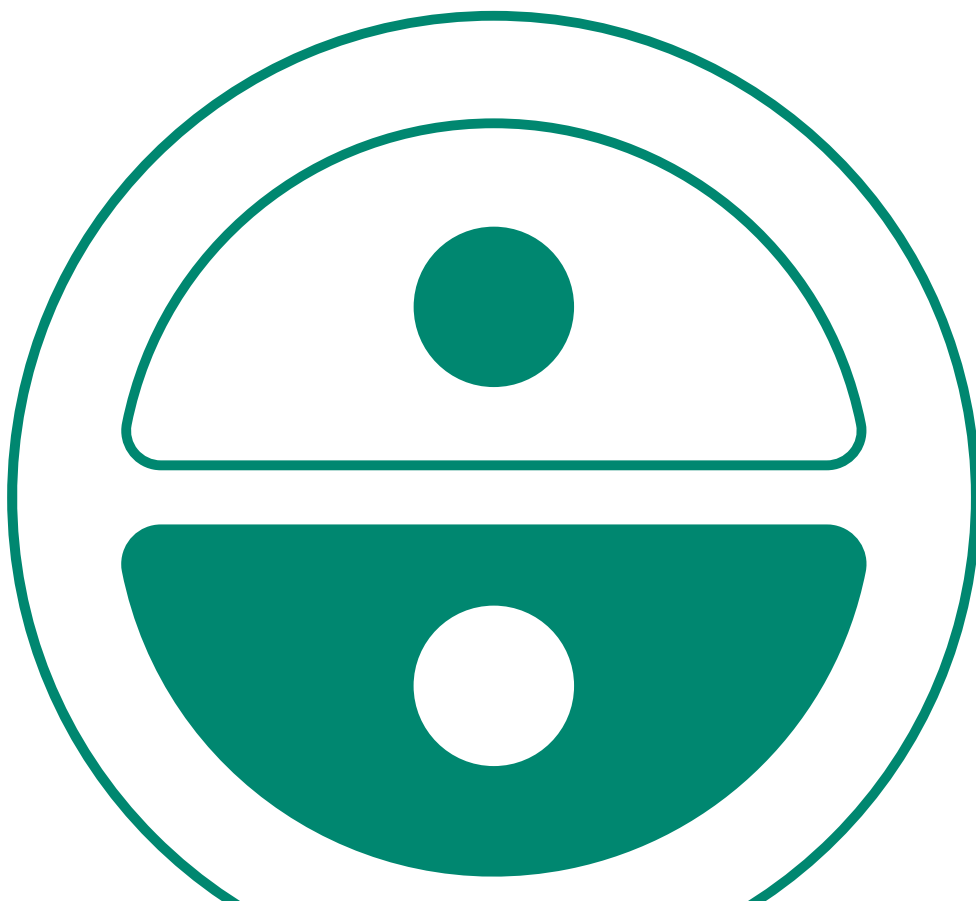


LevMixer 10 L mixer characterization using experiments/ computational fluid dynamics

This application note characterizes the LevMixer™ 10 L single-use mixing system using a combined experimental and computational fluid dynamics (CFD) approach.

- We determined maximum impeller speeds that avoid vortex formation across different volumes (0.1 to 10 L) and viscosities (1.0, 2.67, and 25 cP)—critical for shear-sensitive processes—quantitated experimental mixing time, and measured mixing time (T_{95}) experimentally to validate CFD simulations.
- CFD simulations were used to extend coverage of operating conditions and quantitate velocity, shear rate, and Kolmogorov eddy scales.
- Results show the mixer achieves rapid, homogeneous, vortex-free mixing across tested volumes, with T_{95} as low as 18 s (2.67 cP) and 33 s (25 cP) at 10 L under no-vortex speeds.

CFD showed good agreement with experiments at moderate to high power input (P/V) and supports criterion-based comparison to LevMixer 50 to 1600 L mixers at nominal volumes by matching individual criteria such as P/V or target T91



Introduction

Vortex formation at the air–liquid interface in a mixer can lead to undesirable effects, raising the risk of protein aggregation and denaturation in bioprocesses. For shear-sensitive applications, the goal is to operate below a defined no-vortex impeller speed while still achieving rapid and uniform mixing.

