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ASSESSMENT OF MIXING EFFICIENCY UNDER DIFFERENT IMPELLER GEOMETRIES

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ABSTRACT

The efficiency and effectiveness of mixing processes in various industries are heavily influenced by the configuration and design of impellers used inside mixer tanks. The mixing process plays a critical role in many industrial applications, including chemical, paint, pharmaceutical, and food processing industries, where fluid homogeneity and energy efficiency are paramount. This study investigates the performance characterization of different impeller configurations, focusing on their impact on fluid dynamics, mixing time, power consumption, and overall efficiency within a mixer tank. Five impeller configurations were fabricated for the purpose of agitation in a mixer tank. The impellers were used to mix paint formulations, from which three parameters (viscosity, temperature and electrical conductivity) were measured for different speed of operations (10 rpm, 20 rpm, 30 rpm, 40 rpm and 50 rpm) using times (0 minutes – 50 minutes at 5 minutes intervals). The statistical analysis results for three main factors (speed, type and time) for the partial eta squared (effective size) shows that speed has the highest impact (0.516) on viscosity, followed by time (0.414) and type is the least (0.169), the partial eta squared (effective size) shows that speed has the highest impact (0.998) on temperature, followed by type (0.989) and time is the least (0.980) while the partial eta squared (effective size) shows that type has the

highest impact (0.976) on electrical conductivity, followed by speed (0.966) and time is the least (0.279).

KEYWORDS**:** *impeller configurations, mixer tank, fluid homogeneity, paint formulations, power consumption.*

1. INTRODUCTION

In many fields of engineering, mixing plays an important role in their operations. Mixing has paramount importance in food manufacturing, pharmaceutical produce, chemical engineering, biotechnology, agro-chemical preparations, paint production, water purification and myriads of diverse applications (Zadghaffari et al 2008). The performance of mixing systems is heavily influenced by the type of impeller used, which governs fluid dynamics within the tank, determines energy consumption, and affects the overall efficiency of the mixing process. Selecting the right impeller configuration is critical to achieving desired outcomes, such as improved mass and heat transfer, reduced mixing time, and uniform homogeneity of the materials involved. Different impeller configurations, such as axial, radial, and mixed-flow designs, influence the hydrodynamics of the system, creating diverse flow patterns and shear forces that affect mixing outcomes.

Impeller configurations are traditionally classified based on the flow patterns they generate axial flow, radial flow, and mixed flow. Each configuration offers distinct advantages depending on the application. Axial flow impellers, such as pitched-blade turbines, are typically used for blending large fluid volumes with minimal shear forces, making them suitable for applications like liquid-liquid mixing or solids suspension (Bujalski et al., 2020). Radial flow impellers, such as Rushton turbines, create strong shear forces that are ideal for dispersing gases or breaking up immiscible liquids (Montante & Paglianti, 2018). Mixed flow impellers, which combine axial and radial characteristics, offer a balance between circulation and shear forces, making them versatile for a wide range of mixing scenarios (Aubin et al., 2020). Recent advances in mixing technology have emphasized the need for a deeper understanding of impeller configurations to maximize efficiency. For instance, axial flow impellers, like the pitched-blade turbine, generate flow along the shaft axis and are preferred for applications requiring high circulation with low shear forces (Derksen, 2014). In contrast, radial flow impellers, such as the Rushton turbine, create high-shear zones and are often used in processes that demand rapid dispersion or gas-liquid mixing (Ochieng et al., 2020). Mixed flow impellers provide a hybrid solution by combining axial and radial flow characteristics, offering a balance between circulation and shear, thus making them suitable for a broader range of applications (Makhdoumi et al., 2021).\

Despite the extensive use of various impeller types, optimizing their performance remains an ongoing challenge. Advances in Computational Fluid Dynamics (CFD) have provided engineers with powerful tools to simulate and analyze fluid flow patterns within mixing tanks (Rane et al., 2019). CFD simulations can offer insights into energy consumption, fluid velocity profiles, and mixing efficiency for different impeller configurations. However, simulation results must often be validated through experimental studies to account for the complexities of real-world mixing conditions, especially when dealing with multi-phase systems or non-Newtonian fluids (Najafi et al., 2023). (Musilim et al., 2018) were able to design and fabricate a detergent mixing machine that is easy and economical to sustain and cost effective. The results they obtained for their detergent mixing machine when compared with the performance of the conventional mixer under the same conditions, the efficiency of the mixing machine was found to be 80.7%.

This study aims to evaluate the performance of various impeller configurations regarding mixing efficiency, power consumption, and flow dynamics. By analyzing parameters such as impeller geometry, rotational speed, and fluid properties, this research seeks to identify the most effective impeller designs for specific industrial applications. Ultimately, these findings will contribute to optimized impeller designs, leading to more efficient and cost-effective mixing operations across industries.

