Current Journal of Applied Science and Technology

41(19): 39-56, 2022; Article no.CJAST.88104
ISSN: 2457-1024
(Past name: British Journal of Applied Science & Technology, Past ISSN: 2231-0843,
NLM ID: 101664541)

Development of Operating Model for the Design of Stirrer Arms of Slurries: A Review

S. O. Okpighe [a*], M. U. Shadrack [a] and H. U. Nwosu [a]

[a] *Department of Mechanical Engineering, University of Port Harcourt, Port Harcourt, Nigeria.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2022/v41i1931742

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/88104

Review Article

Received 07 April 2022
Accepted 13 June 2022
Published 18 June 2022

ABSTRACT

An in dept review of the Development of Operating Model for the Design of Stirrer Arms of Slurries is reported. The works of several authors were reviewed. These works covered research on the importance of slurries, application of different slurries in the area of Agriculture and agricultural farming, construction and allied industries, foods and pharmaceutical industries, chemical and paints industries. Also considered were the research works on the design, fabrication and test investigation of performance of different stirrer arms. From the review, three key outcomes from three set of researchers were identified thus: Researcher team 1: the TTP propeller was the most efficient in liquid phase mixing; Researcher team 2: the TEET geometry contributed the best quality of the mixing and significantly reduced the cost of the mixing process; Researcher team 3: the two Z blade stirrer arm was considered as the best in terms of mixing effectiveness. These three outcomes appear as standalone and do not give the user(s) information on comparative advantages for deployment of stirrer arms. Consequent on the above, further theoretical and empirical research will need to be done to evaluate the Order of Merit of these stirrer arms to be called to bar.

Keywords: TEET geometry; planetary mixer; stirrer arms; TTP propeller.

**Corresponding author: E-mail: eloziconsultants@yahoo.com;*

1. INTRODUCTION

Stirring or mixing is a universal concept that has been with us over the ages. The Babylonians and ancient Egyptians made dough for bread through laborious mixing processes. The ancient Africans used elaborately prepared dough of clay and laterite as part of materials to complete their buildings.

According to [1], “mixing or blending is a unit operation in which a uniform mixture is obtained from two or more components, by dispersing one within the other(s)” [1] further posited that mixing has no preservative effect and is intended solely as a processing aid or to alter the eating quality of foods. Hence, mixing or blending is an operation solely geared toward achieving homogeneity of product(s). The purpose of mixing is agreeably correct The mixing process can involve solid – solid, solid – liquid, liquid – liquid, liquid – gas, gas – gas phases. The achieving of the desired homogeneity of product will depend on the:

i. Properties of the mixer machine.
ii. Characteristics of materials to be mixed.

Also [2] deposed that when selecting a bulk solid mixer, the entire process must be considered:

i. The recipe.
ii. Quality requirements.
iii. Batch.
iv. Size.
v. Reaction time.
vi. Materials characteristics.
vii. How the material is fed into and discharged from the mixer.

These factors will determine what type of mixer will give the mixing time and consistency required.

From the foregoing therefore, effective and efficient mixing will be a function of:

i. Mixer properties.
ii. Material characteristics.
iii. Stirrer arm characteristics.

That is to say,

$$Efficiency = f(mixer\ properties; materials\ characteristics; stirrer\ arm\ characteristics) \tag{1}$$

For a comparative analysis of two sets of stirrer arms when the mixer properties and materials characteristics are kept constant, the efficiency is therefore a strict function of the stirrer arms characteristics. That is:

$$Effectiveness\ and\ Efficiency = f(Stirrer\ arm\ charateristics) \tag{2}$$

Since power is the rate of doing work and effectiveness is a function of timeliness, Equation (2) reduces to:

$$Efficiency\ and\ Efficiency = f(P, T) \tag{3}$$

where,

P is the power needed for complete mixing of the slurry by the stirrer arm.
T is the time taken for the mixing to be completed.

Hence, with the power and time for the mixing of the fluid known, the comparative analysis for the different stirrer arms can be done using the Karl Pearon’s Chi Square and the Order of Merit tools. The Karl Pearson’s Chi Square will be used to do “Goodness of Fit” test by comparing the observed distribution of slurry mixing power (O) to a theoretical expected distribution of slurry mixing power (E’). The governing equation for the Chi Square (X^2) is:

$$X^2 = \frac{(O-E')^2}{E'} \tag{4}$$

Also the order of merit is governed by the expression in Equation (5).

$$\frac{Merit\ of\ A}{Merit\ of\ B} = \left(\frac{O_{A1}}{O_{B1}}\right) w_1 * \left(\frac{O_{A2}}{O_{B2}}\right) w_2 * \ \ldots..* \left(\frac{O_{An}}{O_{Bn}}\right) w_n = M_{A/B} \tag{5}$$

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

where, $w_1, w_2, ...w_n$ are weighted factors associated with each set of data. When weighted factors $w_1 = w_2 = w_n = 1$, Equation (5) reduces to Equation (6).

$$\frac{Merit\ of\ A}{Merit\ of\ B} = \frac{O_{A1}}{O_{B1}} * \frac{O_{A2}}{O_{B2}} * . . . .* \frac{O_{An}}{O_{Bn}} = M_{A/B} \quad (6)$$

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

where, N is the number of stirrer arms.

2. LITERATURE REVIEW

While reviewing the technologies of slurry phase hydro-cracking of heavy oil and the latest development of dispersed catalysts, [3] posited that “dispersed catalysts are highly dispersed and have greater surface area to volume ratio and show high catalytic activity and good performance, hence they are desirable for slurry-phase hydro-cracking of heavy oil. The postulation on area to volume ratio appears to be true. This is due to the drop in density as dispersion is done”.

According to [4], “different slurry types require different model parameter values, but it was found that the rheology of many common slurries could be described by a single set of parameter values over a wide range of conditions. This is very educative since the governing parameters are in line with fluid flow parameters for Newtonian and non-Newtonian fluid flows”.

