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A new geometrical model for mixing of highly viscous fluids by combining two-blade and helical screw agitators

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Mixing processes are becoming today a huge concern for industrialists in various domains like the pharmaceutical production, oil refining, food industry and manufacture of cosmetic products especially when the processes are related to the mixing of highly viscous products. So the choice of a stirring system for this category of products or fluids must be rigorously examined before use because of the flows which are laminar in the most cases, something that is not good to obtain homogeneous particles or suspensions after the mixing operation. This CFD study allows developing a new geometrical model of mechanical agitator with high performance for mixing of highly viscous fluids. It consists of a combination of two bladed and helical screw agitators. The investigations of the flow structure generated in the vessel are made by using the computer code ANSYS CFX (version 13.0), which allows us to realize and test the effectiveness of the new stirrer on the resulting mixture and power consumption.

Keywords: CFD; helical agitator; highly viscous fluid; stirred tank; two blade agitator.

INTRODUCTION

Mechanical agitation is a complicated industrial process which aims to get a homogenous mixture from heterogeneous elements or masses. It marked its presence in a wide variety of fields like the chemical processes, petrochemical industry, food production, pharmaceutical and medical processing.

In this paper, we are interested for mixing of fluids with high viscosity, which have becoming a serious problem for the industrials. For this, we thought to develop a new impeller design aiming to have superiority in mixing characteristics.

So the studied system is a cylindrical tank with a flat bottom, containing a highly viscous fluid stirred by a two-blade agitator alone, and then we use a two-blade coupled with helical screw impeller. Each blade of the screw is inserted symmetrically on the flat blade of the two-blade impeller. The geometrical conception is realized by the ICEM CFD 13.0 code. Meshing of all parts of the geometry is generated by using tetrahedral elements with refining mesh on the proximity of the impeller and the tank walls. The number of mesh elements is about 745.689 elements.

Figure 1 gives the geometrical presentation of the agitation system used as reference; it is therefore a two-blade of diameter (d), placed at a height (c) from the bottom of a cylindrical vessel of height (H) in order to not scrape the flat bottom of the tank.

First, the reference geometry of two-blade is realized identically with literature works of (Bertrand et al.[1] and Bouzit et al.[2]), Then, we have processed to the geometrical changes in this impeller by insert of a helical screws on both sides of each blade (Fig. 2). Details of the geometrical characteristics are given in Table 1.

After that, it seems that it is necessary to make a comparative study of the helical forms location on the blade to control our agitator efficiency. Before beginning the computational study, the state of the art in this research area is necessary.

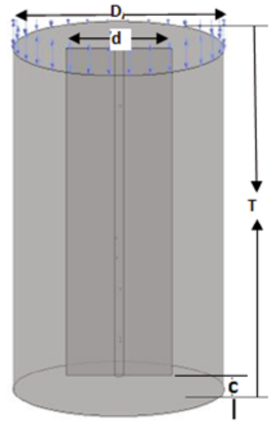

Figure 1. Reference geometry

In an experiment work of granular mixing by helical ribbon blade blender, Simons et al.[3] have found that the fill height and the blade speed rotation are the main factors influencing the mixture homogenization. Gijon-arreortùa and Tecante[4]. have studied the mixing time and the power consumption of horizontal helical double ribbon impeller. They found that the lowest

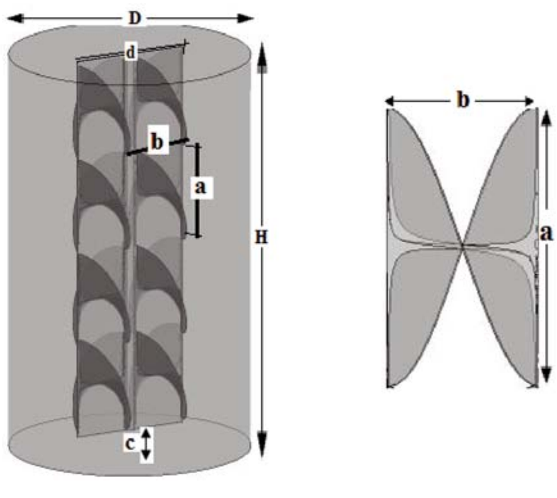

Figure 2. The new geometric model

Table 1. Characteristics of the agitator in [mm]

D	*H*	*d*	*a*	*b*	*c*
300	500	150	120.05	72	0.062
	$H = 1.66D$	$d = D/2$	$a = (H–c)/4$	$b = d/2$	$c/d = 4.13 \cdot 10^{-4}$

