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Effect of Impeller Clearance and Liquid Level on Critical Impeller Speed in an Agitated Vessel using Different Axial and Radial Impellers

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ABSTRACT

The effect of impeller clearance and liquid level on the critical impeller speed (N_{js}) for various radial and axial flow impellers in 0.29 m ID agitated vessel has been studied. Five types of radial impellers: Rushton turbine (RT), Straight blade (SB), Curved blade (CB), Curved blade with disc (CBWD) and R130 impeller and four types of axial impellers: Rushton turbine 45° angle (RT 45), Pitched blade (PBT), A320 and HE3 impeller were used. Tap water and resin particle of 0.506 mm were used as liquid and solid phases, respectively. The impeller clearance to vessel diameter (T) was varied between 0.17 and 0.41. The liquid level (H) was also varied as H/T=0.5, H/T=0.75 and H/T=1. The R130 impeller and A320 impeller was found to be more efficient among radial and axial impellers respectively. A new expression for Zwietering constant 'S' was developed to predict critical impeller speed, considering impeller clearance and liquid level for all the impellers. The results obtained here show that the 'S' values increase with increase in clearance, and decrease with liquid level for all impellers and it also depends on the type of impeller.

Keywords: Solid suspension; Impeller clearance; Critical impeller speed; Agitated vessel; Liquid level; Zwietering constant.