BACKGROUND

The study of impeller performance in mixer tanks has a long history, with numerous theoretical and experimental efforts contributing to the optimization of industrial mixing systems. Early studies focused primarily on the classification of impellers based on their flow characteristics. Axial flow impellers, such as the marine propeller and pitched-blade turbine, were recognized for their ability to induce large-scale circulation, which aids in the suspension of solids and blending of liquids (Nagata, 1975). Radial flow impellers, exemplified by the Rushton turbine, were noted for creating intense localized turbulence, which is particularly beneficial in processes requiring gas dispersion or high shear mixing (Van den Akker, 1996).

Importance of Performance Characterization

Characterizing the performance of impeller configurations is crucial for industries where efficient mixing directly impacts product quality and operational costs. By understanding how impeller design and operating conditions influence flow patterns and energy consumption, industries can select the most appropriate configurations for their specific applications. Additionally, with increasing pressure to reduce energy usage and improve process sustainability, optimizing impeller performance has become a priority for many sectors.

In this study, five different types of impeller configurations labeled impeller A - E were conceived and fabricated to ascertain how their distinguishable design structures influenced flow characteristics in an agitated tank. Experimentation trials were carried out to give comparative performance characteristics.

2. MATERIALS AND METHODS

Experimental activities were carried out in the chemistry laboratory, on the first floor of engineering building, Yaba College of Technology at ambient temperature and pressure. Five different, top-entering agitation impeller configurations were used to mix paint formulations. The impellers were used to mix paint formulations, from which three parameters (viscosity, temperature and electrical conductivity) were measured for different speed of operations (10 rpm, 20 rpm, 30 rpm, 40 rpm and 50 rpm) using times (0 minutes – 50 minutes at 5 minutes intervals). The key variables investigated include viscosity, temperature and electrical conductivity for different impeller configurations—Impeller A – E in order to predict the individual impeller performance.

Set-Up for Experimental analysis

An experimental rig, containing a cylindrical vessel with three baffles organized symmetrically on the vessel's inner walls was designed for the experiment. Figure 1 below displays the experimental vessel, with one baffle sectioned to show off the inner of the experimental rig.

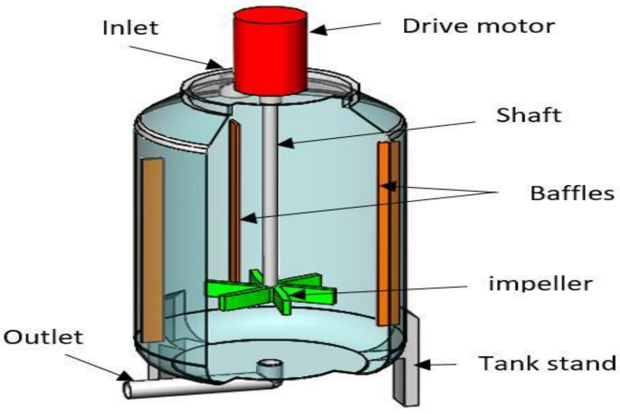


Figure 1: Layout of experimental rig for the study.

The impeller's holding shaft is 0.012 m diameter and was situated coaxially to the centre of the vessel. The functions of the baffles in the set-up are to prevent the liquid from spinning as a single body, minimize vortex formation and ensure efficient mixing. The design of the experimental vessel of the mixer composition is shown in Figure 6.

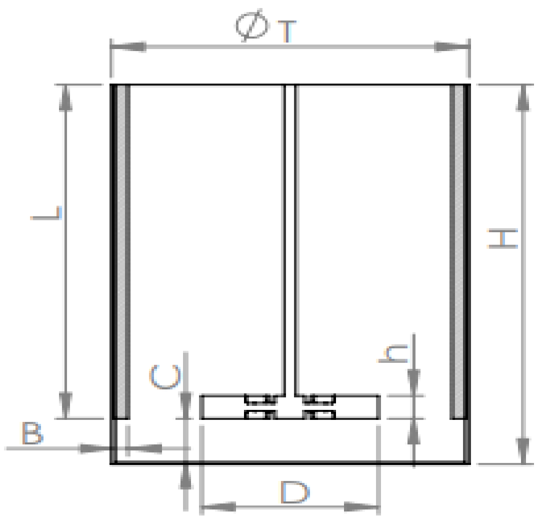


Figure 2: Diagram representing the experimental set-up dimensions.

The specifications of the electric motor used to run the impellers is 240 V, 50 Hz, 1050 W and adjustable speeds of between 0 –50 rpm.

The five distinct configurations of impellers used for the experiment were fabricated in the workshop using mild steel. The thickness of the blade material for the impellers was 2.5 mm with a diameter of 0.180 m (T/D = 0.5).

Plate1 - 5 below shows the fabricated impellers configurations used for the experiment.

Plate 1: Impeller A.

Plate 2: Impeller B.

Plate 3: Impeller C.