mixing time and the highest mixing coefficient rate are obtained for an impeller with 75 rpm and a load ratio of 0.33. Recently, Ameur[5]. found in a comparison between four agitators for mixing highly viscous fluids that the Maxblend is a very effective agitator giving a good mixture quality and reduced power consumption. By a CFD study, Ameur[6]. reported that the classical anchor is not already adequate for mixing yield stress fluids. He proposed a new geometry with horizontal and vertical blades to expand the cavern size and reduce the power consumption. Ameur et al.[7] confirmed that the power required for mixing shear thinning fluids by a helical screw agitator is inversely proportional to the blade pitch because of the increase of the contact area between the impeller blade and the fluid. With a numerical method, Havlica et al.[8] studied the rotational speed effect on granular flow in a vertical blade mixer and they found that the particles follow the periodic movement of two types: one is the more elevated frequency related to the stirrer movement and the second is a low frequency produced because of the recirculation**.** Ameur and Bouzit[9]. developed a new correlation for predicting the power required for mixing shear thinning fluids by a classical two-blade impeller. By a CFD study, Driss et al.[10] have made a comparison between the flows generated by a screw associated with a double helical ribbon, and a double helical ribbon agitator only. Their results show that the velocity fields are much more active for screw with double helical ribbons. They showed that the power number *Np* is inversely proportional to *Re* and it is superior for the screw with double ribbons. Ameur et al.[11] compared the performance of single and double helical ribbon impellers for mixing shear thinning fluids. The double helical configuration is found more efficient than the other design, but with an additional energy cost. Galindo et al.[12] studied the effect of the bottom of three different helical ribbon impellers geometries. They did a comparison between mixing in the same direction of clockwise and vice versa. Their results show that mixing processes in the opposite direction of clockwise give the best performance of mixture, the three geometries realized produce a smaller time of mixing compared with other literatures, this reduction is due to the concave design. Rahimi et al.[13] did a comparative study by CFD between a standard helical agitator and another identical with geometrical modification. They studied the effect of several parameters such the axial flow number, the axial circulation time and the power consumption, so the best performances of mixing are those of the modified agitator and the most significant result were also obtained upon variation of the height of the agitator from the bottom tank. With laser Doppler anemometry (LDA), Jahangiri.[14] studied the shear rates of a viscoelastic fluid provided by a helical agitator. Minge et al.[15] used the MRF (Multiple Reference Frames) technique to study the flow generated by double helical ribbon. They developed a new method using the weighted average viscosity area around the agitator as an effective viscosity to calculate the Metzner constant. Bouzit et al.[2] simulated the flow generated by a two blade impeller and showed that the reduction of the blade height has a considerable effect on the increase of axial velocity.

Delaplace et al.[16] have developed an analytical model to predict the power consumption for mixture of shear thinning fluids mixing by a helical ribbon and another helical screw ribbon in laminar flow. Iranshahi et al.[17] compared the viscous characteristics of the mechanical stirrer with an Ekato agitator type, double helical ribbon and an anchor. They showed that the complex flow fields created by the Ekato can give a homogeneous mixing for fluids having a very high viscosity. Otherwise, the analysis of the flow structures show that the double ribbon is most effective, followed by the Ekato agitator and lastly the anchor in the mixture obtained. Anne-Archard et al.[18] made a numerical simulation of the flow generated by a double helical ribbon and an anchor agitator for Bingham fluid and another non Newtonian fluid with yield stress. They showed that the Metzner constant (*A*) depends on the number of Bingham. Angust and Kraume[19]. provided an experiment result of the energy consumed by the process of phase distribution in a stirred agitated tank of solid/liquid. They found that the power number is inversely proportional to the average value of liquid concentration. Deplace et al.[20] developed a kilometric diagnostic method for determining the mixing time of viscous fluid in a transparent tank stirred by a double helical ribbon. Dieulot et al.[21] studied the performance of the blend of a Newtonian highly viscous fluid, into a vessel mechanically agitated by a helical ribbon. They introduced a mixture study approach under non-stationary flow and they found that the use of a time depending to speed velocity during stirring save energy. Also the non-stationary flow in the mixing domain saves energy with a rate of 60%. Yao et al.[22] made a numerical study of local and total dispersion performance of a double helical ribbon and a Maxblend agitator. The obtained results showed that the double helical ribbon has a very low degree of dispersion especially for the large values of *Re* number. Deplace et al.[23] made an experimental and a numerical study of heat transfer of a viscous fluid stirred by a helical ribbon (Paravisc Ekato). They made a comparison between the effective temperature and the temperature of the stirred volume (average) and clearly show that the temperature removed from the rotation speed and engine torque is closer to the average temperature measured on the volume tank. Rai et al.[24] studied the heat transfer from Newtonian and non-Newtonian fluids in a mechanically stirred vessel with a helical ribbon. They showed that the position of the agitator relative to the bottom of the vessel has a significant effect on the Nusselt number. Kaneko et al.[25] analyzed by the discretization of elements methods the particle characteristics of the mixing obtained by a single helical ribbon. They showed that the particles are in upwards flow along the wall, as against it descends along the middle part of the agitator. The revolution of the agitated particles in the center of the agitator causes a concave part on the fluid surface (vortex). They also found that the thickness of the vortex (difference between the height of the hollow area in the center and the wall) generally increases with the agitator speed. Bertrand et al.[26] have numerically studied the mechanical mixing of second orders fluid with helical ribbon. They showed that in the case of second orders fluids, a simple constitutive equation of rheological model, derived from the delayed expansion movement, was able to predict the elevation of mixing power when the level of elasticity increases $P = P_{(Newtonian)} \cdot (1+\mathrm{Ke\ We})$, where We: is the Weissenberg number. Espinosa-Solares et al.[27] studied the power consumption during the mixing process of a Newtonian fluid and a shear thinning fluid by coupling of a Rushton turbine and a helical ribbon. They found that the power number for the composite (coupling) geometry is not the same of those two agitators. This is explained by taking account of the radial discharge flow for the Rushton turbine and the flow mode from top to bottom of the helical ribbon. They showed that for non-Newtonian fluids and for a giving number of *Re* the power consumption decreases with increasing of shear thinning rheological behavior. Brito De La Fuente et al.[28] confirmed the power consumption relationship ($Np = Kp \cdot Re^{-1}$) by studding of the strong shear thinning behavior effect, and the geometry of the screw associated with a helical ribbon in laminar flow. They also demonstrate that the power consumption is highly dependent on the width of the helical agitator. Tanguy et al.[29] have used a helical ribbon composed by a Rushton turbine and a helical agitator mounted on the same axis and rotating with two different speeds. They noted that the Rushton turbine effect on the dispersion coefficient is remarkable, without it, the particles tend to aggregate following the own pumping up and down the helical ribbon. They showed also that the intense flow generated by the Rushton turbine changing the flow structure in the lower portion of the helical ribbon and increase the macro-mixing in the tank volume.

