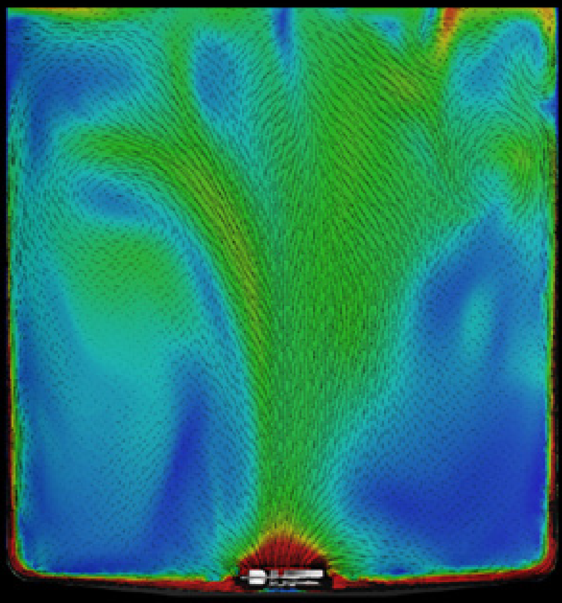
Flexsafe® Pro Mixer

Computational Fluid Dynamic Studies



Technical Note

Scope
A computational fluids dynamic (CFD) study has been performed on Flexsafe® Pro Mixer from 50 to 1,000 L to provide per volume:

- Side and top views of velocity profiles
- An analysis of speed profile evolution, flow patterns and vortex formation
- Dimensionless numbers and characteristic parameters of mixing performance

Executive Summary

The results obtained by CFD simulations of the different volumes considering maximal peformance are summarized in table 1.

Flexsafe® Pro Mixer 50L to 1,000L at 750 rpm.

	Volume					
	50 L	**100 L**	**200 L**	**400 L**	**650 L**	**1.000 L**
Reynolds Number	3.20E+05	3.20E+05	3.20E+05	3.20E+05	3.20E+05	3.20E+05
Regime	Turbulent	Turbulent	Turbulent	Turbulent	Turbulent	Turbulent
Power number N_p	1.82	1.92	2.14	2.28	2.26	2.21
Power (W)	372.7	393.2	438.3	466.9	462.8	452.6
Flow number N_q	0.54	0.52	0.48	0.48	0.45	0.44
Q (m^3/min)	1.66	1.60	1.47	1.47	1.38	1.35
Circulation time tc (sec)	1.8	3.8	8.1	16.3	28.2	44.4
P/V (kW/m^3)	7.45	3.93	2.19	1.17	0.71	0.45

Table 1: Flexsafe® Pro Mixer performances at 750 rpm

CFD Approach

Computational fluid dynamic is a numerical simulation of fluid motion. This technique provides useful information about fluid motion and flow patterns, characteristic dimensionless numbers and specific power consumption.

Simulations of Flexsafe® Pro Mixer volumes were performed for water at 50, 100, 200, 400, 650 and 1000 L. The maximum rotation speed for Pro Mixer is 750 rpm. In order to work under customer conditions, the speed has been adjusted depending on the final volume to avoid foaming effects or splashing.

Bag volume (L)	Agitation speed proposed (rpm)
50	200
100	325
200	450
400	525
650	650
1.000	750

Table 2: Stirrer speed chosen for different CFD studies

This CFD study includes:

- Side and top views that were simulated for the six bag volumes at 50 seconds time step
- An analysis of speed profile evolution, flow patterns and vortex formation.
- Dimensionless numbers and characteristic parameters of mixing performance.

CFD Results

The results of the CFD study are presented through different views, which are representative of a specific moment of the simulation. A chromatic scale is used to represent the different values of the analyzed variable, for example: speed, pressure, vorticity, etc. Usually, the maximum value of the scale is shown in red, medium values in green and the lower values are represented in blue.

Figure 1 presents the simulation of a speed profile performed for 200 L at 450 rpm with a maximum value on the speed scale of 1 m/s. Here, it can be analyzed the evolution of the velocity profile over time, considering the time 31 seconds (first image) to 50 seconds (last image). In addition, the absence of time persistent blue areas are observed.