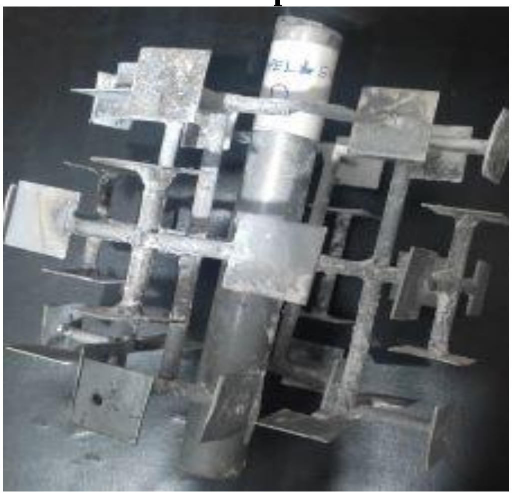


Plate 4: Impeller D.

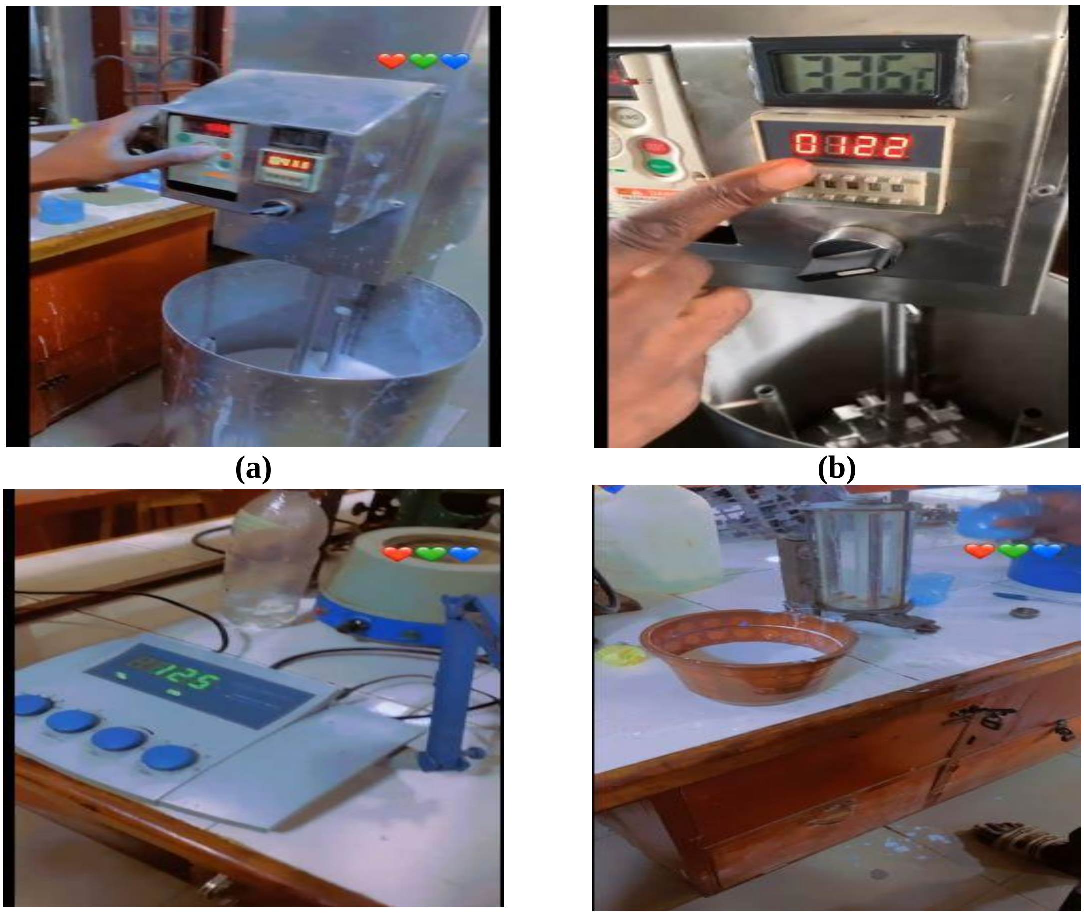
Plate 5: Impeller E

For this study, experimental activities were conducted on paint formulations in order to carry out the performance characterization of the five impeller configurations. Chemical composition for the paint is as shown in Table 1 below:

Table 1: Chemical formulations for the experimental paint.

Materials	Amount (g)
Calcium	1200
Titanium	200
Natrosol	10
Acrylic liquid	150
Ammonia	10

Ten (10) litres of water was used for the paint formulations for every experimental run. The readings were taken for the three variables (viscosity, temperature and electrical conductivity) at times (0, 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50) minutes for speed of operations (10, 20, 30, 40 and 50) revolution per minutes (rpm). The temperatures measurements were taken directly from the mixer tank display while viscosities and electrical conductivities were recorded using their respective measuring instruments in the laboratory.



