ELSEVIER

Chemical Engineering Journal 84 (2001) 325–333

Chemical Engineering Journal

www.elsevier.com/locate/cej

Suspension of floating solids with up-pumping pitched blade impellers; mixing time and power characteristics

N. Kuzmanić*, B. Ljubičić

Faculty of Chemical Technology, Laboratory of Chemical Engineering, University of Split, Teslina 10/V, 21000 Split, Croatia

Received 11 November 1999; received in revised form 13 November 2000; accepted 20 November 2000

Abstract

Floating solids suspension in water has been studied using up-pumping pitched blade turbines (PTU). Studies were performed to determine optimum geometry and hydrodynamic characteristics of agitated systems for floating solids suspension. The impact of floating solids concentrations and particle size on the mixing time, t_{m}, the just completely suspended impeller speeds, N_{JS}, and the power consumption were examined. The effects of impeller diameter and its off-bottom clearance as well as the impeller blade angle on mentioned parameters were also observed. The mixing time of suspended system was measured by a conductivity technique using the sodium chloride solution as tracer, whereas, power consumption was measured by the torque table. The efficiency of PTU impellers was compared to that of other, more conventional impellers. Obtained results point to the fact that the PTU may be a viable option if the floating slurry process requires the state of complete solids suspension and its longer time maintenance.

Keywords: Torque; Suspension; Pitched blade turbines; Mixing time; Floating solids

1. Introduction

Mixing and dispersion of solids in liquid is a process frequently encountered in industrial practice. In many cases successful suspension of solids have a significant influence on the quality and/or quantity of the final product. Most industrial solid/liquid mixing systems involve suspension of solids particles heavier than the liquid, and these suspensions have received extensive research attention. However, there are several applications where solids are lighter than the liquid and require pulling down action to produce homogeneous slurries. The suspension of floating solids is of particular interest in the fields of minerals processing, fermentation and sewage treatment, but so far only a few papers have been published about suspending of this kind of solids [1–5].

The complete drawdown of floating solids by agitated liquids in stirred tanks can be achieved by two different mechanisms. It was found that in the full-baffled tanks, where the formation of the vortex was suppressed by the presence of the baffles, the intensity of turbulence is primarily responsible for particle dispersion. In this case, energy dissipation and position of the impeller with respect to the liquid surface were found to be the controlling parameters. When alternative baffle configurations were used instead, it was found that the liquid swirl in tanks provides a mechanism for pulling down the floating particles into the bulk [6,7].

In designing equipment for this kind of suspension, it is necessary to satisfy many requirements such as the degree of mixing, the reaction rate, an acceptable power input. Often, not all these operations are compatible and some degree of optimization is necessary [8]. Proper choice of reactor system geometry may considerably facilitate and improve the process of floating solids suspension. The choice closely depends on the knowledge of the hydrodynamics in the mixing vessel and power consumption. The mixing time and power consumption are the values which render useful information when making this choice. Whereas the power consumption is defined as the quantity of energy input to the liquid phase by stirrer in unit time, the mixing time is defined as the period necessary for a system to achieve the high level of homogeneity required in technology. The mixing time is often used as an indication of impeller's effectiveness [9–12]. The shorter the mixing time the more effective the blending. For single phase systems, mixing times as a function of the power inputs and geometry of the system are quite well established. However, the influence of the suspended solids on the mixing time has been much less researched. The studies carried so far referred mainly to the impact of suspended settling solids on the homogenization of the liquid phase in a mixing tank [13,14]. The influence of floating suspended solids has not been systematically studied so far.

* Corresponding author. Tel.: +385-21-385-633; fax: +385-21-384-964.
E-mail address: kuzmanic@ktf-split.hr (N. Kuzmanić).

1385-8947/01/$ – see front matter
PII: S1385-8947(00)00382-X

Nomenclature

a	constant in mixing rate equation (Eq. (8))
b	exponent in Eq. (8)
B	baffle width (m)
C	solids concentration ($\mathrm{kg\,m^{-3}}$)
c	impeller clearance from bottom, (m)
d_p	particle diameter (m)
D	agitator diameter (m)
F_b	($= 0.17\pi d_\mathrm{p}^3(\rho_\mathrm{L} - \rho_\mathrm{p})g$) buoyant force (N)
g	gravitational acceleration ($\mathrm{m\,s^{-2}}$)
H	height of liquid from bottom of vessel (m)
k_m	mixing rate constant ($\mathrm{s^{-1}}$)
N	impeller speed (rps or rpm)
N_JS	impeller speed at just suspended conditions (rps or rpm)
$\mathrm{Nt_m}$	dimensionless mixing time
N_P	Power number ($=P/\rho N^3D^5$)
N_Re	Reynolds number ($=ND^2\rho/\mu$)
P	impeller power draw (W)
$(P/m)_\mathrm{JS}$	power consumption per unit mass at just suspended conditions ($\mathrm{W\,kg^{-1}}$)
T	vessel diameter (m)
t_m	mixing time (s)
V	volume of the liquid in the mixing tank ($\mathrm{m^3}$)
v	volume of tracer ($\mathrm{m^3}$)
w	blade width (m)
z_e	location of conductivity probe (m)
z_i	location of injection point (m)

Greek symbols

β	blade angle (°)
μ_L	viscosity of liquid ($\mathrm{N\,s\,m^{-2}}$)
ρ_L	density of liquid ($\mathrm{kg\,m^{-3}}$)
ρ_p	density of particle ($\mathrm{kg\,m^{-3}}$)
ϖ_p	mass fraction of solid (kg/kg)

In practice, the suspension of floating solids is usually achieved with axial-flow impellers whose discharge flow is directed at the base of the mixing tank. Since the floating solids keep at the liquid surface before mixing the main aim of this paper was to define the efficiency of up-pumping pitched-blade impellers in floating solids suspension applications. The up-pumping performance characteristics had been kept unsuitable for a long time, and little design information is available in the literature. Recently, the up-pumping mode of agitation has been growing in popularity, particularly in gas dispersion operations [15].