According to [5], “if the concentration or flow velocity of slurry is increased, then slurry noise power spectral density curve in the logarithmic coordinate system will move to the upper right; if the concentration or flow velocity is reduced, then slurry noise power spectral density curve in the logarithmic coordinate system will move to the lower left. The Autoregressive – Moving - Average Model (ARMA Model) establishes the relationship between slurry noise, the velocity and the concentration of slurry”. This is also a fundamental fact that noise increases with velocity of flow. Hence designs target the avoidance of turbulent flow.

Also [6] employed “a computerized axial tomography scanner (CATSCAN) to measure the spatiotemporal distribution of solidosity for clay slurry flocculated with a cationic polyelectrolyte. According to [6], most of the sedimentation processes considering well-flocculated slurries is governed by sedimentation compaction”. This is absolutely factual and supported by gravitational laws pertaining to stack loading. Recall that stack loading leads to compressive forces which compacts the preceding materials.

In the same vein, [7] investigated “some properties of cement slurry, namely, plastic viscosity, yield point, gel strength, fluid loss and thickening time [7] deposed that for cement slurries, the rheological properties (plastic viscosity, yield point, gel strength and fluid loss) decreases with increase in temperature while the thickening time increases”. This is in line with thermal properties of fluids. As the temperature increases, the kinetic energy of the molecules of the slurry increases and hence the vibrational energy of the molecules. This vibrational energy tends to move the molecules further apart hence weakening the forces of cohesion thereby delaying the thickening process.

Computational fluid dynamics modelling and Experimental study of erosion in slurry jet-flows by [8] revealed “the surface wear-out pattern from profilometry measurements and the total weight loss. Experimental studies show that weight loss has a power-law relation with respect to impingement velocity or sand concentration. The weight loss decreases as the hardness of material increases, but not in a linear fashion”. This is most educative. A clear distinguishing line between chemical composition and mechanical properties is drawn..

According to [8], “two corrosion resistance materials, 304 stainless steel and chrome white alloy, showed the same corrosion and synergism weight loss although their hardness was much different, 190 HV (Vickers Hardness) for 304 steel and 763 HV for chrome white alloy. The corrosion and synergism weight loss is mainly dominated by the chemical composition of the material and not by its mechanical properties”.

Also [9] posited that “Chemical Mechanical planarization (CMP) process now routinely used to planarize metal as well as dielectric films during the fabrication of integrated circuits. This process uses slurries comprised of fine abrasive particles such as Silica, Ceria or Alumina”. This amounts to rationalization of chemical and mechanical properties of slurry in usage.

In another development, [10] presented “the design and implementation of a new kind of agitator called differential agitator. The Differential agitator is an electro-mechanic set consisting of two shafts. For improving efficiency, parametric study and shape optimization has been carried out”. Such a design so fashioned out to add value to mixing efficiency is a laudable development geared towards mixing integrity.

According to [11], Shea Butter mixer components include:

i. Mixing blades.
ii. Mixing tank.
iii. Gear system.
iv. Diesel engine and burner.

In another development, [12] posited that “Magnetic stirring has advantage over the traditional cylindrical stir bar. The better performance of these novel stirrers compared to the traditional cylindrical stir bar design is not only due to the geometry of the stir but also to the utilization of a magnetic material with a stronger magnetic transmission force (Sm_2Co_{17}) compared to standard ferrite or AlNiCo alloys”. Such new development ideas are radically good for the mixing process industry and as such contributes to some savings in production costs.

Materials characteristics dictates what type of mixer will be most efficient for batch mixing.

Furthermore, [2] posited that in order “to achieve the mixing time and consistency required:

i. Low shear and mid shear mixers are suitable for more free flowing materials.
ii. Mid shear, high shear, impact and particle design mixers are suitable for more cohesive materials.
iii. Free flowing materials tend to have low moisture, low aspect ratio (difference between the particle length and width) and low angle of repose.
iv. Mixing free flowing materials present problem of segregation classified into vibration, percolation and transportation segregation”.

Materials characteristics for selecting appropriate mixer as enumerated above are key factual characteristics that will help to achieve the mixing time and consistency required.

In low shear mixing modes, mixers do mixing process by diffusion or convection. Diffusion mixers tend to be less expensive and easier to maintain than convection mixers. So diffusion mixing is the best option if it works for the material. It is highly educative to note that diffusion mixing is the best option in terms of cost saving and maintenance.

According to [2], the three most common mixer types for low-shear mixing of free-flowing materials are:

i. Conical screw mixers.
ii. Tumble mixers.
iii. Ribbon mixers.

For twin blade planetary mixer, decreasing the blade-blade clearance or increasing the helical angle increases the power consumption of the twin-blade planetary mixer. Types of these mixers include:

i. 3D micro-mixers.
ii. Intermig impellers.
iii. Ekato intermig impellers.

Since the basis of efficient and effective operations is minimization of power consumption, due attention will have to be paid to the blade – blade clearance and helical angle of the planetary mixer.

According to [13], while using Ekato Intermig impellers, at low stirring rates, micro mixing performance was found to be independent of agitation speed.

Furthermore [14] deposed that “among the agitators, Rushton turbine, 45^0 pitch-blade turbine, Mixel TT and Twisted Twisted Propeller (TTP propellers), the TTP propeller was the most efficient in liquid phase mixing. The images of the TTP propeller, Mixel TT and the Rushton turbine are as shown in Fig. 1 and 2 respectively. The Rushton turbine (or Rushton Disc turbine) is a radial flow impeller used for many mixing applications in process engineering. The Rushton turbine was invented by John Harry Rushton with a design based on a flat disk with vertical flat blades vertically mounted. The TT propeller’s design allows a high mixing efficiency. The TT Propeller therefore finds applications in homogenization, blending of liquids/miscible liquids, suspending solids and heat transfer”.

