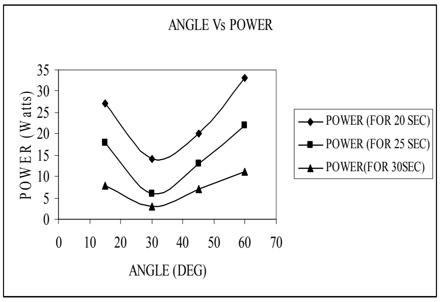


(5.c) Effect of nozzle angle on power requirement (for 15mm)

Nozzle at 2/3rd position

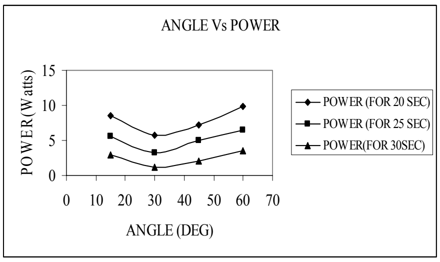


(5.d) Effect of nozzle angle on power requirement (for 5mm)

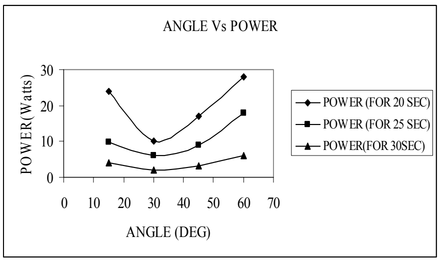


(5.e) Effect of nozzle angle on power requirement (for 10mm)

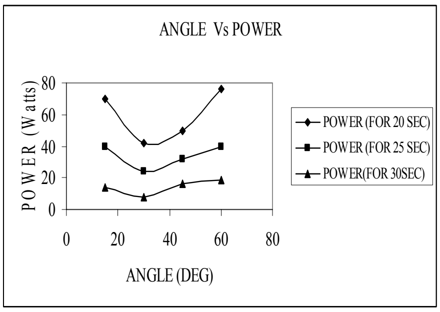
Nozzle at bottom position



(5.f) Effect of nozzle angle on power requirement (for 5mm)



(5.g) Effect of nozzle angle on power requirement (for 10mm)



(5.h) Effect of nozzle angle on power requirement (for 15mm)

Figure-5. Effect of nozzle angle on power required for mixing nozzle at top position.

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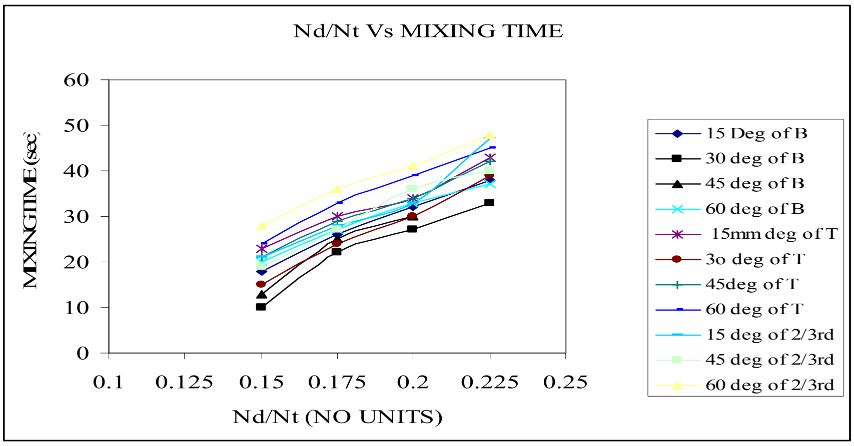
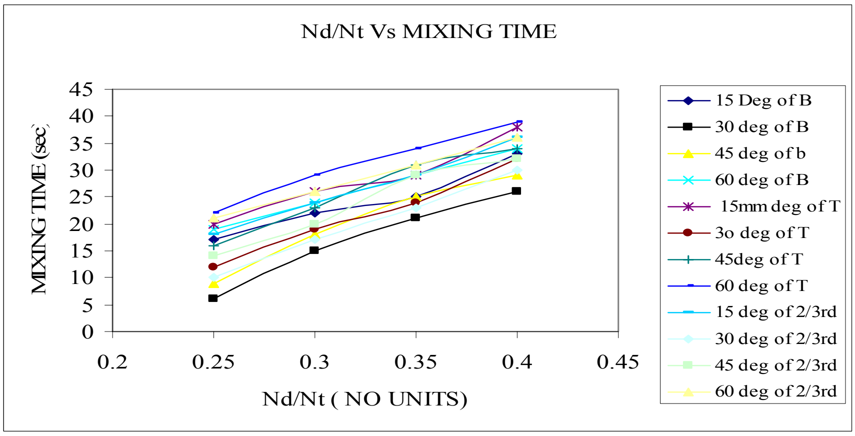
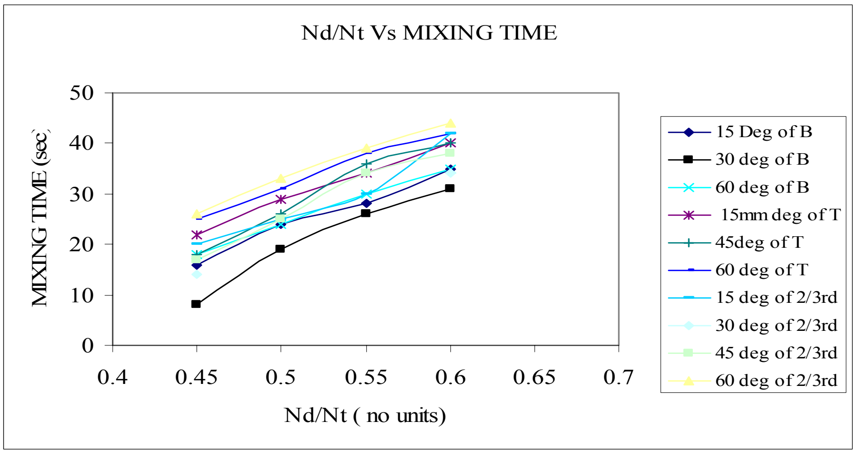


