Development of Operating Model for the Design of Stirrer Arms of Slurries: Empirical Evaluation of Stirrer Arms

Comment [T1]: General Comments
The Title is appropriate
The manuscript is well organized and structured
The introduction is well detailed
The methodology is well spelt out
The results and discussion are presented accurately
The conclusion is properly written
The references are well cited in the body of the article

The table should be mentioned in the body of the paper and labelled in journal sequence order as Table 1 not as Table 1.1. Applicable to others

The Equations should be mentioned in the body of the paper and labelled in journal sequence order as Equation 1 not as Equation 1.1. Applicable to others

**The references listed should be arranged properly
**The journal references format should be followed strictly

Recommendation: Minor Revision
Overall: 65 %

ABSTRACT

The “Development of Operating Model for the Design of Stirrer Arms of Slurries: Empirical Evaluation of Stirrer Arms” is reported. Previous work reviewed the “Operating Model for the Design of Stirrer Arms of Slurries” and identified the Two Z and TETE stirrer arms as the most effective. Furthermore, subsequent work “Development of Operating Model for the Design of Stirrer Arms of Slurries: Design and Fabrication of Stirrer Arms” designed and fabricated the Two Z and TETE stirrer arms, evaluated the theoretical (expected) Slurry Mixing Power and Order of Merit Analysis. The current work did the empirical evaluation of the Two Z and TETE stirrer arms and also the hybrid Two Z - TETE stirrer arms. The Objectives of this research were to investigate the comparative effectiveness and efficiency of the two Z and TETE stirrer arms in terms of mixing power, time and energy. Results obtained were analyzed using the Chi Square and the Order of Merit. There was excellent agreement between the adjusted predicted (expected) slurry mixing power (E’) and Observed slurry mixing power (O) at 5% confidence level. Empirical model was developed to predict expected slurry mixing power. The Order of Merit analysis revealed the TETE stirrer arm as the most energy efficient.

Keywords: Stirrer arms, slurries, operating model, empirical evaluation.

1. INTRODUCTION
1.1 Statement of Problem

Previous review of the works of [1] and [2] by [3] revealed that the Two Z and TETE stirrer arms were the most efficient and effective in their category respectively. Consequent on this finding, the design and fabrication of the Two Z and TETE stirrer arms was done by [4]. The slurry was constituted and the viscosity calibration was done as in Table 1.1 at temperatures maintained at range of 80 – 85 ^{O}C The angular speed of the stirrer arms was determined and the theoretical (predicted or expected) slurry mixing Power was evaluated using Equation (1.1) as proposed by [4] and results shown in Table 1.2.

$$P = 82 * 10^{-7} \mu\omega^2 \qquad (1.1)$$

Where P = Theoretical predicted (or expected) power.
μ = Slurry viscosity
ω = stirrer arm angular speed.

The order of merit of the stirrer arm mixing theoretical (predicted or expected) power indicated that the Two Z was more efficient.[4].

This current work was aimed at the empirical evaluation of the Two Z and TETE stirrer arms using the already constituted slurry by [4] and using the governing Equations (1.2) and (1.3) as recommended by [4]. The outcome of the empirical evaluation will be expected to validate the theoretical (predicted or expected) mixing power values as reported by [4]. The governing equation for the Chi Square(X^2) is:

$$X^2 = \frac{(O-E')^2}{E'} \qquad (1.2)$$

The governing equation for the Order of Merit Analysis is:

$$\frac{Merit\ of\ A}{Merit\ of\ B} = \frac{O_{A1}}{O_{B1}} * \frac{O_{A2}}{O_{B2}} * \ .\ .\ .\ .* \frac{O_{An}}{O_{Bn}} = M_{A/B} \qquad (1.3)$$

$$Number\ of\ Comparisons = \frac{N(N-1)}{2}.$$

where, N is the number of stirrer arms.

$$If\ M_{\frac{A}{B}} > 1\ \ Select\ B$$
$$If\ M_{A/B} < 1\ Select\ A$$

Table 1.1 Slurry viscosity versus mass of pap.

S/No	Pap per 2 litre run (kg)	Pap per litre (kg)	Viscosity (µ) (NS/M^2)
1.	0	0	0.224
2.	0.100	0.050	0.239
3.	0.200	0.100	0.372
4.	0.300	0.150	8.494
5.	0.400	0.200	14.854
6.	0.500	0.250	362.285
7.	0.556	0.278	1,163.416

Source: Data from slurry calibration..[4]

Table 1.2. Viscosity (µ), Angular speed (ω) versus Theoretical (Predicted or Expected) power (E)

S/no.	Viscosity (µ) Ns/m^2	Two Z blade		TETE blade		Two Z – TETE blade	
		Angular speed (ω) Rad.	Power = $82*10^{-7}\mu\omega^2$ watt.	Angular speed (ω) Rad.	Power = $82*10^{-7}\mu\omega^2$ watt.	Angular speed (ω) Rad.	Power = $82*10^{-7}\mu\omega^2$ watt.
1.	0.224	57.11	0.006	85.52	0.0134	67.11	0.00827
2.	0.239		0.0064		0.0143		0.00883
3.	0.372		0.0099		0.0223		0.0137
4.	8.494		0.2270		0.5090		0.3136
5.	14.854		0.397		0.891		0.5486
6.	362.285		9.689		21.727		13.379
7.	1163.416		31.115		69.772		42.966

Source: Data from [4].