This study characterizes the mixing performance of the LevMixer 10 L mixer (Fig 1) using a combination of physical experiments and computational fluid dynamics (CFD) simulations. Experiments were conducted at multiple fill volumes to determine the maximum impeller speed that prevents vortex formation.

Mixing time (T_{95}) was measured experimentally across selected volumes, and impeller speeds and results were used to validate CFD simulations, which were further extended to cover a wider range of operating conditions.

Approaches based on power input (P/V) and mixing time (T_{95}) are presented, enabling characterization of the 10 L mixer in comparison with larger mixers from the LevMixer series.



Fig 1. LevMixer 10 L mixer used in this study.

METHODS: VORTEX AND MIXING EXPERIMENTS

Materials and media used in the experiments

The materials used for the physical experiments are shown in Table 1.

Equipment and consumables	Supplier
LevMixer 10 L mixer	Cytiva
10 L single-use biocontainer	Cytiva
Conductivity sensor (Conducell 4USF Arc 120)	Hamilton
Variocool VC 1200	Lauda
SV-10 viscometer	A&D company, Limited
Demineralized water	NA
Dextrose GMP+	Indufarm
Ammonium chloride $\geq 98\%$	VWR

Three media types were used in the vortex and mixing experiments:

- Medium 1 (mid viscosity): Glucose in WFI, 26.25% w/v; density 1107 kg/m³; viscosity 2.67 cP.
- Medium 2 (high viscosity): Glucose in WFI, 53% w/v; density 1238 kg/m³; viscosity 25 cP.
- Medium 3 (water): WFI; density 998.2 kg/m³; viscosity 1.0 cP

The properties of the mixing tracer used in the mixing experiments were:

- Tracer: NH₄Cl in WFI, 10% w/v; density 1029 kg/m³; viscosity 0.981 cP.
- Tracer dosing: 0.1% of total fill volume during vortex identification; 1% of fill volume during T_{95} tests.

Fill volumes

The fill volumes used in vortex and mixing time experiments are given in Figure 2.

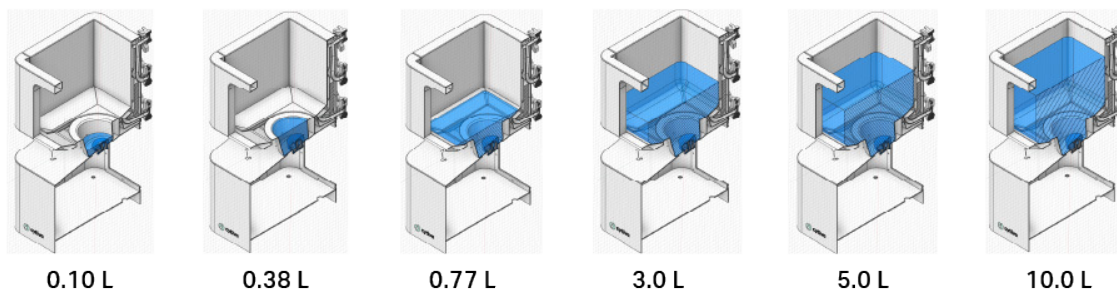


Fig 2. Fill volumes in LevMixer 10 L mixer for the vortex and mixing experiments.

Vortex experimental setup

1. LevMixer 10 L mixer installed according to the operating instructions.
2. Lauda Variocool VC 1200 temperature control unit (TCU) connected for temperature regulation.
3. Biocontainer inflated to a final 3D shape and filled with demineralized water to 50% of nominal volume.
4. Mixing was started at the impeller speed of 1000 rpm, and the TCU was set to 40°C to dissolve dextrose.
5. At approx. 40°C (exact precision not critical), impeller speed increased to max (2900 rpm).
6. Dextrose added through the powder port to achieve a final concentration of 26.25% at the nominal volume.
7. After the dextrose was dissolved, the mixer was filled to 100% of nominal volume with demineralized water.
8. Temperature adjusted to 20°C and maintained throughout testing; viscosity was verified to be within 2.5 to 3.0 cP.

Vortex experiment procedure

1. For each fill volume shown in Figure 2, the impeller speed was set to the low speed of 50 rpm and was gradually increased until a stable vortex formed (Fig 3).
2. Speed was reduced to eliminate the transient unstable vortex, and finally adjusted to achieve the no-vortex condition (Fig 3).
3. Impeller speed corresponding to the no-vortex condition recorded for each fill volume.
4. Experiments repeated for all three media types:
 - Medium 1 (mid viscosity)
 - Medium 2 (high viscosity)
 - Medium 3 (water)
5. No-vortex impeller speeds for each condition documented.