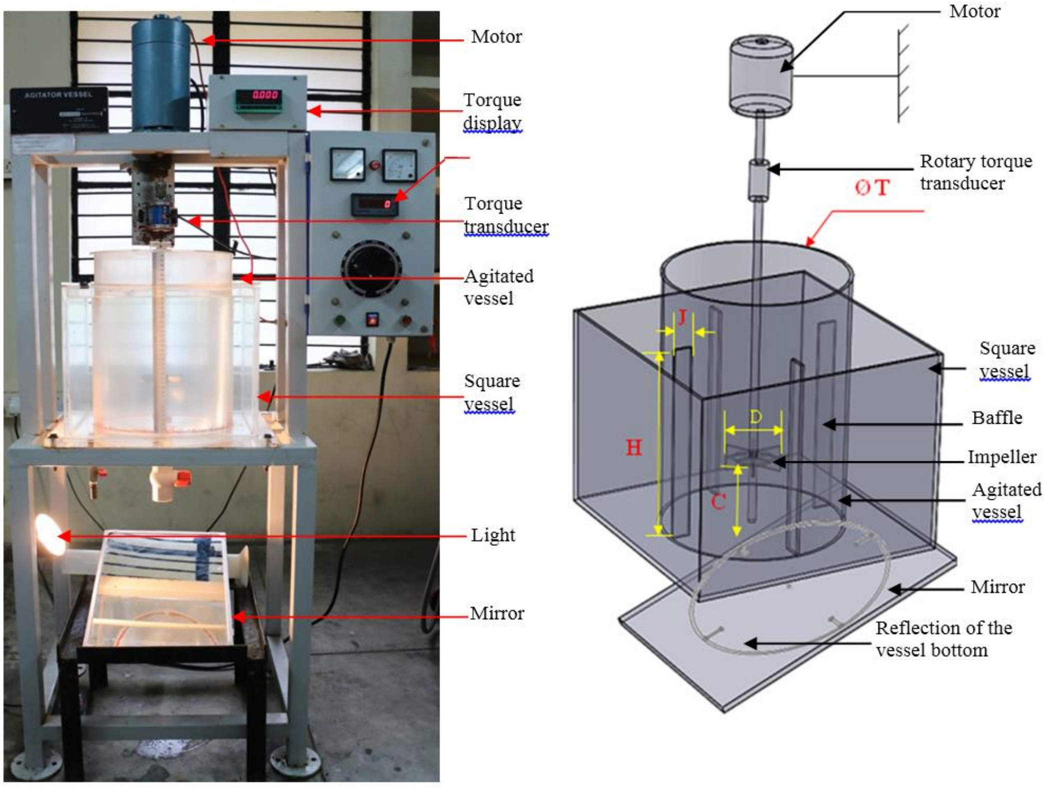
NOMENCLATURE

C	impeller clearance	RT45	Rushton Turbine With Blade Angle 45°
CB	Curved Blade	S	Zwietering constant
CBWD	Curved Blade With Disc	SB	Straight Blade turbine
D	impeller diameter	T	vessel diameter
d_p	particle diameter	X	solid loading
g	acceleration due to gravity		
H	liquid level	τ	Torque
l	impeller blade length	ν	kinematic viscosity
J	width of the baffle	ρ_l	density of liquid
N_{js}	critical impeller speed	ρ_s	density of solid
PBT	Pitched Blade Turbine	P_{js}	power consumption at N_{js}
RT	Rushton Turbine		

1. INTRODUCTION

Solid-liquid mixing in agitated vessel has a wide variety of applications in chemical and process industries. Suspensions of solids in liquids are done in an agitated vessel by rotating impellers. These agitated vessels are usually operated at critical impeller speed, N_{js}, which is the minimum impeller speed at which no particles remain stationary at the bottom of the vessel for more than 1 or 2 s (Zwietering, 1958). Zwietering found an empirical correlation for N_{js} shown in Eq. (1).

$$N_{js} = S\,\nu^{0.1}\left[\frac{g(\rho_s-\rho_l)}{\rho_l}\right]^{0.45} X^{0.13} d_p^{0.2} D^{-0.85} \qquad (1)$$



(a) Pictorial view (b) Schematic diagram

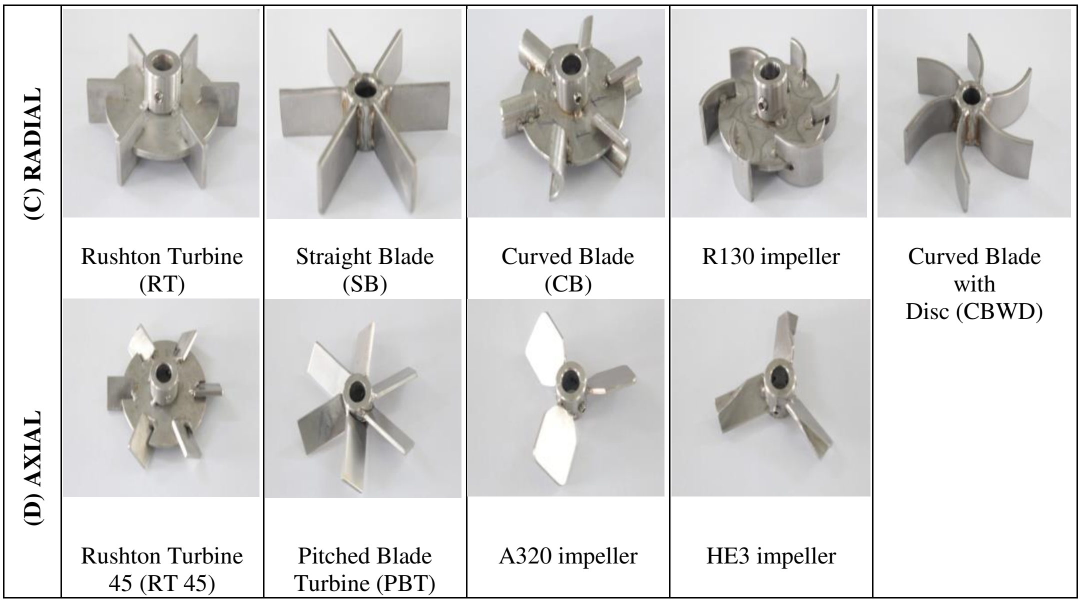


Fig. 1. Experimental setup. (a) Pictorial view. (b) Schematic diagram (c) Radial impellers (d) Axial impellers.