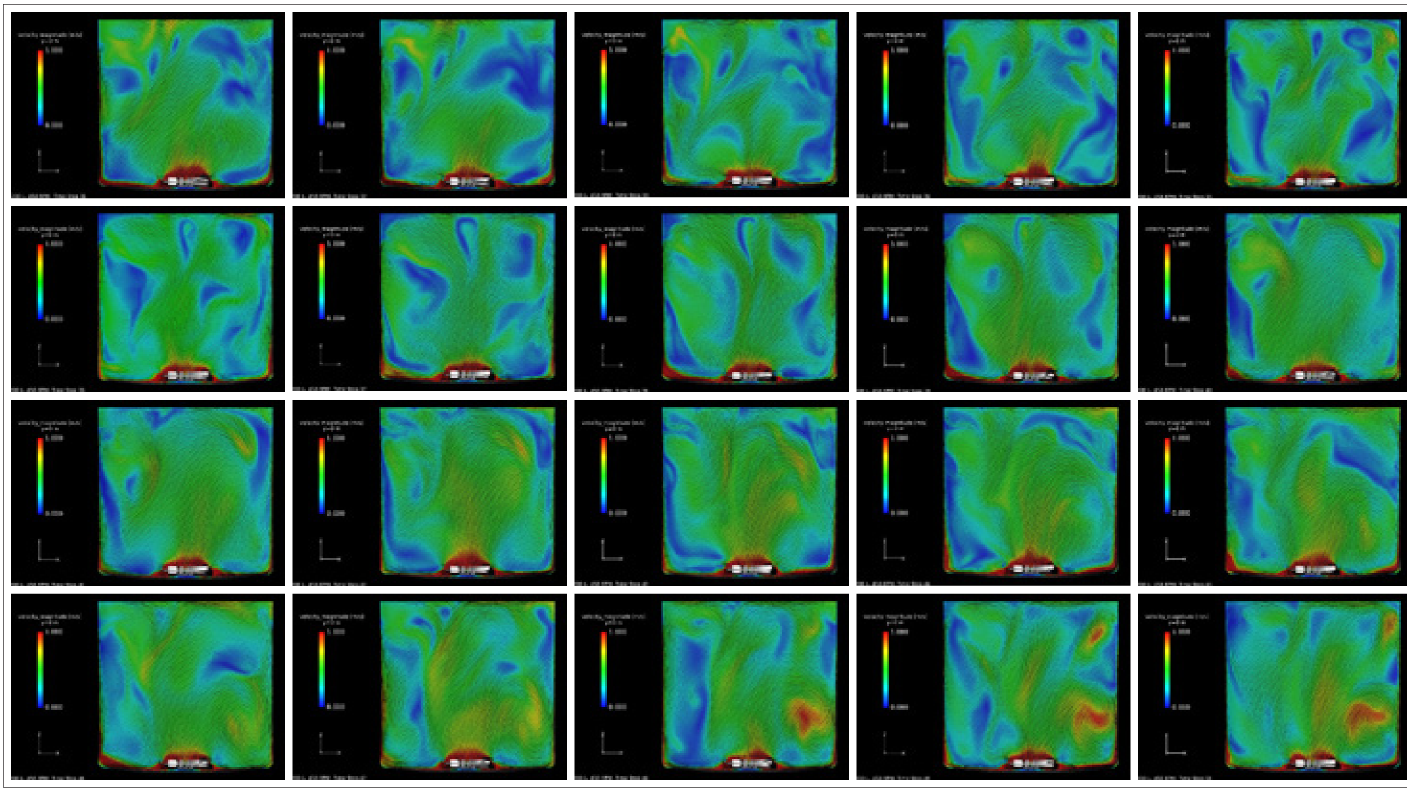


Figure 1: Side views of velocity profile at different times for 200 L at 450 rpm

Speed Profile Analysis

Side views

Side views generated for the six volumes are showed in Figure 2 using a velocity scale between 0 to 1 m/sec. In practically all cases the formation of vortex rings is observed, characterized by yellow and red color, where the fluid moves rapidly. These persistent vorticity elements are beneficial and favor the mixing process. In addition, it is noted that in all cases the surface of the liquid is green, which indicates movement at an estimated speed of 0.5 m/sec. This is important, since the surface of the fluid is the farthest area from the agitator.

Top views

Top views of the six volumes are presented in Figure 3. There it is analyzed speed profile in a plate located at 20 mm from the bottom. The maximum value of the speed scale is 1 m/sec.

Pictures represent pumping activity of the stirrer. Red paths show portions of fluid moving at 1 m/s or greater speed in a radial direction. In fact, the trails turn with the stirrer blades and thus the stirrer pumps fluid in all directions generating a high turbulent zone and a radial flow in the bottom of the bag.