(6.a) Nd/Nt Vs Mixing time (for 5mm diameter)



(6.b) Nd/Nt Vs Mixing time (for10mm diameter)



(6.c) Nd/Nt Vs Mixing time (for 15mm diameter)

Figure-6. Optimum nozzle position and configuration for the tank geometry.

CONCLUSIONS

Experiments were conducted by varying parameters like jet diameter, jet position and jet inclination to find their effects on mixing time. The optimum angle is found to be an injection angle of 30º for jet located either at two-third of the volume of the tank or top and bottom of the tank, which gives the shortest mixing time. This optimum angle is not universal and varies with the location of the jet inlet. In this study, an increase in the nozzle diameter was found to reduce the mixing time at a given level of power consumption and in turn the energy efficiency can be improved. It was found that a diameter of l0 mm gives a shortest mixing time, but diameter of 5mm has a less power consumption compared to 10mm diameter, so the optimum diameter could be between 5 to 10mm for this geometry. In the present work, it was found that jet introduced from a 10mm nozzle at the bottom of the tank at an angle of inclination of 30^0 gave an optimum mixing time for the preferred geometry.

NOMENCLATURE

dj	Diameter of the jet/nozzle, m
H	Liquid height, m
J	Momentum of jet, Kg m /s ^{2}
N_d	Diamter of the Nozzle, m
N_d	Diamter of the tank, m
Pj	Power (input through nozzle), Watts
Qj	Liquid jet flow rate, m^3/s
t	Time, s
T	Diameter of tank, m
T_m	Mixing time, s
Uj	Velocity of jet, m/s

GREEK SYMBOLS

ρ	Density of the fluid, kg/m^3
θ	Jet angle in degrees.
π	Pi

REFERENCES

[1] Patwardhan A. W. 2002. Chemical Engineering Science. Vol. 57, p. 1307.

[2] Zughbi H. D. and Rakib M. A. 2004. Chemical Engineering Science. Vol. 59, p. 829.

[3] Fossett H. and Prosser L.E. 1949. Journal of Institute of Mechanical Engineers. Vol. 160, p. 224.

[4] Fossett, H. 1951. Trans. Instn. Chem. Engrs. Vol. 29, p. 164.

[5] Jayanthi. 2001. Chemical Engineering Science. Vol. 56, p. 193.

[6] Swarnalatha Y. 2005. Studies on jet mixing. M. Tech. Thesis. National Institute of Technology, Thiruchirappalli.

[7] Fox E. A. and Gex V. E. 1956. AIChE journal. Vol. 2, p. 539.

[8] Grenville R. K. and Tilton J. N. 1996. Transactions of the Institution of Chemical Engineers. Vol. 74A, p. 390.

[9] Okita N. and Oyama Y. 1963. Japanese Journal of Chemical Engineers. 31(9): 101.

[10] Grenville R. K. and Tilton J. N. 1997. Proceedings of the 9th European conference on mixing. p. 67.