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Pitched blade impeller design effect on solids distribution in stirred tanks

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Abstract

Mixing processes are ubiquitous in various industries, and their effectiveness hinges on the flow patterns generated by impellers. In solid-liquid mixing applications, such as adsorption in stirred tanks, pitched blade impellers are among the most commonly employed. This study investigates the influence of the geometric characteristics of pitched blade impellers, namely blade inclination angle (θ), impeller diameter to tank diameter ratio (D/T), blade width to tank diameter ratio (W/T), and number of blades (NB), on the distribution of solids within the tank. A central composite design (CCD) coupled with digital image processing and analysis was utilized to assess the impact of these variables. The response was quantified using the parameter of percentage of image area occupied by solids (%A). Under a constant power supplied to the motor, analysis of variance (ANOVA) revealed significant effects of θ and D/T, while W/T and NB exhibited non-significant effects. Response surface methodology (RSM) optimization indicated a maximum value of %A of 83.70% at θ = 61.9º and D/T = 0.555 for the reduced model.

Keywords: Impeller design; Solid-liquid mixing; Design of experiments; Digital image processing and Analysis; Geometry optimization.

1. Introduction

Effective solid-liquid mixing is paramount for numerous industrial operations and applications, encompassing adsorption, heterogeneous catalysis, leaching, crystallization, and precipitation [1]. Mechanically stirred tanks are prominently employed for these processes, with their success heavily influenced by the impeller's geometry and the resultant flow patterns within the tanks [2].

Among the diverse impeller configurations, the pitched blade turbine impeller garners significant attention due to its simplicity and extensive applicability [3,4]. This study delves into the effect of pitched blade turbine impeller geometry on solid distribution by employing digital image processing and analysis techniques.

2. Experimental

2.1 Design of experiments and experimental setup

A central composite design (CCD) was employed to plan the experimental cases. The selected factors were blade angle (θ), impeller diameter to tank diameter ratio (D/T), blade width to tank diameter ratio (W/T), and number of blades (NB). The chosen factors and their corresponding levels are summarized in Table 1.

Table 1. Factors and levels used for impeller design using CCD.

Factor	-2	-1	0	+1	+2
θ (º)	15	30	45	60	75
D/T	0.3	0.4	0.5	0.6	0.7
W/T	0.06	0.08	0.1	0.12	0.14
NB	2	3	4	5	6

Based on the design of experiments, 25 distinct impeller geometries were proposed. The Zwietering criterion [5] was utilized to experimentally determine the power consumption at the just suspended speed of the impeller corresponding to the design's central point (

$P_{js}^{0} = 45.4\,W$). This operating condition was employed to compare the performance of the impellers.

Dolomite particles were suspended in water at a volume fraction of $\alpha = 0.01$. The experiments were conducted in a baffled vessel with a diameter of D = 0.126 m, a liquid level height of H = D, and clearance of C = D/3.

The agitation apparatus comprised a speed controller and a wattmeter for measuring the power draw of the motor. A CMOS digital camera was employed to capture the images.

For each impeller, the system was set to operate at P_{js}^{0}. After allowing the system to stabilize, photographs were captured in triplicate. This procedure was repeated two more times for the impeller at the central point.

2.2 Digital image processing and analysis

Digital image processing and analysis were performed using the open-source software ImageJ. For each image, a region of interest (ROI) was cropped and a mask was applied to exclude areas such as baffles, the shaft, and the impeller from analysis. The image was then converted to 8-bit format to enable binarization using a thresholding technique.

Thresholding in this case was based on the contrast difference between regions with and without solids in the image. The grayscale value used as the threshold was 40, determined through calibration by observing a sample of the images.

Once the image was binarized, the analysis was conducted by calculating the proportion of pixels representing solids relative to the total number of pixels and multiplying by 100. This resulted in the definition of the percentage of image area occupied by solids (%A). This parameter was adopted as the response variable to evaluate the distribution of solids within the stirred tank [6].