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 which is a function of impeller geometry and tank geometry, ν 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. Baldi *et al.*, (1978) proposed new relation for N_{js} based on theoretical approach on energy balance. Zwietering correlation is most widely used for the calculation of N_{js}. Visual method is applied to find N_{js} by most of the researchers, but it is not feasible when the vessel is not transparent. Many investigators (Zweitering, 1958; Nienow, 1968; Baldi *et al.*, 1978; Conti *et al.*, 1981; Chapman *et al.*, 1983; Chudacek, 1985; Gray, 1987; Raghava Rao *et al*., 1988; Armenante *et al*., 1992; Oldshue and Sharma, 1992; Mayers and Fasana, 1992; Myers *et al*., 1994; Armenante and Li, 1993; Arvinth *et al*, 1996) have studied the dependence of number of physical and operational variables on critical impeller speed. These include solid-liquid properties, diameter of impeller, diameter of vessel, impeller clearance, solid concentration, baffle arrangement, impeller type and shape of the vessel bottom. Most of the studies show that impeller off bottom clearance has a significant effect on critical impeller speed (Armenante *et al*., 1998; Nienow 1968; Baldi *et al*., 1978; Ibrahim and Nienow, 1996; Shaik and Sharma 2003). Solid concentration also has a larger effect on critical impeller speed (Micale *et al*., 2002 and Myers *et al*., 1994, 2013). The exponent on solid concentration in Zwietering correlation was confirmed by Nienow (1968) and Baldi *et al*., (1978). Ayranci and Kresta (2014) reported that the existing Zwietering equation is applicable for the solid concentration value up to 2 % (w/w) solids. They modified the Zwietering correlation, with the new exponent on concentration, which provides predictions up to 35 % (w/w). Very little information is available in the literature on the effect of viscosity. Ibrahim and Nienow, (1999, 2009) analyzed the effect of viscosity on critical impeller speed, but it is yet to be compared with the exponent for viscosity given by Zwietering. The bottom shape of the agitated vessel affects the suspension efficiency (Chudacek, 1985; Atiemo-Obeng *et al*., 2004), solid concentration (Shin-ichi Kondo *et al*., 2007), and Zwietering constant S (Kevin J Myers *et al*., 1998). The roughness of the vessel bottom also influences the critical impeller speed. Ghionzoli *et al*., (2007) reported higher N_{js} values in smooth based vessel, than in rough based vessel. The effect of liquid level on the critical impeller speed was analyzed by C.D.Rielly *et al*., (2007). Kasat and Pandit (2005) compiled the exponents of different parameters in Zwietering equation given by many authors and showed that the exponent values are more close to the values given by Zwietering. The 'S' value for a wide range of geometries was reported by Ibrahim and Nienow, 1996; Armanante and Nagamine, 1998; Ayranci and Kresta, 2011. Ayranci and Kresta, (2011) confirmed that the S value also depends on the particle size.

The Zwietering constant 'S' is a function of (i) impeller geometry such as impeller clearance, impeller diameter, impeller width and impeller thickness, (ii) vessel geometry such as bottom shape, bottom roughness and (iii) liquid level. Limited information is available (Raghava Rao *et al*., (1988) on the effect of width and thickness of impeller on N_{js}. The effect of bottom shape, bottom roughness, impeller width, impeller thickness and liquid level remains largely unexplored. Despite the abundant literature on solid suspension, it appears that very few of the published correlation explicitly predict the effect of impeller clearance on N_{js} and for limited impellers.

Hence, the objective of this work is to:

- Investigate and quantify the effect of the impeller clearance and liquid level on N_{js} for various radial and axial impellers under similar operating conditions.
- Develop a relation between the Zwietering constant 'S', impeller clearance and liquid level.

2. EXPERIMENTATION

Pictorial view and a schematic diagram of the experimental setup are shown in Figs 1(a) and 1(b). The agitated vessel consists of a 290 mm diameter (T) and 390 mm high acrylic vessel with a flat bottom, placed inside a rectangular outer acrylic vessel. This outer vessel is filled with water to minimize the optical distortion. Four baffles T/10 in width and equally spaced were installed in the circular agitated vessel. The details pertaining to the agitated vessel is given in Table 1. Five types of radial impellers: Rushton turbine (RT), straight blade turbine (SB), R130 impeller, curved blade turbine (CB) and curved blade with disc turbine (CBWD) and four types of axial impellers: Pitched blade turbine (PBT), A320 impeller, Rushton turbine with 45° angle (RT45) and HE3 impeller were used in the study. The radial and axial impeller photographs were shown in Figs 1(c) and 1(d) respectively. The diameter of impellers was one third of vessel diameter. The design details of the impellers are represented in Table 2. The impellers were attached to a shaft of diameter 12 mm. The shaft was attached to the motor. Tap water and resin particle of 0.506 mm are used as liquid and solid phases. Solid density was 1400 kg/m^3 and the solid loading was equal to 5% (v/v)