(a) (b)

(c) (d)

Figure 3: (a) Set-up showing the test rig with paint mixture inside the tank. (b) Mixer tank showing a shaft connecting the motor to the impeller (c) Electrical conductivity (EC) measurement using an EC-meter and (d) Viscosity measurement using viscometer.

3. RESULTS AND DISCUSSION

The results presented in this section focus on the performance characterization of various impeller configurations—Impeller A – E —inside a mixer tank, using paint as the test fluid. Paint is a non-Newtonian fluid with high viscosity, making it a suitable candidate for evaluating impeller performance under different operating conditions. The study measured key variables including viscosity, temperature, and electrical conductivity, which directly influence the mixing efficiency, power consumption, and homogeneity of the fluid in industrial applications. The values of viscosity, temperature and electrical conductivity gotten from the experiments were used to predict the mixing performance of the different impeller configurations.

Statistical Analysis

All experiments were performed in repeatedly to ensure repeatability, and statistical analyses were conducted using ANOVA to assess the significance of differences between impeller configurations. Differences were considered statistically significant at p<0.05p < 0.05p<0.05. The summaries of statistical analysis for viscosity, temperature and electrical conductivity were shown in Tables 2 – 4:

Table 2: Viscosity.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	6900.279[a]	274	25.183	31.456	0.000	0.887
Intercept	33662.530	1	33662.530	42047.178	0.000	0.975
Speed	940.444	4	235.111	293.672	0.000	0.516
Type	178.943	4	44.736	55.879	0.000	0.169
Time (mins)	620.932	10	62.093	77.559	0.000	0.414
Speed * Type	1043.628	16	65.227	81.473	0.000	0.542
Speed * Time (mins)	892.586	40	22.315	27.873	0.000	0.503
Type * Time (mins)	629.789	40	15.745	19.666	0.000	0.417
Speed * Type * Time(mins)	2593.957	160	16.212	20.250	0.000	0.747
Error	880.648	1100	0.801			
Total	41443.458	1375				
Corrected Total	7780.927	1374				
a. R Squared = .887 (Adjusted R Squared = .859)						

Table 2 shows that viscosity in the mixing process is significantly affected by speed, impeller type, and time, with all three factors and their interactions playing a role. The three factors—speed, type, and time—all significantly affect viscosity ($p < 0.05$). All two-factors (speed*type, speed*time, type*time) and the three-factor (speed*type*time) interactions are also significant. The high partial eta squared value for speed (0.516) suggests that increasing speed generally enhances the efficiency of the viscosity adjustment process, as higher speeds facilitate more thorough mixing and reduction in viscosity. Impeller type also plays a role, though with a lower effect size (0.169) than speed, indicating that choosing the right impeller can improve the consistency of the mixture. Duration is another important aspect, as longer mixing times further decrease viscosity (0.414 effect size), contributing to a more uniform final product.

Table 3: Temperature.

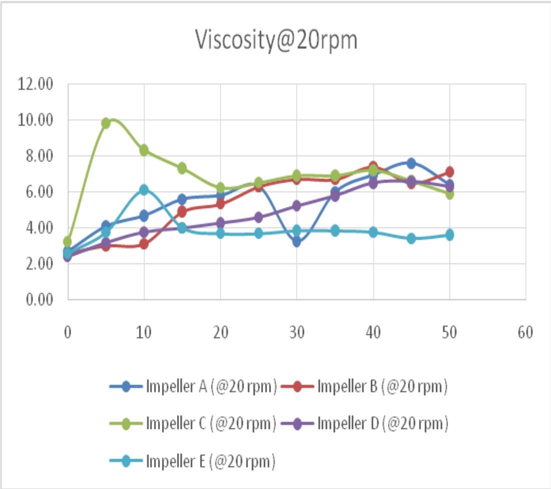
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	205380.086[a]	274	749.562	4964.273	0.000	0.999
Intercept	2132266.995	1	2132266.995	14121781.901	0.000	1.000
Speed	88438.569	4	22109.642	146429.854	0.000	0.998
Type	14560.991	4	3640.248	24108.981	0.000	0.989
Time (mins)	7929.120	10	792.912	5251.373	0.000	0.980
Speed * Type	48255.445	16	3015.965	19974.424	0.000	0.997
Speed * Time (mins)	17394.125	40	434.853	2879.987	0.000	0.991
Type * Time (mins)	5599.017	40	139.975	927.043	0.000	0.971
Speed * Type * Time (mins)	23160.726	160	144.755	958.694	0.000	0.993
Error	165.940	1099	0.151			
Total	2338141.960	1374				
Corrected Total	205546.026	1373				
a. R Squared = .999 (Adjusted R Squared = .999)						

