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Framework for choosing energy efficient mixing equipment whatever motions it induces: Example of application for planetary and helical ribbon mixers

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ABSTRACT

Energy savings in industrial processes have become one of the main goals of the current society. This paper aims to propose a systematic approach for the assessment of mixing equipment energy performance for highly viscous fluids. The framework is illustrated and applied by performing a rational comparison of the homogenization efficiency of classical mixing systems (involving an agitator revolving around a vertical axis centred in the tank) with that of planetary mixers when mixing highly viscous fluids. For that purpose, the pioneering framework of Zlokarnik is first reminded and its limitations with regard to non-traditional mixing equipment are discussed. Then, the theoretical background to extend this approach to these latter is presented. Experimental data on power consumption and mixing time are provided to demonstrate the applicability of the present frame. The results illustrated that a planetary mixer can be an economic solution for performing highly viscous fluids homogenization.

1. Introduction

In order to keep up with the increasing competition, food and bioproducts companies have to be able to respond quickly to the market, providing better quality products meeting consumer wishes. At the same time and with respect to environmental concerns, the supply chain has to be more cost-effective and attempt to minimize work, and thus, global energy consumption for product processing (Maroulis and Saravacos, 2003; Perl, 2016).

In order to meet these objectives for processes involving homogenization operation in tanks, it is crucial to optimize the design of the agitator or to carefully select the type of mechanical solicitations inducing mixing (combining dual revolution motions of the agitator as planetary mixers (Delaplace et al., 2007; Long et al., 2022, 2021; Tanguy et al., 1999, 1996) or inducing fluctuating external perturbations as a soft elastic reactor (Delaplace et al., 2020; Li et al., 2021, 2019; Xiao et al., 2018, 2018; Zou et al., 2020)).

For complex mixing applications, unconventional mixers are recently taking a big sweep in the process industry,

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Nomenclature

b agitator height, m.
C_b bottom clearance for the SER, m.
D diameter of the turbine of the TRIAXE® mixer, m.
d characteristic length, which corresponds to agitator diameter for agitator performing only one revolution motion around a centred vertical axis in the tank, m.
d_c diameter of the crank, m.
d_s distance perpendicular to the centred vertical revolution axis. This distance corresponds to the orbital of the planetary mixer for the TRIAXE® system and to the agitator diameter for PARAVISC System, m.
d_{sw} distance between the crank shaft and the tank wall, m.
f striking frequency of the beater in the wall, s^{-1}.
h bottom clearance for classical mixing systems, m.
h_1 SER tank height, m.
h_2 SER base height, m.
H liquid height, m.
L rod length, m.
l_l length between the rod pin and the piston pin wall, m.
N rotational speed for agitator performing only one revolution around the centred vertical axis in the tank, s^{-1}.
N_G gyrational speed i.e. rotational speed of mixer around the vertical centred axis, s^{-1}.
N_R rotational speed i.e. rotational speed of mixer around the horizontal axis, s^{-1}.
Np power number.
Np_m modified Power number defined by Eq. (24).
P power, W.
p maximum penetration in the SER, m.
Re Reynolds number for agitator performing only one revolution around the centred vertical axis in the tank, s^{-1}.
Re_c modified Reynolds number for the SER, defined by Eq. (16).
Re_m modified Reynolds number defined by Eq. (26).
Re_p modified Reynolds number for the planetary mixer, defined by Eq. (20).
t_m mixing time obtained for a given degree of homogeneity, s.
$t_{m90\%}$ mixing time when homogeneity degree selected is 90 %, s.
t vessel diameter, m.
u_{ch} maximum tip speed of agitator, m s^{-1}.
$u_{impeller\ tip}$

Greek letters

δ width of ribbon impeller, m.
μ dynamic viscosity, Pa s.
ρ liquid density, kg m^{-3}.
Θ mixing time number for agitator performing only one revolution motion at a rotational speed Naround a centred vertical axis in the tank $\Theta = Nt_m$.
Θ_m modified Mixing time number defined by Eq. (27).
$\Theta_{90\%m}$ modified mixing time number for a degree of homogeneity equal to 90 % $\Theta_{90\%m} = t_{m90\%}{\cdot}u_{ch}/d_s$.

fulfilling consumers' need for sophisticated products with specific functionalities (Eda et al., 2020; Miyazaki et al., 2019). Whereas studies dealing with the use of planetary mixers on concrete (Cazacliu and Legrand, 2008; He and Wang, 2021; Valigi et al., 2016) and powders (Hiseman et al., 2002; Laurent, 2005; Miyazaki et al., 2015; Son, 2019) have been widely reported in the literature, those dealing with highly viscous liquids are less frequent (Auger et al., 2015; Connelly and Valenti-Jordan, 2008; Yamagata et al., 2021; Yi et al., 2008). Consequently, some important questions remain still for this application.

The question raised now is: which mixing equipment is able to achieve the desired degree of homogeneity with the minimum mixing work?

In 1967, Zlokarnik attempted to answer such a question for classical stirring equipment (here the word "classical" refers to impellers rotating around a vertical and central shaft in the tank). He showed that the knowledge of mixing time and power consumption of varying agitators allowed ranking them according to their mixing efficiency and/or to select the mixing system allowing to minimize the energy expense to achieve a given homogenization task (Zlokarnik, 1967). Such a pioneering work provides guidelines to determine the most efficient stirring conditions for economic homogenization with classical mixing systems. Unfortunately, this approach has never been extended to other mixing equipment which have been designed thereafter to overcome some technological difficulties arisen from industrial mixing applications. For example, planetary mixers, compared to classical stirring equipment, guarantee that no cavern zone could form in the container since all the volume of the product is periodically swept out at one moment by the agitator (Auger et al., 2013; Tanguy et al., 1999). Consequently, its characteristics seem better suited when a highly viscous matter requires to be intimately homogenized; as known by the scientific mixing community, high values of viscosity (or an apparent viscosity) prevent flow since then the product is no longer in contact with the rotating tool (Adachi et al., 2004). In this context, the risk of not being able to overcome a heterogeneous composition is reduced. On the other hand, the soft elastic reactor is a more appropriate stirring equipment when compared to the classical ones when corrosive media need to be homogenized (Delaplace et al., 2020; Li et al., 2021). Moreover, avoiding contact between the agitator and the medium prevents any risk to introduce polluting constituents in the processed product. Soft elastic reactors can also be interesting when the medium needs to be sterilized as, frequently, the presence of a vertically centred agitator represents an additional limit for sterilization due to the tank sealing difficulties in the vicinity of the rotating parts. To sum up, the current batch market exhibits today different mixing equipment, such as planetary mixers or soft elastic reactors, for which mixing is based on principles other than those implemented in traditional mixers. Currently, it is unfortunately very difficult to assert if a planetary mixer or soft elastic reactor could be an economic solution to guarantee minimum mixing work (energy consumption) for achieving homogenization in a batch reactor?