This work focuses on the effect of floating solids concentration and particle size, as well as system configuration on the mixing time, the just completely suspended speeds, and on the power consumption. This paper also presents an efficiency comparison of this impeller type with other, more conventional impeller types. In this way, it was attempted to throw some light on some phenomena recorded during dispersion of floating solids and to establish how these particles change in mixing behavior of the liquid phase.

2. Experimental set-up and procedure

The experimental set-up is shown schematically in Fig. 1. The experiments were carried out in a cylindrical flat-bottomed agitated tank of internal diameter $T = 0.32$ m with four baffles of standard width ($B = T/10$). The suspension was stirred by an up-pumping four-blade turbine with different angles of blades and positioned at different off-bottom clearances in the mixing tank ($D/T = 0.25$–0.41; $w = 0.19D$; $\beta = 30$–$60°$).

The impeller speed was varied between 200 and 800 rpm. The power requirement and mixing time were measured at intervals of 50 rpm. In the areas in the vicinity of N_JS these measurements were carried out at shorter intervals. The mixing intensity was controlled by an electromotor with a transformer of variable speed and digital controller of the number of revolutions.

The work studied the suspensions of different concentrations of polyethylene particles (PEHD; $\rho_\mathrm{p} = 840\ \mathrm{kg\,m^{-3}}$), and different average particle size ($d_\mathrm{p} = 205$–$600\ \mu\mathrm{m}$). Tap water at 15°C was used as a continuous phase for solids dispersion ($H = T$; $V = 25.72\ \mathrm{dm^3}$; $\rho_\mathrm{L} = 997\ \mathrm{kg\,m^3}$, $\mu_\mathrm{L} = 1.4 \times 10^{-3}$ Pa s).

Mixing time values, t_m, were measured using a conductivity method. Namely, the decolourisation technique is not

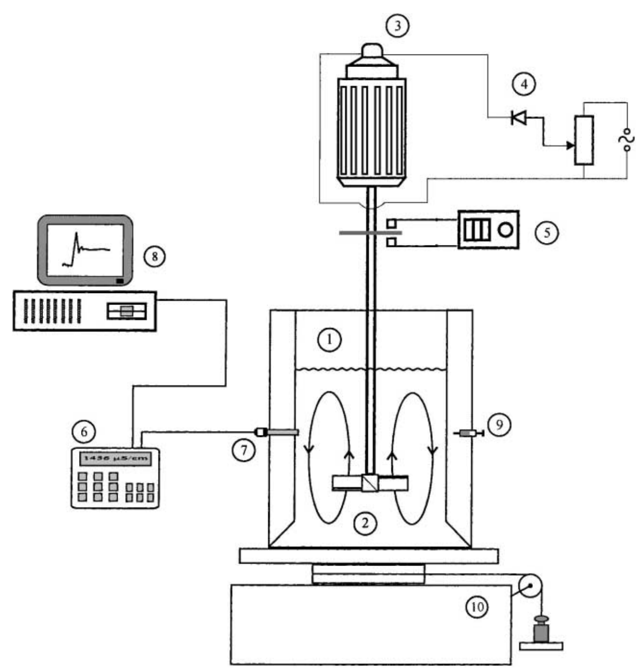

Fig. 1. Experimental set-up: 1, tank; 2, impeller; 3, variable-speed motor; 4, system to convert ac–dc; 5, optical tachometer; 6, conductivity meter; 7, conductivity probe; 8, PC; 9, injection system of tracer addition; 10, torque table.

very effective for the slurry work. Due to the presence and colour of solids it is very difficult to determine the moment of total decolourisation of the system that is reliably the mixing time by decolourisation. On the other hand, irrespective of its high sensitivity, the conductivity method proved more objective for slurry systems. In all the measurements the conductivity probe was placed at the position $z_i/H = 0.66$ clearance from the tank bottom. The tracer was injected at the same position ($z_e/H = 0.66$) but on the opposite side of the stirred vessel. Both these positions were selected as the optimum injection points in our preceding paper [16]. Conductivity probe was connected to the computer through conductivity meter. This connection rendered possible a continuous record of the variations of the conductivity in the stirred system. Sodium chloride solution was used as tracer ($C(\mathrm{NaCl}) = 2\,\mathrm{mol\,dm^{-3}}$; $v = 10\,\mathrm{cm^3}$). Each experimental point was repeated at least three runs, so that the results present the arithmetic mean value of these measurements. The acquired data were processed using a graphical program Grapher 2-D. In preliminary studies, the conductivity probe were checked for the linearity of its response which was found to be very good. The moment of the tracer injection was taken as the initial point of measurement of the mixing time. The truncation point of measurement was taken as the point where conductivity signals remained constant, that is, when there is permanent level of variation of the normalized terminal concentration of ±3%. The reproducibility of the measurement was within 4%.

Visual observations of the distribution of suspended solids in the bulk and of floated layer at the surface of the liquid were also made to aid data interpretation. The critical impeller speed for the complete suspension of floating solid particles was determined using visual method of Joosten [1]. In this case the minimum stirrer speed, N_{JS}, was defined as the speed at which stagnant zones of floating solids at the liquid surface had just disappeared.

Apart from the mixing time, power consumption was measured as well, since, it is one of the more important parameters in establishing the efficiency of reactor system geometry. Power consumption was measured using a torque table, that is, power input of the impeller was calculated from the torque and the impeller speed.

3. Results and discussion

3.1. Effect of floating solid loading and particle size

Fig. 2 shows the effect of mean floating solids concentration on the mixing time. Even though the results of this kind of experiments are ordinarily presented as the dependence of dimensionless numbers $\mathrm{Nt_m} - N_{\mathrm{Re}}$, the results are here shown as a relationship $t_m - N$. This is due to the peculiar form of curves obtained which will be analysed in detail hereinafter.

