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ORIGINAL RESEARCH PAPER

EFFECT OF IMPELLER BLADE THICKNESS ON CRITICAL IMPELLER SPEED IN AN AGITATED VESSEL

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Abstract: The successful design and operation of solid-liquid agitators require proper prediction of critical impeller speed (N_{js}) needed to suspend solids. It depends on system and impeller geometry as well as the properties of both solid and liquid. In this research, the effect of impeller blade thickness on N_{js} required for complete suspension of solid particles was discussed. Experiments were performed in an agitated vessel of 0.29 m diameter with three impellers namely Rushton turbine (RT), Pitched blade turbine (PBT) and A320 impeller. The impeller thickness was varied as 1, 2, 3 and 4 mm. The results showed that with the increase in impeller blade thickness, the critical impeller speed decreased significantly and the power required for complete suspension increased. Modifications are made in the Zwietering correlation by considering the effect of the impeller blade thickness to improve the prediction of critical impeller speed.

Keywords: *agitated vessel, axial impeller, impeller blade thickness, minimum impeller speed, radial impeller, solid suspension, Zwietering constant*

INTRODUCTION

Solid suspension in an agitated vessel has attracted considerable attention from many researchers, as it is one of the important operations in chemical and biochemical industries. Some of the important operations are solid catalyzed reactions, dissolution of solids, adsorption, desorption, leaching, crystallization and precipitation. In an agitated vessel, the impeller on rotation induces a net force due to the combination of the drag and lift forces of the moving fluid on the particles and due to the turbulent eddies originating from bulk flow in the vessel. This net force maintains the suspension of solids or enhances the resuspension of settled solids. The degree of solid suspension is initiated and maintained by the impellers that induce mean fluid velocities and large turbulent eddies. The maximum surface area of the particles exposed to the fluid is required for the effective chemical reaction, mass transfer and heat transfer.
This state of suspension is known as off bottom or complete suspension and is characterized by the complete suspension of all the particles and the corresponding speed is named as critical impeller speed or minimum impeller speed (N_{js}). It is important and therefore many efforts have been done so far for the assessment of critical impeller speed required for complete suspension. The visual method is most widely used to determine N_{js}. Zwietering [1] introduced “one second criterion” for the determination of critical impeller speed and given by equation (1):

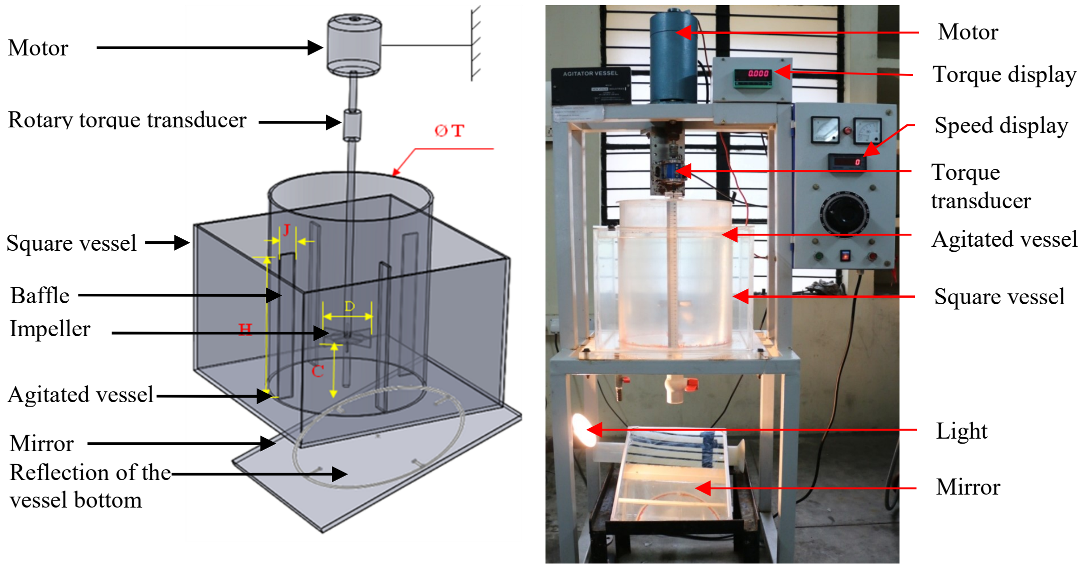
$$N_{js} = S \cdot v^{0.1} \cdot \left[\frac{g \cdot (\rho_S - \rho_L)}{\rho_L} \right]^{0.45} \cdot X^{0.13} \cdot d_p^{0.2} \cdot D^{-0.85} \tag{1}$$