1.2. Aim and Objectives

Aim:

The aim of this research was to do the empirical evaluation of the Two Z blade, TETE blade and the Two Z – TETE hybrid blades with the view of ranking their performances.

Objectives:

The specific objectives of this research were:

i. To do the mixing performance tests in terms of mixing time, power and energy consumed by the Two Z blade, TETE blade and Two Z – TETE hybrid blade using the constituted slurry by [4].
ii. To validate the theoretical (predicted or expected) mixing power for the Two Z blade, TETE blade and Two Z – TETE hybrid blade as generated by [4] by comparison with the empirical power using the Chi Square.
iii. To do the Power, Time and Energy order of merit analysis for the Two Z blade, TETE blade and the Two Z – TETE hybrid blade.

1.3. LIterature

The mixing time and power consumption for:

i. Off – centre impeller.
ii. Inclined impeller.
iii. Impeller with inserted object.

under spatial chaotic mixing method was investigated. The impeller with inserted object gave the shortest mixing time at low power consumption [5]. Also the mixing hydrodynamics in a double planetary mixer was investigated using numerical and experimental approach over cross – linking reaction. Results showed that the mixer radial dispersion was good but its axial (top –to – bottom) pumping was poor for all values of viscosity [6].

In similar vein, the operation of a new coaxial mixer consisting a wall scraping arm and a series of rods and a pitched blade turbine mounted on the same axis of revolution and operated in a contra – rotating mode was investigated using experimental measurements and 3D numerical simulations. The experimental results validated numerical values [7].

Also the standard pitched blade turbine (PBT) was modified to the dual flow pitched blade turbine (DT – PBT) with upward and down ward flow simultaneously to induce chaotic flow. The effect of the impeller modification with eccentricity was investigated. Results showed that effectiveness of mixing increased with the increase in impeller eccentricity over RPM increase alone in the reduction of isolated mixing region size. [8].

Methods to visualize and analyze the mixing process happening in the planetary kneading mixers (which are used to mix non-Newtonian and viscoplastic fluids) include:

Developing three dimensional model of the stirring blade.

Establishing the physical and mathematical models of flow field in the mixing tank of the planetary kneading mixers.

Determining the boundary condition of numerical simulation by virtue of rheological theory and rules, and deeply investigating the characteristics of velocity field and flow pattern of the mixing field numerically simulated by using CFD software [9]

Furthermore, results of investigation showed that preferable mixing efficiency can be achieved on the proper choice of:

The value of the helix angle mounting.

Central distance.

Mounting clearance of the stirring blades [9]

On similar note, the effect of vessel configuration (un-baffled, baffled and vessel with slot placed at the external periphery of the vessel) and agitation rates on the flow structure and power was investigated. There was good agreement between predicted and experimental data [10].

In another development, the helical blade and anchor blade were designed and fabricated. The two blades were tested (using a fluid of known viscosity) for mixing effectiveness. The torque of 0.25 Nm was produced by the helical blade and 0.28 Nm by the anchor blade. The empirical torque values agreed with calculated values with 8% error. Hence the helical blade was more efficient in mixing at less time and lower power [11].

Also the impact of double shaft mixing paddle undergoing planetary motion on laminar flow mixing system using flow field visualization experiments and computational fluid dynamics simulation was investigated. The findings were as follows:

The double – shaft mixing paddle undergoing planetary motion would not produce isolated mixing regions in the laminar flow mixing systems.

Its mixing efficiency in counter – rotating modes was higher than in co – rotating modes especially at low rotating speeds.

Axial and tangential flows produced in co – rotating and counter – modes have similar flow velocity but opposite flow directions.

Axial flow was the main reason for causing different co – rotating and counter – rotating modes [12]

In the same vein the power consumption characteristics of a double arm planetary mixer using non – Newtonian and viscoelastic fluids was investigated. Experimental measurement of torque as a function of speed and rheology was done. Results obtained were satisfactory.[13].

Also the effects of multiple intermig impeller configuration on hydrodynamic mixing performance in a stirred tank was investigated using computational fluid dynamics. The intermig impeller was rotated 450 with respect to its neighbor instead of the 900 as recommended by the manufacturers. This impeller rotation gave a wider range of operating conditions. Also decreasing the distance between the lower two impellers achieved fluid exchange between the impellers down to Re = 27 [14].

In another development, Rushton turbine, 450 pitch-blade turbine, MIXEL TT and TTP propellers agitators were used to investigate the influence of the stirrer type and the geometrical parameters of the tank and agitator. Key parameters considered include:

Clearance of impeller from tank bottom.

Impeller diameter.

Draft tube.

Geometry of the tank bottom.

While using power consumed per unit mass of liquid as a basis, the TTP propeller was classified as most efficient. [15].

Also the design, fabrication and testing of shea butter mixer was done. Results of test showed that shea butter yield was significantly affected by:

The blade type.

Container diameter.

Speed of mixing [16].