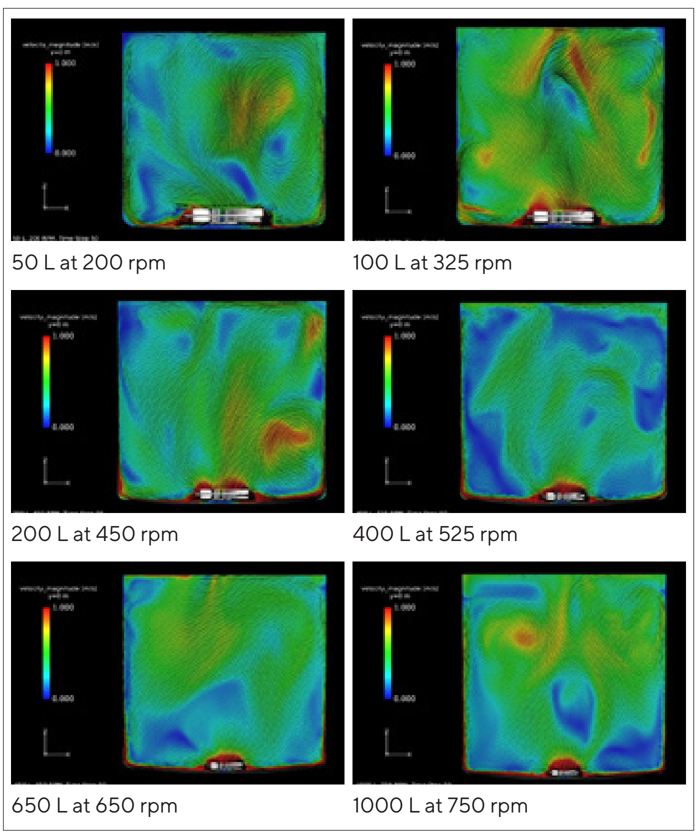


Figure 2: Velocity profile. Side views at 50 seconds with a constant velocity range of 0 to 1 m/sec

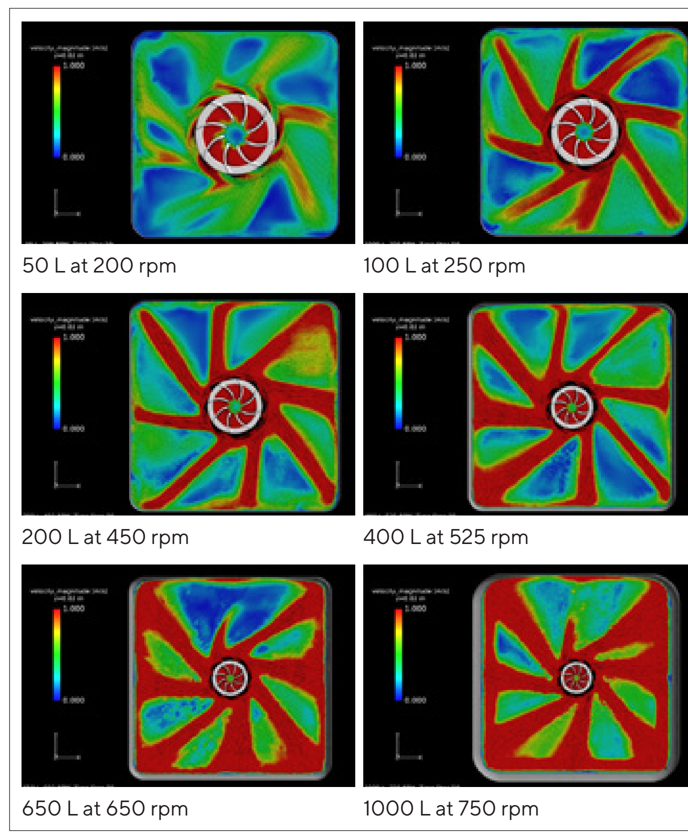
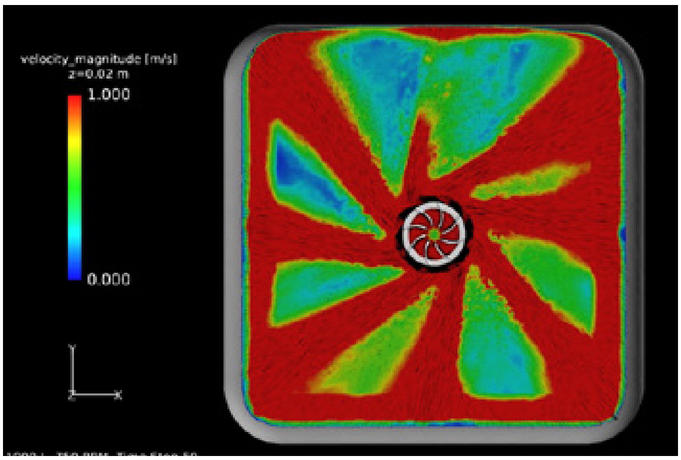