where: D is the impeller diameter, d_p is the mass-mean particle diameter, X is the percentage mass proportion of solids to liquid, S is the Zwietering constant, v is the kinematic viscosity of the liquid, g_c is the gravitational acceleration constant and ρ_s and ρ_l are the density of particle and density of liquid respectively. It was a purely empirical expression based on the dimensional analysis. The Zwietering correlation relates the physical properties of both solid and liquid and the impeller diameter to the critical impeller speed through the parameter ‘S’. The Zwietering constant ‘S’ is independent of solid and liquid properties and solid loading, but depends on the impeller geometry and system geometry such as impeller diameter, impeller blade width, impeller blade thickness, vessel bottom shape, bottom roughness and baffling.
The effect of solid and liquid properties [2 – 7], impeller clearance [8 – 11], bottom roughness [12] and impeller type [13 – 16] on critical impeller speed (N_{js}) was investigated by many researchers. The effects of impeller dimensions such as impeller thickness and impeller width were not commonly reported. Very few researchers [17, 18] had studied the effect of impeller blade thickness and impeller blade width for pitched blade turbine. In another research [19] the effect of impeller blade width for PBT, RT and A320 impellers was studied. The results from the above literature had shown that the critical impeller speed decreases with an increase in blade width and the extent of reduction decreases with an increase in the blade width. It also reveals that the critical impeller speed slightly decreases with an increase in the blade thickness of pitched blade turbine. In the present research work, the aim is to study the effect of impeller blade thickness on critical impeller speed for three different impellers, namely Rushton turbine, pitched blade turbine and A320 impeller. A further objective of this

work is to express Zwietering correlation as a function of impeller clearance and impeller blade thickness using regression analysis.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental apparatus consisted of a flat bottom cylindrical vessel of inner diameter 0.29 m and was placed in a square tank to minimize optical distortion. The agitated vessel and square tank were fixed with a steel platform to increase the steadiness of the unit at high impeller speeds. The agitated vessel and square tank was made of a transparent acrylic material to observe solid movement in the vessel while conducting the experiments. Figure 1a shows the schematic diagram of the experimental setup used in the present study and Figure 1b is the photographic view of the experimental setup.



(a) ***(b)***

Figure 1. *Experimental apparatus: a) schematic diagram; b) photographic view*

To avert the formation of vortex, the vessel was built-in with four vertical strip baffles of height equal to liquid level and width of the baffle (J) is equal to 1/10th of the vessel diameter and divided 90^{o} separated around the circumference of the vessel. The mirror was adjusted so that the bottom of the agitated vessel could be clearly observed, and the set up was illuminated with a 60 W lamp. The impeller clearance (C) was calculated from the vessel base to the impeller center line. The impellers diameter is equal to 1/3 of vessel diameter and these impellers are mounted on the impeller shaft. The experimental study covered a clearance range from T/5.8 to T/2.42; the liquid level (H) was equivalent to the diameter of the vessel, for all investigations. The design details of the agitated vessel are shown in Table 1.

Table 1. *Design details of agitated vessel*

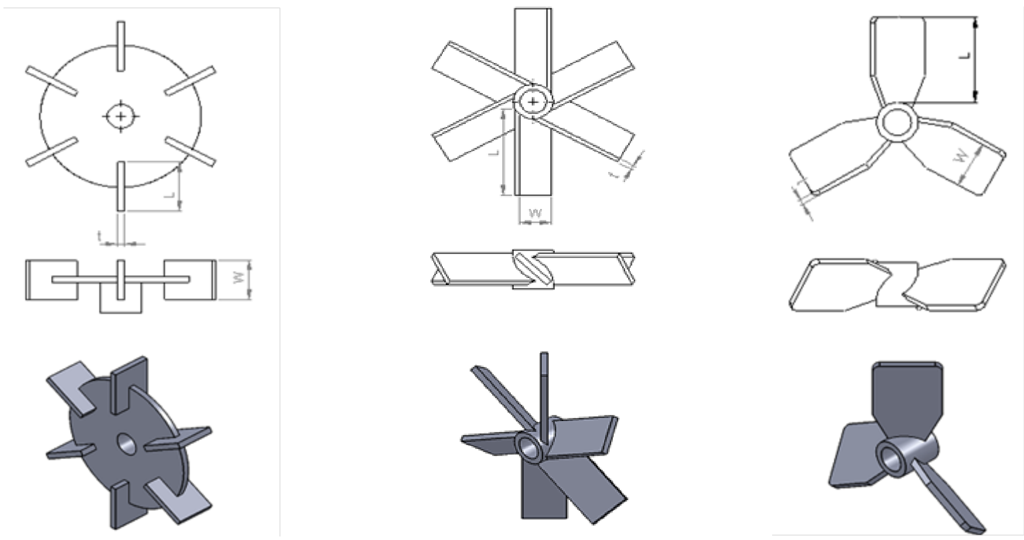
Parameter	Value
Diameter of agitated vessel (T)	0.29 m
Liquid level to vessel diameter (H/T)	1
Baffle width	T/10
No. of baffles	4
Material	Transparent acrylic
Geometry	Cylindrical with flat bottom
Impeller position from vessel bottom (C)	50, 70, 90 and 120 mm

The solid used was resin of 0.506 mm diameter and the liquid used was water. The properties of solid and liquid are given in Table 2.