THEORICAL ASPECT AND BOUNDARY CONDITIONS

We are interested in the present work to the hydrodynamic part of engineering to develop our geometric model of agitator for the highly viscous fluids. We assumed that the flow is fully periodic. The using fluid is assumed to be incompressible for an isothermal process with *Re* values less than 50 (laminar flow). The equations conducting the flow in this process are:

$$\rho\ [V\ grad\ V + \ \omega(\omega r) + 2\omega r] + grad\ P\text{-}div\ (2\eta\ (\dot{\gamma})\ \dot{\gamma}] = 0 \quad (1)$$

$$div\ V = 0 \quad (2)$$

The free surface is considerate to be flat and horizontal. The boundary conditions are imposed as follow:

– at the vessel wall and bottom $V = wr$;
– at the free surface $Vz = 0$,
– on the impeller $V = 0$.

To make the dimensionless problem, we used as reference variables, the radius of vessel ($D/2$), the linear velocity of the tank (πND) and the density of the fluid (ϱ).

The power consumption is controlled by the following equations:

$$P = \eta \int Q_v dv \quad (3)$$

$$dv = r\ dr\ d\theta\ dz \quad (4)$$

$$Q_v = 2\tau_{rr}^2 + 2\tau_{\theta\theta}^2 + 2\tau_{zz}^2 + \tau_{rz}^2 + \tau_{r\theta}^2 + \tau_{z\theta}^2 \quad (5)$$

$$\tau_{rr} = -\eta 2 \frac{\partial V_r}{\partial r} \quad (6)$$

$$\tau_{r\theta} = -\eta \left[r \frac{\partial \left(\frac{V_\theta}{r} \right)}{\partial r} + \frac{1}{r} \frac{\partial V_r}{\partial \theta} \right] \quad (7)$$

$$\tau_{rz} = -\eta \left[\frac{\partial V_r}{\partial z} + \frac{\partial V_z}{\partial r} \right] \quad (8)$$

The power number is calculated in this numerical study by:

$$N_P = \frac{P}{\rho N^3 D5} \quad (9)$$

For a Newtonian fluid in the laminar flow, the power consumption is controlled by the relationship:

$$N_p\ Re = A \quad (10)$$

This relationship can be written also as:

$$P = A\eta N^2 D^3 \quad (11)$$

RESULTS AND DISCUSSIONS

In order to give some reliability to our work, we have seen necessary to validate and compare it with other scientific works. For this, we are proceeding to realize a similar geometry as that undertaken by Bertrand et al.[29] (experimental) and Bouzit et all.[14] (numerical). It is a two blade agitator with the same geometric characteristic represented in Figure 1.

Figure 3 shows the variation of the tangential component of the velocity for a value of ($Re = 10$). The maximum value of the tangential velocity is located at the impeller tip. It is remarked that the velocity curves of our work and those of Bertrand et al.[29] have the same profile. The difference between the curves is mainly due to the thickness of the blade (sheet) of the impeller made by Bertrand et al.[29] and which is slightly thick for our model.