Table 3 shows the general linear model of the three-factor analysis of variance with interactions. Speed, type, and time significantly influence temperature; with all interactions between factors being statistically significant ($p < 0.05$). Speed has the highest impact on temperature (0.998), while time has the least effect (0.980). This result reveals that speed, impeller type, and time all have significant impacts on the temperature during the mixing process, with speed showing the highest impact on temperature increases. The three-factor interaction (speed*type*time) is also significant, showing that changes in all three factors together have a meaningful effect on temperature. Higher speeds improve mixing efficiency but at the cost of raising the temperature, which could affect temperature-sensitive components in the paint formulation. This insight highlights the need for balance in selecting operational speeds. Impeller type and mixing time are crucial in controlling the temperature rise. The choice of impeller with lower temperature gene

Table 4: Electrical conductivity.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	537111.501[a]	274	1960.261	379.548	0.000	0.990
Intercept	14329786.299	1	14329786.299	2774548.498	0.000	1.000
Speed	159261.319	4	39815.330	7709.087	0.000	0.966
Type	228332.243	4	57083.061	11052.483	0.000	0.976
Time (mins)	2198.749	10	219.875	42.572	0.000	0.279
Speed * Type	53212.812	16	3325.801	643.945	0.000	0.904
Speed * Time (mins)	29815.673	40	745.392	144.324	0.000	0.840
Type * Time (mins)	8849.389	40	221.235	42.836	0.000	0.609
Speed *Type *Time (mins)	55441.316	160	346.508	67.091	0.000	0.907
Error	5681.200	1100	5.165			
Total	14872579.000	1375				
Corrected Total	542792.701	1374				
a. R Squared = .990 (Adjusted R Squared = .987)						

This table shows that all three main factors—speed, impeller type, and time—significantly impact electrical conductivity, a key indicator of particle dispersion quality in the mixture. Speed, type, and time significantly impact electrical conductivity, with each factor and their interactions (two-factor and three-factor) being statistically significant ($p < 0.050$). The high effect sizes for both impeller type (0.976) and speed (0.966) show that efficient dispersion is achieved through optimal impeller selection and higher speeds, leading to better particle breakdown and distribution. Time has the least effect (0.279). For industrial paint formulation, achieving consistent EC values reflects effective particle dispersion, reducing clumping and ensuring that pigments are uniformly distributed.



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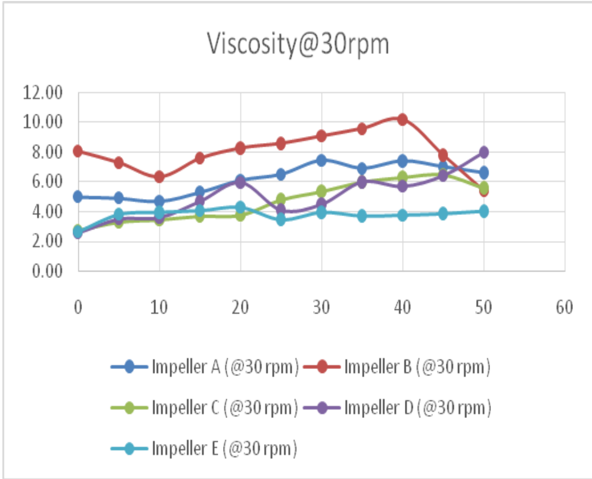

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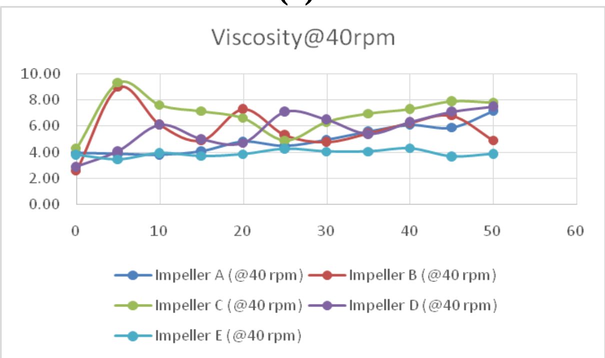

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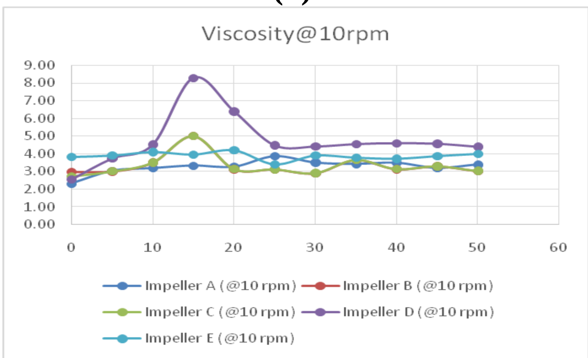