Table 2. *Properties of solid and liquid*

Properties	Liquid	Solid
Density [$kg \cdot m^{-3}$]	996	1400
Viscosity [Pa·s]	8.12×10^{-3}	-
Particle diameter [mm]	-	0.506
Sphericity		1

Three types of impellers namely Rushton turbine (RT), pitched blade turbine (PBT) and A320 impeller were used in the study. The schematic representations of these impellers are shown in Figure 2.

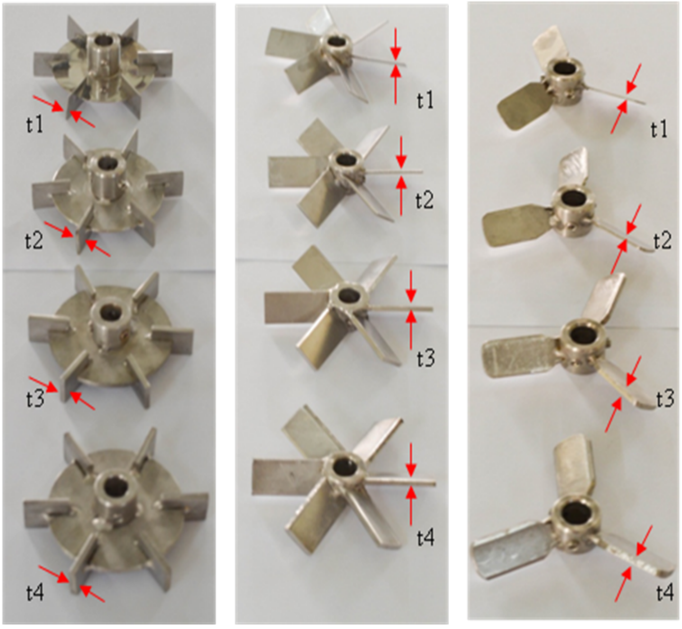


(a) ***(b)*** ***(c)***

Figure 2. *Schematic representations of impellers*
(a) Ruston turbine impeller; (b) Pitched blade turbine impeller; (c) A320 impeller

The blade width (w) of the three impellers were equivalent to 20 % of the impeller diameter (w = 0.20 D). The impeller blade thickness (t) was varied as 1, 2, 3 and 4 mm.

The photograph of varying impeller thickness is represented in Figure 3. The design details of the impellers are shown in Table 3.



(a) *(b)* *(c)*

Figure 3. *Varying thickness of impellers*
(a) Ruston turbine impeller (b) Pitched blade turbine impeller (c) A320 impeller

Table 3. *Design details of impellers*

Impeller type	Impeller name	Number of blades	Diameter [mm]	Width [mm]	Thickness [mm]
Radial	Rushton Turbine (RT)	6	96.7	19.34	1, 2, 3, 4
Axial	Pitched Blade Turbine (PBT)	6	96.7	19.34	1, 2, 3, 4
	A320 impeller	3	96.7	19.34	1, 2, 3, 4

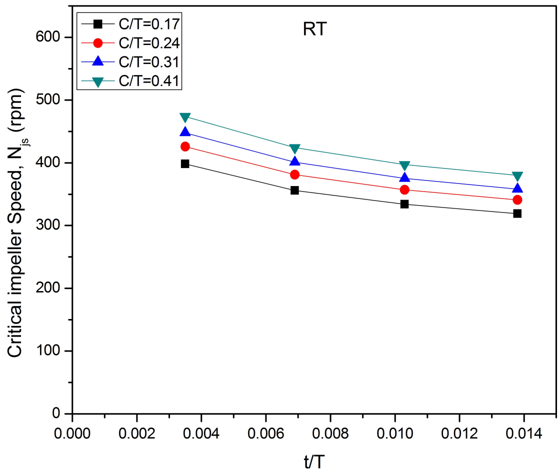
The impeller mounted on the shaft was driven by an electric motor to provide agitation. The maximum operating speed of motor was 1500 rpm. The speed can be observed from the RPM indicator and it can be adjusted by using the speed regulator. The torque was calculated by a rotary torque transducer fixed to the impeller shaft. It was pre calibrated rotary torque sensor with a range from 0 to 5 N·m and the precision is ± 0.05. The instrument (Make: Burster Measurement Systems Private Limited) quantifies the torque (τ) generated on the shaft. The particle behaviour at the vessel bottom was carefully observed via the mirror set up over the entire vessel bottom at each agitation speed. The impeller speed was raised until no particle stayed stationary at the base of the vessel for more than 1 or 2 seconds [1]. The corresponding speed was recorded as critical impeller speed (N_{js}). Each observation was performed at least thrice to ensure accuracy and repeatability of observation, and the results showed are the averages of each observed value. The impeller power consumption at critical impeller speed was found using a calibrated rotating torque transducer.