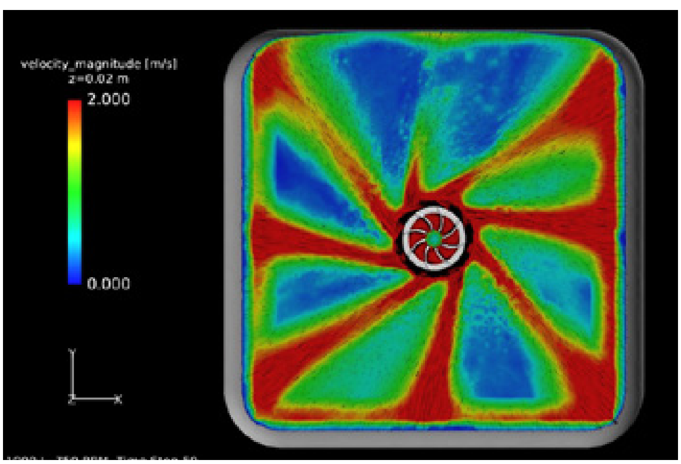
Figure 3: Velocity profile. Top views for different volumes at 50 seconds, z = 20 mm

For the 1000 L system, the red color occupies a large portion of the simulated plane. Hence, in order to provide more details for Flexsafe® Pro Mixer 1000 L speed profile, it is possible to increase the maximum speed value of the scale, first to 2 m/sec and finally to 3 m/sec. Thus, it is possible to partially remove the observed red zone and have a wider description of the velocity profile in the plate. This is presented in figure 4.

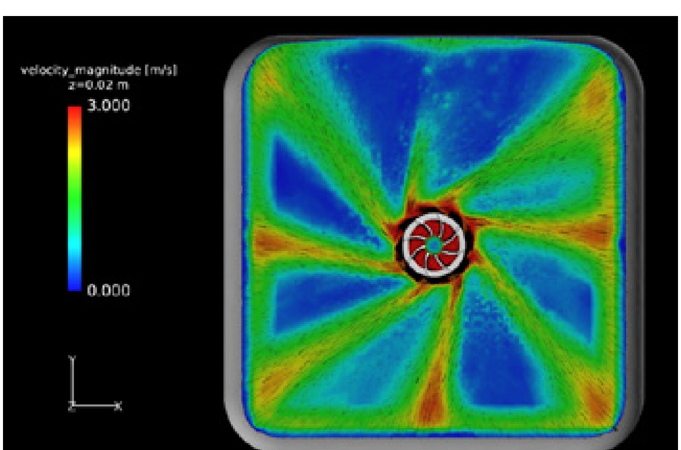
In this manner, it is possible to note that even in the greatest size geometry, a speed of about 3 m/sec is reached, which ensures a high turbulence zone. This important turbulence and speed acquired by the radial flow allows then the axial circulation throughout the volume of the bag avoiding dead zones or low movement areas.



0 – 1 m/s speed range



0 – 2 m/s speed range



0 – 3 m/s speed range

Figure 4: Velocity profiles. Top views at various velocity scales, V = 1.000 L, z = 20 mm

Flow Patterns Simulation

A flow pattern is a qualitative image of the flow produced by an agitator in the medium that contains it, in this case in a homogeneous medium. Flow patterns of stirrers traditionally used in industry, such as the propeller and the Rushton turbine are well known. The set of simulations generated for Pro Mixer allows to analyze and to describe flow patterns generated.

Below, some of the views generated for a volume of 1.000 L at 750 rpm showing speed profile evolution in time. A value of 1 m/sec was used as maximum speed value of the scale.