The critical impeller speed was measured as discussed by Zwietering by visually observing the solid suspension at the bottom of the vessel by placing a mirror below the vessel bottom, which was well illuminated. At a constant solid loading, the impeller speed was gradually increased, more and more particles are started to suspend. When the stirrer reached a particular speed, all the particles moved vigorously at the bottom of the vessel and solids are suspended, corresponds to the critical impeller speed (N_{js}) and it was noted. A pre calibrated rotating torque transducer (0 to 5 Nm ±0.05) was used (Make: Burster Measurement Systems Private Limited) to measure instantaneous torque (τ) values developed on shaft.

The power consumption at critical impeller speed in the agitation system was determined using Eq. (2).

$$P_{js} = 2\pi N_{js} \tau \qquad (2)$$

Where P_{js} is the power consumption (W) and N_{js} is the critical impeller speed in revolutions per second (rps). Experimentally observed value of N_{js} was validated by plotting power number against impeller speed. (Rewatkar *et al*., 1991a). At a particular impeller speed, the power number remains constant, referred as critical impeller speed (N_{js}). Using the experimental N_{js}, Zwietering constant 'S' were calculated by re-arranging Eq. (1)

for all the impellers of different clearances and liquid levels.

3. RESULTS AND DISCUSSION

The experimental data of the present study covers the impeller clearance value of C/T = 0.17 to 0.41 measured from the bottom of vessel, liquid level of H/T = 0.5 to 1.0 for nine impellers. Experiments were repeated thrice to evaluate the reproducibility of N_{js} value. A detailed analysis of performance of various impellers under similar operating conditions was reported and an expression for Zwietering constant 'S' as function of impeller clearance and liquid level was proposed.

3.1 Effect of Impeller Clearance on Critical Impeller Speed

The values of N_{js} have been plotted against the impeller clearance (C/T = 0.17 to 0.41) for different liquid levels in Figs 2 and 3. It shows the effect of clearance and liquid level on critical impeller speed for 5 % (v/v) and 0.506 mm diameter solids. It was observed that the critical impeller speed (N_{js}) strongly depends on the impeller clearance. The value of N_{js} decreased with a decrease in the impeller clearance for all the impellers. It was seen that the dependence of N_{js} on clearance was much stronger for straight blade and curved blade impellers for C/T < 0.25. This finding suggested that these two impellers might be much better suited than other impellers at low clearances. Rushton turbine had a smaller N_{js} value than any other impellers. The straight blade turbine gave N_{js} values closer to Rushton turbine. It can be observed from Fig. 2, that the PBT impeller has a smaller value of N_{js} than other axial impellers. Sharma and Shaikh (2003) observed the change in flow pattern at C/T = 0.35 for pitched blade turbine. Similar results were observed for C/T = 0.3 and the critical impeller speed increased with increase in C/T, as shown in Figs. 3. The curved blade with disc (CBWD) impeller shows the highest value of N_{js} among radial impellers and HE3 impeller shows highest among axial impellers. Notably most of the N_{js} values obtained for axial impellers were significantly smaller than the relevant values for radial impellers.