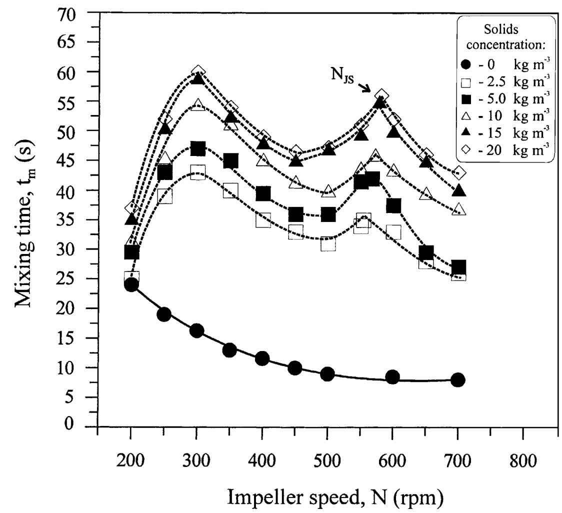

Fig. 2. Effect of floating solid loading on mixing time; $d_p = 205\,\mu\mathrm{m}$, $D/T = 0.33$, $\beta = 45^\circ$, $c/H = 0.33$.

Mixing time measurements were made over a wide range of solid loading $C = 2.5$–$20\,\mathrm{kg\,m^{-3}}$ at particle size of $d_p = 205\,\mu\mathrm{m}$. For as complete analysis as possible of this effect, the mixing time values in liquid alone are also plotted in the same figure ($C = 0\,\mathrm{kg\,m^{-3}}$). It can be seen from the Fig. 2 that mixing time of liquid alone decreases exponentially with the increase of impeller speed. The results showed that the mixing time values of liquid alone in function of impeller speed were found to be similar with use of other, more conventional types of impeller.

The presence of floating solid particles in the liquid leads to a pronounced decrease of the liquid circulation velocity, which directly affects the extension of the mixing time. This extension of mixing time with respect to liquid alone was recorded for the whole range of impeller speeds examined. At some solids concentrations and mixing intensities it amounts to over five times that for the liquid alone. When floating solids are present in the liquid, dependence curves t_m–N for this kind of suspension are characterized by two marked peaks occurring at different mixing intensity. The first peak occurs within the range of relatively low impeller speed, $N \approx 300\,\mathrm{rpm}$. The occurrence of this first peak may be accounted for by the fact of gradual incorporation of solids into the liquid from the liquid surface. Namely, if the mixing intensity in the system is weak, the particles are still in their initial position at the liquid surface forming fillets at the vessel walls and in the close vicinity of the baffles. The results obtained at $N = 200\,\mathrm{rpm}$, particularly at low particle concentrations ($C = 2.5\,\mathrm{kg\,m^3}$), show that the mixing time is still the result of the agitated liquid alone. In such a case the values of t_m of the liquid alone and those of suspension differ very little or their differences may be neglected. As the impeller speed increases, the incorporation of solids into the bulk liquid becomes more intensive, which directly affects t_m values of the system. This is a main reason of the

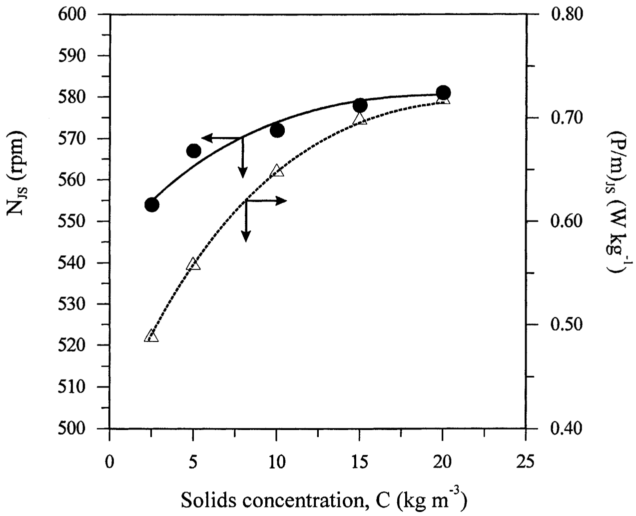

Fig. 3. Influence of floating solids concentration on N_{JS} and $(P/m)_{JS}$; $d_p = 205\,\mu$m, $D/T = 0.33$, $\beta = 45°$, $c/H = 0.33$.

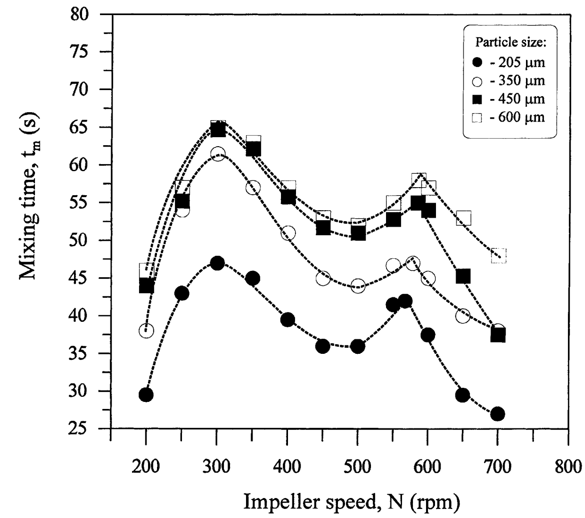

Fig. 4. Effect of particle size on the mixing time; $C = 5\,\mathrm{kg\,m^{-3}}$, $D/T = 0.33$, $\beta = 45°$, $c/H = 0.33$.

occurrence of the first peak on the mentioned curve. This means that the range of $N = 200$–300 rpm may be defined as the period of initial incorporation of particles from the surface into the liquid. In the successive range of studied rpm, that is $N = 300$–500 rpm, t_m values of suspension exponentially decrease with an increase of impeller speed. However, at $N > 500$ rpm a new peak occurs on the t_m–N curve. This peak occurs at the impeller speed required for the complete suspension state of floating solids (N_{JS}). Namely, during the preliminary studies of this work, the values of N_{JS} were determined, according, to the Joosten visual criterion of drawdown of stagnant zones from the liquid surface. A very good agreement was observed of these results with the values of impeller speed at which the second peak occurs on the t_m–N curve. With respect to very small departures of N_{JS} values (about ±12.5%) obtained by these two methods, the method of determination of t_m dependent on the N could be accepted as an appropriate method of determination of complete suspension state of floating solids.