The major reason which explains such a lack of knowledge for non-conventional mixers compared to classical mixing equipment is the fact that:

Studies of unconventional mixer performances (namely power consumption and mixing time) such as planetary mixing systems and/or soft elastic reactors are not as frequent as traditional mixing equipment. In reality, some of them have just started to be more systematically investigated in scientific literature.

More importantly, for planetary mixers, only a small number of works appeared during the last twenty years (Andre et al., 2014, 2012; Auger et al., 2015, 2013; Delaplace et al., 2007, 2004; Delaplace et al., 2005a; Jongen, 2000; Landin et al., 1999; Tanguy et al., 1999, 1996; Zhou et al., 2000) providing power and mixing time data, while pioneer studies on soft elastic reactors have only recently emerged (Delaplace et al., 2020, 2018; Xiao et al., 2018)).

Mixing and power characteristics of equipment dealing with the homogenization of highly viscous fluid cannot be easily established; thus, the scientific community is facing a severe obstacle in comparing these systems with the traditional ones due to the fact that the set of dimensionless numbers governing the evolution of mixing and power numbers (corresponding to dimensionless numbers associated respectively to mixing time and power consumption) are not the same for the different the mixing systems (Antsiferov et al., 2018; Liang et al., 2017; Modestov, 2002; Zhou et al., 2000). Above all, different physical parameters have to be considered depending on the mixer type. For example, compared to a traditional mixer, an additional revolution speed due to the dual motion of the agitator has also to be listed to correctly describe the hydrodynamic condition and for the soft elastic reactor, the depth of external deformation has to be taken into account as it is also a lever which can be used to influence the course of the homogenization process.

The objective of this work is to show that it is possible to extend the primary work of Zlokarnik (Zlokarnik, 1967) for ranking different mixing equipment according to their mixing efficiency, and to show that it is possible to set a single frame to compare all types of mixing equipment. To sum up, to provide guidelines in order i) to be able to compare the mixing performance of unconventional mixers with classical mixers on the same plot ii) to select both the mixing system and the range of operating conditions which allow obtaining the degree of homogeneity desired in a given time and with a minimum work demand. In order to illustrate all this, the authors collected experimental data and present an example comparing two different mixing equipment. As the work of Zlokarnik is not largely broadcast; firstly, we will remind his work in the next section.

2. Optimum conditions for the homogenization of liquid mixtures

2.1. *Previous works with classical mixing systems*

Zlokarnik was one of the first authors who cared about the following question: for a given volume of fluid to be homogenized in a lapse of time, which stirrer demands the lowest power consumption and hence uses the minimum mixing work for achieving the homogenization operation?

To answer this question for classical mixing systems and Newtonian fluids, Zlokarnik first listed the relevant physical parameters which influence the power consumption P and the mixing time t_m of a Newtonian fluid being homogenized by an agitator, vertically and centrally placed in a vessel, in the absence of vortex. This analysis led him to establish that the two target variables (P and t_m) are dependent on the following causal variables:

$$P = f_1(t, d, \rho, \mu, h, H, \{\text{system geometry}\}_1, N) \quad (1)$$

$$t_m = f_2(t, d, \rho, \mu, h, H, \{\text{system geometry}\}_1, N) \quad (2)$$

The causal variables in Eqs. (1) and (2) are composed of i) *common* and *specific* geometrical parameters of the mixing system and ii) the density and Newtonian viscosity of the agitated medium, respectively (ρ, μ).

The *common* geometrical parameters are: the agitator diameter *d* (characteristic length perpendicular to the revolution axis); the position of the agitator as regards the bottom of the tank *h*; the tank diameter *t* and the liquid height *H*, which are reported in Fig. 1.

Otherwise, the {system geometry}$_1$ refers to the *specific* geometrical parameters which are required to fully define the shape of the agitator and/or the container; these parameters are not generic to all mixing equipment. For Rushton turbines, it could be for example, the number of blades appearing in the central disk, and the width and height of each blade; while for helical ribbon impeller, specific parameters are more likely to be: the number of ribbons, the pitch or width of the ribbon, etc… as illustrated in Fig. 2. A geometrical parameter could also refer to the dimensions of baffles and their numbers.

Using (t, ρ, μ) as repeated physical variables, Zlokarnik obtained a first set of dimensionless numbers governing the target variables chosen:

$$\pi_1 = \frac{P\,t\,\rho^2}{\mu^3} = F_1\left(\frac{d}{t}, \frac{h}{t}, \frac{H}{t}, \{\text{system geometry}^*\}_1, \frac{\rho\,N\,t^2}{\mu}\right) \quad (3)$$

$$\pi_2 = \frac{t_m\,\mu}{t^2\rho} = F_2\left(\frac{d}{t}, \frac{h}{t}, \frac{H}{t}, \{\text{system geometry}^*\}_1, \frac{\rho\,N\,t^2}{\mu}\right) \quad (4)$$

Note that in Eqs. (3) and (4), {system geometry*}$_1$ refers to the set of dimensionless number which would be obtained by nondimensionalizing {system geometry}$_1$.

Then Zlokarnik re-wrote the two pi-numbers π_1 and π_2 as well-known dimensionless numbers such as the power number, mixing number and Reynolds number (noted respectively as N_p, Θ and Re) which are commonly involved in the characterization of mixing system performances:

$$N_p = \frac{P}{\rho \cdot N^3 \cdot d^5}, \quad (5)$$

$$\Theta = N \cdot t_m \quad (6)$$

$$Re = \frac{\rho N d^2}{\mu} \quad (7)$$

Indeed, it can be shown that:

$$\pi_1 = N_p\,Re^3\,\frac{t}{d} \quad (8)$$

$$\pi_2 = \frac{\Theta}{Re}\left(\frac{t}{d}\right)^{-2} \quad (9)$$

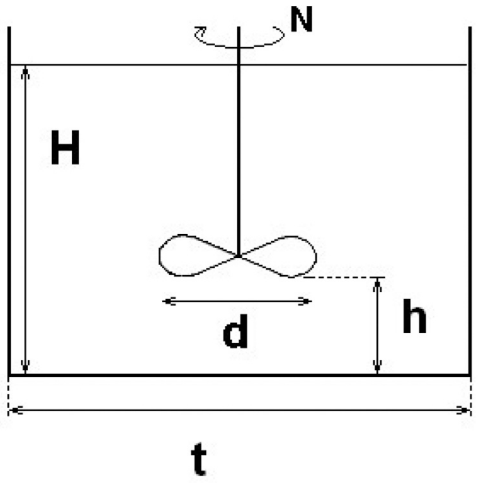

Fig. 1 – : Geometric parameters of a mixing vessel equipped with an impeller vertically and centrally mounted in the tank. Only *common* geometrical parameters defining the generic configuration of a mixing system are reported.