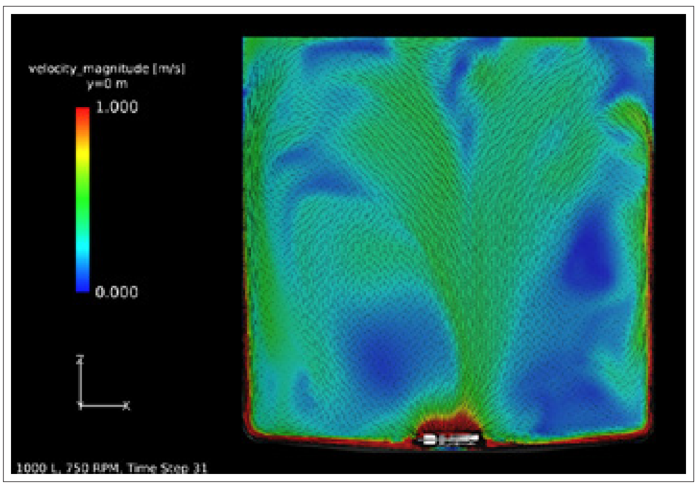


Figure 5: Side view, time step 31

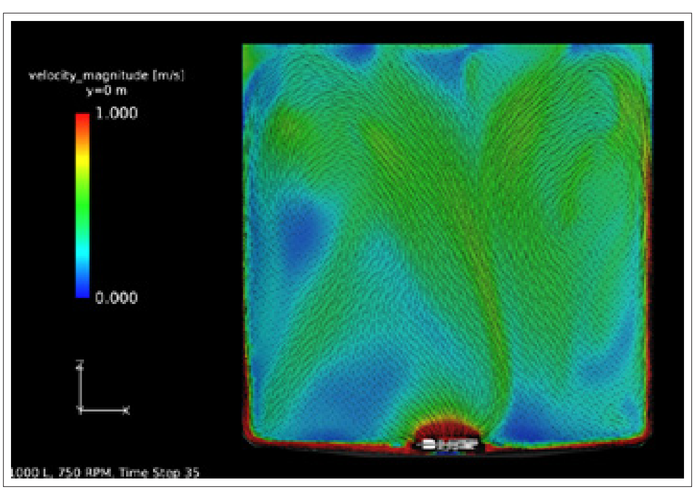


Figure 6: Side view, time step 35

The use of small black vectors in the pictures permits to observe the flow lines generated during the operation of the system. Indeed, the stirrer presents a central area of aspiration. Then, a radial flow in red at high speed is generated. When this radial flow reaches the wall of the bag it rises, reaching superior zone of the bag. Then it approaches to the central zone, when it begins to descend and to approximate to the aspiration zone of the agitator. In this way, an axial flow is developed in the bag with the formation of a recirculating loop above the stirrer.

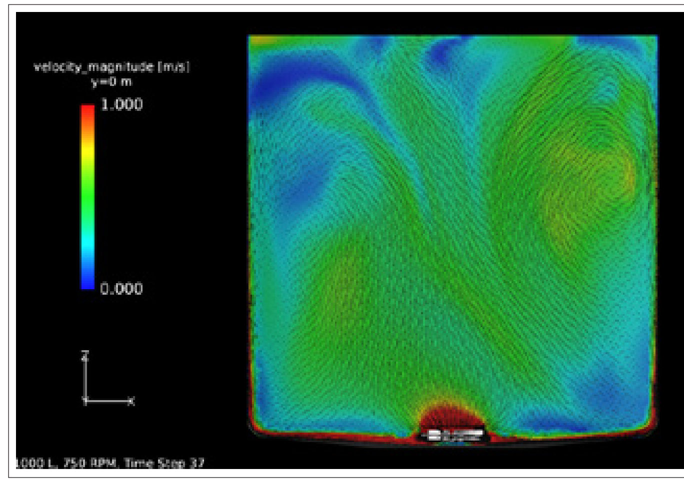


Figure 7: Side view, time step 37

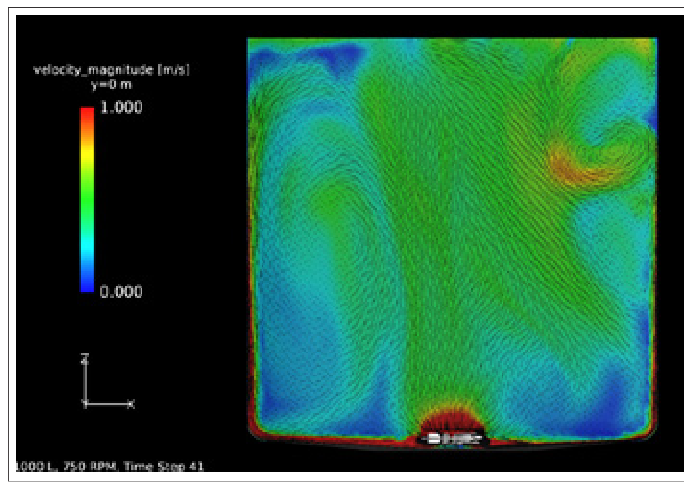


Figure 8: Side view, time step 41

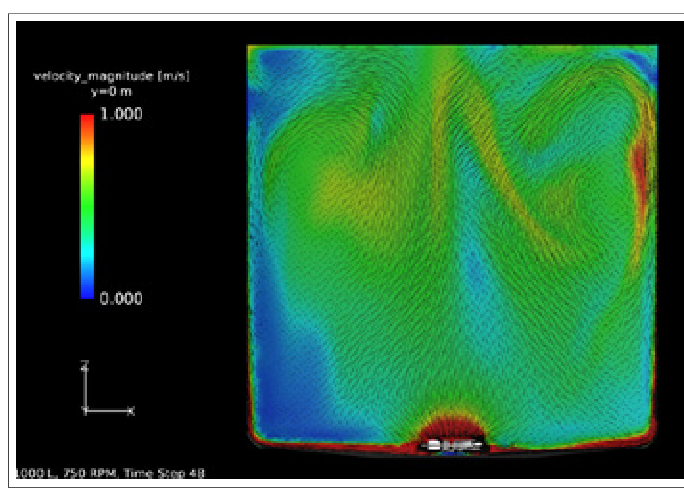


Figure 9: Side view, time step 48

Analyzing the set of simulated images it is observed the presence of vorticity elements that are favorable for the mixing process. Finally, the absence of permanently blue areas can be observed.