Results of studies show that an increase of the solids bulk concentration affects a rise of N_{JS} values and appertaining values of $(P/m)_{JS}$ (Fig. 3). Apparently, an increase in solid loading requires greater liquid circulation velocity to achieve complete suspension of the floating solids. Further, this directly affects the power consumption values. The relationship between N_{JS} and C can be given by the following relations:

$$N_{JS} \propto C^{0.022} \tag{1}$$

In addition, the effect of particle size on analyzed parameters was also examined (Fig. 4). The measurements were made over a floating particle size range of $d_p = 205$–$600\,\mu$m at average solids concentration of $C = 5\,\mathrm{kg\,m^{-3}}$.

The results given in Fig. 4 show that an increase in particle size causes the lengthening of mixing time. The N_{JS} values and $(P/m)_{JS}$ are also increased with greater particle size (Fig. 5). The dependence of N_{JS} on particle size is given by the following relations:

$$N_{JS} \propto d_p^{0.032} \tag{2}$$

The exponent values obtained in this work point to a considerably smaller effect of C and d_p on the N_{JS} values than is the case with settling particles. As shown by the literature [17], if radial impellers and axial-flow impellers pumping downward are used for settling particles, these relations are as follows:

$$N_{JS} \propto d_p^{0.2\text{–}0.5} \tag{3}$$

$$N_{JS} \propto C^{0.12\text{–}0.22} \tag{4}$$

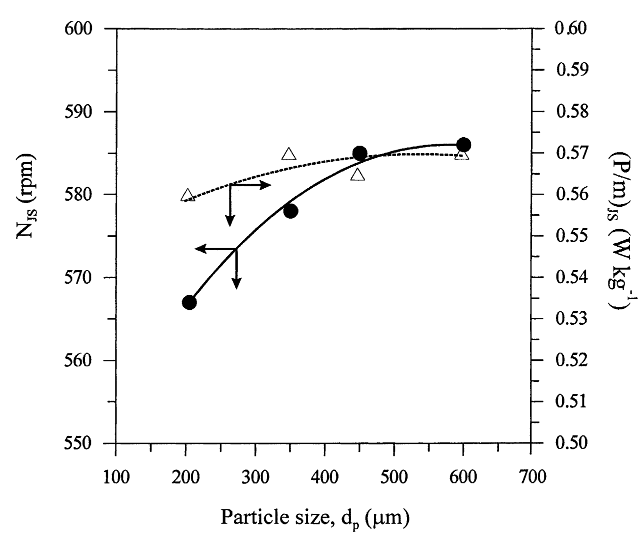

Fig. 5. Effect of particle size on N_{JS} and $(P/m)_{JS}$; $d_p = 205\,\mu$m, $D/T = 0.33$, $\beta = 45°$, $c/H = 0.33$.

Joosten et al. [1] also carried out some experiments with the floating solids (corks and rubber particles, d_p = 2–10 mm, pitched turbine downflow (PTD)-impeller) and they concluded that the effect of the particle size of floating solids was so small that could be practically neglected. They pointed to the fact that this effect should be studied further in greater detail.

Thring and Edwards [8] studied the effects of floating solids concentration on the N_{JS} value. They conducted experiments for increasing concentrations of solids from 0.75 to 3.75%, at an impeller clearance $c = H/3$, using three different impeller types. They came to the conclusion that an increase of C did not affect N_{JS}. It should be pointed out that these authors determined N_{JS} values by exclusively visual method which are known to be quite subjective.

Our results, on the contrary, show that these parameters affect N_{JS}, and however little this effect might be it could be noticed. If taken logically, this points to the fact that we were right since it is quite difficult to accept that the particle size and concentration of floating solids do not affect N_{JS}. Recorded differences between values of N_{JS} for different particle size could more likely be attributed to the effect of the buoyant force F_b. This upward buoyant force is opposed by the downward directed drag force which incorporates solids into the liquid. F_b is proportional to d_p^3, and it significantly increases with an increase in the diameter of solids which should be incorporated into the liquid [7]. This means that the liquid velocity at the surface should exceed the buoyant force so as to incorporate the floating solids into liquid. This is probably the main cause of the rise in N_{JS} values with greater particle size.

3.2. Effect of impeller geometry and its off-bottom clearance

The next set of measurements was performed to establish the optimum geometry of the PTU impeller in floating solids suspension applications. As first, the effect of impeller diameter was studied. The studies were carried out with four different diameters of PTU positioned at a distance of 0.106 m from the tank bottom ($c/H = 0.33$).

Results were shown as the relationship between dimensionless mixing time and Reynolds number (Fig. 6), as well as between power number and Reynolds number (Fig. 7). It should be mentioned that the dimensionless power number of the impeller and *Re* numbers were based on liquid density alone. For multi-phase systems, the density of the liquid, ρ_L, has been traditionally adopted as the reference value due to the difficulty in establishing the real density of suspension. Such an approximation is particularly suitable in systems such as the studied one, where the mass fraction of low density particle is relatively small (ω_p = 0.5–2%).

From Fig. 6 it can be seen that with an increase in the impeller diameter the value of Nt_m decreases. The lowest values of dimensionless mixing time were obtained with the impeller of greater studied diameter $D_4 = 0.132$ m ($D_4/T = 0.14$). In fullbaffled tank the intensity of turbulence is primarily responsible for floating solids dispersion. However, the turbulence intensity decays along the length of the flow path. With an increase in the impeller diameter, less decay in the turbulence will occur because of reduction in path length. Moreover, the liquid velocity also increases with an increase in the impeller diameter. The overall effect of increased liquid velocity and lesser decay in turbulence makes the dependence on impeller diameter significant. In addition, an increase in the impeller diameter increases the average circulation velocity which results into a decrease in the t_m value.