The literature above can be summarized thus:

Effectiveness and efficiency in the mixing process depends on the mixer type (including the stirrer arms) and properties of fluid to be mixed.

That mixing time and power measurement are essential parameters for evaluating the performance of the mixing process.

That validation of mixers is done by relating theoretical (predicted or expected) values to the empirical/experimental values.

That relative performance of mixers/stirrer arms are done by order of merit analysis.

2. material and methods

2.1. Materials

Materials for this research include: the Philip mixer Model HR 1565, the fabricated stirrer arms Two Z, TETE and hybrid Two Z – TETE, Digital AC/DC Clamp Meter (MASTECH MS2001), Digital Stop Clock, Digital Weighing scale, Cylindrical measuring jar and Food Grade thermometer. The details of the measuring instruments are as shown on Table 2.1.; Constituted Pap slurry maintained at 80 – 85 OC as shown on Table 3.1.

Table 2.1. Measuring instruments.

S/No	Instrument		Rating		Accuracy
1.	Digital AC/DC Clamp Meter (MASTECH MS2001)		20A/200A		+ (2.0% +5)

2.	Digital Stop Clock (Samsung A 10S)	99 Hours.	+ 0.01 Second
3.	Photo/Contact Type Digital Tachometer	2.5 to 99,999 RPM	+ (0.05 + 1 digit)
4.	Digital Weighing Scale (SF400)	10 Kilogramme	+ 1g
5.	Cylindrical Measuring Jar	250 ml (EX 20OC	+ 2 ml
6.	Food Grade Thermometer	360OC	+ 2OC

Source [4]

2.2 Methods

Methods for the mixing of the slurry using the Two Z-Blade stirrer arms, TETE stirrer arms and the Two Z - TETE Stirrer arms are presented below.

Plate 1. Mixing the Slurry with the Two Z-Blade Stirrer Arm.

Plate 2.   Mixing the Slurry with the TETE Blade Stirrer Arm.

Plate 3. Mixing the Slurry with the Two Z - TETE Blades Hybrid Stirrer Arm.

2.2.1 Mixing the Slurry with the Two Z Blade Stirrer Arms

The Akamu (pap) was poured into the bowl of the mixer (Shown in Plate 1). The Milo solution was equally poured into the bowl of the mixer. The power supply to the mixer was turned on. The time taken for proper and complete mixing was noted through a stop Clock and the current drawn was recorded by a Digital Clamp Meter. The process was repeated for several operations and the average mixing time and current drawn was computed and tabulated on Table 3.3

2.2.2 Mixing the Slurry with the TETE Blade Stirrer Arm

The mixing process as in Section 2.2.1 was repeated with the TETE Blade Stirrer Arms (Shown in Plate 2).and results are as shown on Table 3.3.

2.2.3 Mixing the Slurry with the Two Z - TETE Blades Hybrid Stirrer Arms

The mixing process as in Section 2.2.1 was repeated with the Two Z - TETE Blades hybrid Stirrer Arms (Shown in Plate 3) and results as recorded on Table 3.3.

2.2.4 Computation and Comparison of Data from the Two Z, TETE and the Two Z - TETE hybrid Stirrer Arms.

The values of current drawn versus mixing time for the three sets of mixing blades (Stirrer Arms) from sections 2.2.1, 2.2.2 and 2.2.3 were compared. Consequent on this, the mixing blades (Stirrer Arms) were ranked.

3. results

Table 3.1. Slurry viscosity versus mass of pap.

S/No	Pap per 2 litre run(kg)	Pap per litre(kg)	Viscosity (μ) (NS/M2)
1.	0	0	0.224
2.	0.100	0.050	0.239
3.	0.200	0.100	0.372
4.	0.300	0.150	8.494
5.	0.400	0.200	14.854
6.	0.500	0.250	362.285
7.	0.556	0.278	1,163.416

Source: Data from slurry calibration..[4]

Table 3.2. Viscosity (μ), Angular speed (ω) versus Expected Power (E).

S/No.	Viscosity (μ)	ZZ blade		TETE blade		ZZ – TETE blade	
	NS/M^2	Angular speed (ω) (Rad)	Power = $82{*}10^{-7}\mu\omega^2$ (Watt)	Angular speed (ω) (Rad)	Power = $82{*}10^{-7}\mu\omega^2$ (Watt)	Angular speed (ω) (Rad)	Power = $82{*}10^{7}\mu\omega^2$ (Watt)
1.	0.224	57.11	0.006	85.52	0.0134	67.11	0.00827
2.	0.239		0.0064		0.0143		0.00883
3.	0.372		0.0099.		0.0223		0.0137
4.	8.494		0.2270		.5090		0.3136
5.	14.854		0.397		0.891		0.5486
6.	362.285		9.689		21.727		13.379
7.	1163.416		31.115		69.772		42.966

Source:[4].

Table 3.3. Viscosity versus Observed mixing Current, Time and Power.