RESULTS AND DISCUSSION

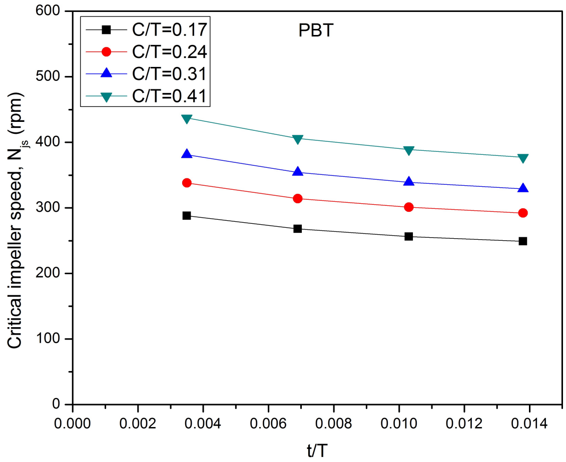
To examine the effect of impeller blade thickness, three impellers: Rushton turbine, pitched blade turbine and A320 impellers were selected. The impeller blade thickness (t) was varied as 1, 2, 3 and 4 mm. The blade width of the three impellers were equal to 20 % of the impeller diameter (w = 0.20 D). The solid used was resin of diameter 0.506 mm and the solid loading was 5 % by volume.

Effect of impeller blade thickness on critical impeller speed

The Figure 4 shows the effect of impeller blade thickness on critical impeller speed for Rushton turbine (Figure 4a), pitched blade turbine (Figure 4b) and A320 (Figure 4c) impellers respectively for a tank diameter of T = 0.29 m, solid loading of 5 % by volume and various impeller clearances (C/T = 0.17, 0.24, 0.31, 0.41).



(a)



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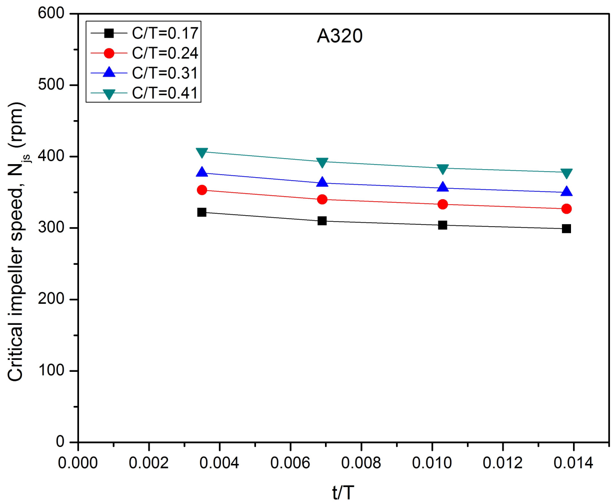


(c)

Figure 4. *Effect of impeller blade thickness on critical impeller speed:*
(a) Ruston turbine impeller; (b) Pitched blade turbine impeller; (c) A320 impeller

It shows that the critical impeller speed slightly decreases as impeller blade thickness increases. This might be due to increase in liquid flow and turbulence as the impeller blade thickness increases. In Figure 4b, it is observed that impeller clearance has significant effect on critical impeller speed for pitched blade turbine. With the available experimental data using regression, the modified Zwietering correlation was developed which includes the effect of impeller thickness and it is shown in Table 4.

Table 4. *Modified Zwietering correlation*

Impeller	Modified Zwietering correlation
Rushton Turbine (RT)	$N_{js} = \left[7.28 \cdot \left(\frac{C}{T}\right)^{0.198} \cdot \left(\frac{t}{T}\right)^{-0.079}\right] \cdot \nu^{0.1} \cdot \left[\frac{g \cdot (\rho_s - \rho_L)}{\rho_L}\right]^{0.45} \cdot X^{0.13} \cdot d_p^{\,0.2} \cdot D^{-0.85}$
Pitched Blade Turbine (PBT)	$N_{js} = \left[11.66 \cdot \left(\frac{C}{T}\right)^{0.472} \cdot \left(\frac{t}{T}\right)^{-0.106}\right] \cdot \nu^{0.1} \cdot \left[\frac{g \cdot (\rho_s - \rho_L)}{\rho_L}\right]^{0.45} \cdot X^{0.13} \cdot d_p^{\,0.2} \cdot D^{-0.85}$
A320 impeller	$N_{js} = \left[12.19 \cdot \left(\frac{C}{T}\right)^{0.266} \cdot \left(\frac{t}{T}\right)^{-0.160}\right] \cdot \nu^{0.1} \cdot \left[\frac{g \cdot (\rho_s - \rho_L)}{\rho_L}\right]^{0.45} \cdot X^{0.13} \cdot d_p^{\,0.2} \cdot D^{-0.85}$

where: C is the impeller clearance, T is the vessel diameter and t is the impeller blade thickness. The dependence of critical impeller speed on impeller blade thickness was shown in equations 2, 3 and 4 for Rushton turbine, pitched blade turbine and A320 impellers respectively.