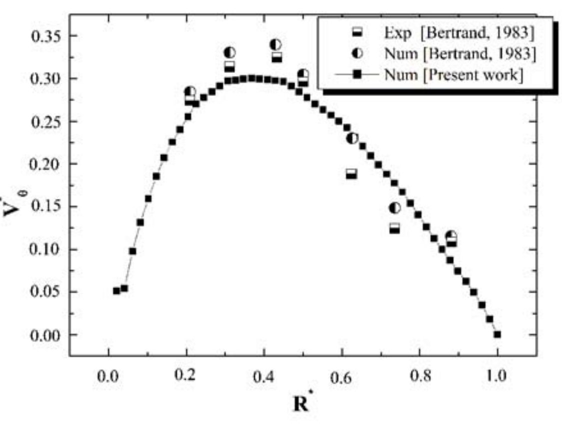

Figure 3. Validation of experimental results

The graphics of Figure 4 shows the precision order of our work compared to the numerical work of Bouzit et al.[14]. The maximum values of the radial velocity are obtained at the tip of the blades for the angular position (θ = 15°), while the speed is reduced to zero in the vicinity of the wall of the tank. It can be noted also that the radial velocity is negative close the surface of the impeller.

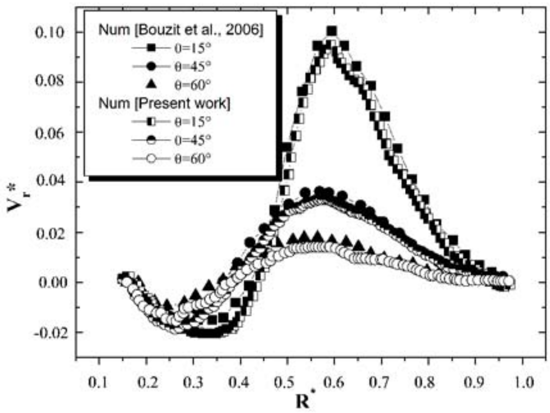

Figure 4. Validation of numerical results

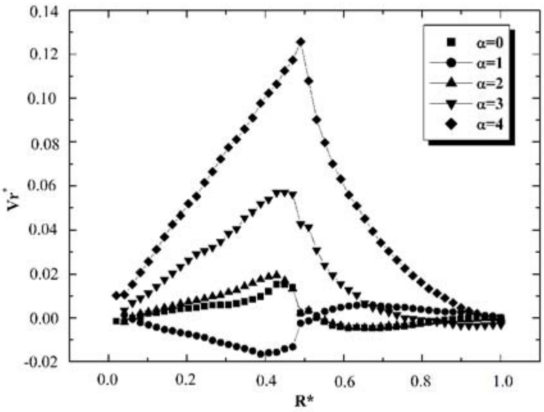

Figure 5. Radial component of velocity (Z^* = 0.2, Re = 10, θ = 0°)

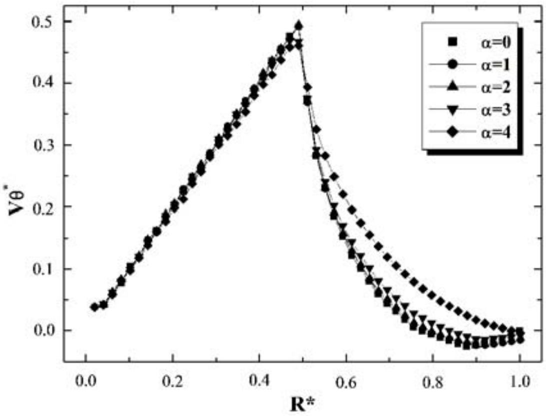

Figure 6. Tangential component of velocity (Re = 10, θ = 0°)

First part: energetic and hydrodynamic comparison between geometries

Effect of the helical forms with two blades on the flow generated

In the industrial processes of stirring highly viscous fluids, a wide range of mixers is used to obtain a good mixture such as two blade and helical agitators.

The idea of making a stirrer which regroups the two agitators was birth intended to intensify the radial and tangential flow. It is in good clearance by the two components of the velocity curves (Figs. 5–6), where the maximum values of the velocity components are obtained by the coupling agitators (two blade + helical screw). We can say here that the velocity is in proportional relation with the screw number α.

By analysis of Figure 7, it is remarkable that the cave of the agitated medium has expended because of the radial flow generated in the tank by the helical forms.

Effect of the helical number on the flow

By visual analysis of flow fields generated by coupling agitators (two blade + helical), it is remarkable also that the flow generated around the new agitator is more intensified compared to the two blade used alone. Increasing the number of the helical elements will intensify the radial flow and increase the size of the mixing region.

Otherwise, the appearance of fluid recirculation zone (vortex) is considered as favorable for the mixing processes. Their sizes, positions and their number must be strictly controlled.