S/No.	Viscosity (u) NS/M2	Two Z Blade			TETE Blade			Two Z-TETE Blade		
		Current (A)	Time (S)	Power (O)	Current (A)	Time (S)	Power (O)	Current (A)	Time (S)	Power (O)
1.	0.224	0.15	34.55	33.00	0.15	14.5	33.00	0.12	35.30	26.40
2.	0.239	0.44	7.39	95.92	0.35	6.83	77.88	0.41	4.67	89.10
3.	0.372	0.41	21.90	89.32	0.22	16.42	47.96	0.20	13.03	44.88
4.	0.494	0.30	28.96	66.66	0.25	23.73	55.66	0.14	42.17	31.68
5.	14.854	0,20	49.44	43.12	0.23	63.01	51.48	0.16	67.57	35.42
6.	362.285	0.24	12.42	52.80	0.34	22.24	72.60	0.15	46.55	44.00
7.	1163.416	0.52	91.31	114.62	0.34	75.49	74.14	0.43	66.54	99.66

Table 3.4. Expected Power (E) Versus Observed Power (O).

S/No.	Viscosity µ	Expected Power (E) (Watt)			Observed Power (O) (Watt)		
	NS/M^2	Two Z	TETE	Two Z- TETE	Two Z	TETE	Two Z - TETE
1.	0.224	0.006	0.0134	0.00827	33.00	33.00	26.40
2.	0.239	0.0064	0.0143	0.00883	95.92	77.88	89.10
3.	0.372	0.0099	0.0223	0.0137	89.32	47.96	44.88
4.	8.494	0.2270	0.5090	0.3136	66.66	55.66	31.68
5.	14.853	0.397	0.891	0.5486	43.12	51.48	35.42
6.	362.285	9.689	21.727	13.379	52.80	72.60	44.00
7.	1163.416	31.115	69.772	42.966	114.62	74.14	99.66

Source: Data from Tables 3.2 and 3.3.

From Table 3.4, a critical look at the Expected Power (E) and the Observed Power (O) for the three types of Stirrer Arms appear to be wide apart. Hence there is need to do adjustment to the Expected Power by regressing the Expected Power (E) on Observed Power (O). To do this, we find the Natural logarithm of the Expected Power (E) and the Observed Power (O) for each type of Stirrer Arm. (See Data on Tables 3.5, 3.6 and 3.7).

Table 3.5. Two Z Stirrer Arm (Natural Logarithm of Expected Power (E) Versus Observed Power (O)).

S/No.	Two Z stirrer arm			
	Expected Power (E)	ln E	Observed Power (O)	ln O
1.	0.006	-5.116	33.00	3.497
2.	0.0064	-5.051	95.92	4.564
3.	0.0099	-4.615	89.32	4.458
4.	0.2270	-1.483	66.66	4.200
5.	0.397	-0.924	43.62	3.764
6.	9.689	2.710	52.80	3.967
7.	31.115	3.438	114.62	4.742

Source: Data from Table 3.4.

Table 3.6. TETE Stirrer Arm (Natural Logarithm of Expected Power (E) Versus Observed Power (O)).

S/No.	TETE Stirrer Arm

	Expected Power(E)	ln E	Observed Power (O)	ln O
1.	0.0134	-4.313	33.00	3.497
2.	0.0143	-4.248	77.88	4.355
3.	0.0223	-3.803	47.96	3.870
4.	0.509	-0.675	55.66	4.019
5.	0.891	-0.115	51.48	3.941
6.	21.727	3.079	72.60	4.285
7.	69.772	4.245	74.14	4.306

Source: Data from Table 3.4..

Table 3.7. Two Z – TETE Stirrer Arm (Natural Logarithm of Expected Power (E) Versus Observed Power (O)).

S/No.	Two Z – TETE Stirrer Arm			
	Expected Power(E)	ln E	Observed Power (O)	ln O
1.	0.00827	-4.795	26.40	3.273
2.	0.00883	-4.730	89.10	4.490
3.	0.0139	-4.290	44.88	3.804
4.	0.3136	-1.160	31.68	3.456
5.	0.5486	-0.600	35.42	3.567
6.	13.379	2.594	44.00	3.784
7.	42.966	3.760	99.66	4.602

Source: Data from Table 3.4

Using Microsoft Excel Scatter Diagram, the data of Tables 3.5, 3.6 and 3.7 (that is ln E versus ln O) were plotted as shown in Figures 1, 2 and 3 respectively.

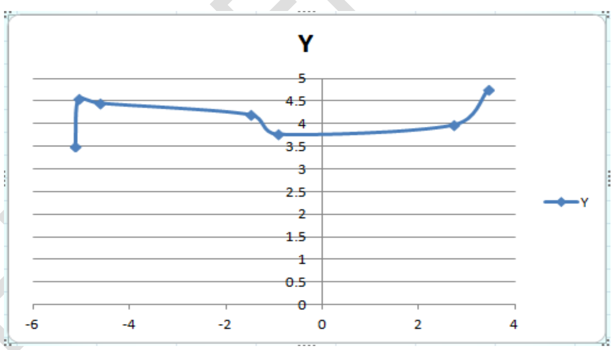

Fig. 1. Two Z: lnY Versus lnX.

Where: ln Y = ln O. ln X =ln E.

Source: Data from Table 3.5.