3.2 Effect of Liquid Level on Critical Impeller Speed

The values of N_{js} are also significantly affected by the liquid level at constant solid loading condition. The results in Figs. 2 and 3 shows that the N_{js} value increased with decrease in liquid level as already pointed out by Reilly et.al. (2007), with decreasing liquid levels, the particles became harder to suspend. It was due to the fact that the liquid level decreased, the energy required for suspending solids increased. At H/T=0.5, splashing occurred so it was very difficult to obtain the data. In radial flow impellers suspension of solid particles initiated from center, as particles from circumference moved towards centre, got lifted. In axial flow impellers, solid moved from centre to circumference and got lifted. The flow pattern of an axial flow impeller favors easier suspension in comparison to the flow pattern produced by a radial flow impeller. The lowest value of N_{js} was obtained for straight blade turbine at low clearance value. The critical impeller speed was not visually observable at high clearances for SB and CB impellers, due to the splashing of liquid. Similar results could be seen for liquid levels H/T=0.75 and H/T=1 respectively. Interestingly, the straight blade turbine and curved blade turbine shows the smallest N_{js} values for all liquid levels at lower impeller clearances. Among radial impellers, Rushton turbine showed the lowest value of N_{js}.

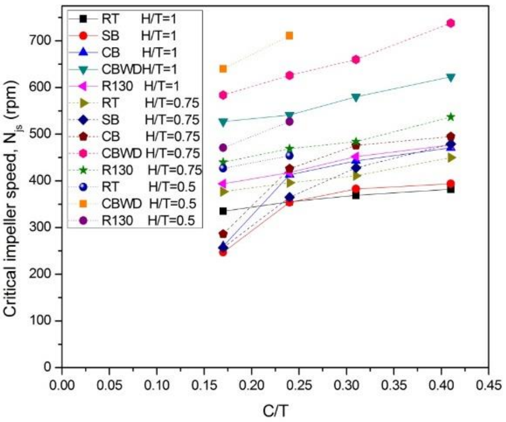


Fig. 2. Effect of impeller clearance and liquid level on critical impeller speed for various radial impellers.

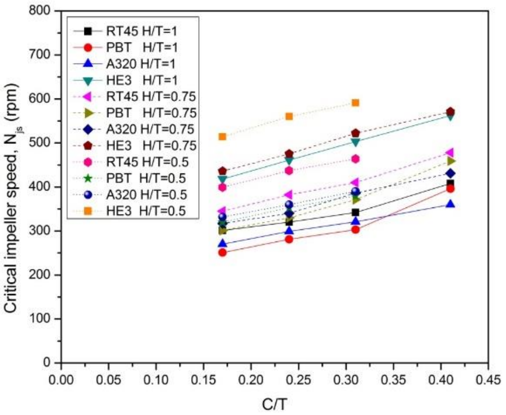


Fig. 3. Effect of impeller clearance and liquid level on critical impeller speed for various axial impellers.

3.3 Effect of Impeller Type on Power Consumption and Critical Impeller Speed

The effect of impeller clearance and liquid level was analyzed all impellers. The Zwietering constant 'S' was expressed as a function of impeller clearance and liquid level using regression analysis and shown in Eq. (3).

$$S = \left[a \left(\frac{C}{T} \right)^{b} \left(\frac{H}{T} \right)^{c} \right] \tag{3}$$

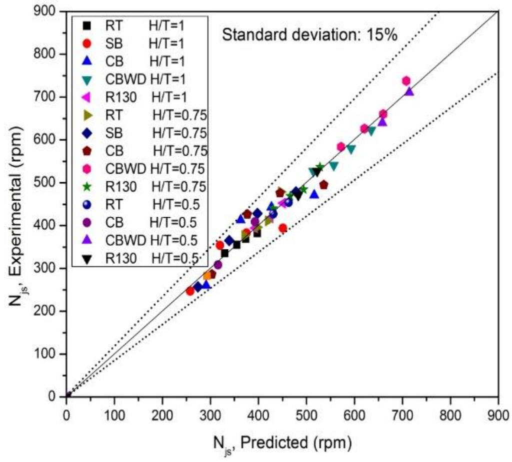


Fig. 4. Comparison of experimental N$_{js}$ values with the predicted values for various radial impellers.

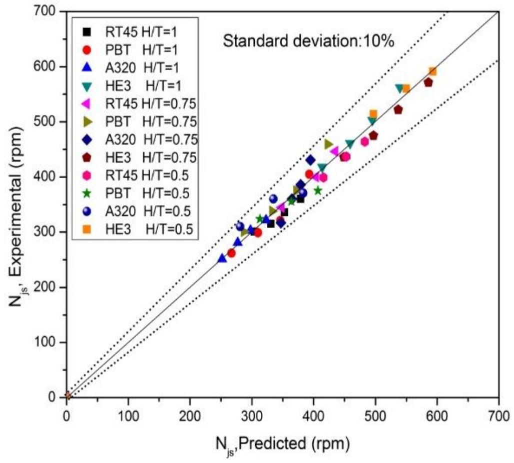


Fig. 5. Comparison of experimental N$_{js}$ values with the predicted values for various axial impellers.