Fig 3. Visual classification of vortex conditions in the LevMixer 10 L mixer.

RESULTS: VORTEX STUDY

The no-vortex impeller speeds obtained from the experiments are plotted in Figure 4 and the corresponding data is summarized in Table 2.

Key findings include:

- At a 10 L fill volume, the mixer can operate at the following speeds without generating a vortex:
 - 1000 rpm with a fluid viscosity of 2.67 cP (Medium 1)
 - 1650 rpm with a fluid viscosity of 25 cP (Medium 2)
 - 625 rpm with a fluid viscosity of 1.0 cP (Medium 3)
- Higher fill volumes and more viscous fluids allow for higher impeller speeds without vortex formation, indicating that operating conditions significantly influence vortex behavior.

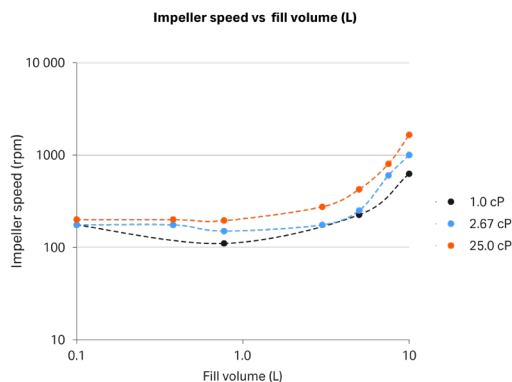


Fig 4. No-vortex impeller speeds (rpm) across different fluid viscosities and fill volumes in the LevMixer 10 L mixer.

Table 2. Volumes and no vortex impeller speeds

Volume (L)	No vortex impeller speed (rpm)		
1 cP	2.67 cP	25 cP	6.080
0.10	175	175	200
0.38	ND*	175	200
0.77	110	150	195
3.0	ND	175	275
5.0	225	250	425
7.5	ND	600	800
10.0	625	1000	1650

ND* = No data: Only intermediate speeds were tested at 1 cP only for information as this represents the easiest condition.

METHODS: MIXING EXPERIMENTS

Mixing experiment setup

1. LevMixer 10 L mixer installed as described in the vortex experiments section above.
2. The TCU was connected for temperature regulation, and a precalibrated conductivity sensor was positioned at the predefined location (Fig 5).
3. Note: The 10 L mixer is supplied by default with an optional single-use pH sensor. However, for this experiment, a conductivity sensor was used to align with the established protocol for the mixer and to enable comparison of the results with 50 to 1600 L systems.
4. Experiments were conducted using two media types:
 - Medium 1: Mid-viscosity fluid (glucose in WFI, 26.25% w/v; viscosity \approx 2.67 cP)
 - Medium 2: High-viscosity fluid (glucose in WFI, 53% w/v; viscosity \approx 25 cP)

Mixing experiment procedure

1. Following the same initial steps as the vortex experiments, the SU system was inflated to its final shape and partially filled with demineralized water to 50% of nominal volume.
2. Mixing was started at max. impeller speed, the TCU was set to 40°C to dissolve dextrose.
3. At approx. 40°C (exact precision not critical), dextrose was added through the powder port to achieve the target concentration for each medium.
4. After addition, the mixer was filled to 100% of nominal volume, and the temperature was adjusted and maintained at 20°C for all mixing experiments, with tracer addition to ensure consistent conditions throughout testing.

Mixing experiment data collection

- Conductivity data recorded with a sample rate of 1 data point every 3 s (Table 3). For each impeller speed change, 1 min was allowed for stabilization before introducing the tracer:
 - Tracer: 0.1% of fill volume from a 10% ammonium chloride (NH_4Cl) solution.
 - Addition method: Graduated cylinder via fixed funnel on the left side of the tank (Fig 5).
- Mixing times measured in duplicate for each impeller speed tested.
- After each test at maximum volume, the mixer was partially drained to achieve the next target volume.
- Five minutes of stabilization was allowed after tracer addition to confirm complete mixing.
- Impeller speeds tested were determined by CFD simulations to maintain a constant power-to-volume ratio across different fill volumes.