Finally, rearranging the right-hand side of Eqs. (3) and (4), in order that i) the geometrical ratio contains the diameter of the agitator instead of that of the tank; ii) the dimensionless number containing impeller rotational speed looks like the classical agitation Reynolds number, and thus, Eqs. (3) and (4) become:

$$\pi_1 = \frac{Pt\rho^2}{\mu^3} = N_p \,\mathrm{Re}^3 \frac{t}{d} = F_3\left(\frac{t}{d}, \frac{h}{d}, \frac{H}{d}, \{system\ geometry^*\}_1, \mathrm{Re} = \frac{\rho N d^2}{\mu}\right) \quad (10)$$

$$\pi_2 = \frac{t_m \mu}{t^2 \rho} = \frac{\Theta}{\mathrm{Re}}\left(\frac{t}{d}\right)^{-2} = F_4\left(\frac{t}{d}, \frac{h}{d}, \frac{H}{d}, \{system\ geometry^*\}_1, \mathrm{Re} = \frac{\rho N d^2}{\mu}\right) \quad (11)$$

From the analysis of Eqs. (10) and (11), it can be observed that:

the set of dimensionless causal numbers governing the evolution of power consumption dimensionless number (π_1) and mixing time dimensionless number (π_2), in absence of vortex is composed of several geometrical ratios and one internal measure (i.e. Reynolds number) taking account the effect of impeller rotational speed.

for a given mixing system arrangement (i.e. a given agitator, vertically centred in a tank and located at a clearance bottom value for the tank), dimensionless numbers π_1 (containing power) and π_2 (containing mixing time) depend only of Re = $(\rho N d^2)/\mu$. Indeed, for a given mixing arrangement, constant values of $(\frac{t}{d}, \frac{h}{d}, \frac{H}{d}, \{\text{system geometry}^*\}_1)$ are obtained.

Then, Zlokarnik plotted the evolution of π_1 as a function of π_2 for various mixing systems in which both, the mixing curve ($\Theta = N \cdot t_m = F_5(\mathrm{Re})$) and power curve ($N_p = F_6(\mathrm{Re})$), have been previously established by experiments. Fig. 2 illustrates the original worksheet resulting from such representation.

From the analysis of Fig. 2, Zlokarnik established rationally the stirrer types exhibiting the lowest π_1 values within a specific range of the dimensionless number π_2. The basic interest of the worksheet proposed by Zlokarnik, is to visualize the optimum stirrer type and select the stirrer speed for minimizing the mixing work for achieving a homogenization task for a desired mixing time.

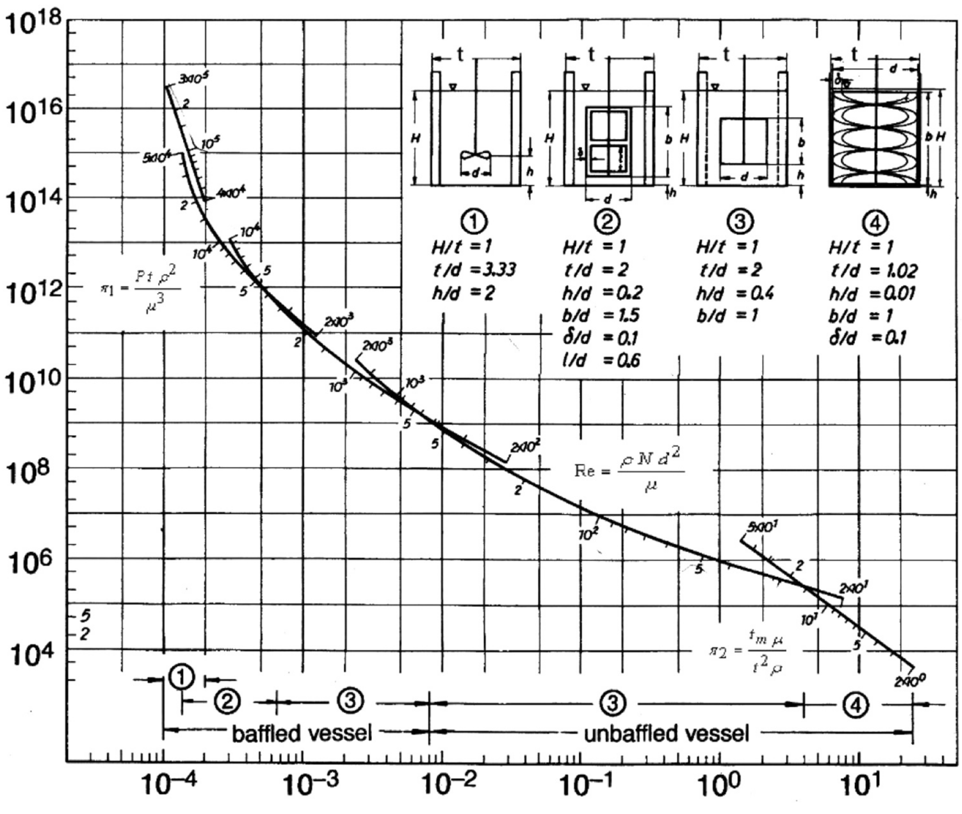

Fig. 2 – : Worksheet for determining the most favourable stirrer type and stirring conditions to obtain the smallest mixing work. This worksheet is used for mixing vessels equipped with an impeller vertically and centrally mounted in the tank. Extracted and adapted from Zlokarnik (2001).

Indeed, when the physical properties of the agitated medium, the diameter of the vessel and the desired mixing time are known, it is very easy to compute the dimensionless number π_2 (using the left-hand side of Eq. (4)). Hence, the numerical values of π_1 can be read off at the intersection of the π_2 value with the curve appearing on the worksheet. The power consumption, P, can be then deduced by knowing π_1 values. Then the following information can be brought out:

-the stirrer type, tank and baffling conditions which have to be used; can be read off from the abscissa. Then, the diameter of the stirrer can be determined from data on the stirrer geometry in the sketch.