The comparison of different impeller diameters on the basis of power consumption is shown in Fig. 7. The values of

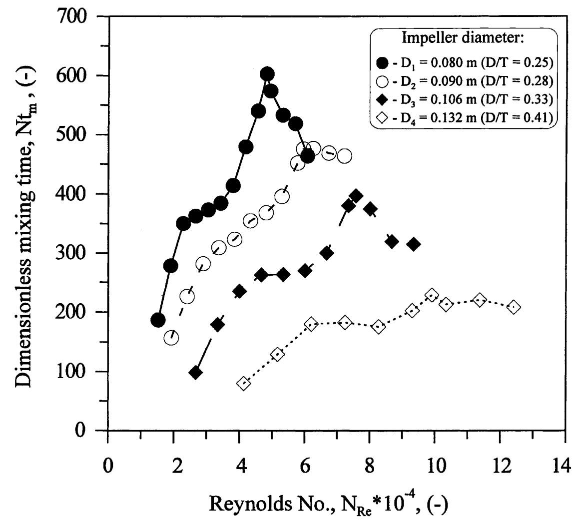

Fig. 6. Effect of Reynolds number on dimensionless mixing time for the different impeller diameters; $C = 5\,\mathrm{kg\,m^{-3}}$, $d_p = 205$ mm, $\beta = 45°$, $c/H = 0.33$.

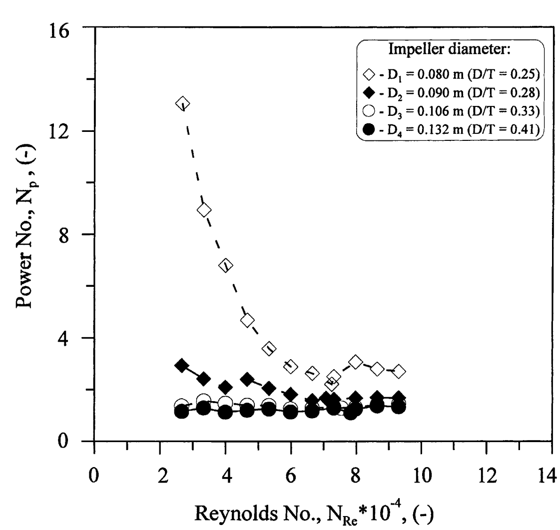

Fig. 7. Effect of Reynolds number on power number for the different impeller diameters; $C = 5\,\mathrm{kg\,m^{-3}}$, $d_p = 205$ mm, $\beta = 45°$, $c/H = 0.33$.

power number of studied impellers decrease with an increase in impeller diameter. It can be seen that performance of 0.106 and 0.132 m diameter impellers is fairly close to each other. On the basis of these data, it may be recommended that the energy efficient impeller diameter is in the range of $D/T = 0.33$–0.41.

The measurements have shown that the just-suspended speed decreases with increasing impeller diameter to tank diameter ratio. On the other hand, just-suspended power requirements increase with increasing D/T ratio. The dependence of the critical impeller speed for solid suspension on impeller diameter may be given by the following expression:

$$N_{JS} \propto D^{-0.57} \tag{5}$$

The data were correlated using linear regression. The regression coefficients for this correlations was found to be equal to 0.965.

The value of obtained exponent is markedly lower than that obtained by Armenante et al. [6] working with floating suspended solids. They established the following dependence of $N_{JS} \propto D^{-1.74}$. The difference between coefficients is due to different impeller geometries. These authors used PTU type impeller with six straight blades. In addition, in their experiment the headspace is removed from the vessel, then floating solids adjacent to the tank top cover behave similar to settling solids on the bottom of a tank. This caused the coefficient they obtained to be very similar to that obtained for settling particles. For better comparison at settling particle suspension using PTD impellers, Chapman et al. [18] and Raghav Rao and Joshi [13] have reported the exponent over D to be from -1.15 to -1.50. Zwietering [19] gives the following relationship: $N_{JS} \propto D^{-0.85}$. It may be pointed out that Zwietering used propellers, whereas Chapman et al. used PTD impeller with four blades. In the case of a disc turbine, Zwietering and Chapman have obtained exponents over D of -2.35 and -2.45, respectively.

The location of the impeller, that is, its off-bottom clearance may also affect the Nt_m and N_p values. These effects were studied with the PTU impeller of $D = 0.106$ m ($D/T = 0.33$) positioned at four distances from the bottom of the tank within the c/H range 0.07–0.49.

Fig. 8 points to the fact that dimensionless mixing time decreases with the greater off-bottom clearance of the impeller. The lowest Nt_m values were obtained for the impeller position $c/H = 0.49$, that is, closest to the liquid surface. However, the Nt_m values for the $c/H = 0.33$ and 0.49 positions differ very little. This leads to the conclusion that greater the off-bottom impeller clearance the less significant become the effect of this parameter.