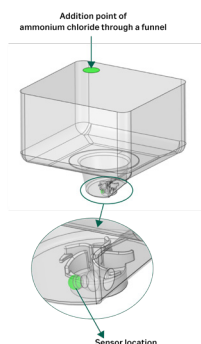


Fig 5. Schematic drawing of a LevMixer 10 L biocontainer with conductivity sensor location and point of salt addition.

Table 3. Volumes and speeds tested

Medium 1 (2.67 cP)	
Volume (L)	Agitation (rpm)
0.38	54
	98
	150 (NV*)
0.77	216
	122
5.0	221
	250 (NV)
	397
10.0	152
	278
	498
	1000 (NV)
Medium 2 (25 cP)	
Volume (L)	Agitation (rpm)
0.38	200 (NV)
0.77	195 (NV)
5.0	425 (NV)
10.0	1650 (NV)

* NV = No vortex.

Mixing time determination and results

The mixing time, T_{95} , is defined as the time required for the system to reach 95% of the final value and remain stable within a tolerance range of $\pm 5\%$ (i.e., between 95% and 105% of the end value). The method used to determine T_{95} is illustrated in Figure 6.

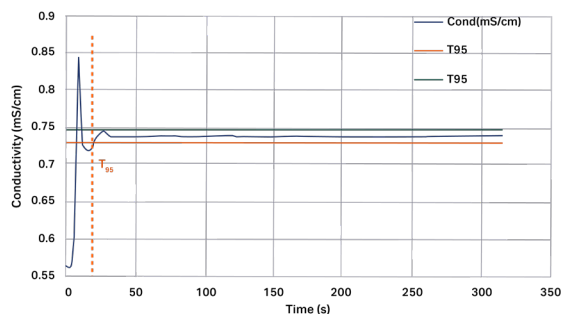


Fig 6. Example of a chart showing a conductivity shift with stable reading in the range of $\pm 5\%$.

RESULTS: MIXING TIME EXPERIMENTS

The mixing time (T_{95}) was evaluated for each experiment, and the results are summarized in Table 4. Key observations include:

- Homogeneity was achieved at all tested fill volumes.
- At the maximum fill volume of 10 L, the mixer reached 95% homogeneity without vortex formation within:
 - 18 s for Medium 1 (viscosity ≈ 2.67 cP)
 - 33 s for Medium 2 (viscosity ≈ 25 cP)
- Across all fill volumes, higher impeller speeds resulted in shorter mixing times.
- The tested volume (0.77 L) exhibited the slower mixing times, even at higher impeller speeds. This is attributed to the limited fluid depth near the bottom of the container, which requires more time to achieve uniformity. Nevertheless, homogeneity was achieved at all tested speeds for this volume.

Table 4. Results of mixing time experiments

Volume (L)	Agitation (rpm)	P/V (W/m ³)	Experimental mixing time, T_{95} (s)		
			MT1	MT2	Mean
Medium 1 (2.67 cP)					
0.38	54	0.55	21	24	22.5
	98	2.8	9	15	12
	172	13.7	12	12	12
0.77	150 (NV)	5	372	396	384
	216	14	288	264	276
5.0	122	0.46	549	525	537
	221	2.5	141	141	141
	250 (NV)	3.6	135	117	126
	397	13.9	45	30	37.5
10.0	152	0.4	1113	NA	1113
	278	2.5	150	168	159
	498	13.4	60	33	46.5
	1000 (NV)	102.8	18	12	15
Medium 2 (25 cP)					
0.38	200 (NV)	40.1	12	12	12
0.77	195 (NV)	18.7	498	432	465
5.0	425 (NV)	26.3	252	246	249
10.0	1650 (NV)	602.5	21	33	27

* NV = No vortex, MT1: First replicate of the experiment, MT2: Second replicate of the experiment.
P/V was computed using CFD simulations.

CFD SETUP AND SIMULATIONS

- Computational fluid dynamics (CFD) is a numerical approach used to simulate fluid flow and related phenomena such as mixing, shear, and turbulence.
- By solving the fundamental governing equations of fluid motion—the Navier–Stokes equations—CFD provides detailed insights into velocity fields, tracer species distribution, and shear rates within a mixing system.