Vortex Formation

Vortex formation was studied in the mixing system.
A moderate vortex is necessary to favor the rapid inclusion and dispersion of floating powders into the liquid. A large vortex, such as the one generated in cylindrical tanks without baffles, generates long blend times because the fluid rotates in block with no axial motion. In these cases, there is a strong prevalence of tangential speed favoring a rotation of the fluid but without mixing. In traditional cylindrical geometries, the use of baffles eliminates vortex formation but then including floating powders is difficult because surface becomes stationary and powders float with slowly inclusion into the liquid. Producing a moderate vortex is important in mixing floating powders applications. A moderate vortex favors the rapid inclusion of floating powders into the liquid, facilitating its subsequent dispersion by the agitator and following dissolution. A rapid dissolution into the liquid is crucial for foaming product. Flexsafe® Pro Mixer square corners create a partially baffle effect in the bag, so as to create a moderate vortex. Views of the surface of Flexsafe® Pro Mixer 100, 650 and 1000 L are presented, where the vortex generated in the three cases can be observed.

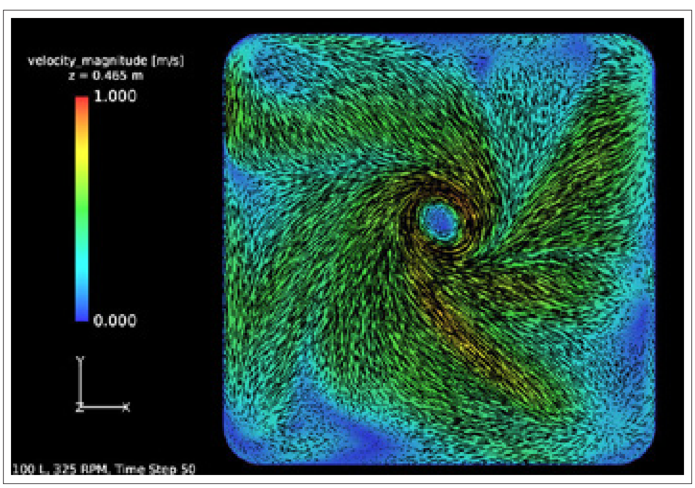


Figure 10: Top view. Vortex formation in 100 L bag at 325 rpm

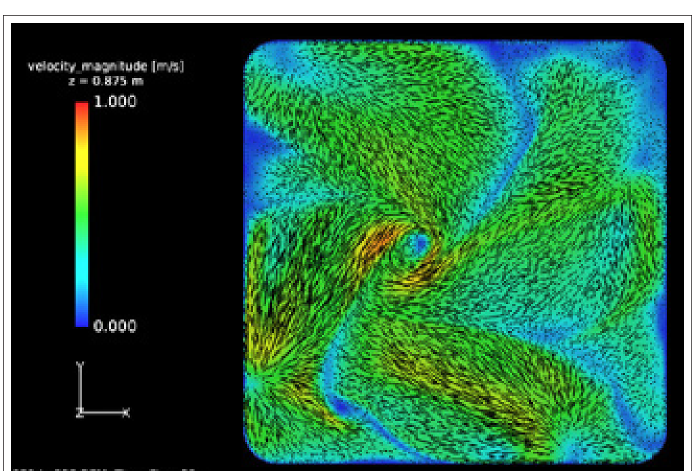


Figure 11: Top view. Vortex formation in 650 L bag at 650 rpm

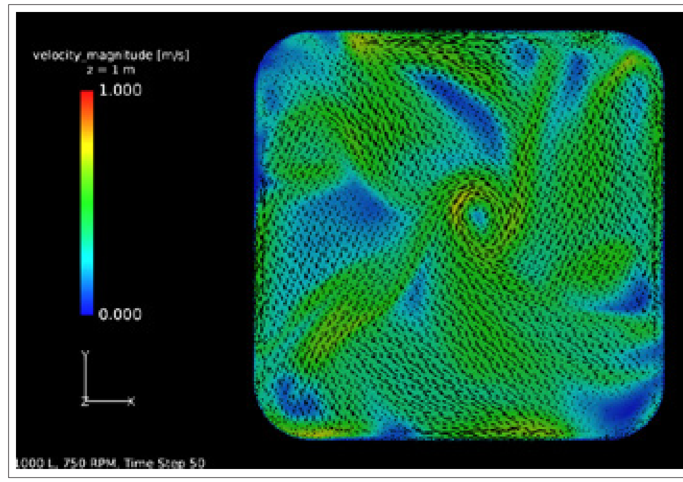


Figure 12: Top view. Vortex formation in 1000 L bag at 750 rpm

Figure 13 shows a three-dimensional view of the 1.000 L bag. In this case, the vertical component of the velocity (on the z-axis) is represented in colors. A positive velocity value corresponds to a fluid that travels upward (orange) and a negative value corresponds to a downward movement (in light blue). For this volume, there is a suction zone, where the fluid is directed to the agitator with a z-speed of the order of 0.3 m/sec. No green areas are observed, which would correspond to stagnant areas in the z direction. This image allows confirming the existence of ascending and descending flows which favor the mixing process.