-finally, the numerical value of Re can be read off its proper scale at the same intersection. This, in turn, it makes possible to determine the stirrer's rotational speed, which should be selected to reach such optimum mixing efficiency.

It should be clarified that Fig. 2 shows only the stirrers that were investigated by Zlokarnik's group. The mixing and power curves of these classical mixing system were both established without vortex and cover sometimes both laminar and turbulent regimes, as indicate in the Reynolds scale. To be more exhaustive and be able to have a more accurate point of view on which stirrer type is currently the most suitable for achieving a homogenization operation in an efficient way, non-conventional stirrer types must be evaluated and documented according to this frame.

It should be also mentioned that the degree of mixing chosen for the mixing operation can influence this classification diagram. For example, Zlokarnik chose a very high degree of homogeneity (99 %). However, there are certainly many mixing operations for which a much lower degree of mixing would be sufficient. Furthermore, it is also well known that the method used for the determination of mixing times (including the location of injection) may seriously impact the mixing time values and consequently the ranking. For that reason, it is crucial to select a unique method for the determination of mixing time and fixed degree of homogeneity for all the mixing systems evaluated. It is clear that the method proposed by Zlokarnik is useful for ranking classical mixing systems and its interest has not been looked over with the careful attention as it deserved, although some performance characteristic on mixers are continuously produced by different groups, available in the scientific literature and could be used to feed this worksheet.

For example, in 2000, Delaplace et al. had already gathered from literature the power consumption, mixing time (through reporting respectively Np. Re and N.tm values under laminar regime) and geometrical parameters (tank agitator diameter ratio, helical ribbon pitch ratio, ribbon blade width ratio).of more than 100 helical ribbon mixing systems (see Table 1 - in original publication of (Delaplace et al. 2000a)) and even if the method and criterion for determining mixing time are not the same for the whole set of data, a part of them could be used to compare and select the geometrical parameters which provide the most eco-efficient mixers. For example, the data of Rieger et al. 1986 for which a conductivity method was used to obtain mixing times (mixing times was defined as that at which the fluctuation of electrical conductivity is less than 2 %) are well fitted for that, as it can be seen on Fig. 3, where we represented 5 of them using the method presented in this work (Rieger et al. 1986).

Table 1 – Characteristic length and velocity for the different mixing equipment considered.

	L_{ch}	u_{ch}
Traditional mixer	d	$N.\ d$
Planetary mixer (TRIAXE®)	d_s	$\sqrt{[N_R^2 + N_G^2][d_s^2 + D^2]}$ if $N_R{\cdot}d_s/(N_G{\cdot}D) \geq 1$ $(N_R{\cdot}D + N_G{\cdot}d_s)$ if $N_R{\cdot}d_s/(N_G{\cdot}D) < 1$
Soft elastic reactor	d_c	$f.\ d_c$

From Fig. 3, among the helical ribbon mixing equipment plotted, it can be concluded that the most eco-efficient mixing system is that represented by square full symbol which corresponds to a dual helical ribbon mixing system defined by the following geometrical parameters (a tank diameter ratio of 1.06, an helical ribbon pitch ratio equal of 1, a ribbon width ratio of 0.2, a ribbon height ratio, $\frac{b}{d}$ of 1, a liquid height ratio, $\frac{H}{d}$ of 1 and flat bottom tank with a diameter of 0.15 m).

The present article mainly aims at addressing what should be done to compare the efficiency of different mixing systems when they induce different principles of motions to achieve homogeneity (dual revolution motions of the tool for planetary mixer or striking with the hammer outside of a wall for the soft container).

One major difficulty to extend the approach proposed by Zlokarnik to other mixing equipment (namely planetary mixers and the soft elastic reactor) is the fact that the π-spaces governing power and mixing time evolutions for the three types of mixing equipment (classical mixing systems, planetary mixers and the soft elastic reactor) are not similar. Hence, the worksheet proposed by Zlokarnik to compare mixing work should be reconsidered. Before presenting the theoretical background to extend this issue to non-traditional mixer equipment, the state of the art concerning the π-spaces governing the mixing work of planetary mixers and the soft elastic reactor are presented.

2.2. *Set of dimensionless numbers governing mixing work for the soft elastic reactor*

The soft elastic reactor consists of a soft container that can achieve homogenization through vibrations of the tank wall. Vibrations are generated by fluctuating external perturbations arisen from the crank/slider device as represented in Fig. 4.

(Delaplace et al., 2018) have recently performed dimensional analysis for such reactor, highlighting the parameters influencing the mixing time. Rewriting Delaplace et al.'s analysis by using the notations and repeated variables adopted previously by (Zlokarnik, 1967) for mixing times and extending it to power consumption, allows establishing that for a given tank (of diameter t) containing a fixed liquid height, H and a striking beater on the reactor's outside wall at a given position, h:

$$\pi_1 = \frac{Pt\rho^2}{\mu^3} = F_5\left(\frac{t}{d_c}, \frac{h}{d_c}, \frac{H}{d_c}, \{system\ geometry^*\}_2, \frac{\rho f d_c^2}{\mu}, \frac{p}{d_c}\right) \quad (12)$$

$$\pi_2 = \frac{t_m\mu}{t^2\rho} = F_6\left(\frac{t}{d_c}, \frac{h}{d_c}, \frac{H}{d_c}, \{system\ geometry^*\}_2, \frac{\rho f d_c^2}{\mu}, \frac{p}{d_c}\right) \quad (13)$$

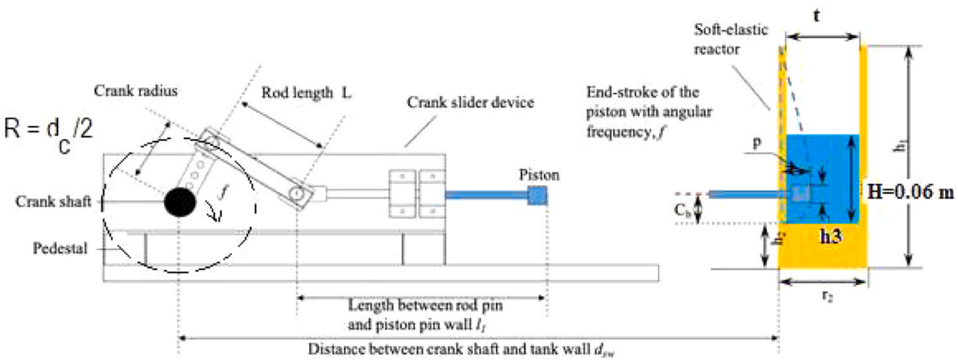

Fig. 3 – Worksheet for determining the most favourable helical ribbon mixing equipment to attain a given mixing time with the smallest mixing work for different geometries. Calculated from data extracted from (Rieger et al. 1986).