For this study, CFD was employed to:

- Calculate power drawn by the impeller, supporting energy-based scaling and process optimization.
- Estimate mixing performance across different fill volumes and impeller speeds.
- Analyze shear rate distribution, ensuring suitability for shear-sensitive applications.
- Visualize flow patterns, including velocity profiles and turbulence characteristics, to complement experimental observations.

CFD enables predictive modeling under various operating conditions, reducing reliance on extensive physical testing and supporting scalable design decisions for larger mixers.

Geometry and mesh

- The fluid domain—including the tank and impeller regions—was extracted from the 3D geometry for each fill volume (Fig 7).
- Impeller rotation was modeled using the moving reference frame (MRF) approach to represent steady-state flow around the rotating blades.
- A polyhedral mesh was generated in Fluent’s meshing mode, with local refinement near the impeller and along the curved bottom of the square tank to accurately capture velocity gradients and flow details.

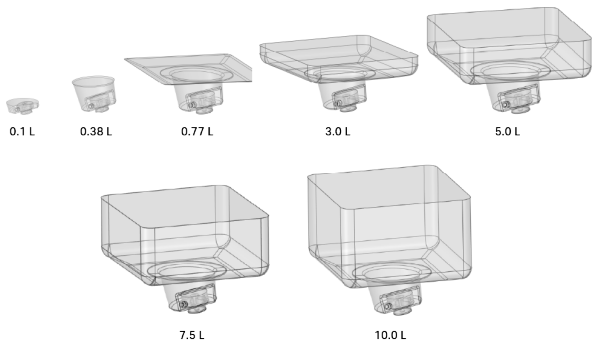


Fig 7. Fluid domains of LevMixer 10 L mixer showing different fill volumes considered for the CFD simulations.

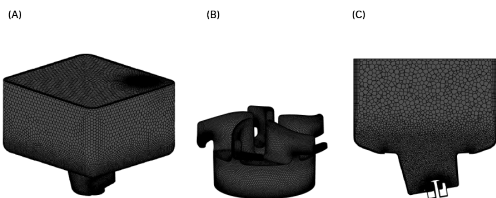


Fig 8. (A) 3D view of meshed fluid domain of the LevMixer 10 L mixer, (B) impeller surface mesh, and (C) cross-sectional view of the meshed fluid domain showing the refined elements near the impeller and extended up to the curved bottom region of the square tank.

Models and equations used in CFD

- CFD simulations were performed using ANSYS Fluent 2025R2 with the GPU solver for enhanced computational efficiency. Two modeling strategies were applied:
 - Single-phase analysis: Used to determine impeller speeds corresponding to specified power density (P/V) values.
 - Multispecies model: Applied to predict mixing time (T_{95}) by tracking concentration uniformity across the domain.
- The calculations for power, power number, power input, and Kolmogorov eddy scale were based on standard mixing correlations and are presented in Equations 1 to 4 below.

$$\text{Power (P, Watt)} = 2\pi NT \text{ (Eq 1)}$$

$$\text{Power number, (Np)} = \frac{P}{\rho N^3 D^5} \text{ (Eq 2)}$$

$$\text{Power input} = \frac{P}{V} \text{ (Eq 3)}$$

$$\text{Kolmogorov eddy scale, } (\lambda) = \left(\frac{(\mu/\rho)^3}{\varepsilon} \right)^{1/4} \text{ (Eq 4)}$$

N = Impeller speed, rpm

T = Torque, Nm

D = Impeller diameter, m

ρ = Density of medium, kg/m³

μ = Dynamic viscosity of medium, kg/ms

V = Working volume of the fluid in the vessel, m³

ε = Turbulence dissipation rate, m²/s³

Operating conditions analyzed using CFD simulations.

For each fill volume, mixing time was evaluated at four impeller speeds:

- Three speeds determined by power-per-unit-volume (P/V) normalization; and one speed corresponding to the no-vortex rpm identified in physical experiments.
- The complete set of operating conditions for all volumes and speeds is summarized in Table 5.

Table 5. Operating conditions used for CFD mixing analysis

P/V, W/m ³	Fill volume (L)							
0.5								
3.0	0.1	0.38	0.77	3.0	5.0	7.5	10.0	
15.0								
No vortex								

Probe map and mixing time estimation

Virtual probes were added to monitor tracer concentration during CFD simulations, as shown in Figure 9. These probes were strategically positioned at seven levels throughout the system to capture mixing behavior across both the main tank and the bottom container.