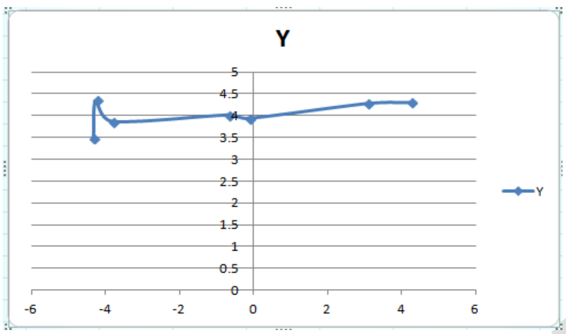

Fig. 2. TETE: lnY Versus lnX.

Where: ln Y = ln O. ln X =ln E.

Source: Data from Table 3.6.

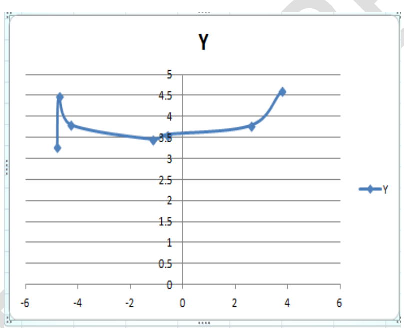

Fig. 3. Two Z -TETE: lnY Versus lnX.

Where: ln Y = ln O. ln X =ln E.

Source: Data from Table 3.7.

Hence from Fig. 1, the adjusted Expected Power (E') for the Two Z stirrer arm is:

$\ln E' = -0.198\, lnE + 3.5 \qquad \mu \leq 14.853$

$\ln E' = 0.145 \ln E + 3.7 \qquad \mu \geq 14.853 \qquad (3.1)$

and the adjusted values of Expected Power (E') corresponding to the Observed Power (O) are as shown on Table 3.8.

Also, from Fig. 2, for the TETE Stirrer Arm, the regression equation for the adjusted Expected Power is:

$\ln E' = 0.066 \ln E + 4.1 \qquad (3.2)$

and the adjusted values of Expected Power (E') corresponding to the Observed Power (O) are as shown on Table 3.8.

Similarly, from Fig. 3, for the Two Z – TETE Stirrer Arm, the regression equation for the adjusted Expected Power is:

$\ln E' = -0.111 \ln E + 3.3 \qquad \mu \leq 14.853$

$\ln E' = 0.185 \ln E + 3.6 \qquad \mu \geq 14.853 \qquad (3.3)$

and the adjusted values of Expected Power (E') corresponding to the Observed Power (O) are as shown on Table 3.8

Table 3.8: Stirrer Arm: Adjusted Expected Power (E') Versus Observed Power (O).

S/No	Adjusted Expected Power (lnE')			Observed Power (lnO)		
	Two Z blade	TETE blade	Two Z – TETE blade	Two Z blade	TETE blade	Two Z - TETE blade
1.	4.513	3.815	3.832	3.497	3.497	3.273
2.	4.5001	3.820	3.825	4.564	4.355	4.490
3.	4.414	3.849	3.776	4.458	3.870	3.8704
4.	3.794	4.056	3.429	4.200	4.019	3.456
5.	3.683	4.092	3.489	3.764	3.941	3.567
6.	4.093	4.303	4.080	3.967	4.285	3.784
7.	4.199	4.380	4.296	4.742	4.306	4.602

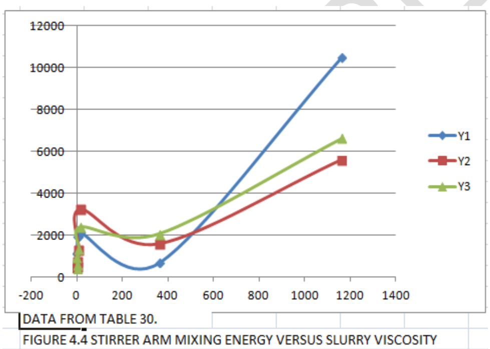

Figure 4: Stirrer Arm Mixing Energy Versus Slurry Viscosity.
Y1 = Two Z Blade. Y2 = TETE Blade. Y3 = Two Z – TETE Blade.

Source: Data from Tables 3.4 and 3.12.

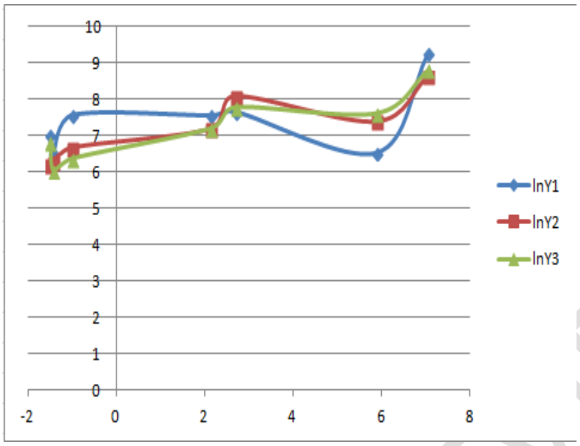

Fig. 5. ln(Energy) Versus ln(Viscosity).
lnY1 = Two Z Blade. lnY2 = TETE Blade. lnY3 = Two Z – TETE Blade.
Source: Data from Table 3.4 and 3.12.