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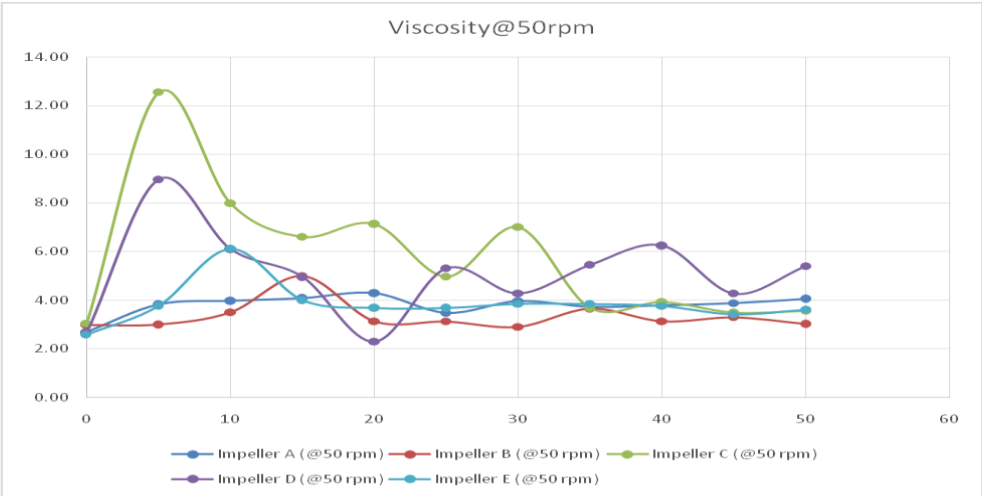
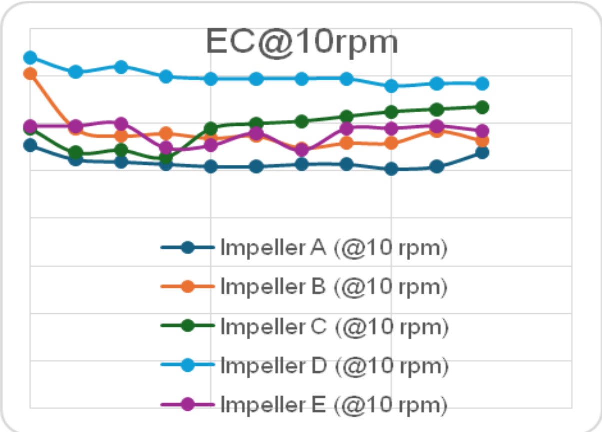


(e)

Figure 4: Graph comparing the performance characteristics of impellers under investigation (Impeller A - E). (a) Viscosity @10 rpm, (b) Viscosity @ 20 rpm, (c) Viscosity @ 30 rpm, (d) Viscosity @ 40 rpm and (e) Viscosity @ 50 rpm.

This figure displays viscosity across five impeller types (A-E) at varying speeds (10 to 50 rpm), showing how viscosity changes with speed for each impeller. Efficiency Implication of this is that Impellers that cause a more significant decrease in viscosity with increased speed are more efficient, as they enhance flowability and homogeneity in the paint mixture. Effectiveness Implication: The optimal impeller choice for each speed level is evident from this trend; choosing an impeller that consistently lowers viscosity ensures a smoother and more uniform paint texture.



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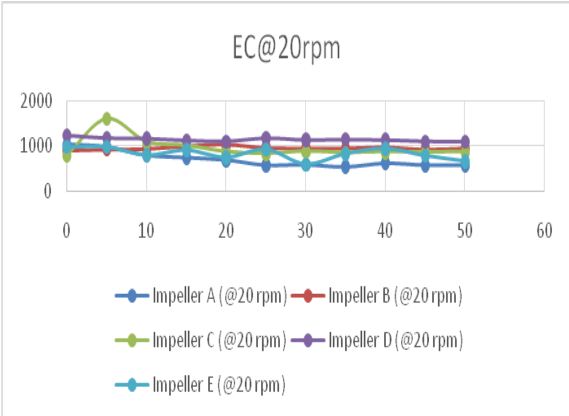

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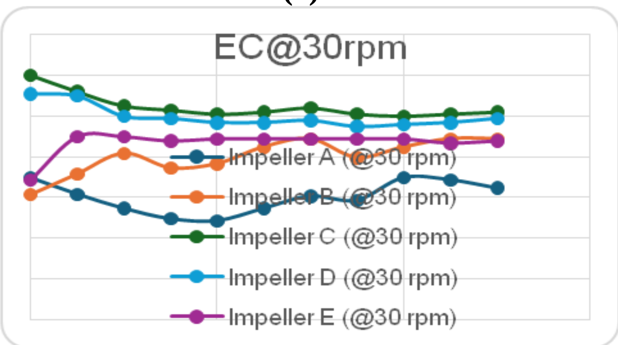

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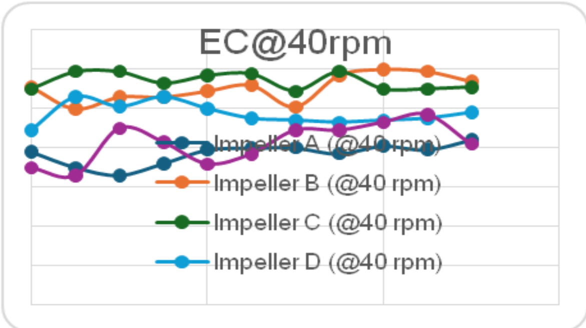