Fig. 1. Mixel TTP Propeller

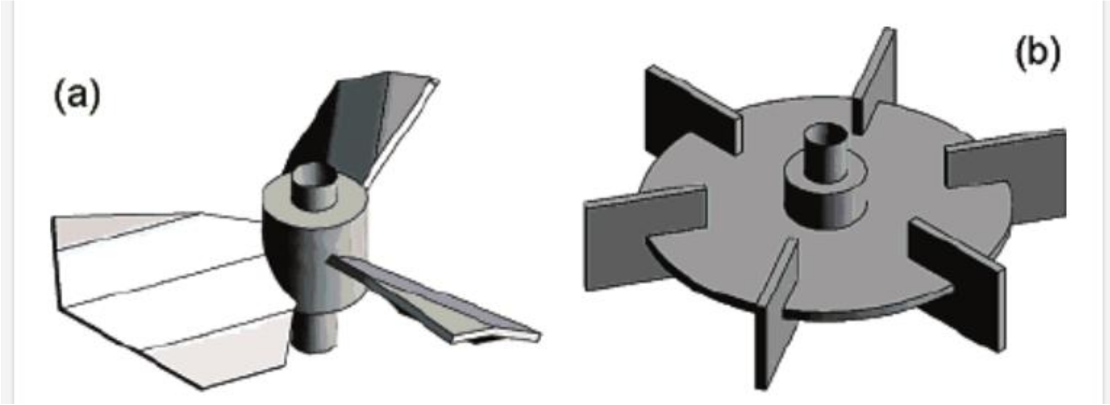


Fig. 2. Impellers; a) Mixel TT; b) Rushton Turbine

According to [15], for mixing of liquids:

i. Time periodicity leaves unmixed islands – symmetries may prevent mixing.
ii. Lessons from 2D can be extended to 3D flows – new design suggested.
iii. Steady flows are poor mixers – a secondary baffle can improve mixing.
iv. Faster mixing – more energy – does not imply more mixing.

Mixing of solids:

i. Non-mixing regions have causes – more energy – does not imply more mixing.
ii. Symmetry impedes mixing - new design suggested.
iii. Steady flows are poor mixers.

It implies that time periodicity and steady flow mixing conditions must be avoided through modifications in order to achieve the desired mixing quality and time.

In another development, [16] deposed that enhancing global mixing in a stirred tank, using unsteady stirring approaches include:

i. Co-reverse periodic rotation.
ii. Time-periodic fluctuation of rotational speed.

The application of co – reverse periodic rotation and time periodic fluctuation of rotational speed in enhancing global mixing in a stirred tank is a welcome development that appear to have revolutionized the mixing process industry.

Also [16] posited that quantitative methods to compare mixing performance under unsteady stirring include: The relational complete de-colorization time with Re and with mean energy dissipation per unit volumetric weight. The identification of the colorization time with Re and energy dissipation per unit volumetric weight as indicators for comparative mixing performance is a welcome development that will ensure qualitative mixing processes.

Consequently, [16] summarized their findings as follows:

i. That mixing time can be significantly reduced in stirred tanks when unsteady stirring approaches are used.
ii. That for the method of co-reverse periodic rotation, only when Re is larger than a critical value, can significant enhancement in mixing be obtained.
iii. For the case of time periodic RPM, fluctuations such a critical value is not easy to define.
iv. That the higher the frequency of periodic co-reverse rotation and the larger of time-periodic fluctuation, the shorter is the mixing time.
v. That in both cases, after Re becomes larger than a certain value, further increases in Re yields relatively small returns.
vi. The agitator used is a non-standard helical ribbon impeller fitted with an anchor at the bottom

The findings by [17] are:

i. That the use of time-dependent rotational speed during the mixing process allows energy savings.
ii. For the unsteady stirring approaches tested, energy savings can reach up to 60% compared to the energy required to obtain the same mixing time with constant impeller rotational speed.

Among four types of mixers investigated by [18] for the Newtonian and Shear-thinning fluids:

1. Rectangular blade.
2. One Z-blade.
3. Two Z-blades and
4. Three rotating pins.

The two Z-blade mixer was considered the best in terms of mixing effectiveness. The identification of the Two Z blade mixer as the best in effectiveness is highly informative and points the way to progressive success in quest for better mixing procedures. The images of the mixer types by [18] are depicted in Fig. 3 and 4.

In a similar development, [19] posited that flow pattern and power number in a vessel depend on the:

i. Impeller blade angle.
ii. Number of blades.
iii. Blade width.
iv. Blade twist.
v. Blade thickness.
vi. Pumping direction.
vii. Interaction of flow with the vessel wall.

Also [20] opined that “the effectiveness of mixing depends on:

i. The state of mixed phases.
ii. Temperatures.
iii. Viscosity and density of liquids.
iv. Mutual solubility of mixed fluids.
v. Type of stirrer.
vi. And what is the most critical property, the shape of the impeller”.

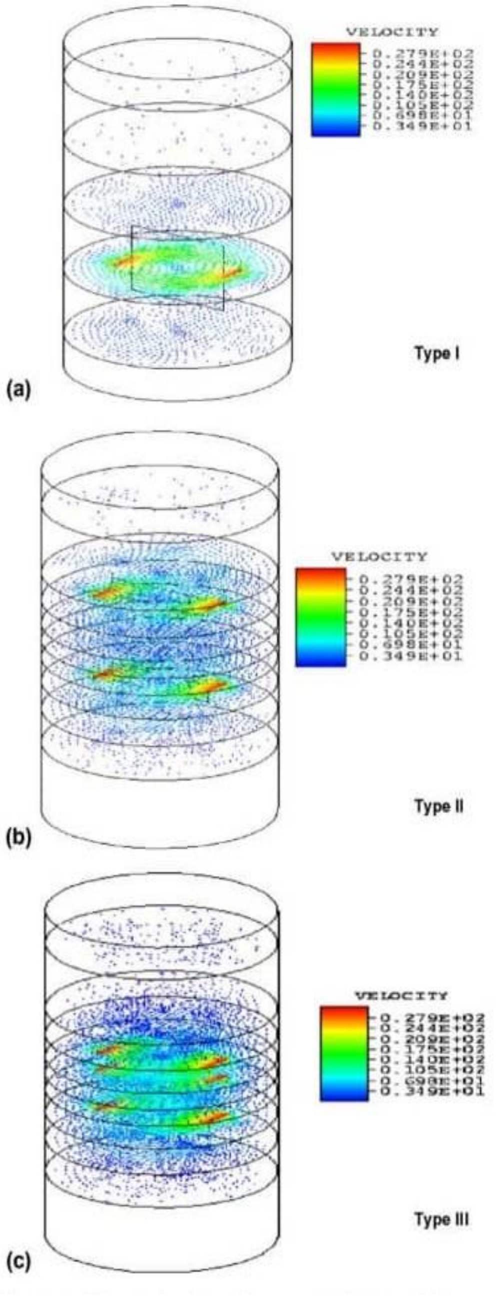
The above opinion is absolutely correct as all the parametric indicators are considered to achieve quality mixing.