Chi Square Analysis:
From Table 3.9:
Degree of freedom (df) = k – 1 = 7- 1 = 6. Where k is number of operations and is equal to 7. For a confidence level of x = 5% = 0.05, critical values of the Chi Square distribution with 6 degrees of freedom is 12.592. This is the probability of exceeding the critical value. From Table 3.9, the Chi Square value is 0.349.
$0.349 < 12.592$
Hence, there is agreement between the adjusted Expected Power(E') and Observed Power (O).
From Table 3.10:
Also, Chi Square value is 0-10875.
$0.10875 < 12.592$
Hence there is agreement between the adjusted Expected Power (E') and Observed Power (O).
From Table 3.11:
The Chi Square value is 0.24483.
$0.24483 < 12.592$
Hence, there is also agreement between the adjusted Expected Power (E') and Observed Power (O).

Table 3.9: Two Z Stirrer Arm: Chi Square Analysis.

S/No.	E'	O	O – E'	$(O – E')^2$	$(O – E')^2/E'$
1.	4.513	3.497	-1.016	1.032	0.229
2.	4.5001	4.564	0.0639	0.0041	0.000
3.	4.414	4.458	0.018	0.00032	0.00007
4.	3.794	4.200	0.406	0.16484	0.04345
5.	3.683	3.764	0.081	0.00656	0.00178
6.	4.093	3.967	-0.126	0.01588	0.00388
7.	4.199	4.742	0.543	0.2948	0.0702
Total					0.34928

Source: Data from Table 3.8

Table 3.10: TETE Stirrer Arm: Chi Square Analysis.

S/No.	E'	O	O – E'	$(O – E')^2$	$(O – E')^2/E'$
1.	3.815	3.497	-0.318	0.1011	0.0265

2.	3.820	4.355	0.535	0.286	0.0749
3.	3.849	3.870	0.021	0.00044	0.000115
4.	4.056	4.019	-0.037	0.00137	0.000338
5.	4.092	3.941	-0.151	0.0228	0.005572
6.	4.303	4.285	-0.018	0.00032	0.0000753
7.	4.380	4.306	-0.074	0.0055	0.00125
Total					0.10875

Source: Data from Table 3.8.

Table 3.11: Two Z - TETE Stirrer Arm: Chi Square Analysis.

S/No.	E'	O	O – E'	$(O – E')^2$	$(O – E')^2/E'$
1.	3.832	3.273	-0.559	0.3105	0.08155
2.	3.825	4.490	0.665	0.4422	0.1156
3.	3.776	3.8704	0.0944	0.0089	0.00236
4.	3.429	3.456	0.027	0.00073	0.000213
5.	3.489	3.567	0.080	0.0064	0.00183
6.	4.080	3.784	-0.296	0.08762	0.02148
7.	4.296	4.602	0.306	0.09364	0.02180
Total					0.244833

Source: Data from Table 3.8

Table 3.12: Observed Power (O), Slurry Mixing Time and Energy.

S/No.	Two Z			TETE			Two Z - TETE		
	Power	Time	Energy	Power	Time	Energy	Power	Time	Energy
1.	33.00	34.55	1140.15	33.00	14.50	478.50	26.40	35.30	931.92
2.	95.92	7.35	695.42	77.88	6.83	531.92	89.10	4.67	416.10
3.	89.32	21.90	1956.16	47.96	16.42	787.50	44.88	13.03	584.79
4.	66.66	28.96	1930.47	55.66	23.73	1320.81	31.68	42.17	1335.95
5.	43.12	49.44	2131.85	51.48	63.01	3243.76	35.42	67.57	2393.33
6.	55.80	12.45	694.71	72.60	22.24	1614.62	44.00	46.95	2065.80
7.	114.62	91.31	10465.95	74.14	75.47	5595.35	99.66	66.54	6631.38

Source: Data from Table 3.3

Power Economy:

Using Equation (1.3) and Observed Power data on Table 3.12, the Power Economy can be computed as follows:

$$\frac{Merit\ of\ Two\ Z}{Merit\ of\ TETE} = \frac{33}{33} * \frac{95.92}{77.88} * \frac{89.32}{47.96} * \frac{66.66}{55.66} * \frac{43.12}{51.48} * \frac{55.80}{72.60} * \frac{114.62}{74.14} = 2.734$$

TETE is preferred.

$$\frac{Merit\ of\ Two\ Z}{Merit\ of\ Two\ Z - TETE} = \frac{33}{26.4} * \frac{95.92}{89.10} * \frac{89.32}{44.88} * \frac{66.66}{31.68} * \frac{43.12}{35.42} * \frac{55.80}{44.00} * \frac{114.62}{99.66} = 10.006$$

Two Z – TETE is preferred to Two Z.

$$\frac{Merit\ of\ TETE}{Merit\ of\ Two\ Z - TETE} = \frac{33}{26.4} * \frac{77.88}{89.10} * \frac{47.96}{44.88} * \frac{55.66}{31.68} * \frac{51.48}{35.42} * \frac{72.60}{44.00} * \frac{74.14}{99.66} = 3.16$$

Therefore, Two Z – TETE is preferred to TETE.