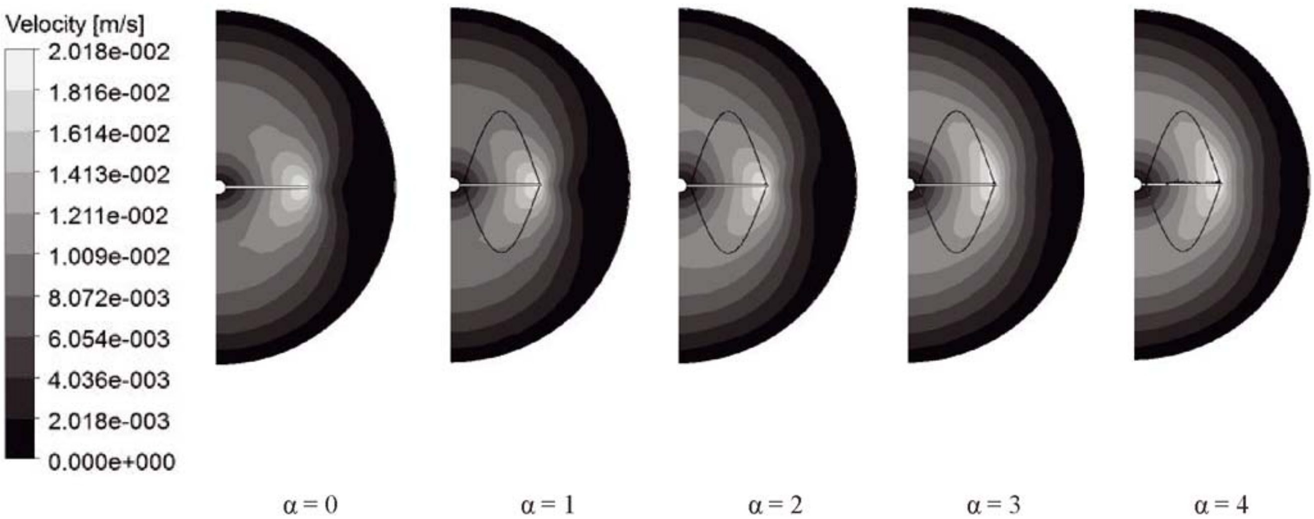

Figure 7. Velocity contour for the using geometries (Re = 20, Z^* = 0.625)

From Figure 8, the vortices are generated for the first two configurations. However, for the other geometrical configurations, these recirculation loops are gradually disappeared because of the good geometric distribution of the helical forms (screws) on the two-blade agitator. In other words, the continuity of the chain of helical screw and their predominant component flow (radial flow) minimize the vortices size. This is due to the counter flow regenerated by the wall which have become increasingly at the same wavelength with the flow generated by the stiller[6].

The obtained results of the power consumption for the geometric models having one screw, two screws, three screws and four screws, demonstrate the dissipated power excess by the system, and respectively estimated at 8.3%, 14.1%, 17.4% and 23.5%.

The geometrical model with three helical screws consumes an over power of 17% compared to the two-blade agitator. But on the other hand, this power supply has a positively impact on the mixing process where the cavern is striking expanded, and the vortices are eliminated especially for high value of *Re* in laminar flow.

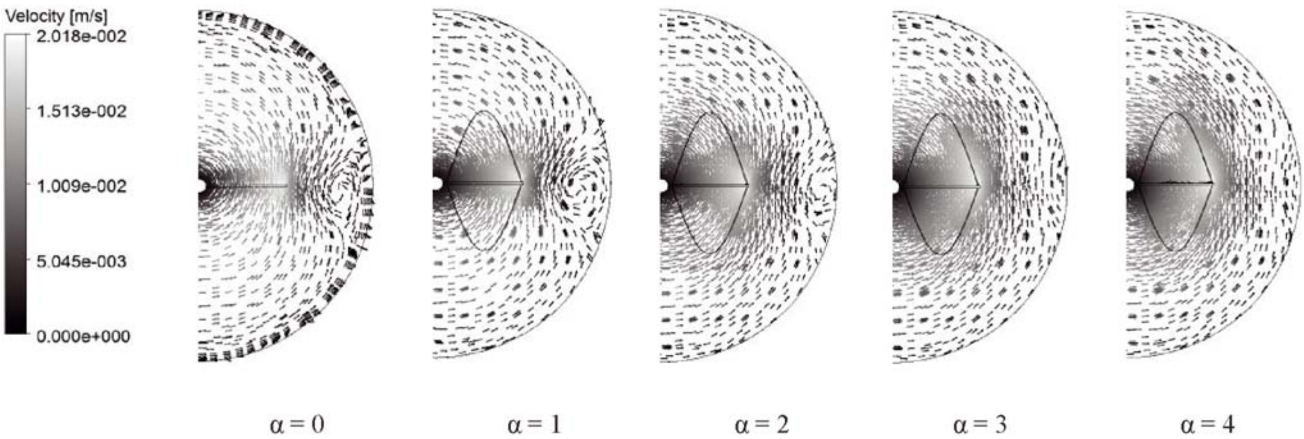

Figure 8. Velocity vectors for the using geometries (Re = 20, Z^* = 0.5)

Effect of the helical positions on the blades

The 3rd geometrical configuration having 3 screw helical elements proves a wide mixing region with an asset flow in proximity of the agitator. Otherwise this geometry represents a transitional case between all tested geometries, fact of the matter is that the vortices are concealed to better justify the effectiveness of this geometry, an energy study seems necessary.

The power consumption

After the previous geometric study, the power consumption of the agitators was calculated to obtain an optimal geometrical model. So the power consumption is proportional to the increase of the helical screw number (Fig. 9). This proportional relationship is mainly due to the increase of the contact area between the fluid and the screw.