Furthermore, [21] said that “it is important to consider a balance between the equipment and ingredient properties in order to obtain an effective size of (foods) production without using a large quantity of time and energy consumption”. This is very true as implied in materials and energy balance for plant engineering. According to [21], “in the food industry, hygienic design and suitability of cleaning are very important issues to consider because of the consequences that could result from a poor hygienic standard e.g. the contamination of the product by microbial growth”. This is very accurate and in line world best practice in quality assurance and reliability. For the mixing of fluids, some of the most important equipment, items used are:

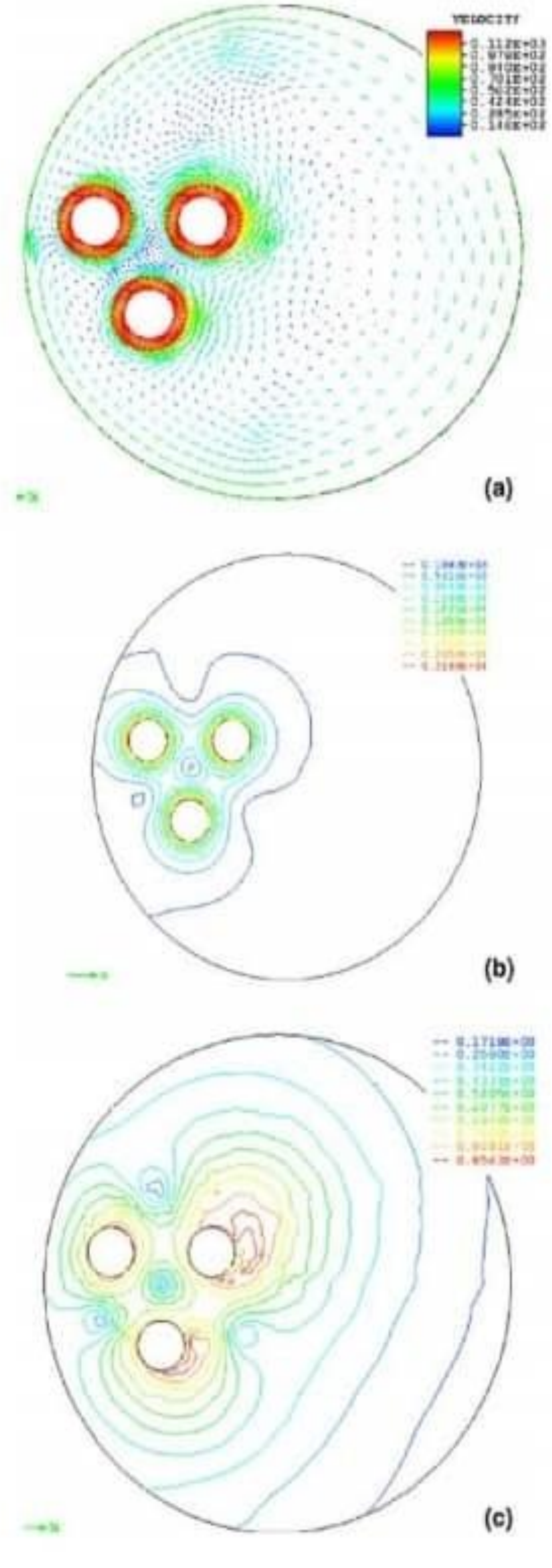
i. The paddle mixer.
ii. Anchor mixers.
iii. Turbine mixers (different impellers).
iv. Propeller mixers.
v. And the new generation of static mixers.

In another development, [22] investigated “two special techniques (high-speed slurry mixing and external re-vibration) in a research program designed to measure their effectiveness in increasing the compressive strength of high-strength concrete in the range of 10,000 to 12,000psi (70 to 84 MPa). Re-vibration was found to produce significant strength increase at all water -cement ratios tested and at all test ages. The high-speed slurry mixing technique employed in this program did not produce strength increases”.

In a similar vein; [23] presented “the rheological behaviour of three types of coal-water slurry in the presence of a dispersant Saponin isolated from the fruit of *Sapindous Mukorossi*. The critical micelle concentration of the saponin was 0.016 and 0.007 g/cc through aqueous extraction and chemical extraction processes, respectively. The rheological characteristics of slurry were measured in the function of coal loadings, pH, saponin concentration, and temperature. The zeta potential of the slurry without additive was found to be 120 mV which exhibited a decreasing trend with the adoption of additives. The static stability of the slurry could be maintained up to a maximum period of 30 days”.



Type i – Mixer with one Rectangular Blade
Type ii – Mixer with one Z Shape Blade
Type iii – Mixer with two Z Shape Blades
Fig. 3. Mixers Source [18]



Type iv. Mixer with three Rotating Pins
Fig. 4. Mixers Source: [18]

According to [24], “paint mixing is conventionally done in a mixing machine with fixed container and a rotating blade. This method generates a vortex type action where in the particles of paint either move towards the periphery of container and tend to stick to walls of container; that is stirrer of conventional mixer rotates in one direction only which create a particular flow pattern hence particles tend to stick to the wall of container due to centrifugal force or keep rotating in a regular pattern of generator of cone resulting in a poor quality mixture”. Accordingly, [24] investigated the limitations of the conventional mixer and that developed by the Schatz geometry theory. And [24] observed that “the exceptional efficiency of the Schatz geometry shaker-mixer arises from the use of rotation, translation and inversion”. According to [24], “mixers based on the Schatz geometric theory have the capability to mix wet and dry components or different wet components in which production process is hygienic and dust-free; making the Schatz geometry easy to clean. It is design, development, and analysis of driving system of Schatz mechanism with 3D-motion mixer to produce desired motion pattern, increase mixing rate and quality”. The findings of [24] appear to throw more light on the developmental contributions to the mixing process industry by the Schatz geometry theory.