$$\text{RT:} \qquad N_{js} \cdot \alpha \cdot \left(\frac{t}{T}\right)^{-0.079} \tag{2}$$

$$\text{PBT:} \qquad N_{js} \cdot \alpha \cdot \left(\frac{t}{T}\right)^{-0.106} \tag{3}$$

$$\text{A320:} \qquad N_{js} \cdot \alpha \cdot \left(\frac{t}{T}\right)^{-0.160} \tag{4}$$

A320 impeller exhibits a strong dependence of critical impeller speed on impeller blade thickness compared to the other two impellers whereas Rushton turbine shows less dependence of critical impeller speed on impeller blade thickness. It is observed that the N_{js} for an A320 impeller is lowest in comparison with the other impellers of same thickness because of its wide blade geometry. The Zwietering constant ‘S’ expressed as a function of impeller clearance and impeller blade thickness using regression analysis is as follows:

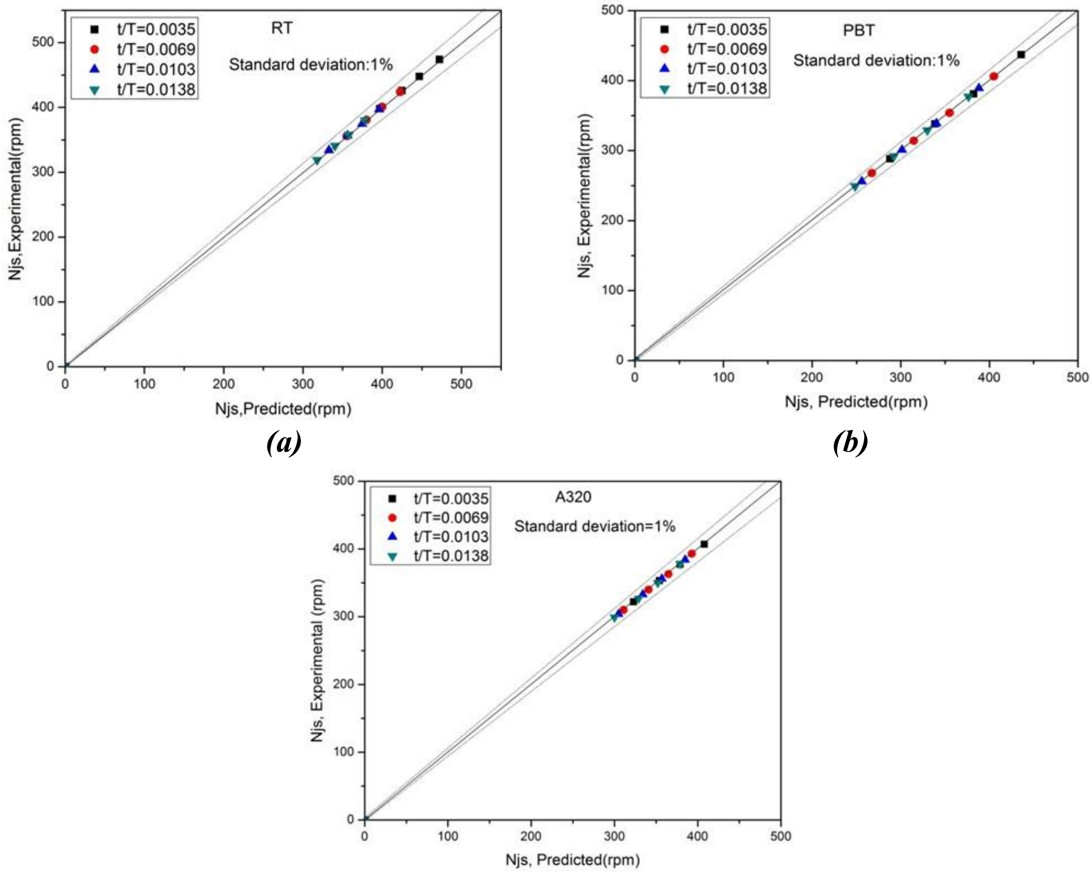
$$S = \left[a \cdot \left(\frac{C}{T}\right)^{b} \cdot \left(\frac{t}{T}\right)^{c}\right] \tag{5}$$

where a, b and c are constants and these values for different impellers are given in Table 5.

Table 5. *Values of the constants used in the expression for S*

Impeller	a	b	c
Rushton Turbine (RT)	7.28	0.198	- 0.079
Pitched Blade Turbine (PBT)	11.66	0.472	- 0.106
A320 impeller	12.19	0.266	- 0.160

A comparison of experimental critical impeller speed with the one calculated according to the modified Zwietering correlation given in Table 4 is presented in Figure 5 for all the three impellers. It shows that the critical impeller speed observed from the experiment and calculated by modified Zwietering correlation were closer. It concludes that the modified Zwietering correlation provides a better prediction of critical impeller speed.