3. Results and discussion

The response variable analyzed in this study was the percentage of image area occupied by solids (%A). A higher %A value indicates a more homogeneous distribution of the solid phase in the liquid medium [6].

The experiments were conducted under the same power condition supplied to the motor. For a given impeller, a higher %A value indicates that it exhibits greater energy efficiency, meaning it provides a better distribution of solids per unit of energy supplied.

A curve fit using linear regression on the results obtained for each impeller configuration indicates a correlation coefficient of R2 = 0.82 and a p-value less than 0.0001. This signifies a correlation between the variables and the response, suggesting the model's statistical significance.

The analysis of variance (ANOVA) identified the linear term of the blade angle (θ), the quadratic terms of θ and the D/T ratio, and the interaction term between θ and D/T as significant factors influencing the response. None of the terms involving the W/T ratio and the number of blades (NB) were found to be statistically significant for this response (Table 2).

Table 2. Parameters estimates for the %A model.

Term	Coefficient	p-value
Intersection	**77.07**	**<0.0001**
θ	**11.96**	**<0.0001**
D/T	0.64	0.4539
W/T	1.58	0.0689
NB	0.74	0.3909
θ*D/T	**3.86**	**0.0005**
θ*W/T	-0.65	0.5350
θ*NB	1.38	0.1924
DT*W/T	-1,50	0,1565
DT*NB	-1,97	0,0643
W/T*NB	1,44	0,1735
θ*θ	**-6,38**	**<0.0001**
D/T*D/T	**-4,67**	**<0.0001**
W/T*W/T	-0,26	0,7791
NB*NB	-0,29	0,7533

Beyond identifying significant effects, the analysis of variance (ANOVA) also quantifies these effects, revealing which factors contribute most to the variation in the response. In this case, the angle of the impeller blades emerged as the most influential factor.

Both the linear and quadratic terms associated with this factor exhibited p-values close to zero. The negative sign of the quadratic coefficient indicates the presence of a maximum point within the range of levels studied in this work.

Among the investigated impeller configurations, Case 18 (θ=75º, D/T=0.5, W/T=0.1, NB=4) exhibited the superior distribution of solids across the analyzed plane, occupying 83.98% of the image space (Fig. 1-b). This case achieved the highest percentage of area occupied by solids (%A) compared to all other configurations.

Case 12 (θ=60º, D/T=0.4, W/T=0.12, NB=5) demonstrated the second-highest %A, reaching 80.60%. Notably, this impeller also possesses an inclination angle exceeding 45º.

Conversely, Case 17 (θ=55º, D/T=0.5, W/T=0.1, NB=4), featuring the lowest inclination angle, exhibited the least favorable outcome with only 18.95% of the area occupied by solids (Fig. 1-a). Case 6 (θ=30º, D/T=0.6, W/T=0.08, NB=5) followed closely with a %A of 38.24% and an inclination angle of 30º, representing the second-lowest response.

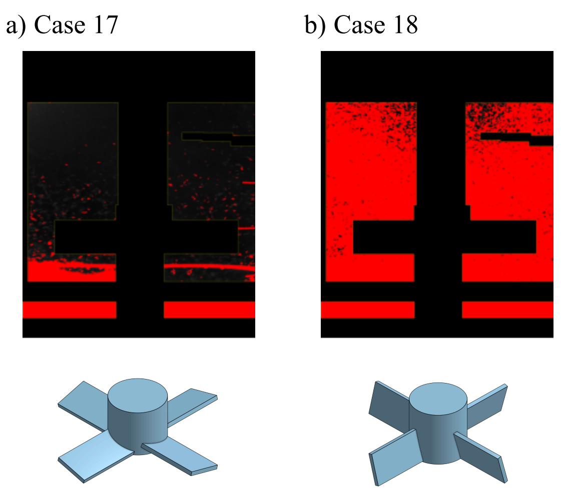

Fig. 1. Porcentage of image area occupied by solids at constant power for CCD axial points of blade angle of a) θ = 15º and b) θ = 75º.