Also [25] proposed “a new twisted 3D micro-fluidic mixer fabricated by a laser writing/micro-fabrication technique. Effective and efficient mixing using the twisted micro-mixers can be obtained by combining two general chaotic mixing mechanisms: splitting/recombining and chaotic advection. The lamination of mixer units provides the splitting and recombination mechanism when the quadrant of circles is arranged in a two-layered serial arrangement of mixing units”. “The overall 3D path of the micro-channel introduces the advection. An experimental investigation using chemical solutions revealed that these novel 3D passive micro-fluidic mixers were stable and could be operated at a wide range of flow rates. This micro-mixer finds application in the manipulation of tiny volumes of liquids that are crucial in diagnostics. The mixing performance was evaluated by dye visualization, and using a pH test that determined the chemical reaction of the solutions. A comparison of the tornado-mixer with this twisted micro-mixer was made to evaluate the efficiency of mixing. The efficiency of mixing was calculated within the channel by acquiring intensities using Image J software. Results suggested that efficient mixing can be obtained when more than 3 units were consecutively placed. The geometry of the device, which has a length of 30 mm, enables the device to be integrated with micro total analysis systems and other lab-on-chip devices”. From the foregoing, it appears the work of [25] has added much value to the body of knowledge on mixing process.

Also [26] reported “the investigation of the effect of multiple intermig impeller configuration on hydrodynamic and mixing performance in a stirred tank, using computational fluid dynamic (CFD)”. Furthermore, [26] posited that “by rotating the intermig impeller by 45^0 with respect to its neighbours instead of a 90^0 rotation as recommended by manufacturers enabled a wider range of operating conditions. Also, that by slightly decreasing the distance between the lower two impellers, fluid exchange between the impellers is ensured down to Re =27”.

In similar vein, “a study of the mixing performance of different impeller designs in stirred vessels using Computational Fluid Dynamics has been reported by” [27]. In this work, [27] reported “the outcome of investigation of turbulent flow fields using a baffled vessel stirred by counter-axial flow impeller in comparison to the Rushton turbine. The resultant turbulence was numerically predicted using computational fluid dynamics (CFD). The authors concluded that the counter-axial flow impeller could provide better turbulence characteristics that would improve the quality of mixing systems”.

Similarly, [28] posited that “isolated mixing regions (IMRs) are fluid regions that may or may not have interior mixing and are usually located far away from boundaries and that they do not exchange material with regions of active global mixing and they therefore present a substantial obstacle to global mixing”. According to [28], “islands in two dimensions and tubes and tori in three dimensions are examples of IMRs”. Results of [28]’s investigations indicated that “it is possible to manipulate the area of IMRs in a controlled fashion, hence creating an analogue of a controlled release capsule within a chaotic flow”.

Also [29] proposed and did “experimental investigation of mixing performance of a very unique method to insert an object into a vessel agitated by an impeller. The objects inserted move so as to destroy the isolated mixing regions above and below the impeller, which are usually observed for vessels stirred by ordinary small impellers under steady mixing conditions. Findings indicate that proposed method has a significant enhancement of mixing efficiency at low Reynolds numbers".

Similarly, [30] presented "the analysis of changes of dye concentration during chaotic mixing over the processing time for different diameters of holes within balls and for variable concentration of Rokrysol WFI. The mixing process has been accurately analyzed during the release of dye via the holes in the ball according to the framework. "The colour and concentration in the mixer became stable after specific times. The final time is the time after which the solution of malachite green and polycrylamide Rokryol WFI has been completely released from the disturbing element". Findings of [30] were:

i. That the fastest mixing occurred for the balls with 3mm holes for solution of 2000 ppm and 3000 ppm. The longest time was obtained for the ball with 1mm holes.
ii. Almost the same mixing times have been obtained for solutions of 2000 ppm and 3000 ppm.
iii. That in general, mixing time decreases with increase of hole diameter.

In another development, [31] posited that "while the chaotic degree could be efficiently increased by the temporal terms such as co-reverse periodic rotational impeller speed and time-periodic fluctuation of rotational impeller, speed, the approach is never the less limited in practical applications because of the restriction of the motor and the speed reducer machine". Hence, [31] measured "the mixing times and power consumptions for several different spatial chaotic mixing methods, such as an off-centre impeller, inclined impeller and inserting an object in identical agitated vessels agitated by the same impeller, and the comparison of mixing performances among these methods". Consequent on the foregoing, [31] found that "the inserting of an object is the best method among the spatial chaotic mixing methods to achieve a short mixing time at low power consumption".

Also [32] studied "the effect of impeller modification in addition to eccentricity. Quantitative measurements such as percentage of uncovered area and coefficient of variance (COV) of a tracer solution distributed inside the vessel were obtained using planar laser-induced fluorescence (PLIF) method. Increased eccentricity was found to be more effective than increasing RPM alone in reducing isolated mixing regions size (determined by percentage of uncovered area). The dual flow pitched blade turbine (DF-PBT), which was the modified version of a standard pitched blade turbine (PBT) was designed to provide both upward and downward flow at the same time to induce more chaotic flow. Though numerical analysis showed this type of flow generated, DF-PBT did not return lower values for the percentage of uncovered area and COV than PBT did".