(a) ***(b)***

(c)

Figure 5. *Comparison of the experimental N_{js} values with the predicted values (a) Rushton turbine impeller; (b) Pitched blade turbine impeller; (c) A320 impeller*

Raghava Rao *et al*. [17, 18] studied the effect of impeller blade thickness and found that the critical impeller speed depends on the impeller thickness raised to the power of 0.07 for pitched blade turbine.

Figure 6 compares the effect of impeller thickness using the data obtained from this study and Raghava Rao *et al*. [17] for pitched blade turbine. It is inferred that the experimental data follows the same trend with the literature. The minimal difference in values is due to the difference in vessel diameter and solid concentration.

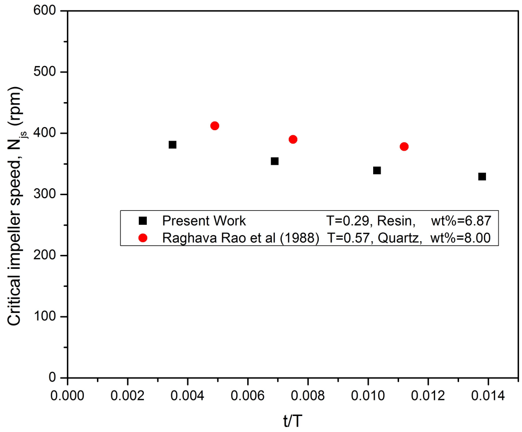


Figure 6. *Effect of impeller thickness on critical impeller speed (comparison of present work with Raghava Rao et al. [17])*

Effect of impeller blade thickness on Zwietering constant 'S'

The Zwietering constant 'S' was calculated using equation (1). The effect of impeller blade thickness on Zwietering constant 'S' shown in Figure 7a for the Rushton turbine, Figure 7b for the pitched blade turbine and Figure 7c for the A320 impeller.

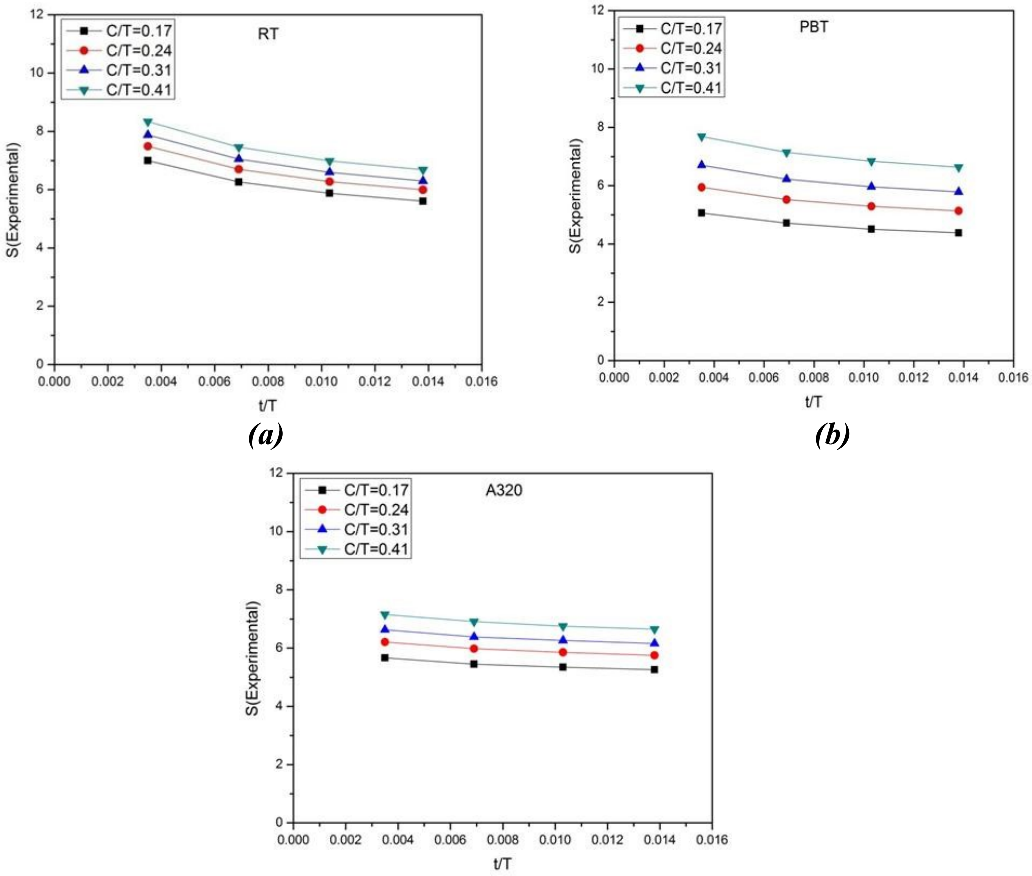
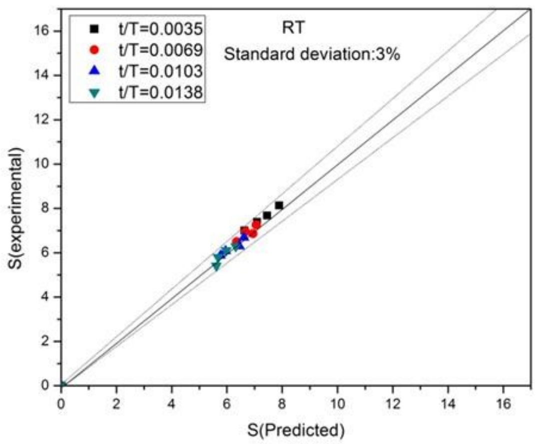
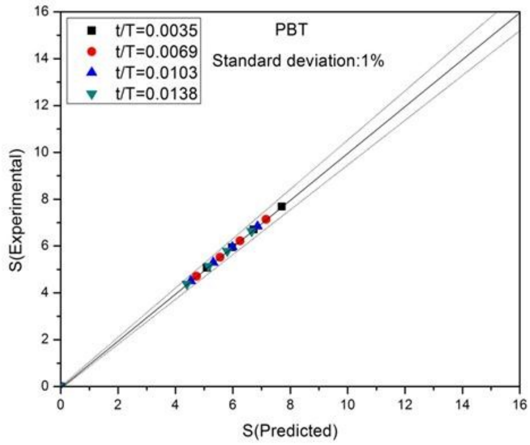