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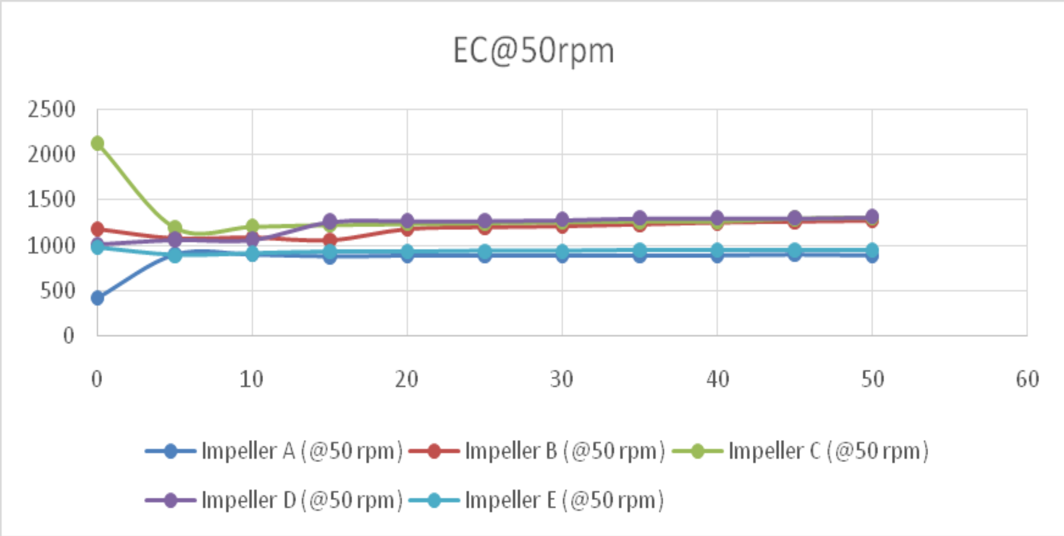
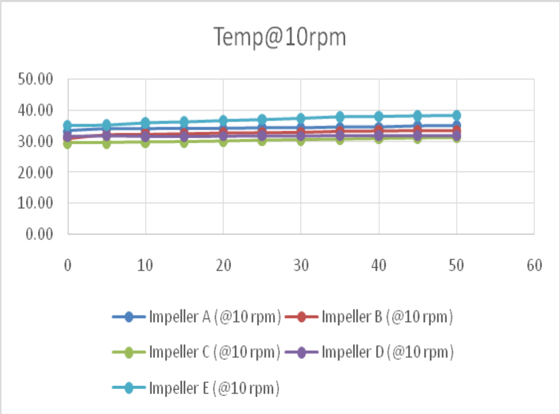


(e)

Figure 5: Graph comparing the performance characteristics of impellers under investigation (Impeller A - E). (a) EC @ 10 rpm, (b) EC @ 20 rpm, (c) EC @ 30 rpm, (d) EC @ 40 rpm and (e) EC @ 50 rpm.

This graph shows EC changes across impeller types at various speeds, indicating how well each impeller disperses particles in the paint. High EC values correlate with better dispersion efficiency, suggesting that impellers generating higher EC at given speeds are more effective at breaking down and evenly distributing solid particles. Impellers that produce high EC at higher speeds contribute to a high-quality paint mix by ensuring that pigments and additives are well-dispersed, preventing agglomeration and improving the final product’s stability. For industrial paint formulation, achieving consistent EC values reflects effective particle dispersion, reducing clumping and ensuring that pigments are uniformly distributed. Effective impellers (as indicated in Figure 9) enhance EC with increased speeds, essential for high-quality and stable paint.



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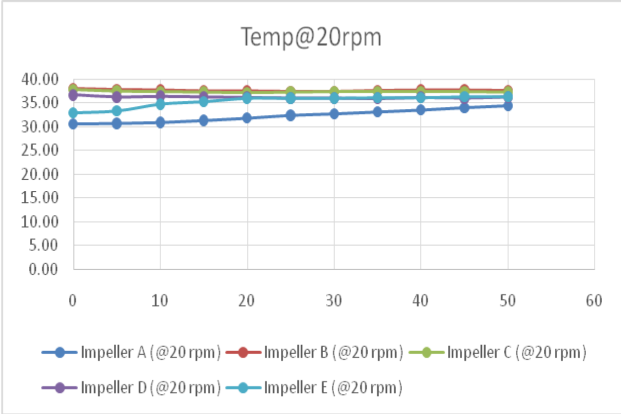