- Main tank: Four levels were defined to span the width and height—Top (TH), Middle (TM), and three bottom levels (TL, TB, and TC).
- Bottom container: Three levels were placed—Top (CH), Middle (CM), and Bottom (CL)—to capture flow characteristics within its geometry.
- Additionally, a probe labeled PP1 was positioned near the physical probe location used in the experimental setup for direct comparison.

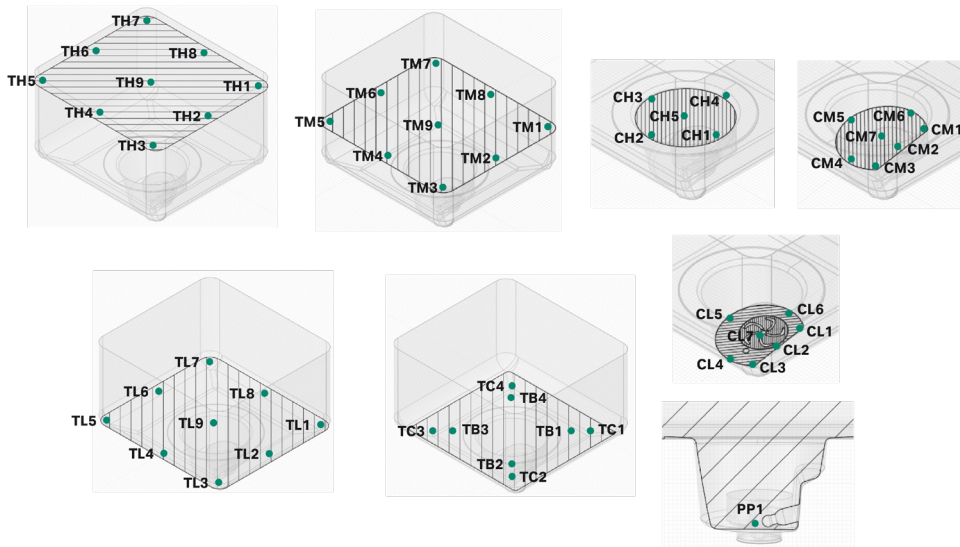


Fig 9. Location of virtual probes shown on the seven horizontal cross-section planes and one vertical cross-section of LevMixer 10 L mixer.

- In Figure 10, the horizontal lines represent 95% and 105% of the tracer concentration, defining the tolerance band for homogeneity. For each virtual probe, the time required to reach 95% of the final concentration was calculated and recorded as the T_{95} mixing time, indicated by the vertical line in Figure 10.
- “Average T_{95} mixing time” was obtained by averaging the T_{95} values across all probes for a given operating condition.
- “Slowest T_{95} mixing time” refers to the probe location that required the longest time to reach 95% homogeneity under each operating condition.

These two metrics provide a comprehensive view of mixing performance, capturing both overall efficiency and localized mixing challenges.

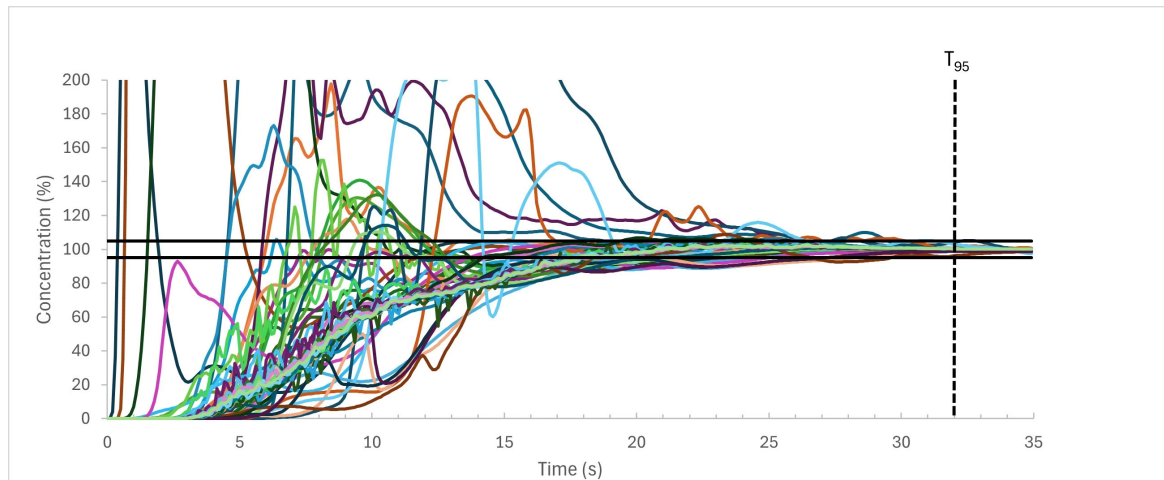


Fig 10. The tracer concentration was captured over time and the slowest T_{95} mixing time for all probes was estimated, which is termed as the slowest T_{95} mixing time.