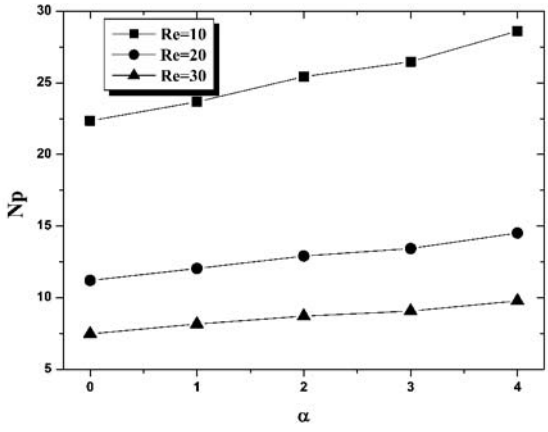

Figure 9. Power number for all geometric models

The flow fields generated from this geometric model (with 3 screws), with the fields of against flow back regenerated by the wall are much harmonized in terms of wavelength. For this reason, the vortices are eliminated.

Otherwise, the intense fluid flow caused by the helical profiles has an amplifying effect on the velocity fields produced by the back-flow of wall; a phenomenon wish remains practically low for the simple two-bladed impeller.

Reynolds number effect on the power consumption

The study of mixing of the high viscous fluids has become a concern for all industrial researchers, that the flow generated by the stirring system is laminar, while a calculated turbulence has a positive effect on the mixing of heterogeneous particles. The power consumption is studied on a range of *Re* (from 0.1 to 30) where the flow is laminar[7]. So it is quite clear that for the low values of *Re*, the energy consumed by the agitator is highly heavy because of the viscous dissipation, this value decreases with the decreasing of the viscous dissipation practically and in the most cases of the mixing operations of the non-Newtonian fluids (shear thinning fluids), the Re number has a very important effect on the decreasing of the viscosity values because of the heat generated at the time of the contact between molecules[22].

Second part: adjustment of the best model

After the study of the first part, we were able to develop an efficient model of a two-blade impeller coupled with three helical screws (α = 3), and it has argued by several geometric and hydrodynamic advantages.

In what follows, we will make a comparative study in order to adjust and justify our model efficiency. For this, three geometries of our coupling mixers are realized and simulated by the ANSYS CFX 13.0 code (Fig. 10), the

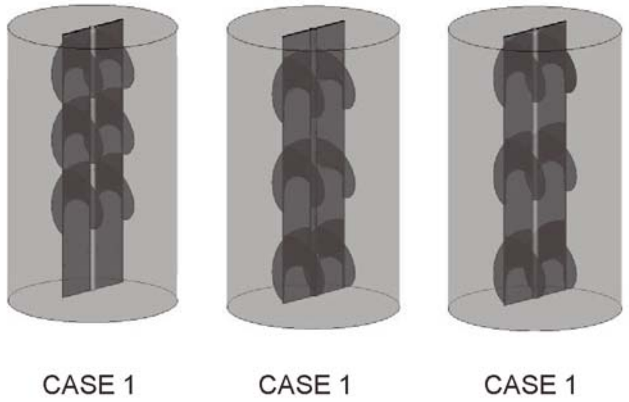

Figure 10. The geometries with α = 3

dimensions of the tank agitator assembly are presented in the (Table 2).The space distance between the helical screws is also showed in the Figure 11.

Table 2. Geometrical parameters of the new agitators

Geometric parameters	CASES		
	1	2	3
H / D	1.66	1.66	1.66
h_1/D	0	0.12	0
h_2/D	0	0.135	0.2
h_3/D	0.4	0	0
c / D	0.066	0.066	0.066
d / D	0.5	0.5	0.5

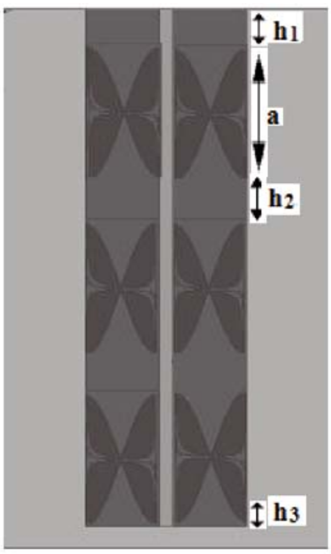

Figure 11. Space distance between screws

By hydrodynamic analysis and for the *Re* values in range of (10–20) where the flow is purely laminar[7], and for a highly viscous fluid stirred in the tank, the first case of geometric model (h_1/D = 0, h_2/D = 0, h_3/D = 0, 4) scrapes the fluid with relatively height velocity compared with the other models.

The maximum values in peak are obtained for this model for both velocity components, Radial and Tangential (Fig. 12).