Furthermore, [33] investigated the motion of particles and air flow in static mixer with six different blade geometries using numerical simulation based on a couple DEM-FEM model. The six blade patterns were:

i. Four180^0 twisted blades (TTTT).
ii. Four 90^0elliptical blades (EEEE).
iii. Four combined geometries of two twisted blades and two elliptical blades TETE, ETET, TEET and ETTE were chosen for the investigation of their mixing performance.

where,

TETE = Twisted, Elliptical, Twisted and Elliptical blades.
ETET = Elliptical, Twisted, Elliptical and Twisted blades.
TEET = Twisted, Elliptical, Elliptical and Twisted blades.
ETTE = Elliptical, Twisted, Twisted and Elliptical blades.
TTTT = Twisted, Twisted, Twisted and Twisted.
EEEE = Elliptical, Elliptical, Elliptical and Elliptical.

The quality of mixing performance was determined by the trajectory of suspended particles through the static mixer and magnitude of the pressure drop along the flow path. According to [33,] "the air velocity and the pressure field were calculated by the FEM method. Newton's laws of motion were used to solve the interaction of particle and particle and the interaction of particle and mixer wall. At the bottom of static mixer, particle positions were used to estimate the quality of the mixing process by using the relative standard deviation". Based on the results obtained by [33], "they posited that the mixing quality was significantly higher and the pressure drop was incontrovertibly lower for TTTT than other designs”. Then [33] concluded that “the TEET geometry contributed the best quality of the mixing and significantly reduced the cost of the mixing process”. Also the identification of the TEET geometry as the best quality mixing among the group considered is also quite informative and goes a long way in improvement /enhancement of mixing processes. The images of mixer blades considered by [33] are depicted in Fig. 5 and 6.

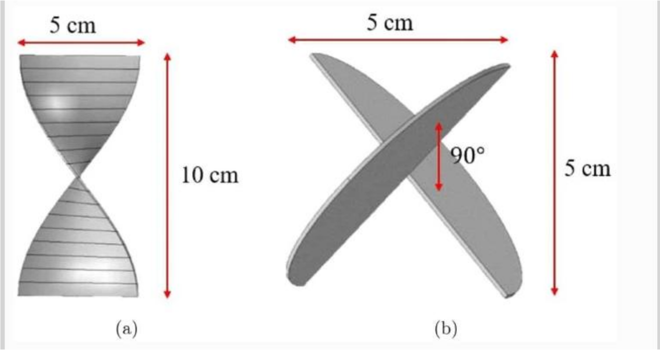
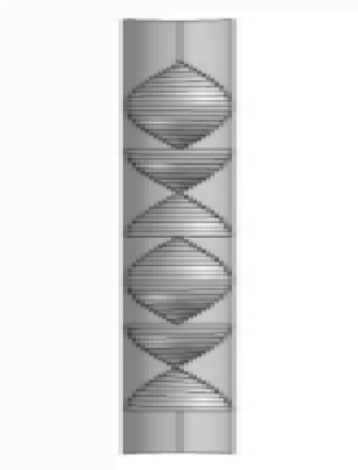
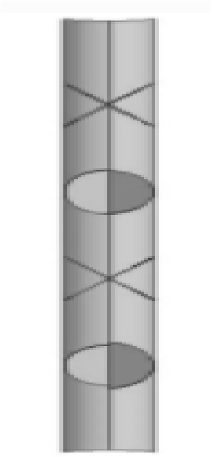


Fig. 5 Blade Geometry; Source: [33]
a) Twisted Blade; b) Elliptical Blade



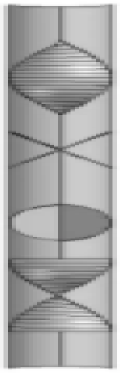
a) TTTT Blade
Fig. 2.6a. Static Blade Geometry; Source: [33]



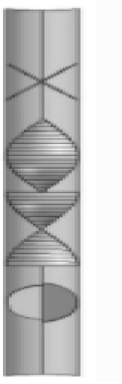
b) ETET Blade.
Fig. 2.6b. Static Blade Geometry; Source: [33]

c) TETE Blade
Fig. 2.6c. Static Blade Geometry; Source: [33]

d) ETET Blade
Fig. 2.6d. Static Blade Geometry; Source: [33]



e) TETT



f) ETTT
Fig. 2.6e and f: Static Blade Geometry; Source: [33]

In another development, [34] posited that the role of baffles in mechanically stirred tanks was to promote the stability of power drawn by the impeller and to avoid the fluid swirling, thus enhancing mixing. Hence [34] numerically investigated the baffles effects in a vessel stirred by a Rushton turbine. The geometric factor of interest was the baffle inclination which was varying between 25^0, 32.5^0, 45^0, 70^0 and 90^0 at different impeller rotational direction had also been varied. The vortex size and power consumption were evaluated for each geometrical configuration. It was found that the best configuration was the baffle inclination by α = 70^0 at a negative angular velocity.

Similarly, [35] did a CFD characterization of the hydrodynamics of the maxblend impeller with experimental validation with viscous Newtonian and non-Newtonian inelastic fluids. The mixing cases investigated were the non-baffled configuration with Newtonian and shear-thinning fluids, and the baffled configuration with only Newtonian fluids. The focus of [35] was on the effect of the Reynolds number on the power characteristics, the distribution of shear rates and the overall flow conditions in the vessel. Consequently, [35] found that:

i. The bottom clearance played a significant role on the power consumption.
ii. The value of the Reynolds number and the power law index strongly affected the axial pumping efficiency and the shear rate profile.
iii. The best performance was obtained when the impeller Reynolds number was superior to 10.

Furthermore, [36] investigated “the hydrodynamic characteristics of the maxblend impeller. A commercial CFD package (CFX 12.0) was used to solve the 3D hydrodynamics and to characterize the flow patterns at every point. A shear thinning fluid with yield stress was modelled in the laminar regime and transition regime. The study focused on the effect of fluid rheology, agitator speed, impeller clearance from the tank bottom and blade size on the fluid flow and power consumption. Predictions have been compared with literature data and a satisfactory agreement has been found”.