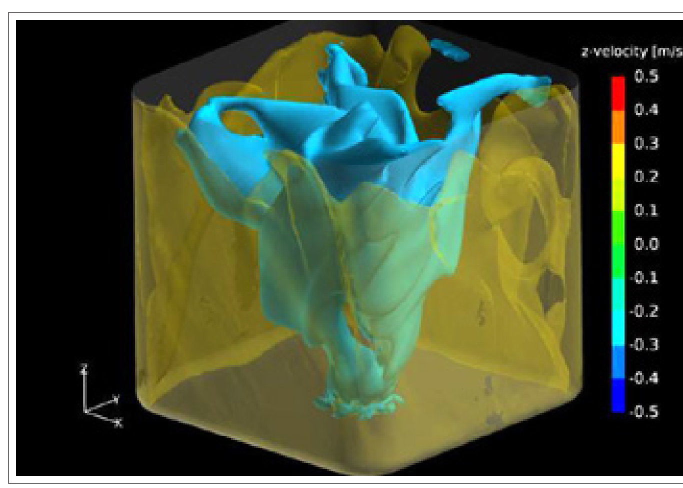


Figure 13: 3D view: simulation of vertical velocity in Pro Mixer 1.000 L at 750 rpm

Dimensionless Agitation Numbers and Specific Power Consumption

Power number NP is a dimensionless number defined as:

$$N_P = \frac{P}{\rho N^3 D^5} \qquad (1)$$

Where P is the power delivered to fluid (in watts), ρ is the density of the fluid (in kg/m^3), N is agitation frequency (in revolutions per second, s^{-1}) and D is the stirrer diameter (in meters). Power Number is a dimensionless parameter used for estimating the power consumed by the agitating impeller. In addition, it depends on Reynolds number (Re), Froude number and geometrical standard ratios of agitation system. Power number is constant at turbulent regime, which is reached when Re is greater to 10^4. Laminar flow is considered when Re is lower than 10.

Specific volumetric power consumption P/V is defined as the ratio between power to liquid volume in the vessel.

When the agitator rotates, a torque or a force moment (expressed in N.m) is applied on its base. In fact, power delivered to fluid can also be calculated using the torque value τ, as equation 2 shows:

$$P = \tau\omega = 2\pi N\tau \qquad (2)$$

Where ω is angular speed expressed in rad/sec.

Reynolds number represents a ratio between inertial and viscous forces and is defined, in agitation, as:

$$Re = \frac{\rho N D^2}{\mu} \qquad (3)$$

Where μ is the fluid dynamic viscosity (in Pa.sec).

Flow number N_Q is related to fluid flow Q pumped in the vessel by the stirrer. N_Q is dimensionless and is defined as:

$$N_Q = \frac{Q}{ND^3} \qquad (3)$$

Flow number depends on the impeller type, geometrical ratios of the system and impeller Reynolds number. In turbulent flow, N_Q is about 0.4 to 0.8 for commonly used impellers.

The recirculation time t_c can be considered as the time needed to pump an amount of fluid equal to that contained in the vessel. In fact, recirculation time is linked empirically to blend time. Then, t_c is defined as:

$$t_c = \frac{V}{Q}$$

The next tables summarize average results, standard deviation and relative standard deviation obtained by numerical simulations of different Flexsafe® Pro Mixer volumes.

50 Lt, N = 200 rpm D = 0.16 m	**Average value**	**Standard deviation**	**Related Standard deviation (%)**
N_p	1.82	0.17	9.5
Torque (N.m)	0.34	0.03	9.5
P (W)	7.08	0.67	9.5
N_q	0.54	0.03	5.05
Q (m^3/min)	0.44	0.02	5.05
t_c (s)	6.8		
P/V (kW/m^3)	0.142		

100 Lt, N = 325 rpm D = 0.16 m	**Average value**	**Standard deviation**	**Related Standard deviation (%)**
N_p	1.92	0.12	6.41
Torque (N.m)	0.94	0.06	6.41
P (W)	31.96	2.05	6.41
N_q	0.52	0.04	8.41
Q (m^3/min)	0.69	0.06	8.41
t_c (s)	8.7		
P/V (kW/m^3)	0.320		

200 Lt, N = 450 rpm D = 0.16 m	**Average value**	**Standard deviation**	**Related Standard deviation (%)**
N_p	2.14	0.08	3.58
Torque (N.m)	2.01	0.07	3.58
P (W)	94.79	3.4	3.58
N_q	0.48	0.02	3.96
Q (m^3/min)	0.88	0.04	3.96
t_c (s)	13.6		
P/V (kW/m^3)	0.474		