This magnitude in flow components is mainly due to the good distribution of the helical screws on the two-blades. It has no gap between the screws that consist (h_2 = 0). Otherwise, the forms (shapes) in this later are continuous. It may be noted here that the flow within the vessel is subdivided on two parts, one at the lower part that covers (0.4 *H*) of the fluid height, the flow generated is

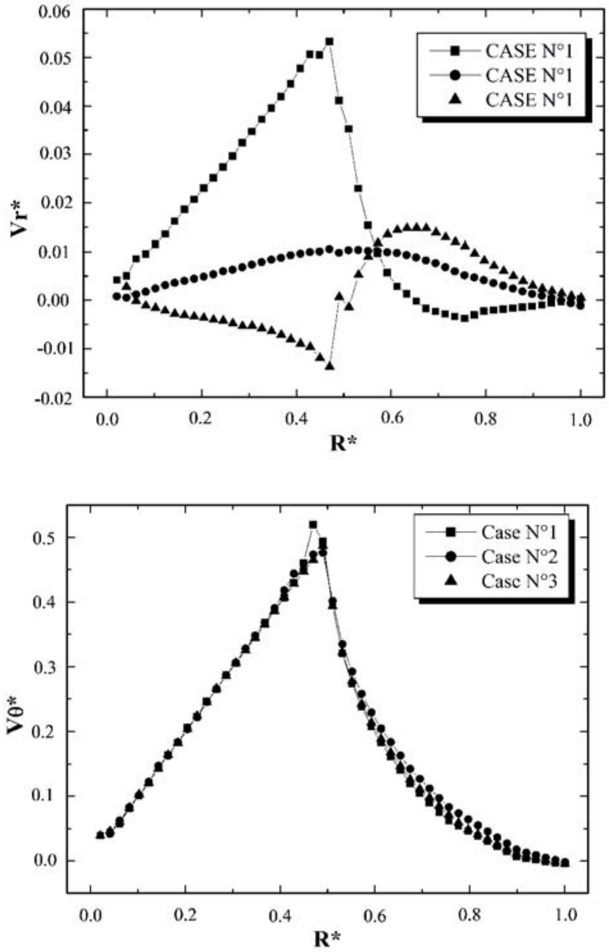

Figure 12. Radial and tangential components of velocity Z^* = 0.5, Re = 20, θ = 0°, α = 3

highly tangential. The second part is the one that is on the top of the tank, its covers (0.6 *H*) of the height of the fluid, its flow is strongly radial[14]. The continuity of the flow of the both part made the agitated medium in a homogeneous state with three directional flow fields.

In other words, the ideal configuration (Fig. 10, CASE 1) in realty and by geometric analysis, it's only an two-blade divided on two part, the first is an helical form and the second represent an two blade surfaces with (h_3/D = 0.4).

This design allows the flow generated by the upper part of the agitator (strongly radial) to get on contact with that generated by the lower part (highly tangential).

This two dimensional flow in fluid interaction, actively contribute to making the lower part of the tank in much accentuated hydrodynamic state, and with very good particle homogeneity (Fig. 13).

In the other two cases, the flow is not the same of the previous case; the fluid training follows an alternating flow. In other words, for the second case, the flows generated following the Z axis are present as follow:

– The upper portion of agitator from ($c+3a+2h_2$) to ($c+3a+2h_2+h_1$), the flow generated is tangential.

– The second portion of agitator from ($c+2a+2h_2$) to ($c+3a+2h_2$), the flow generated is radial.

– The third portion of agitator from ($c+2a+h_2$) to ($c+2a+2h_2$), the flow generated is tangential.

– The fourth portion of agitator from ($c+a+h_2$) to ($c+2a+h_2$), the flow generated is radial.

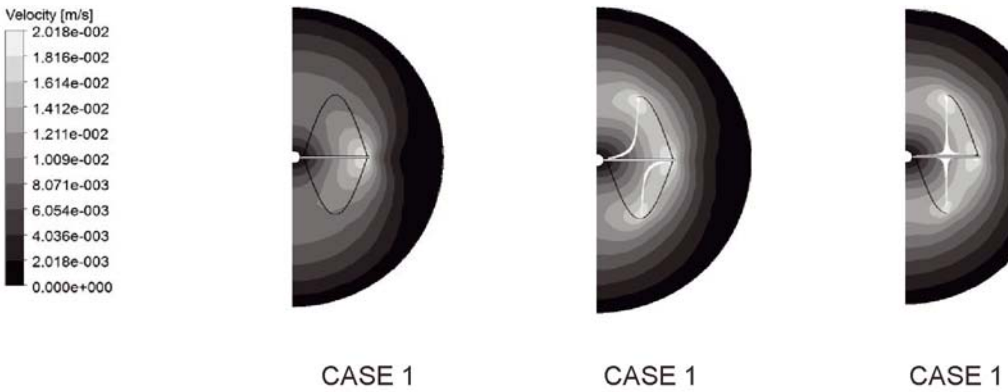

Figure 13. Contours in position $Z^* = 0.5$, $Re = 20$, $\alpha = 3$

– The fifth portion of agitator from (c+a) to (c+a+h_2), the flow generated is tangential.

– The sixth portion of agitator from (c) to (c+a), the flow generated is radial.

The third case is also subdivided on five parts that are presented as follows:

– The upper portion of agitator from (c+2a+2h_2) to (c+3a+2h_2), the flow generated is radial.