Also [37] investigated “the relationship between the flow pattern and blending. The flow patterns generated by around 40 axial flow impellers were examined. The impellers differed in blade angle, blade twist, blade width, impeller diameter, impeller location and pumping direction. The mean flow and turbulence characteristics generated by all of the impellers have been measured using Laser Doppler Velocimetry (LDV). It has been shown that the dimensionless mixing time (θ) varied inversely with the secondary flow number of the impeller. Comparison of the impellers on the basis of equal power consumption per unit mass has shown that $\theta_{max} \infty N_p^{1/3} \frac{T^{2/3}}{N_{QS}}$. According to [37] the present CFD model has shown the possibility of reducing the eddy diffusivity to about 20% of the actual value and still achieving the same mixing time. This reduction in eddy viscosity represents substantial savings in operating costs”.

Furthermore, [38] reported “outcome of a study aimed to determine the flow pattern and mixing time as a function of impeller diameter, impeller rotation speed and number of impeller blades. The single phase system with water as working fluid inside the stirred tank was modelled using the combination of multiple reference frame (MRF) and k-E turbulence model and calculated using the computational fluid dynamics (CFD) method. The size of stirred tank was 0.4M and 0.6M for diameter and height respectively. The agitated tank was equipped with 45^0 inclined blade turbine impeller. Four different impellers in diameter and number of blades have been elucidated under various operating condition of impeller rotation speed from 100 rpm to 400 rpm”.

According to [38], “the simulation results showed that the flow pattern formed was single –loop circulation and vortex, depended on stirred tank configuration and operating conditions. Also, there were variations in flow patterns change over time for each simulation. This also affected mixing performance in terms of mixing time to achieve homogenous mixture”.

Also [39] numerically investigated “the performance of a coaxial mixer in the laminar-transitional flow regime with Newtonian and non-Newtonian fluids. These mixers comprised of two shafts: a central fast speed shaft mounted with an open turbine and a slow speed shaft fitted with a wall scraping anchor arm. To model the complex hydrodynamics inside the vessel, the virtual finite element method (Poly 3D software) coupled with a Lagrange multiple approach to cope with the non-linearity coming from the rheological model was employed. Co-rotation and counter-rotation mode were compared based on several numerical criteria, namely, mixing time, power consumption and pumping rate. It was found that co-rotating mode was more efficient than counter-rotating mode in terms of energy, pumping rate and homogenization time".

In the same vein, [40] investigated "the effects of the central impeller speed, anchor impeller speed, operation mode and the speed ratio of an anchor-scaba coaxial impeller on its power consumption, mixing time and flow pattern using electrical resistance tomography (ERT) and computational fluid dynamics (CFD). An ERT system with a five-plane assembly of peripheral sensing rings, each containing 16 stainless steel electrodes was utilized to measure the mixing time for the coaxial mixer". Hence [40] posited that "the CFD results for power consumption were compared to the experimental data. The mixing times were correlated using the specific power consumption model".

Similarly, [41] studied "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. Digital image processing was conducted to analyze the mixing efficiency of mixing paddle in co-rotating and counter rotating modes. It was found that the double – shaft mixing paddle undergoing planetary motion would not produce the isolated mixing regions in the laminar flow mixing system, and its mixing efficiency in counter-rotating modes was higher than in co-rotating modes, especially at low rotating speeds".

Consequently, [41] deduced "from the Tracer Trajectory of the experiment that the path line of the tracer in the flow field in co-rotating modes was distributed in the opposite direction to the path line in counter-rotating modes. Planetary motion of mixing paddle had stretching, shearing and folding effects on the trajectory of the tracer". Hence [41] further posited that "by means of computational fluid dynamics simulation, it was found that axial flows and tangential flows produced in co-rotating and counter-rotating modes have similar flow velocity but opposite flow directions. It was deduced from the distribution rule of axial flow, radial flow and tangential flow in the flow field that axial flow is the main reason for causing different co-rotating and counter-rotating modes". The findings of [41] are very informative and extremely useful to the mixing process industry. This principle of planetary and counter – rotating modes have found applications in many industrial and domestic mixers.

Also [42] posited that "the three-blade planetary mixer is one of the important solid propellant mixing equipment. That the layout of blades will affect the blades torque load and the power consumption". Hence [42] investigated "the effects of the eccentric distance (Es = 0 – 16mm), the solid blade form (two paddles), and the blade arrangement (linear arrangement, triangle arrangement) on the blades' torque load during the mixer stirring the solid propellant process". According to [42], the definition of the modified power number N_{pm} and the modified Reynolds number R_{em} are:

$$P = T\omega \tag{7}$$

$$N_{pm} = \frac{P}{\rho u_{ch}^3 d_G^2} = \frac{2\pi NT}{\rho u_{ch}^2 d_G^2} \tag{8}$$

$$K_p = N_{pm} R_m \tag{9}$$

where,

d_G= diameter of the gyrational motion (m).
P = Power (Watts).
N = rotational speed of blade (rev/min).
T = Torque (NM).
ω = the rotational speed of blade (rad/s).

The comparison between the numerical and experimental results: the mechanical efficiency of the planetary mixer was 0.45, the value of proportionality constant K_p of experimental results was 48.6 while the K_p of numerical results was 49.4. The error was 1.65%, which may be attributed to the difference between the experimental device and numerical model. Hence [42] concluded that:

i. The maximum value of the instantaneous torque load of the hollow blade was 2.52 times more than that of the solid blade, and the period T of blades' instantaneous torque load changing curves equals to the rotating period of the hollow blade.
ii. Changing the E affected the kneading action between the hollow blade 2 and the mixing vessel, which in turn affected blade's instantaneous torque load. The kneading action played an important role in the blade's torque load.

iii. Increasing the paddles of the solid blade increased the change frequency of the torque load curves and increasing the kneading action led to the increment of the blade’s torque load.

Also, [43] researched into Computer Simulation of Optimization Models for the Determination of Optimal Power Requirements for Liquid-Solute mixer During Mixing Action. According to [43], power required to drive the mixer assembly for n number of mixing rods is expressed as in Equation (10).

$$P = nM_A\omega_D \qquad (10)$$

where,

M_A is the restoring moment resulting from the interaction of all the external forces on the drive shaft-mixing rod acting at the base of the mixing rod (NM)..