: The ratio of power consumption of the TETE and Two Z Stirrer Arms (for values of viscosity of pap slurry considered) is 1:2.734. Similarly, the ratio of power consumption of the Two Z – TETE and Two Z Stirrer Arms (for values of viscosity of pap slurry considered) is 1:10.006.

In the same vein, the ratio of power consumption of Two Z – TETE and TETE (for values of viscosity of pap slurry considered) is 1:3.66.

From the foregoing, the order of call to bar (deployment) of the Stirrer Arms based on power economy is:

First deployment: Two Z – TETE.

Second deployment: TETE.

Third deployment: Two Z.

Time Economy:
Using Equation (1.3) and Observed Slurry Mixing Time data on Table 3.12, the Time Economy can be computed as follows:

$$\frac{Merit\ of\ Two\ Z}{Merit\ of\ TETE} = \frac{34.55}{14.5} * \frac{7.35}{6.83} * \frac{21.9}{16.42} * \frac{28.96}{23.73} * \frac{49.44}{63.01} * \frac{12.45}{22.24} * \frac{91.31}{75.47} = 2.218$$

$$\frac{Merit\ of\ Two\ Z}{Merit\ of Two\ Z - TETE} = \frac{34.55}{35.30} * \frac{7.35}{4.67} * \frac{21.9}{13.03} * \frac{28.96}{42.17} * \frac{49.44}{67.57} * \frac{12.45}{46.95} * \frac{91.31}{66.54} = 0.473$$

$$\frac{Merit\ of\ TETE}{Merit\ of Two\ Z - TETE} = \frac{14.5}{35.30} * \frac{6.83}{4.67} * \frac{16.42}{13.03} * \frac{23.73}{42.17} * \frac{63.01}{67.57} * \frac{22.24}{46.95} * \frac{75.47}{66.54} = 0.213$$

The interpretation of the results is as follows:
The ratio of slurry mixing time for TETE and Two Z Stirrer Arm (for values of viscosity of pap slurry considered) is 1:2.218.
Also, the ratio of slurry mixing time of the Two Z and Two Z – TETE Stirrer Arm (for values of viscosity of pap slurry considered) is 1:0.473.
In the same vein, the ratio of slurry mixing time of the TETE and Two Z – TETE (for values of viscosity considered) is 1:0,213.
From the foregoing, the order of call to bar (deployment) of the Stirrer Arms based on Time Economy is:
First deployment: TETE
Second deployment: Two Z.
Third deployment: Two Z – TETE.

Energy Economy:
Using Equation (1.3) and Observed Energy data on Table 3.12, the Energy Economy can be computed as follows:

$$\frac{Merit\ of\ Two\ Z}{Merit\ of\ TETE} = \frac{1140.15}{478.5} * \frac{695.42}{531.92} * \frac{1956.16}{787.50} * \frac{1930.47}{1320.81} * \frac{2131.85}{3243.76} * \frac{694.71}{1614.62} * \frac{10465.95}{5595.35} = 5.982$$

$$\frac{Merit\ of\ Two\ Z}{Merit\ of\ Two\ Z - TETE} = \frac{1140.15}{931.92} * \frac{695.42}{416.10} * \frac{1956.16}{584.79} * \frac{1930.47}{1335.95} * \frac{2131.85}{2393.33} * \frac{694.71}{2065.8} * \frac{10465.95}{6631.38} = 4.673$$

$$\frac{Merit\ of\ TETE}{Merit\ of\ Two\ Z - TETE} = \frac{478.5}{931.92} * \frac{531.97}{416.10} * \frac{787.56}{584.79} * \frac{1320.81}{1335.95} * \frac{3243.76}{2393.33} * \frac{1614.62}{2065.8} * \frac{5595.35}{6631.38} = 0.781$$

From the above, the Stirrer Arm with the best energy economy is TETE, followed by Two Z – TETE and Two Z. Hence, the order of call to bar (deployment) of the Stirrer Arms based on energy economy is:
First choice deployment: TETE
Second choice deployment: Two Z – TETE and
Third choice deployment: Two Z.

4. DISCUSSION

4.1 Discussion of findings is hereby summarized:

i. Adjusted Predicted Power (E') versus Observed Power (O).

There was a high level of agreement between the adjusted predicted power (E') and observed power (O) at 5% confidence level for the Two Z, TETE and Two-TETE stirrer arms. The Chi Square values of the Two Z, TETE and

Two Z- TETE were 0.34928, 0.10875 and 0.24483 respectively. The Chi Square values indicated that the TETE had the best agreement, followed by the Two Z- TETE and lastly the Two Z.

This implied that for a given mixer angular speed and known viscosity of the slurry, the predicted adjusted power (E') represented the true mixing power to be consumed within acceptable error limits.

ii. Order of Merit Based on Power Deployment.

For the deployment of mixer based strictly on power efficiency, the merit level of Two Z – TETE came first followed by TETE and Two Z. This mixer order saved power consumption and hence highly advantageous. This result therefore has overridden the findings of [4] in the order of merit based on theoretical (Expected) Power (E).

iii. Order of Merit Based on Time Deployment.