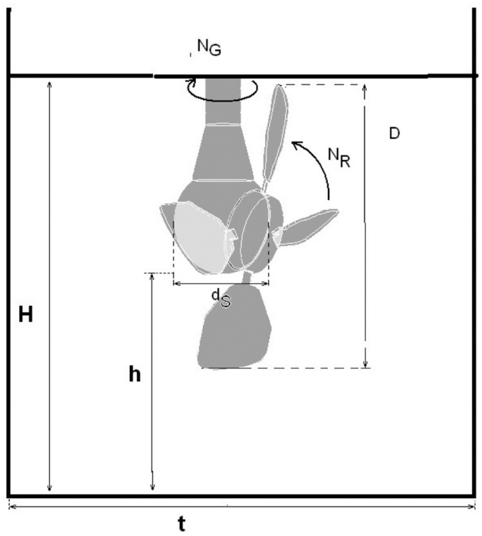

Fig. 4 – Sketch and geometrical parameters of the crank/slider device and the soft elastic reactor (from Delaplace et al., 2018).

In Eqs. (12) and (13), d_c is the diameter of the crank radius while p/d_c is a ratio considering that different maximum penetration depths could be tuned. p represents the maximum penetration depth imposed at the soft elastic wall of the container before being released.

Otherwise, $Re_c = (\rho\ f\ d_c^2)/\mu$ is a kind of Reynolds number using respectively the rotational speed of the crank f and the diameter of the crank d_c as characteristic angular speed and characteristic length. For this mixing equipment, the rotating device inducing mixing (i.e. the crank) is not located in the container but outside and it is supposed that the transmission between the crank and the slider happens without energy loss.

In addition, $\{\text{system geometry}^*\}_2$ contains the ratios which define the geometrical features of the beater (beater width and height) but also the deformation and recovery properties of the soft elastic reactor (elastic modulus and thickness of the wall, thickness) as well as some additional geometrical parameters characterizing the soft elastic reactor behaviour in recovery (tank height h_1, base height h_2, thickness of wall, elastic properties of wall). Of course, the list of geometrical ratios appearing in $\{\text{system geometry}^*\}_2$ for soft elastic reactor are not the same as those in $\{\text{system geometry}^*\}_1$ for classical mixing system.

Finally, by analysing Eqs. (12) and (13), it can be retained that for a given crank/slider device (namely fixed values of $\left(\frac{t}{d_c}, \frac{h}{d_c}, \frac{H}{d_c}, \{\text{system geometry}^*\}_2\right)$ located at a given clearance bottom ratio from the soft elastic container, the power and mixing times variables depend on two expressions: $Re_c = (\rho\ f\ d_c^2)/\mu$ and an internal measure of maximum deformation imposed, p/d_c. Consequently, an additional lever p/d_c exists and the approach proposed by Zlokarnik cannot be extended straight away.

Note that the p/d_c ratio can also be expressed by knowing both, the geometrical parameters of the crank/slider device and the distance from the crank center axis to tank wall:

$$\frac{p}{d_c} = \frac{(d_{SW} - d_c/2 - L - l_1)}{d_c} \tag{14}$$

where d_{SW}, L and l_1 refers respectively to the distance from the crankshaft center to the vertical tank wall, the rod length and the distance from the rod pin to the piston pin as shown in Fig. 4. Therefore, Eqs. (12) and (13) can be rewritten as:

$$\pi_1 = \frac{Pt\rho^2}{\mu^3} = F_7\left(\frac{t}{d_c}, \frac{h}{d_c}, \frac{H}{d_c}, \{\text{system geometry}^*\}_2, \frac{\rho f d_c^2}{\mu}, \frac{(d_{SW})}{d_c}, \frac{(L)}{d_c}, \frac{(l_1)}{d_c}\right) \tag{15}$$

$$\pi_2 = \frac{t_m\mu}{t^2\rho} = F_8\left(\frac{t}{d_c}, \frac{h}{d_c}, \frac{H}{d_c}, \{\text{system geometry}^*\}_2, \frac{\rho f d_c^2}{\mu}, \frac{(d_{SW})}{d_c}, \frac{(L)}{d_c}, \frac{(l_1)}{d_c}\right) \tag{16}$$

It can be observed that $(d_{SW})/d_c$, $(L)/d_c$, $(l_1)/d_c$ are in fact additional geometrical ratios so another expression of Eqs. (15) and (16) can be written as:

$$\pi_1 = \frac{Pt\rho^2}{\mu^3} = F_9\left(\frac{t}{d_c}, \frac{h}{d_c}, \frac{H}{d_c}, \{\text{system geometry}^*\}_3, Re_c = \frac{\rho f d_c^2}{\mu}\right) \tag{17}$$

$$\pi_2 = \frac{t_m\mu}{t^2\rho} = F_{10}\left(\frac{t}{d_c}, \frac{h}{d_c}, \frac{H}{d_c}, \{\text{system geometry}^*\}_3, Re_c = \frac{\rho f d_c^2}{\mu}\right) \tag{18}$$

In Eqs. (17) and (18), $\{\text{system geometry}^*\}_3 = \left\{\{\text{system geometry}^*\}_2, \frac{(d_{SW})}{d_c}, \frac{(L)}{d_c}, \frac{(l_1)}{d_c}\right\}$. It can be observed this time that the π-spaces appearing in (Eqs. (17) and (18)) look like those obtained in (Eqs. (10) and (11)); only the expression of the Reynolds number and the set of geometrical ratios required to define fully the mixing equipment are different.

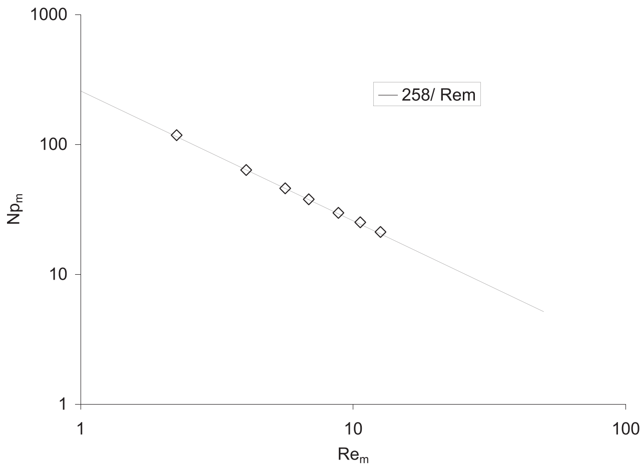

Fig. 5 – Schematic representation of the TRIAXE® system investigated, vertically and centrally mounted in the tank and geometrical parameters of the planetary mixer in the tank.