The power consumption is also the function of the impeller off-bottom clearance. With an increase of off-bottom impeller clearance the dimensionless N_P decreases (Fig. 9). At impeller position $c/H = 0.33$ and 0.49, a pronounced N_p increase could be noticed at higher N_{Re}. One of the basic causes of this effect is the surface aeration, that is, air

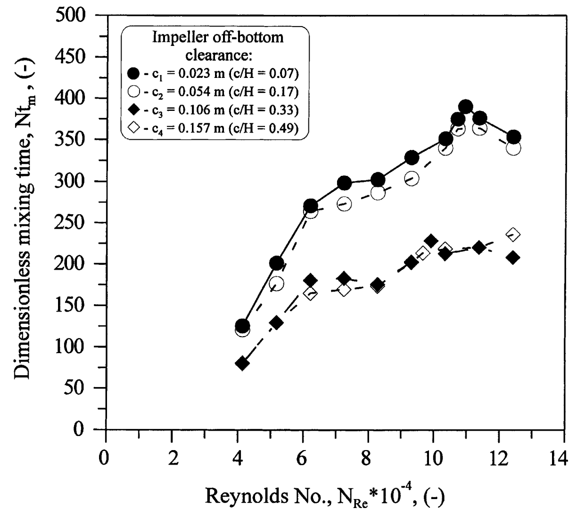

Fig. 8. Effect of Reynolds number on dimensionless mixing time for the different impeller clearances; $C = 5\,\mathrm{kg\,m^{-3}}$, $d_p = 205$ mm, $D/T = 0.33$, $\beta = 45°$.

incorporation into the liquid which occurs at intensive system mixing. The closer the impeller is to the liquid surface the more pronounced is the aeration. Introduction of air into the liquid decreases the density of agitated mixture. Since, the mixing power is directly proportional to this density ($P = N_p \rho N^3 D^5$), the power consumption will be lower with more intensive air incorporation into the suspension bulk.

The dependence of N_{JS} values on impeller off-bottom clearance may be described with the following relation:

$$N_{JS} \propto \left(\frac{c}{H}\right)^{-0.032} \tag{6}$$

Then, with the greater PTU impeller off-bottom clearance the N_{JS} value is also decreased. As an addition to the analysis of the PTU impeller position effect, the literature

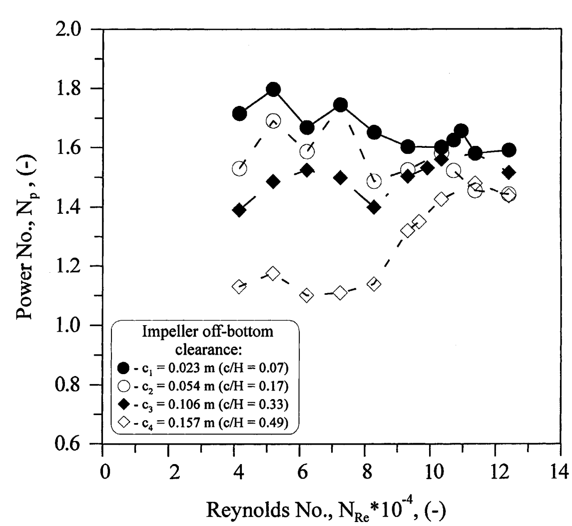

Fig. 9. N_p vs. N_{Re} for the different c/H; $C = 5\,\mathrm{kg\,m^{-3}}$, $d_p = 205$ mm, $D/T = 0.33$, $\beta = 45°$.

data on local velocities of liquid alone, determined by the digital particle image velocimetry (DPIV) technique were observed for the geometrically identical system [20]. In this way, very useful data on liquid flow in the tank caused by PTU are obtained accounting for the effects of impeller position on the mixing time. At the lowest impeller off-bottom clearance ($c/H = 0.05$) the flow pattern is opposite of what is expected, with the inlet flow to the impeller being from above and the discharge flow being radial. At $c/H = 0.15$ the flow pattern is up-pumping with the impeller discharge flow flaring out towards the vessel wall. This leads to a secondary flow loop in the upper half of the vessel. This secondary flow characterized by relatively low local fluid velocities is of significant influence, that is, it may increase the mixing time of the agitated system. At $c/H = 0.45$ this secondary flow decreases and the time required for system homogenization of the system is reduced. This agrees well with the mixing time values determined and analyzed in this paper.

The impeller blade angle to the horizontal axis β also affects the Nt_m, N_p, and N_{JS} values. This effect was studied with PTU impeller of $D/T = 0.33$, at the off-bottom clearance $c/H = 0.33$. The impeller blade angle to the horizontal axis was varied from 30° to 90° (Fig. 10).

It may be noted that the PTU having an angle of 90° is the straight-bladed turbine (SBT). This kind of impeller will be used for maintaining the continuity of the discussion on the effect of blade angle. Fig. 10 shows that with an increase of the impeller blade angle to the horizontal axis the dimensionless mixing time decreased.

For a given impeller of fixed diameter and blade width, the projected blade width (on the vertical y–z plane) increases with an increase in the blade angle. Due to low projected blade width, less dissipation of energy occurs behind the impeller blades and therefore, the PTU-30° has the lowest power number. When the angle is 45 or 60° there will be more projected width in the vertical direction when compared to the PTU-30°. Thereby, dissipation of energy behind the impeller blades increases. As a result power consumption increases (Fig. 11).

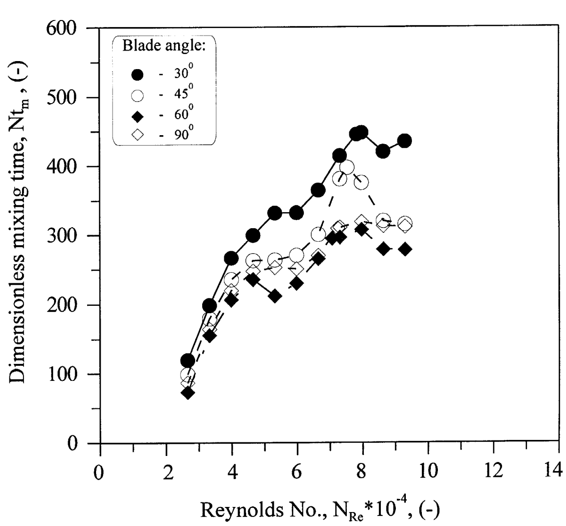

Fig. 10. Effect of N_{Re} on Nt_m for the different blade impeller angle; $C = 5\,kg\,m^{-3}$, $d_p = 205\,\mu m$, $D/T = 0.33$, $c/H = 0.33$.