In similar terms, for the deployment of mixer based strictly on time efficiency, the merit level of TETE came first followed by Two Z and Two Z- TETE. The mixer deployment order saved time and hence highly advantageous where time constraint is critical.

iv. Order of Merit Based on Energy Deployment.

Also, for the deployment of mixer based strictly on energy efficiency, the merit level of TETE came first followed by Two Z – TETE and Two Z. since energy saving was the total focus of power and time savings, the energy efficiency index constituted the best yardstick for the deployment of the mixers. In this regard therefore, the TETE stirrer arm stood tall over the Two Z – TETE and Two Z stirrer arms.

4.2 Addressing Objectives:

Objective (i): Do the mixing of slurry performance tests in terms of mixing time, power and energy consumed using the mixer with Two Z stirrer arm, TETE stirrer arm and Two Z – TETE stirrer arm:

This mixing process was done and also using the hybrid Two Z – TETE stirrer arms and the results so obtained are as displayed on Table 3.12. Hence, objective (i) had been realized.

Objective (ii): To validate the theoretical (predicted or expected) mixing power for the Two Z, TETE and Two Z – TETE hybrid blade as generated by [4] by comparison with the empirical power using the Chi Square:

The computation of data was done. Analysis was done using the Regression approach and application of natural logarithms for the linearization of non-linear expression. (See Tables 3.5 to 3.7, 3.9 to 3.11 and Figures 1 to 3). Hence objective (ii) was accomplished.

Objective (iii): To do the power, Time and Energy order of merit analysis for the Two Z blade, TETE and TETE and Two Z – TETE hybrid blade:

Also, comparison of mixing power, time and energy was done for the Two Z, TETE and Two Z – TETE stirrer arms using the order of merit system analysis. (See Table 3.12 and also Fig. 4 and 5). Hence, objective (iii) was also accomplished.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Findings

The following findings are summarized:

i. There is high level of agreement at 5% confidence level between the adjusted predicted power (E') consumption and observed power (O) consumption of the Two Z stirrer arms as represented by the empirical equation/model developed:

$$\ln E' = -0.198\, lnE + 3.5 \qquad \mu \le 14.853$$
$$\ln E' = 0.145 \ln E + 3.7 \qquad \mu \ge 14.853$$

ii. In similar vein, there is high level of agreement (at 5% confidence level between the adjusted predicted power (E') consumption and observed power (O) consumption of the TETE stirrer arm as represented by the empirical relationship/model developed:

$$\ln E' = 0.066 \ln E + 4.1$$

iii. Also there is high level of agreement (5% confidence level) between the adjusted predicted power (E') consumption and observed power (O) consumption of the Two Z – TETE stirrer arm as represented by the empirical relationship/model developed:

$$\ln E' = -0.111 \ln E + 3.3 \qquad \mu \le 14.853$$
$$\ln E' = 0.185 \ln E + 3.6 \qquad \mu \ge 14.853$$

iv. For merit order based power deployment:

First call to bar: Two Z- TETE

Second call to bar: TETE

Third call to bar: Two Z

v. For merit order based time deployment:

First call to bar: TETE

Second call to bar: Two Z

Third call to bar: Two Z – TETE.

vi. For merit order based energy deployment:

First call to bar: TETE

Second call to bar: Two Z – TETE

Third call to bar: Two Z.

5..2 **Conclusions**

The following conclusions are summarized:

i. Empirical relationships/models have been developed for the predicted mixing power (E') and observed mixing power (O) for the Two Z, TETE and Two Z – TETE stirrer arms.

ii. The TETE stirrer arm has the most efficient mixing energy followed by the Two Z – TETE and the Two Z stirrer arms.

iii. The static TETE stirrer arms has been effectively and efficiently converted to dynamic (Rotary) TETE stirrer arm.

iv. Conversion from static stirrer arms to dynamic stirrer arms lead to versatility of applications and hence huge economic benefits.

5.3 **Recommendations**

The deployment and application of the TETE stirrer arm and the hybrid Two Z – TETE are highly recommended for the slurry industries, most especially in the area of foods and beverages. The economic benefits cannot be over emphasized.

Further investigation is equally recommended for the comparative advantage test of TTP Propeller and TETE stirrer arms. Similar comparative advantage tests can be conducted for TTP Propeller and the Two Z – TETE stirrer arms.

5.4 **Contributions to Knowledge**.

The following contributions to knowledge are summarized:

i. Successfully converted Bunkluarb et al. (2019)'s TETE static stirrer arm into dynamic (Rotary) TETE stirrer arm.

ii. Comparative testing of the Rotary TETE stirrer arm against Yu and Gunasekaran (2005)'s Two Z stirrer arm. Results showed the superiority of the TETE stirrer arm over the Two Z rotary stirrer arm.

iii. Testing the Two Z – TETE hybrid rotary stirrer arm against the Two Z and the TETE rotary stirrer arm. Results showed that Two Z – TETE hybrid rotary stirrer arm performance iwas middle of the road between the TETE and Two Z stirrer arms.

iv. Empirical relationships/models relating the predicted slurry mixing power (E') and observed slurry mixing power (O) of stirrer arms of mixer have been developed.

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