2.3. *Set of dimensionless numbers governing mixing work for planetary mixers*

Studies done by (Delaplace et al., 2007; Delaplace et al., 2005b) have shown that the set of π-numbers required for building performance characteristics (power and mixing times) of a planetary mixer is enlarged compared to a classical mixer due to the fact that additional physical parameters, shown in Fig. 5, must be added in the relevant list:

-an additional angular speed which corresponds to the second revolution motion allowed to the agitator. For the planetary mixer such as the TRIAXE® system which appears in Fig. 5, this angular speed corresponds to N_R;.

-a characteristic length, defined as the length perpendicular to the additional axis of revolution. For the TRIAXE® system, this characteristic length is the distance D.

Precisely, when no deformation of the free surface occurs, the power and mixing time of such mixing equipment follow Eqs. (12) and (13):

$$\pi_1 = \frac{Pt\rho^2}{\mu^3} = F_{11}\left(\frac{t}{d_s}, \frac{h}{d_s}, \frac{H}{d_s}, \{system\ geometry^*\}_4, \frac{\rho N_G d_s^{\,2}}{\mu}, \frac{N_G}{N_R}\right) \tag{19}$$

$$\pi_2 = \frac{t_m\mu}{t^2\rho} = F_{12}\left(\frac{t}{d_s}, \frac{h}{d_s}, \frac{H}{d_s}, \{system\ geometry^*\}_4, \frac{\rho N_G d_s^{\,2}}{\mu}, \frac{N_G}{N_R}\right) \tag{20}$$

In Eqs. (19) and (20), {system geometry*}$_4$ contains the specific geometrical ratios to define the mixing equipment and from now on D/d_s. Otherwise, $Re_G = (\rho\ N_G d_s^2)/\mu$ is a kind of Reynolds number using the rotational speed N_G and the distance d_s (corresponding to the diameter of the agitator perpendicular to the vertical axis of revolution) as repeated physical variables.

Considering Eqs. (19) and (20), it can be deduced that for a given planetary mixer (namely fixed values of $(\frac{t}{d_s}, \frac{h}{d_s}, \frac{H}{d_s}$, {system geometry*}$_4$), dimensionless numbers π_1 (containing Power) and π_2 (containing mixing times) depend both on $(\rho\ N_G d_s^2)/\mu$ and speed ratio, (N_G/N_R). Consequently, not only a kind of Reynolds number governs mixing work but an additional relation (N_G/N_R) exists and the worksheet proposed by Zlokarnik cannot be directly applied. The π-spaces, appearing in Eqs. (19) and (20), should be reduced in order to compare planetary and classical mixing systems. For such comparison purposes, it is mandatory that the π-space responsible for the evolutions of the mixing time and the power consumption resumes that of the classical mixing systems and depends only on a single type of Reynolds number and geometrical ratios as shown, in Eqs. (10)–(11).

(Delaplace et al., 2007; Delaplace et al., 2005a) have explained and demonstrated that such desired reduction of π-space for planetary mixer homogenizing Newtonian fluids is possible when an analytical expression of a linear velocity, u_{ch} (proportional to maximum impeller tip speed) is introduced in the relevant list of physical quantities, replacing the two individual rotational speeds (N_G and N_R) of the impeller. This method of reducing the number of physical quantities is known as variable fusion and has been previously presented in various works dealing with applied dimensional analysis (Delaplace et al., 2015; Szirtes, 2007).

Consequently, Eqs. (19) and (20) can be rewritten as:

$$\pi_1 = \frac{Pt\rho^2}{\mu^3} = F_{13}\left(\frac{t}{d_s}, \frac{h}{d_s}, \frac{H}{d_s}, \{system\ geometry^*\}_4, Re_p = \frac{\rho u_{ch} d_s}{\mu}\right) \tag{21}$$

$$\pi_2 = \frac{t_m\mu}{t^2\rho} = F_{14}\left(\frac{t}{d_s}, \frac{h}{d_s}, \frac{H}{d_s}, \{system\ geometry^*\}_4, Re_p = \frac{\rho u_{ch} d_s}{\mu}\right) \tag{22}$$

In Eqs. (21) and (22): $Re_p = (\rho\ u_{ch} d_s)/\mu$ represents the Reynolds number for the planetary mixer; where $d_s$is the distance perpendicular to the vertical revolution axis and stands for the orbital of the planetary mixer around a vertical centred axis (Fig. 5); where u_{ch} corresponds to the maximum instantaneous linear velocity of the planetary mixer (m.s^{-1}) divided by π. This division by π is mandatory to guarantee that the u_{ch} value introduced in Eqs. (21) and (22) is consistent with the expression of the characteristic speed interfering in the Reynolds number for classical mixing system.

For the TRIAXE® planetary mixer, the expression of u_{ch} can be analytically computed and it has been shown in our previous work (Delaplace et al., 2005a) that this expression is dependent on the speed ratios $N_R \cdot d_s/(N_G \cdot D)$:

$$u_{ch} = \sqrt{[N_R^2 + N_G^2][d_s^2 + D^2]}\ \text{if} N_R \cdot d_s/(N_G \cdot D) \geq 1 \tag{23}$$

$$u_{ch} = (N_R \cdot D + N_G \cdot d_s)\ \text{if} N_R \cdot d_s/(N_G \cdot D) < 1 \tag{24}$$

2.4. *Analysis of the of π-space governing the mixing work for various mixing equipment*

By comparing Eqs. (10)-(11), (17)-(18), and (21)-(22), it can be observed that the structure of the π-spaces governing power and mixing time evolutions is generic for the three types of mixing equipment (classical mixing system, planetary mixers and soft elastic reactor). As a matter of fact, each π-space represents a set of internal measures of physical quantities which are the tank diameter, bottom clearance of the mixing tool, liquid height in the tank, Newtonian viscosity and specific geometrical ratios of the mixing equipment. Of course, the set of physical quantities (repeated variables) used to make the aforementioned dimensionless parameters is dependent on the studied mixing equipment (classical mixing system, planetary mixers and soft elastic reactor). Consequently, for a given mixing equipment, the geometrical ratios are fixed and the π-space adopts a generic structure. In the next section, we will detail the notations which should be used to extend the worksheet of Zlokarnik to different mixing equipment (namely planetary mixers and soft elastic reactor) allowing us to compare the mixing work of three mixing types of equipment by using a unique plot.