400 Lt, N = 525 rpm D = 0.16 m	**Average value**	**Standard deviation**	**Related Standard deviation (%)**
N_p	2.28	0.06	2.81
Torque (N.m)	2.91	0.08	2.81
P (W)	159.97	4.49	2.81
N_q	0.48	0.02	3.71
Q (m^3/min)	1.02	0.04	3.71
t_c (s)	23.5		
P/V (kW/m^3)	0.400		

650 Lt, N = 650 rpm D = 0.16 m	**Average value**	**Standard deviation**	**Related Standard deviation (%)**
N_p	2.26	0.04	1.64
Torque (N.m)	4.42	0.07	1.64
P (W)	301.08	4.95	1.64
N_q	0.45	0.01	3.01
Q (m^3/min)	1.21	0.04	3.01
t_c (s)	32.3		
P/V (kW/m^3)	0.463		

1000 Lt, N = 750 rpm D = 0.16 m	**Average value**	**Standard deviation**	**Related Standard deviation (%)**
N_p	2.21	0.06	2.55
Torque (N.m)	5.75	0.15	2.55
P (W)	451.84	11.52	2.55
N_q	0.44	0.01	2.25
Q (m^3/min)	1.35	0.03	2.25
t_c (s)	44.6		
P/V (kW/m^3)	0.452		

Flexsafe® Pro Mixer presents a constant agitator diameter for all bag volumes. Due to this, power number varies slightly between the different volumes (geometrical ratios of the system are not constant) as it is showed. The power number is directly linked to the power consumption, as observed in equation 1. The N_p of traditionally used agitation mobiles are known, being approximately 5 to 4 for a Rushton turbine (which depends on the number of blades of the turbine) and 1 to 0.5 for propeller-type mobiles and hydrofoils. The values obtained for Pro Mixer mixing solutions are approximately between both ranges of values mentioned above.

A common strategy used in scale-up mixing processes is to conserve specific power volumetric consumption between different sizes. For volumes between 400 Lt and 1000 Lt, it is observed that almost the same specific power value is dissipated, while for 100 Lt and 200 Lt the values are lower. The latter occurs due to the speed selected to perform the simulation. In fact, for these two volumes, increasing the stirring speed can achieve similar P/V values. The fact of increasing the speed as the volume scales allows to maintain a constant power per unit volume, an aspect strongly linked to heat and mass transfer.

Flexsafe® Pro Mixer Performances at Maxixum Speed'

The next table provides the Flexsafe® Pro Mixer performances at 750 rpm'.

	Volume					
	50 L	**100 L**	**200 L**	**400 L**	**650 L**	**1.000 L**
Reynolds Number	3.20E+05	3.20E+05	3.20E+05	3.20E+05	3.20E+05	3.20E+05
Regime	Turbulent	Turbulent	Turbulent	Turbulent	Turbulent	Turbulent
Power number N_p	1.82	1.92	2.14	2.28	2.26	2.21
Power (W)	372.7	393.2	438.3	466.9	462.8	452.6
Flow number N_q	0.54	0.52	0.48	0.48	0.45	0.44
Q (m^3/min)	1.66	1.60	1.47	1.47	1.38	1.35
Circulation time tc (sec)	1.8	3.8	8.1	16.3	28.2	44.4
P/V (kW/m^3)	7.45	3.93	2.19	1.17	0.71	0.45

Table 3: Flexsafe® Pro Mixer performances at 750 rpm

Conclusion

CFD studies developed on Flexsafe® Pro Mixer achieved to analyze mixing performance. First of all, the geometry of the agitator allows to generate a radial flow and when it reaches the walls of the bag, it acquires an axial motion. In consequence we observe the formation of a recirculation loop above the stirrer, which is favorable for mixing process. In a second place, a moderate vortex generated by square corners partially baffled effect facilitates floating powder inclusion into the liquid. All simulations showed mixing systems with permanently agitated zones, even those farthest from the stirrer.

Flexsafe® Pro Mixer is a flexible single use mixing solution that can increase speed up to 750 rpm thus allowing each client to use the speed or specific power that best fits the needs of its bioprocess. Considering this, a constant P/V strategy in scale-up of bioprocesses could be applied.

References

- Paul, Atiemo-Obeng, Kresta, Handbook of Industrial Mixing. Science and Practice, Wiley, 2004.
- Harnby, Edwards, Nienow, Mixing in the Process Industries, Butterworth- Heinemann, 1992.

Germany
Sartorius Stedim Biotech GmbH
August-Spindler-Strasse 11
37079 Goettingen
Phone +49 551 308 0

USA
Sartorius Stedim North America Inc.
565 Johnson Avenue
Bohemia, NY 11716
Toll-Free +1 800 368 7178

For further contacts, visit
www.sartorius.com

DIR No.: 2548199-000-00 | Status: 01 | 12 | 2021