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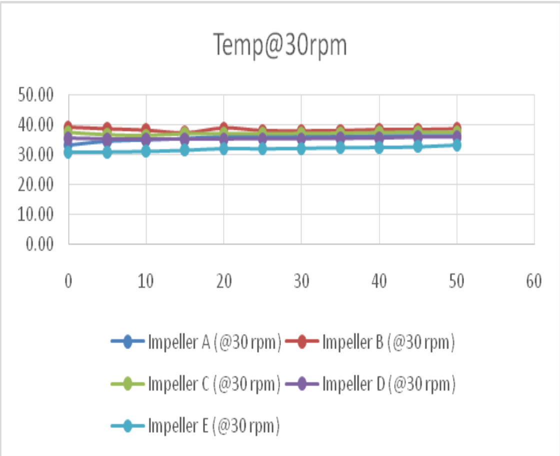

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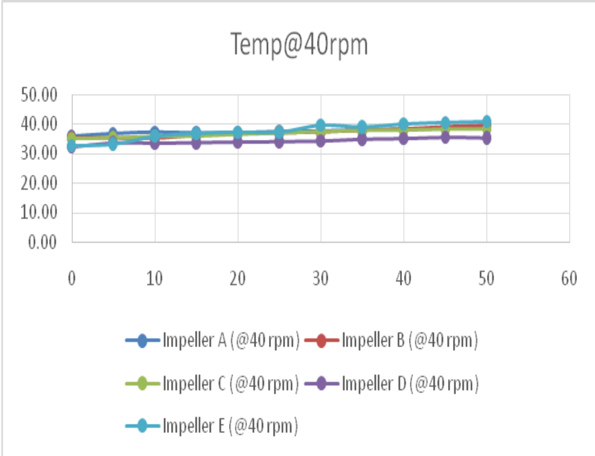

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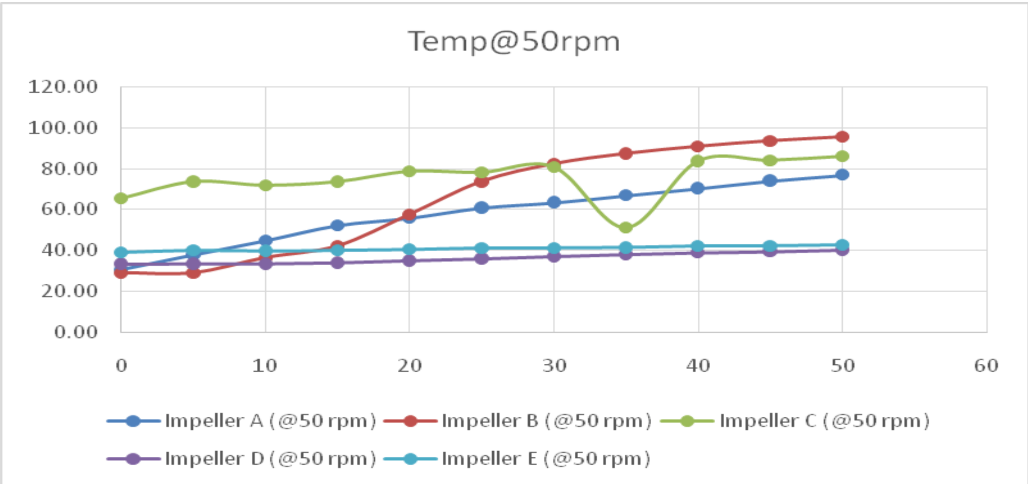

(e)

Figure 6: Graph comparing the performance characteristics of impellers under investigation (Impeller A - E). (a) Temperature @10 rpm, (b) Temperature @ 20 rpm, (c) Temperature @ 30 rpm, (d) Temperature @ 40 rpm and (e) Temperature @ 50 rpm.

This figure presents the temperature variation for each impeller at different speeds (10 to 50 rpm), showing how temperature rises with speed. The graph indicates that higher speeds lead to higher temperatures, so impellers that maintain lower temperatures at increased speeds are more efficient for heat-sensitive paint formulations. Effective mixing in this context is achieved when the temperature remains within acceptable limits, allowing for consistent mixing without compromising the formulation. Choosing impellers that minimize heat generation ensures stability and component integrity.

4. CONCLUSIONS

The method of analysis employed in this work showed dynamics of mixing in agitated vessels, which are oftentimes rigorous to forecast. This method gave relative facts practically turbulent flow properties. The patterns of flow of disparate impeller configurations used in this study were adequately depicted by way of experimental analysis. It was established that the configuration of impeller-blade substantially impacted the performance of an agitated stirred mixer. Achieving the best mixing designs will improve the quality of mixing and establish a good degree of homogeneity, as a function of the design. This study will be applied in choosing the appropriate type of impellers that will guarantee favorable outcome and efficient use of valuable chemicals and other mixing factors. It will also give a basis on which substantial mixing techniques can be prepared and regulated using least possible costs, time and space.

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