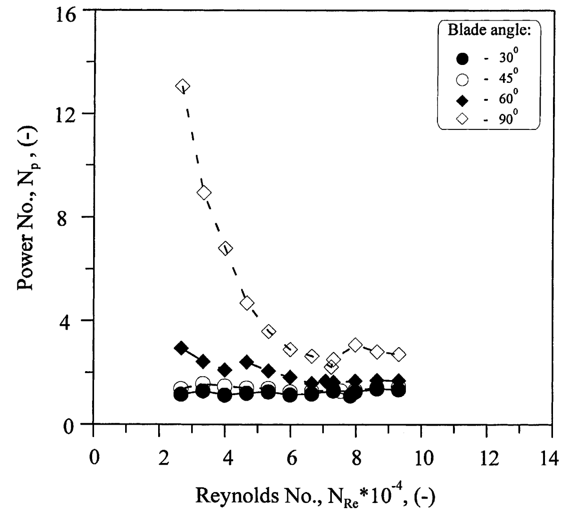

Fig. 11. N_p vs. N_{Re} for the different blade impeller angle; $C = 5\,kg\,m^{-3}$, $d_p = 205\,\mu m$, $D/T = 0.33$, $c/H = 0.33$.

Blade angles of PTU impeller affects also the N_{JS} values as shown in Table 1. With an increase in blade angle the impeller speed required for complete suspension is reduced.

In this sense we were looking for the possibility of the use of PTU impellers for floating solids suspension. It is really a specific case of suspension where all the solids are located on the liquid surface at the beginning of mixing and where impeller discharges liquid axially towards the surface. The time required to achieve a certain degree of uniformity of such a system is one of the most frequently specified process requirements [21]. In this paper, the time required to achieve 97% homogeneity was observed, and in that case mixing time can be expressed as

$$t_m = \frac{3.5}{k_m} \tag{7}$$

The experimental data can then be used to determine k_m as a function of number of operating and geometric variables. It is well known that the dimensionless mixing rate constant, k_m/N, in standard baffled tanks is a function of Reynolds number and geometry. When $N_{Re} > 10\,000$, k_m/N is only a function of geometry and is independent of N_{Re}. In most

Table 1
Effect of blade angle of PTU impeller on N_{JS} and $(P/m)_{JS}$ ($C = 5\,kg\,m^{-3}$, $d_p = 205\,\mu m$, $D/T = 0.33$, $c/H = 0.33$)

Blade angle (°)	N_{JS} (rpm)	$(P/m)_{JS}$ (W/kg)
30	589	0.53
45	567	0.56
60	532	0.60

Table 2
The mixing rate constants for different impeller blade angle of PTU impeller ($C = 5\,\text{kg}\,\text{m}^{-3}$, $d_p = 205\,\mu\text{m}$, $D/T = 0.33$, $c/H = 0.33$)

Blade angle of PTU (°)	a	b
30	0.102	1.15
45	0.109	1.53
60	0.123	1.65

cases of practical interest the expression for k_m takes the form

$$\frac{k_m}{N} = a\left(\frac{D}{T}\right)^b \left(\frac{T}{H}\right)^{0.5} \tag{8}$$

Analysing the results obtained in this paper with a ITU impeller used for floating solids suspension in a tank at $T = H$. the dependence of mentioned parameters is as

$$\frac{k_m}{N} = 0.109\left(\frac{D}{T}\right)^{1.53} \left(\frac{c}{H}\right)^{0.33} \tag{9}$$

with an average deviation of ±7%.

This relation is applicable to the case of blade angle of 45°. With the change of blade angle the a and b parameters are also changed (Table 2).

The efficiency of PTU-45° in systems with floating solids was also compared to the axial pitch-blade impeller of the same geometry, pumping downward (PTD) as well as with the radial impeller with four straight blades (SBT) (Figs. 12 and 13).

Fig. 12 shows that within the studied range of N_{Re}, the lowest mixing times are achieved with PTD. The impeller studied in this work, PTU, gives the highest values of this parameter. The SBT applications give the mixing time somewhere between the values given by the above-mentioned impellers. However, power consumption with SBT are so high that it can by no means be recommended in floating solids suspension applications. The lowest N_{JS} values as well as $(N_p)_{JS}$ are obtained using PTU impellers (Table 3).

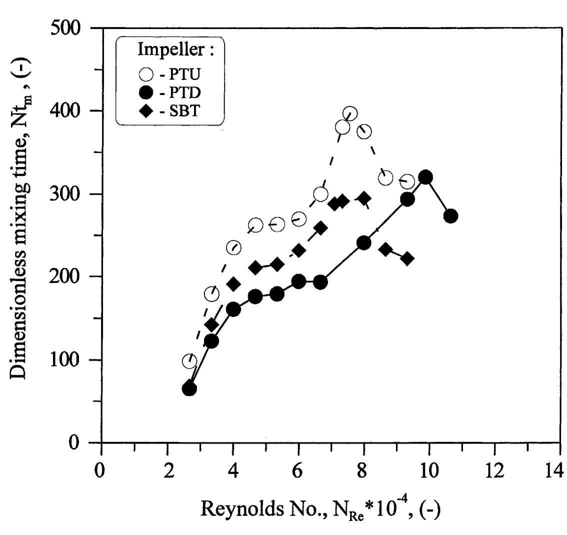

Fig. 12. Effect of N_{Re} on Nt_m for the different impellers; $C = 5\,\text{kg}\,\text{m}^{-3}$, $d_p = 205\,\mu\text{m}$, $D/T = 0.33$, $c/H = 0.33$, $\beta = 45°$.