2.5. Extension of Zlokarnik worksheet

Zlokarnik's worksheet required two dimensionless numbers:

$$\pi_1 = \frac{Pt\rho^2}{\mu^3} \text{and} \pi_2 = \frac{t_m\mu}{t^2\rho} \quad (25)$$

The two pi-numbers π_1 and π_2 can be also re-written by introducing the specific power, mixing time and Reynolds numbers of each mixing equipment (respectively noted as N_{p_m}, Θ_m and Re_m).

These 3 dimensionless numbers can be defined in a generic way if a characteristic velocity, u_{ch} and a characteristic length, L_{ch} specific to each mixing equipment and reported in Table 1 are introduced:

$$N_{p_m} = \frac{P}{\rho \cdot u_{ch}{}^3 \cdot L_{ch}{}^2} \quad (26)$$

$$Re_m = \frac{\rho u_{ch} L_{ch}}{\mu} \quad (27)$$

$$\Theta_m = \frac{u_{ch}}{L_{ch}} \cdot t_m \quad (28)$$

As a result, and regardless of the mixing equipment, π_1 and π_2 can be re-written as:

$$\pi_1 = N_{p_m} Re_m^3 \frac{t}{L_{ch}} \quad (29)$$

$$\pi_2 = \frac{\Theta_m}{Re_m} \left(\frac{t}{L_{ch}}\right)^{-2} \quad (30)$$

Consequently, information concerning the mixing times $\Theta_m = f(Re_m)$ and power curves $N_{p_m} = f(Re_m)$ for the different mixing equipment are the only experimental data which are required to establish the plot $\pi_1 = f(\pi_2)$. From this representation, we will be able to select the mixing equipment exhibiting the lowest mixing work for the desired mixing time.

3. Application of the proposed framework to compare two mixing systems for the homogenization of viscous liquids

The selection of the most suitable stirrer type for the homogenization of a liquid mixture, under a particular material and geometric conditions (without density and viscosity differences), can only be performed whether both the same tank volume and similar method for the determination of mixing times are used. Unfortunately, this is rarely the case in the scientific literature. Indeed, homogenization efficiency is rarely established for almost similar volumes of agitated media. Moreover, when the same volume is employed, the mixing times determination method vary. Presently, there is also a lack of studies providing power and mixing curves for non-traditional equipment such as planetary mixers or soft elastic reactors. Consequently, there is currently a limited number of mixers for which the plot π_1 versus π_2 can be obtained.

In the past, (Delaplace et al., 2007; Delaplace et al., 2005b) has brought experimental data dealing with the power and mixing curves when 30 liters of Newtonian fluids are homogenized in laminar regime with a particular planetary mixer. The degree of homogeneity selected for measuring mixing time was 90 %.

Besides, using a similar methodology for the mixing time determination (same place of injection located at the free surface, equal fluid volume and degree of homogeneity and same method used for measuring mixing times), the mixing efficiency of an atypical helical ribbon impeller (PARAVISC) was also studied (Delaplace et al., 2004, 2000b). Details about the PARAVISC geometry and associated data can be found in a previous work (Delaplace et al., 2000a).

Consequently, it is possible to use the π-space (π_1 vs π_2) defined by Eq. (25) to compare the mixing efficiency of these two mixing equipment for homogenizing highly viscous fluids. Both of them are known to be adapted to this mixing task. However, one is a classical mixing system while the other is a planetary mixer.

(Delaplace et al., 2004; Delaplace et al., 2005a) have established that when the tank contained 30 litres of highly viscous Newtonian fluids, the power consumption and mixing time curves for a degree of homogeneity of 90 % can be respectively described for the TRIAXE® planetary mixer under laminar regime ($0.1 < Re_m < 100$) by:

$$N_{p_m} = \frac{343}{Re_m} \quad (31)$$

$$\Theta_{90\%m} = 172 \quad (32)$$

For the same conditions (tank containing 30 litres of highly Newtonian fluids, degree of homogeneity of 90 %, laminar regime ($0.1 < Re_m < 10$)), (Delaplace et al., 2005a) have also established that the mixing time curve for a of the PARAVISC helical ribbon system can be described by

$$\Theta_{90\%m} = 108 \quad (33)$$

$$\text{with} u_{ch} = (N\ d_s) \quad (34)$$

In these conditions, the power curve of the PARAVISC helical ribbon system, corresponding to an agitator partially immersed, is described by Eq. (35) as shown in Fig. 6.

$$N_{p_m} = \frac{258}{Re_m} \quad (35)$$

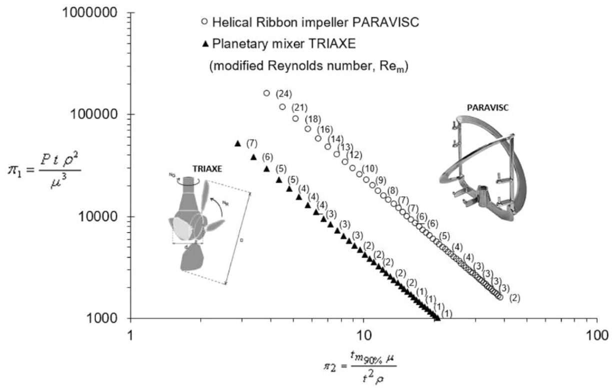

Fig. 6 – Power consumption curve of the helical ribbon mixer PARAVISC using the pi-set (N_{p_m}, Re_m). Empty diamonds correspond to experimental measurements.