Figure 7. *Effect of impeller blade thickness on Zwietering constant 'S': (a) Ruston turbine impeller; (b) Pitched blade turbine impeller; (c) A320 impeller*

From the above plots the inference is that the Zwietering constant ‘S’ decreases as the impeller blade thickness increases. Also, the 'S' value depends on the impeller clearance. The plot shows that the 'S' value was increased with increase in impeller clearance. Similar findings were observed in the literature [9, 20, 21]. The constant 'S' was calculated using present correlation and it was compared with the 'S' obtained from Zwietering correlation given in equation (1).
Figure 8 compares the 'S' value calculated using present correlation to the 'S' obtained from Zwietering correlation. The standard deviation between the experimental ‘S’ value and predicted ‘S’ value is closer for all three types of impellers.



(a)



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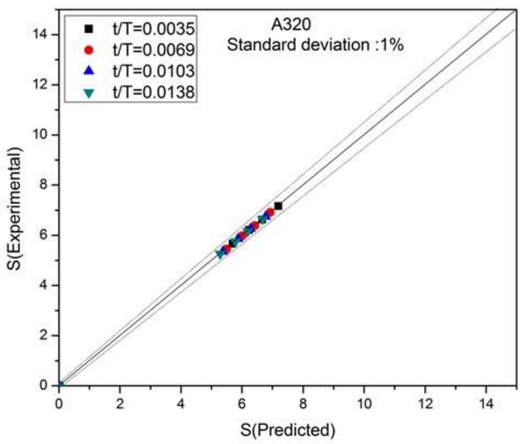


(c)

Figure 8. *Comparison of the experimental ‘S’ values with the predicted ‘S ‘values (a) Ruston turbine impeller; (b) Pitched blade turbine; (c) A320 impeller*

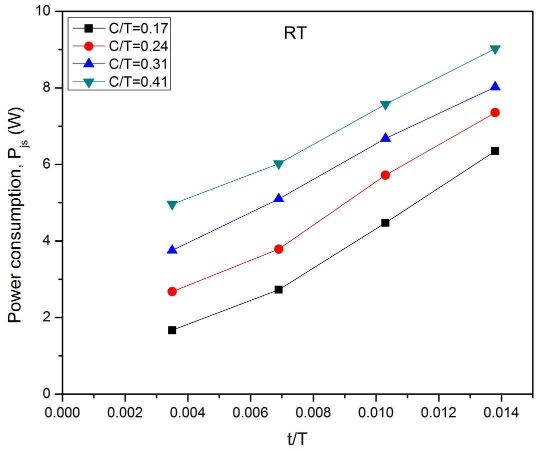
It concludes that the modified Zwietering correlation efficiently predicts the critical impeller speed within the specified range of variables considered in this study.

Effect of impeller blade thickness on impeller power consumption

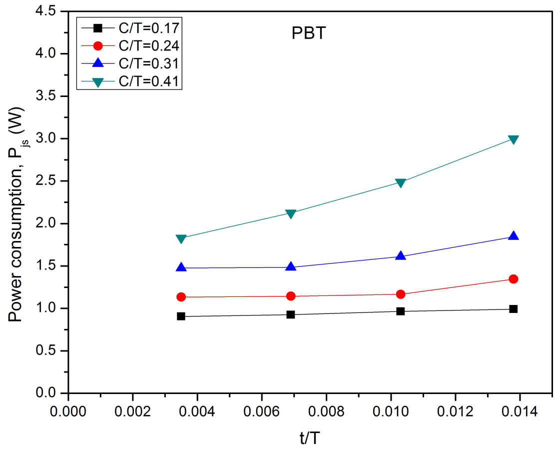
The power consumption at critical impeller speed was found using a calibrated rotating torque transducer attached to the shaft. The torque (τ) values were observed from the torque display unit. The power consumption at critical impeller speed was determined using equation 6.

$$P_{js} = 2\pi \cdot N_{js} \cdot \tau \tag{6}$$

where: P_{js} is the power consumption (W) and N_{js} is the critical impeller speed in revolutions per second (rps).
The effect of impeller blade thickness on impeller power consumption for Rushton turbine, pitched blade turbine and A320 impeller was shown in Figure 9a, Figure 9b and Figure 9c respectively.