P = Power required to drive the mixer (Watt).
ω_D = the rotational speed of the drive (rad/s).

According to [43], the VISIMIX Software was applied. Results showed that the optimum power to drive the mixer assembly increased as the clearance space (space between the tip of the rods and drum wall) decreased. The findings of [43] appear to support that of [19] pertaining to clearance between mixer blade (rod) and mixer container.

Also [44] studied “extensively the influence of stirrer blade design on the dispersion of reinforcement particles in the Aluminum metal matrix through experiments and also simulated them using Computational Fluid Dynamics (CFD) method. The microstructure and mechanical properties of the produced metal matrix composites (MMCs) was studied. The analysis of the microstructure was performed using an optical microscope to visualize the reinforcement distribution and binding within the matrix. Further the MMCs were also characterized by Field Emission Scanning Electron Microscope (FESEM) and X-ray Diffraction (XRD)”.

According to [44], “the method of Archimedes was used to assess the experimental density and the theoretical density was determined using the mixture law to determine the percentage of porosity in the MMCs. Hardness, compression and tensile testing were performed on the produced samples. A three-dimensional computational method was used to predict the flow field of Aluminum melt and study the influence of the blade design on the distribution of the reinforcement”. Experimental results validated the CFD recommendation on the blade design. The CFD recommendation was based on the structure, power number and the number of blades and accordingly, the four-blade flat stirrer (B4) design was the best. Hence [44] deposed that the experimental results also corroborated the CFD recommendation with the four-blade flat stirrer design achieving the highest compressive strength (642 MPa), highest hardness (45 HRB), and highest tensile strength (206 MPa) among the five different blade designs investigated.

3. KEY LITERATURE REVIEW SUMMARY

While using Ekato Intermig impellers, at low stirring rates, micro mixing performance is independent of agitation speed. Among the agitators, Rushton turbine, 45^0 pitch-blade turbine, Mixel TT and TTP propellers, the TTP propeller is the most efficient in liquid phase mixing.

Among four types of mixers investigated for the Newtonian and shear-thinning fluids, i) Rectangular blade, ii) one Z-blade, iii) two Z-blades and iv) three rotating pins, the two Z-blades mixer was considered the best in terms of mixing effectiveness.

That among the six blade patterns i) four 180^0 twisted blade (TTTT), ii) four 90^0 elliptical blades (EEEE), iii) four combined geometries of two twisted blades and two elliptical blades TETE, ETET, TEET, and ETTE; the TEET geometry contributed the best quality of the mixing and can significantly reduce the cost of the mixing process.

From the foregoing, the two Z-blade mixer and the TEET geometry blade mixer have not been compared for efficiency and effectiveness. This comparison need to be done to establish the better of the two mixer types. Hence, there will be need to do a comparative test of the two Z-blade and TEET geometry blade for efficiency and effectiveness.

Also, the TTP Propeller blade has not been compared with the two Z-blade or the TEET geometry blade for efficiency and effectiveness. These gaps therefore constitute the identified Research Gaps. These identified gaps are displayed on Table 1.

4. RESEARCH GAP

Table 1. Research Gaps

S/No	Authors	Work Done	Results	Gaps
1.	Houcine et al. (2000) [14].	Effects of the stirred tank's design on power consumption and mixing time in liquid phase.	Among the agitators: i. Rushton turbine, ii. 45^0 pitch-blade turbine, iii. Mixel TT turbine and iv. TTP propellers, The TTP propeller is the most efficient in liquid phase mixing.	TTP Propeller not compared with TEET or Two Z-blade.
2.	Bunkluarb et al. (2019) [33].	Numerical Simulation of Granular Mixing in Static Mixers with Different Geometries	Among the six blade patterns: i. Four 180^0 twisted blade (TTTT). ii. Four 90^0 elliptical blades (EEEE). iii. Four combined geometries of two twisted blades and two elliptical blades TETE, ETET, TEET and ETTE. The TEET geometry contributed the best quality of the mixing and can significantly reduce the cost of the mixing process.	TEET blade not compared with TTP propeller or two Z-blade.
3..	Yu and Gunasekaran (2005) [18].	Performance Evaluation of Different Model of Mixers by Numerical Simulation	Among four types of mixers investigated for the Newtonian and shear-thinning fluids: i. Rectangular blade ii. One Z-blade iii. Two Z-blade and iv. Three rotating pins. The two Z-blade mixer was considered the best in terms of mixing effectiveness	Two Z-blade not compared with TTP propeller or TEET blade

5. DISCUSSION

From the Research Gap Table, TTP Propeller, the TEET and the Two Z blade stirrer arms have been identified as having excellent performances over other considered stirrer arms. These outcomes are very useful for the mixing /stirring operations of the various industries. It will be imperative to do further comparative performance investigations on these three types of stirrer arms, namely: TTP Propeller, TEET and Two Z blade stirrer arms. In order to setup a comparative platform for these stirrer arms, there will be the need to:

i. Model and fabricate the stirrer arms.
ii. Do a conversion from static to rotary form for the TEET stirrer arm.
iii. Test run the stirrer arms with selected slurry.
iv. Use the Chi Square (Equation 4) to correlate the Theoretical (Expected) and the Empirical (Observed) data for each type of stirrer arm.
v. Do the ranking of the stirrer arms using the Order of Merit Analysis (See Equation 6).

The ranking outcome will indicate the order of call to bar (deployment) of the stirrer arms. This information will give optimal and beneficial advantages to the slurry mixing/stirring industry, hence improved economic slurry mixing/stirring operations.

6. CONCLUSION

A thorough literature review of Slurries (types and applications, stirrer arms and designs and mixing processes has been done. The TTP Propeller, TEET and Two Z blade stirrer arms have been identified as most efficient by three groups of researchers respectively. The outcome of these researchers' works has uplifted the slurries mixing technology in industry. But further work/investigation will be necessary to establish the order of Merit of calling these stirrer arms (TTP, TEET and Two Z blade) to bar. The outcome of these further investigations will constitute contribution to the body of knowledge.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/88104