These observations suggest a positive correlation between the angle of the impeller blades and the homogeneity of the solids distribution. Impellers with higher angles (like Cases 18 and 12) achieved significantly better results compared to those with lower angles (like Cases 17 and 6).

Thus, it can be observed that impellers with low inclination are incapable of generating a velocity field with a sufficient distribution of turbulent kinetic energy to promote solids suspension [2]. Conversely, higher inclinations induce greater turbulence intensity [3].

The analysis investigated the effect of the impeller diameter to tank ratio (D/T) on how solids are distributed within the tank. The quadratic term of D/T was found to be significant with a negative sign, suggesting a maximum point for optimal mixing performance within the studied range.

Impellers with high D/T ratios exhibited deficiencies in achieving homogeneous solids suspension [7]. In these configurations, the axial recirculation vortex was incompletely formed, hindering resuspension mechanisms and causing a substantial portion of the granular material to remain trapped in the radial vortex below the impeller [8].

While impellers with low D/T ratios (not shown) demonstrated the ability to remove particles from the tank bottom and maintain their movement, these particles failed to achieve a uniform distribution throughout the tank. This resulted in a low solids cloud height and localized regions of particle agglomeration near the walls, consequently reducing the overall area occupied by solids in the analyzed plane.

The interaction effect between θ (inclination angle) and D/T was also found to be significant, with a positive coefficient indicating a proportional relationship. The fraction of area occupied by solids displayed a heightened sensitivity for impellers with D/T less than 0.5 when the inclination angle (θ) increased from values below 45°. Impellers with both low inclination angles and low D/T ratios presented the scenario leading to the lowest %A values. These findings emphasize the crucial role of considering both impeller blade angle (θ) and impeller diameter to tank ratio (D/T) when designing agitated tanks for efficient solids suspension.

The statistical analysis of the experimental results suggests a reduced model for predicting the percentage of area occupied by solids (%A) as a function θ and D/T. This model is represented by Equation 1:

$$\%A = 77.07 + 11.96x_{\theta} + 3.86x_{\theta}x_{D/T} - 6.38x_{\theta}^{2} - 4.67x_{D/T}^{2} \quad (1)$$

Where,

$$x_{\theta} = (\theta - 45)/15 \quad (2)$$

$$x_{D/T} = (D/T - 0.5)/0.1 \quad (3)$$

The optimization procedure employing the full response surface methodology (RSM) model identified a saddle point at: θ = 62.6º, D/T = 0.57, W/T = 0.085 and NB = 3.9. This saddle point corresponds to a predicted %A value of 83.70%.

In contrast, the optimization using the reduced RSM model yielded a maximum point at: θ = 61.9º and D/T = 0.555. This maximum point results in a predicted %A of 83.27%.

It is noteworthy that both optimization approaches produced values close to the experimentally determined maximum %A value of 83.98% achieved with axial point for maximum angle.

It is important to remember that these models assume continuous variables. However, the number of impeller blades (NB) is a discrete variable. This limitation should be considered when interpreting the results [9].

4. Conclusions

The geometric variables of pitched-blade impellers significantly influence the distribution of solids within agitated tanks. This influence has been investigated using the percentage of image area occupied by solids as a parameter to quantify the solids distribution. Statistical analysis of variance revealed that the inclination of the blades and the ratio between the impeller and tank diameters have significant effects on solids distribution. In contrast, the ratio between blade width and tank diameter and the number of blades do not exhibit significant effects on this response.

The response surface methodology indicated a saddle point for the complete model of percentage of occupied area of A% = 83.70 for an impeller with settings of θ = 62.6º, D/T = 0.57, W/T = 0.085 and NB = 3.9. And a maximum point of %A = 83.27% for the reduced model for an impeller with θ = 61.9º and D/T = 0.555.

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