(a)



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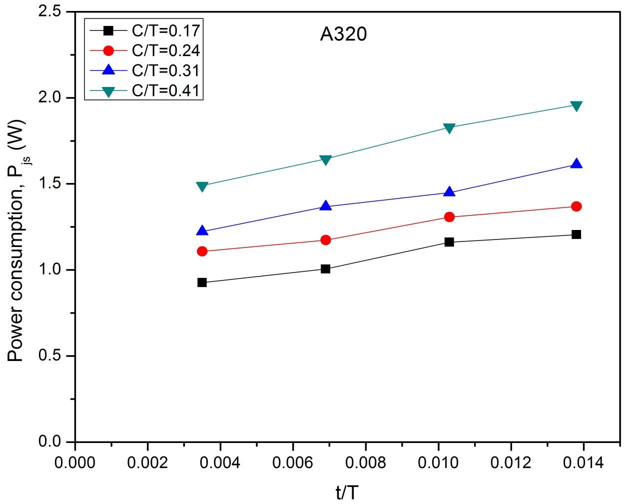

(c)

Figure 9. *Effect of impeller blade thickness on power consumption:*
(a) Ruston turbine impeller; (b) Pitched blade turbine impeller; (c) A320 impeller

It was observed that the power consumption increases as the impeller blade thickness increases, while keeping the other design parameters constant. Also, it was found that the power consumption increased with the increase in impeller clearance due to the energy required for suspending the solid particles increases. At impeller positions closer to the vessel base, higher suspension power is required as recorded by Chudacek [15]. It could be observed from Figure 9a, that the power consumption for Rushton turbine is steeply increased as the impeller blade thickness increases and it consumes more power as compared to pitched blade turbine and A320 impeller.

The power consumption for the pitched blade turbine was significantly higher than A320. The A320 impeller had the lowest power consumption values among three impellers because it attains off bottom condition at lower impeller speeds. It indicates that it is more energy efficient for solid suspension than other two impellers used in this study. Rushton turbine required more power as compared to pitched blade turbine. This was consistent with the findings in the literature [22 – 24].

CONCLUSIONS

The influence of impeller clearance and impeller blade thickness on the critical impeller speed (N_{js}) and power consumption (P_{js}) was investigated in a 0.29 m diameter (T) agitated vessel using Rushton turbine, pitched blade turbine and A320 impellers. The solid loading was 5 % by volume of a mean particle diameter of 0.506 mm and impeller clearance varied from 0.17T to 0.41T. The Zwietering constant 'S' was expressed as a function of impeller clearance and impeller blade thickness using regression analysis for Rushton turbine, pitched blade turbine and A320 impellers.

The experimental data for three impeller geometries of different thicknesses leads to the following conclusions:

- The critical impeller speed decreases with increase in impeller blade thickness.
- The impeller power consumption at critical impeller speed increases as the impeller blade thickness increases.
- The Zwietering constant ‘S’ decreases as the impeller blade thickness increases.
- The impeller clearance had a significant effect on critical impeller speed for pitched blade turbine.
- Rushton turbine shows the strong dependence of the impeller blade thickness on critical impeller speed.
- Pitched blade turbine shows the strong dependence of the impeller clearance on critical impeller speed.
- A320 impeller was found to be more energy efficient than pitched blade turbine and Rushton turbine impellers.
- The modified Zwietering correlation better predicts the critical impeller speed within the specified range of impeller clearance and impeller blade thickness used in this study.

ACKNOWLEDGEMENT

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NOMENCLATURE

C	impeller bottom clearance, m
D	impeller diameter, m
d_p	particle diameter, mm
g	acceleration due to gravity, $m \cdot s^{-2}$
H	liquid level, m
L	impeller blade length, m
N_{js}	critical impeller speed, rpm
P_{js}	power consumption at N_{js}, W
T	vessel diameter, m
t	impeller blade thickness, m
w	impeller blade width, m
X	solid loading (mass of solid/mass of liquid x 100)

SYMBOLS

μ	viscosity of liquid, Pa·s
ν	kinematic viscosity, $m^2 \cdot sec^{-1}$
ρ_s	density of solid, $kg \cdot m^{-3}$
ρ_L	density of liquid, $kg \cdot m^{-3}$
τ	torque, N·m

ABBREVIATIONS

PBT	Pitched Blade Turbine
RT	Ruston Turbine

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