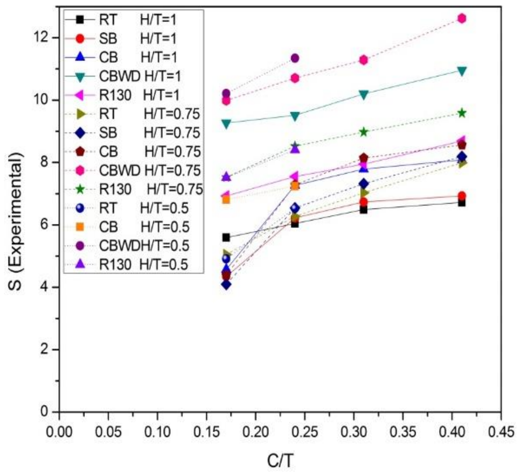


Fig. 6. Effect of clearance on 'S' for various radial impellers.

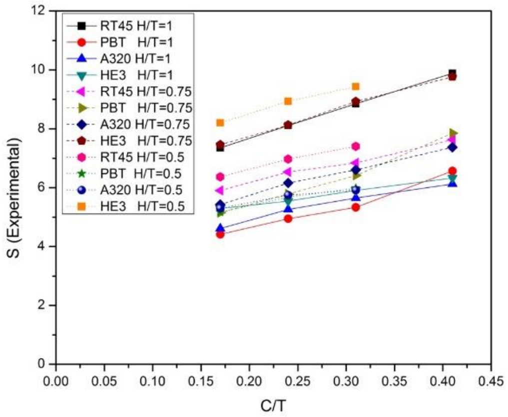


Fig. 7. Effect of clearance on 'S' for various axial impellers.

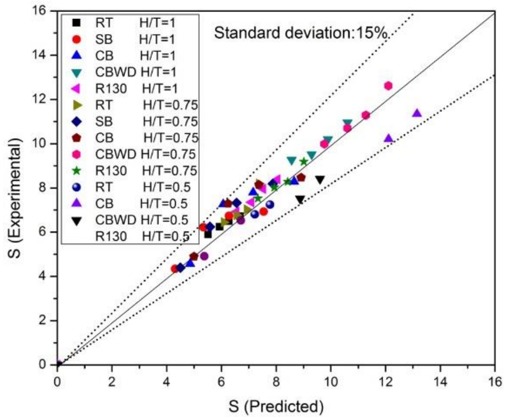


Fig. 8. Comparison of experimental' 'S' values with the predicted values according to equation in Table 3 for various radial impellers.

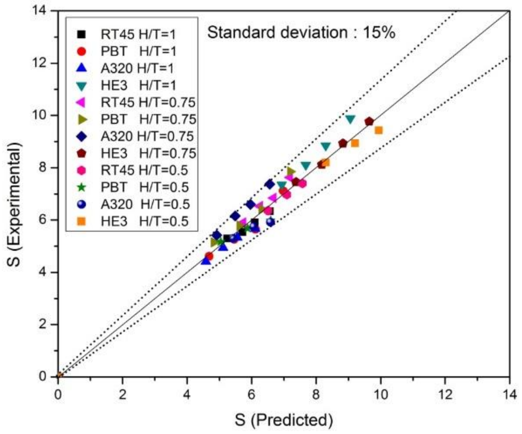


Fig. 9. Comparison of experimental 'S' values with the predicted values according to equation in Table 3 for various axial impellers.