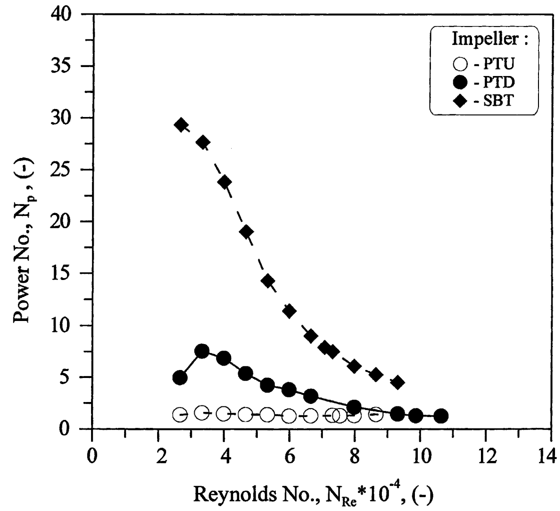

Fig. 13. N_p vs. N_{Re} for the different impellers; $C = 5\,\text{kg}\,\text{m}^{-3}$, $d_p = 205\,\mu\text{m}$, $D/T = 0.33$, $c/H = 0.33$, $\beta = 45°$.

This is obviously due to the liquid flow in the tank affected by different impeller types. Namely, in the case of SBT impeller, the liquid flow is generated by the impeller travels in the radial direction and splits into two streams. Each stream creates a circulations loop, one below and one above the impeller. Only a part of the energy supplied by the impeller, which is associated with higher loop, is available for suspension. PTD impeller pumps the flow downward towards the bottom of the tank, and after bumping changes direction, rises to the liquid surface and is now available for the solids suspension. PTU impeller directs the liquid flow towards the surface of liquid and is directly available for suspension. The length of the liquid path and the number of direction changes are greater in the case of PTD flow than in PTU flow. In addition, turbulence is generated above the impeller in the case of PTU flow, whereas the turbulence is generated below impeller in the case of PTD flow. Therefore, a PTU impeller may be taken as more efficient when the state of complete suspension of floating solids in a system should be obtained and maintained.

Table 3
Effect of type of impeller on N_{JS} and $(P/m)_{JS}$ ($C = 5\,\text{kg}\,\text{m}^{-3}$, $d_p = 205\,\mu\text{m}$, $D/T = 0.33$, $c/H = 0.33$, $\beta = 45°$)

Type of impeller	N_{JS} (rpm)	$(P/m)_{JS}$ (W/kg)
PTD	742	1.52
PTU	567	0.56
SBT	533	2.84

4. Conclusions

The following conclusions may be drawn from the results of studies of suspension of floating solids with up-pumping pitched-blade impeller.

- The presence of floating solids in the liquid significantly affects the mixing time of the liquid. With PTU application, in some cases, an increase of the mixing time of suspension as related to the mixing time of liquid alone may amount to as high as five times. The mixing time of suspension increases with an increase of mean bulk concentration of solids and their particle size. However, these parameters do not markedly affect the impeller speed required for complete suspension N_{JS}.
- Measurements of the mixing time as affected by the impeller speed may be suggested as a method for the determination of critical impeller speed for complete suspension of floating solids, N_{JS}.
- With an increase of impeller diameter as well as with an increase of blade angle, the value of dimensionless mixing time decreases, but the impeller power consumption increases. However, with an increase of the off-bottom impeller clearance the power consumption is reduced.
- If a process requires a state of complete floating solids suspension and its longer time maintenance, the up-pumping pitched blade impeller may be considered as a viable option.

References

[1] G.E.H. Joosten, J.G.M. Schilder, A.M. Broere, Trans. I. Chem. E. 55 (1977) 220–222.
[2] A. Bakker, J.J. Frijlink, Chem. Eng. Res. Des. 67 (1989) 208–210.
[3] N. Kuzmanić, E. Kessler, Ind. Eng. Chem. Res. 36 (1997) 5015–5022.
[4] N. Kuzmanić, D. Rušić, Ind. Eng. Chem. Res. 38 (1999) 2794–2802.
[5] N. Kuzmanić, Recents Progres Genie Procedes 11 (52) (1997) 49–56.
[6] P.M. Armenante, J.P. Mmbaga, R.R. Hemrajani, in: Proceedings of the Seventh European Conference on Mixing, Brugge, Belgium, 1991, pp. 555–564.
[7] R.R. Hemrajani, D.L. Smith, R.M. Koros, B.L. Tarmy, in: Proceedings of the Sixth European Conference on Mixing, Pavia, Italy, 1988, pp. 259–265.
[8] R.W. Thring, M.F. Edwards, Ind. Eng. Chem. Res. 29 (1990) 676–682.
[9] E. Rzyski, Chem. Eng. J. 31 (1985) 75–81.
[10] M. Kraume, Chem. Eng. Technol. 15 (1992) 313–318.
[11] W.A. Stein, Int. Chem. Eng. 32 (3) (1992) 449–474.
[12] S. Ruszkowski, in: Proceedings of the Eighth European Conference on Mixing, Cambridge, UK, 1994, pp. 283–291.
[13] K.S.M.S. Raghav Rao, J.B. Joshi, Chem. Eng. J. 39 (1988) 111–124.
[14] K.L. Harrop, W.H. Spanfelner, M. Jahoda, N. Otomo, A.W. Etchells, W. Bujalski, A.W. Nienow, Recents Progres Genie Procedes 11 (52) (1997) 41–48.
[15] V.P. Mishra, K.N. Dyster, Z. Javorski, A.W. Nienow, J. Mckemmie, Can. J. Chem. Eng. 76 (1998) 577–588.
[16] N. Kuzmanić, R. Ženetić, Chem. Eng. Technol. 22 (1999) 11–18.
[17] R. Conti, A. Gianetto, in: N.P. Cheremisinoft (Ed.), Encyclopedia of Fluid Mechanics, Vol. 2, 1986, Chapter 31, pp. 886–900.
[18] C.M. Chapman, A.W. Nienow, M. Cooke, J.C. Middleton, Chem. Eng. Res. Des. 61 (1983) 71–81.
[19] N. Zwietering, Chem. Eng. Sci. 8 (1958) 244–253.
[20] K.J. Mayers, A. Bakker, Can. J. Chem. Eng. 76 (1998) 433–440.
[21] J.B. Fasano, A. Bakker, Chem. Eng. (1994) 110–116.