– The second portion of agitator from (c+2a+h_2) to (c+2a+2h_2) ,the flow generated is tangential.

– The third portion of agitator from (c+a+h_2) to (c+2a+h_2), the flow generated is radial.

– The fourth portion of agitator from (c+a) to (c+a+h_2), the flow generated is tangential.

– The fifth portion of agitator from (c) to (c+a), the flow generated is radial.

This flow discontinuity is favorable for the energy consumed, but in the other part, it remains unfavorable for the fluid homogeneity (Fig. 13). We explain: the first geometry (CASE 1) generates a radial flow in its upper part; this field descends gradually in the gravity direction[11] under the effect of centrifugal forces until it comes into contact with the tangential flows of the lower part. This interaction between the two different flows (radial+ tangential) ascent because of its bump on the tank bottom, this circulation loop help the mixture to keep an good concentration and a good homogeneity (Fig. 12).

In contrary, the two other configurations (Figure 10, CASES 2 and 3) generate radial and tangential flows that are alternately distributed along the blade. This dispersion helps the mixture to be actively moved but not quite homogeneous, this is clearly shown in the figure of the caves in the tank (Fig. 12).

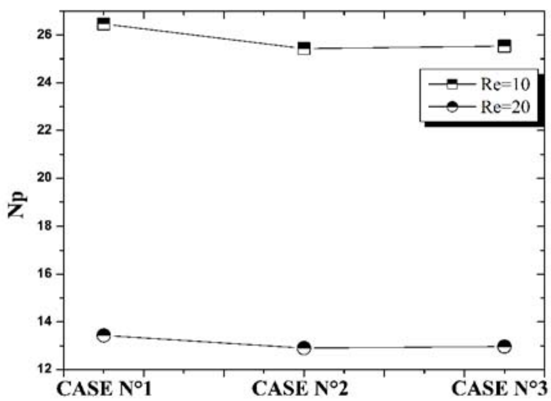

Figure 14. Power consumption for the three cases

In refers to the results obtained in numerical simulations, Table 3 gives the values of *Np* for a purely laminar flow (*Re* = 10–20).

Table 3. *Np* values for the three cases

	Re = 10	*Re* = 20
CASE 1	26.47	13.43
CASE 2	25.42	12.89
CASE 3	25.53	12.96

The geometric model selected above, is a perfect agitator for highly viscous fluid mixing, it is able to make the mixture in a very high degree of homogenous and hydrodynamic with a slight increase on the power consumption.

Figure 14 shows that the other two geometric configurations save more of energy because of their geometric forms. However, its generated flow is not satisfactory for the mixing process.

Finally, from all results, the distribution of three flow generated by the configuration of (Fig. 10, CASE 1), the moderate energetic consumption and the size and the homogeneity of his cave, these are all criteria that can calcify the chosen model, as a powerful agitator for stirring of highly viscous fluids.

CONCLUSION

Mechanical stirring of the highly viscous fluids has become today a huge concern for all industrial, in this work we saw that the mixers association or coupling agitators is a good design that gives promising results for the mixing processes.

First, the helical screw and the two-blade agitators remain always very adequate for mixing of highly viscous fluids. Then, the idea of coupling the two types of mixers was birth for the combination of axial and radial flows generated by both impellers. After that and after all the CFD investigations of this study, we concluded that the combination of three helical screws with the two-blade impeller is the most efficient configuration due to the important size of the cavern and the moderate power consumption.

Finally, the following geometrical parameters (h_1/D, h_2/D, h_3/D, a, b, H/D) are the key parameters influencing the hydrodynamic and the dissipated power of our new geometry.

NOMENCLATURE

Alphabetic symbols

A – Metzner constant, ($Np.Re$)
a – width of screw, (m)
b – pitch of the screw, (m)
c – Impeller off-bottomed clearance, (m)
D – Vessel diameter, (m)
d – two- blade diameter, (m)
H – Vessel height, (m)
h_1 – Space between helical screw and the free surface, (m)
h_2 – Space between helical screws, (m)
h_3 – Space between bottom and helical screw, (m)
r – Radial coordinate, (m)
N – Impeller rotational speed, (1/S)
P – power, (W)
R* – Dimension less radial coordinate, ($R^* = 2r/D$)
Re – Reynolds number (Dimension less), ($\varrho ND^2/\eta$)
Q_v – Viscous dissipation function, ($1/s^2$)
V – Velocity, (m / s)
V* – Dimension less velocity, ($V^* = V/\pi ND$)
v – Volume of the tank, (m^3)
z – Axial coordinate, (m)
Z^* – Dimension less axial coordinate, (z/D)

Greek letters

α – number of screw on the two blade, dimensionless
ϱ – fluid density, ($kg \cdot m^{-3}$)
ω – angular velocity, ($rad \cdot s^{-1}$)
γ – shear rate, (s^{-1})
η – dynamic viscosity, ($kg \cdot m^{-1} \cdot s^{-1}$)
τ – shear stress, (Pa)
θ – Tangential coordinate, (m)

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