The 'S' expression for different impellers are given in Table 3. The critical impeller speed (N$_{js}$) was calculated using obtained correlation and these values were compared with the experimental N$_{js}$ value. Figs. 4 and 5 compares the N$_{js}$ obtained by fitting the present 'S' expression in Zwietering equation to the experimental N$_{js}$ value. It represents the best possible predictions using the current form of the Zwietering correlation. The standard deviation between the experimental and predicted value is found to be 15% for radial impellers and 10% for axial impellers. Axial impellers gives less value of N_{js} compared to radial impellers because of the difference in flow pattern. Among axial impellers, PBT impeller show lowest value of N_{js} and among radial impellers, Rushton turbine show lowest value of N_{js}. The power required at critical impeller speed was calculated using Eq. (2). Fig. 10 and Fig. 11 shows the variation of power consumption as a function of impeller clearance for different liquid levels for radial and axial impellers respectively. It was observed that the R130 impeller consumed lowest power and curved blade impeller consumed the highest among radial impellers. Fig. 11 showed that the power consumed by PBT impeller is significantly higher than A320 impeller and A320 impeller showed the lowest value of power consumption as compared to other axial impellers. The power consumed by HE3 impeller is significantly lower than the PBT. It was also found that the power consumption was less for axial impellers compared to radial impellers.

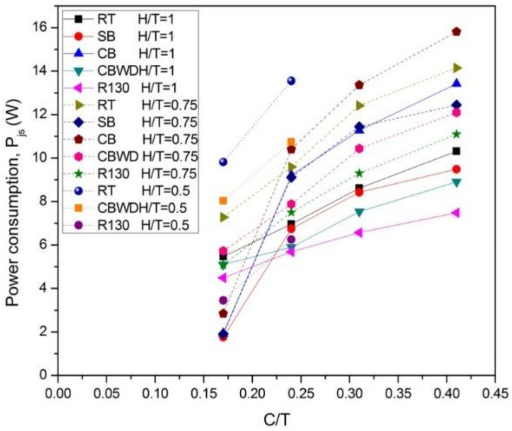


Fig. 10. Effect of clearance on power consumption for various radial impellers.

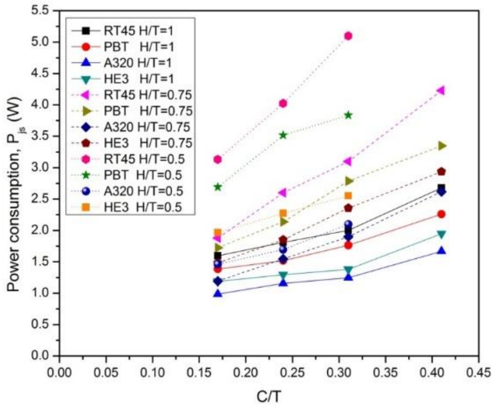


Fig. 11. Effect of clearance on power consumption for various axial impellers

3.4 Effect of Impeller Clearance on S Value

Figs. 6 and 7 show the variation of ‘S’ value for radial and axial impeller respectively. It is observed that ‘S’ value increased with clearance, but significantly decreased with liquid level in the vessel. It was also observed that the 'S' value was higher for curved blade with disc impeller for different liquid levels. The SB impeller shows the lowest value of 'S' at lower impeller clearance. Among axial impellers, the S value was highest for HE3 impeller and lowest for pitched blade turbine for different liquid levels. The 'S' value for A320 and PBT impellers was found to be closer. The effect of impeller clearance and liquid level on Zwietering constant ‘S’ was analyzed using regression method for all radial and axial impellers. The developed expression for ‘S’ by regression is given in Table 3. The comparison of experimental ‘S’ value and calculated ‘S’ value obtained by regression was shown in Figs. 8 and 9. It is observed that the standard deviation is 15% for both axial and radial impellers.

3.5 Effect of Impeller Clearance on Power Consumption

Power consumption depends on the impeller geometry, fluid properties, vessel geometry and the location of the impeller in the vessel. Figs. 10 and 11 shows effect of impeller clearance on power consumption for all impellers. The power consumption is sensitive to clearance; it increases with increase in clearance and decreases in liquid level. Pitched blade turbine showed a bigger dependence on clearance compared to other axial impellers as reported by Ayranci and Kresta (2011). Straight blade turbine (SB) and curved blade turbine (CB) showed a bigger dependence on clearance compared to other radial turbines considered in this study.