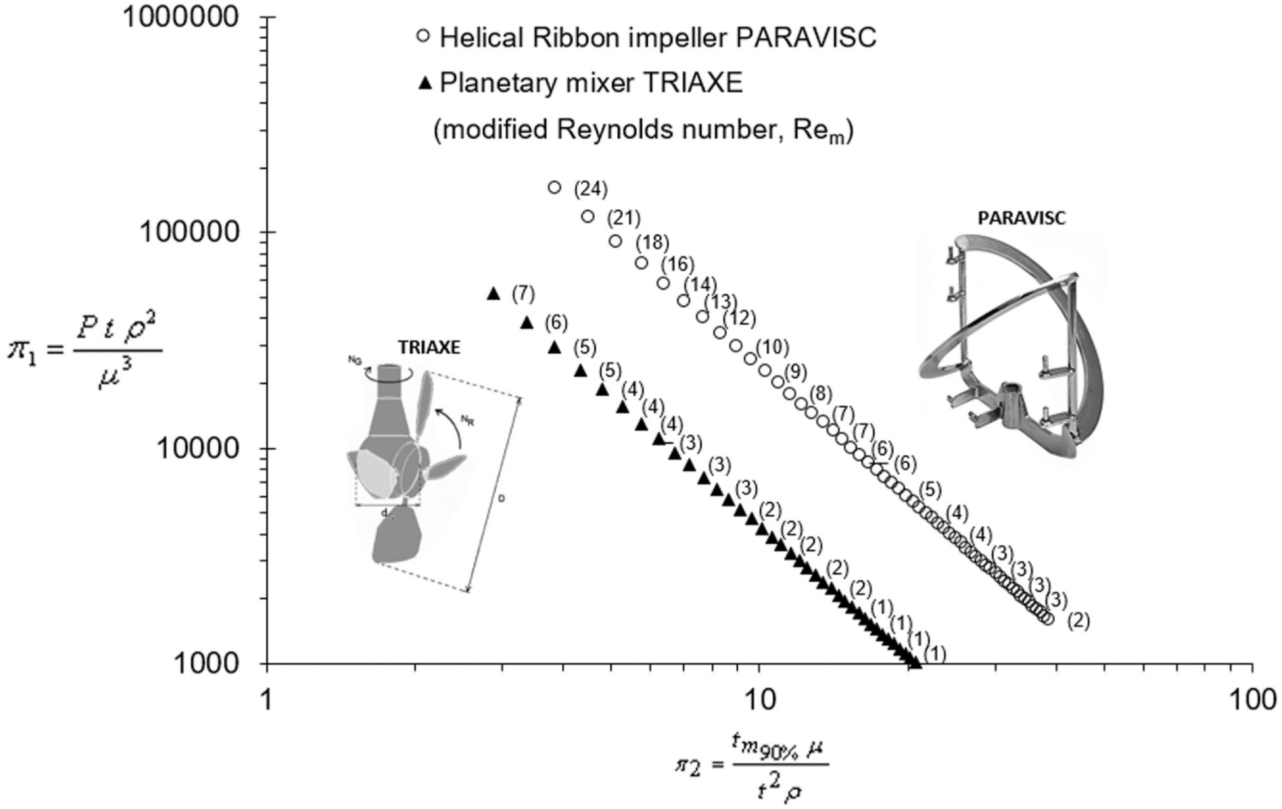

Fig. 7 – Worksheet for determining the most favourable mixing equipment (conventional or planetary mixers) to attain a given mixing time with the smallest mixing work. The corresponding Reynolds number is indicated in the brackets.

Note that the power consumption of a fully immerged agitator (34 litres of highly Newtonian fluids) under laminar regime ($0.1 < Re_m < 10$), leads logically to a power curve translated to higher values, as obtained in (Delaplace et al., 2000a).

$$N_{p_m} = \frac{315}{Re_m} \quad (36)$$

Combining Eqs. (15–22) and (25), we are able to plot π_1 versus π_2 for the two stirrers and determine the equipment inducing the less mixing work for the desired mixing time (Fig. 7).

Analysis of Fig. 7 shows that planetary mixers can be an economic solution despite the dual-motor required to move the agitator. In this sense, the apparatus provides a new way of mixing products.

Another interest of using this framework is the ability to select the optimum characteristic speed. Indeed, as the physical properties of the material system, the diameter of the vessel and the desired mixing time are all known, it is easy to compute the dimensionless number π_2 (Eq. 4). The numerical values of π_1 can be read off at the intersection of the π_2 value with the curve. The power consumption P can then be calculated from Eq. (3), $P = (\pi_1\, \mu^3)/t\, \rho^2$. Then the numerical value of characteristic speed u_{ch} can be deduced from Eq. (31), $u_{ch} = \sqrt{P/343.\ \mu.\ d_s}$ and the corresponding value of Re_m can be obtained: $Re_m = (\rho.\ u_{ch}.\ d_s)/\mu$.

Note that for the planetary mixer, various combinations of angular speeds N_R and N_G allow to achieve a given characteristic speed. This additional degree of freedom can be of great advantage when optimizing the dynamic of the mixing process. As shown in Fig. 7, the simplicity of the resulting plot makes this method easy to implement in any type of industry and user level of education.

The above section is proof of concept that it is possible to compare and select a mixing technology according its energy performance. A further challenge will be to use this framework to plot the mixing performance of other mixing equipment for the homogenization of liquids; namely those for which a characteristic velocity can be used for obtaining power and mixing curves. Notably, the SER presented in the previous section of this work and also the planetary mixers with different agitator design or those composing a dual revolution motion around vertical axis as planetary mixer used for dough process shown in (Auger et al. 2015). However, the characterisation of the SER systems is still hindered by the fact that power data has not been measured with satisfactory significance in order to provide accurate calculations of π_1, and its plot with the other mixing equipment studied in this work remains hazardous. In the same way, for the planetary mixers composing a dual revolution motion around vertical axis like those used for dough process, the mixing data are missing and doesn't allow to rank it against the classical one.

Since mixing is an essential operation, at several stages and in many industrial sectors, and responsible for high energy demands, it is crucial that this framework, allowing mixing work minimization, is rapidly grasped especially for achieving the challenges enclosed within the sustainable development.

4. Conclusions

In this work, the approach to address the challenging question of which mixing equipment is able to satisfy the degree of homogeneity in a given time with the lowest energy possible? has been extended to planetary mixers and soft elastic reactor. This work provides guidelines to compare planetary mixer efficiency with other conventional mixing systems (involving an agitator revolving around a vertical axis centred in the tank) for homogenizing viscous fluids. Indeed, based on the present data, it was shown that planetary mixers present higher efficiency than the ribbon impeller when mixing highly viscous fluids.

To be more exhaustive and be able to have a more accurate point of view on which mixing equipment is actually most suitable for a given degree of mixing and a way of injection, a whole range of planetary mixers or soft elastic reactor must up to now be evaluated and documented.

In the same way, this framework doesn't consider the techno-economic analysis (capital cost, maintenance…) and cost and environmental life cycle assessment of mixing system which could also be of great interest, along with operating time before definitively selecting a mixing equipment. Unfortunately, solving this issue of optimization of a multivariable function required much more data (which are currently impossible to found and far to be fully objective in a competitive sector). It vastly exceeds the scope of this work which is devoted to provide an efficient and generic framework to compare different types of mixing equipment according to their energy consumption for a determined homogenization task.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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