4. CONCLUSION

The influence of impeller clearance and liquid level, on the Zwietering constant ‘S’ and on critical impeller speed, N_{js}, in a 0.29 m agitated vessel was investigated using different axial and radial impellers. The solid loading was 5 % (v/v), mean particle diameter of 0.506 mm, liquid level from 0.5T to 1.0T and the impeller clearance from 0.17 T to 0.41 T. Zwietering constant ‘S’ was developed as a function of impeller clearance and liquid level for all impellers using regression. On the basis of suspension measurements and by regression, expressions are developed for the calculation of Zwietering constant ‘S’ of nine impeller types. The following conclusions were reached from the experimental results.

- At higher clearance, the power required and critical impeller speed was higher to suspend solids, and the effect was enhanced for lower liquid level with constant solid loading.
- Pitched blade turbine and Rushton turbine showed lower critical impeller speed among axial impellers and radial impellers considered in this study respectively.
- The straight blade and curved blade impellers were very effective for C/T < 0.25.

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)	T/5.8, T/4.14, T/3.22, T/2.42 mm

Table 2 Design details of impellers used in this study

Impeller	No of blades	Diameter (D), m	Blade width(w),m	Blade length(l), m	Blade thickness(t), m	Disc thickness, m	Disc diameter, m
Rushton Turbine (RT)	6	0.0967	0.020	0.024	0.003	0.003	0.072
Straight Blade (SB)	6	0.0967	0.020	0.024	0.003	-	-
Curved Blade (CB)	6	0.0967	0.020	-	0.003	-	-
Curved Blade with Disc (CBWB)	6	0.0967	0.020	-	0.003	0.003	0.072
R130	6	0.0967	-	0.024	0.003	0.003	0.072
Rushton Turbine 45 (RT 45)	6	0.0967	0.020	0.024	0.003	0.003	0.072
Pitched Blade Turbine (PBT)	6	0.0967	0.020	0.024	0.003	-	-
A320	3	0.0967	0.030	0.035	0.003	-	-
HE3	3	0.0967	0.020	0.035	0.003	-	-

Table 3 'S' expression in Zwietering correlation – Radial and Axial impellers

Impeller type	Impeller	Expression 'S'
RADIAL	Rushton Turbine (RT)	$8.54\left(\frac{C}{T}\right)^{0.218}\left(\frac{H}{T}\right)^{-0.248}$
	Straight Blade (SB)	$13.98\left(\frac{C}{T}\right)^{0.639}\left(\frac{H}{T}\right)^{-0.055}$
	Curved Blade (CB)	$16.36\left(\frac{C}{T}\right)^{0.661}\left(\frac{H}{T}\right)^{-0.006}$
	Curved Blade with Disc (CBWB)	$13.90\left(\frac{C}{T}\right)^{0.249}\left(\frac{H}{T}\right)^{-0.359}$
	R130 impeller	$10.44\left(\frac{C}{T}\right)^{0.235}\left(\frac{H}{T}\right)^{-0.298}$
AXIAL	Rushton Turbine 45 (RT 45)	$8.24\left(\frac{C}{T}\right)^{0.257}\left(\frac{H}{T}\right)^{-0.312}$
	Pitched Blade Turbine (PBT)	$10.42\left(\frac{C}{T}\right)^{0.455}\left(\frac{H}{T}\right)^{-0.107}$
	A320 impeller	$8.17\left(\frac{C}{T}\right)^{0.329}\left(\frac{H}{T}\right)^{-0.244}$
	HE3 impeller	$12.53\left(\frac{C}{T}\right)^{0.306}\left(\frac{H}{T}\right)^{-0.120}$

Where C is the impeller clearance, H is the liquid level and T is the vessel diameter

- It was observed that there was a steep increase in N_{js} value for pitched blade turbine for C/T > 0.31
- The 'S' values increased with increase in clearance but decreased with increase in liquid level for all the impellers and it also depends on the type of impeller.
- Since 'S' value does not only change with geometry, but also vary significantly with other operating parameters, it is very much important to use the values that exactly match the particular system and geometry to be used.

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