RESULTS: CFD SIMULATIONS

Single-phase simulations

- Single-phase CFD simulations were performed for the operating conditions listed in Table 6 to estimate the power number (Fig 11) and determine the impeller speeds (Fig 12) corresponding to the required power-per-unit-volume (P/V) at each fill volume.
- These calculations ensure consistent energy input across different volumes, supporting scalability and process optimization.

A detailed summary of all computed values is provided in the Appendix (Table 6) for reference.

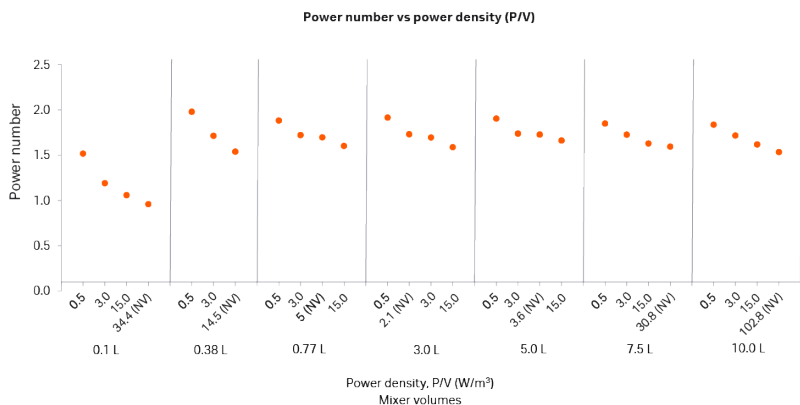


Fig 11. Power number with respect to power density (P/V) for each volume, analyzed at four different power densities (P/V).

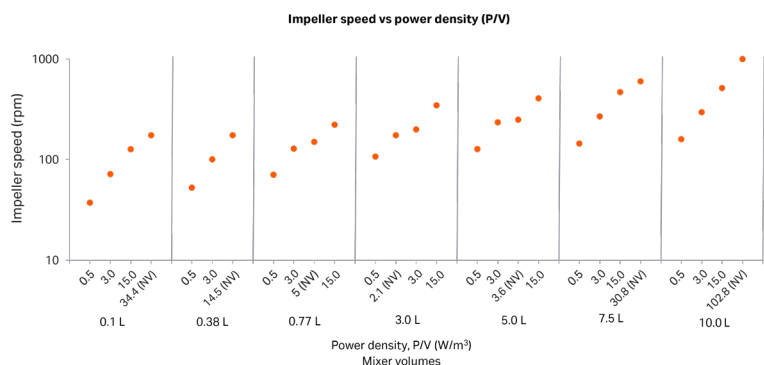


Fig 12. Impeller speed with respect to power density (P/V) for each volume, analyzed at four different power densities (P/V).

Mixing analysis simulations

- Mixing time simulations were performed using the species transport model for all fill volumes at the impeller speeds determined through single-phase analysis.
- Figure 13 illustrates the relationship between the slowest T_{95} mixing time and power-per-unit-volume (P/V).
- The results show a clear trend: Faster mixing time was observed in the single-use mixing base compared to mixing speeds that occur at the transition area between the base and the film.
- For given P/V ratios, mixing times are longer but homogeneity was achieved. Volumes which required the longest time to achieve homogeneity was 0.77 L.
- Higher P/V values lead to faster mixing times, which is attributed to the increased turbulence and energy dissipation.

For lower fill volumes, fewer probes were sufficient:

- At 3 L, only three levels were used in the tank (TH, TL, TB, and TC) to cover the fluid domain.
- At 0.77 L, two levels (TL, TB, and TC) were adequate to capture mixing time, as they span the entire fluid region.

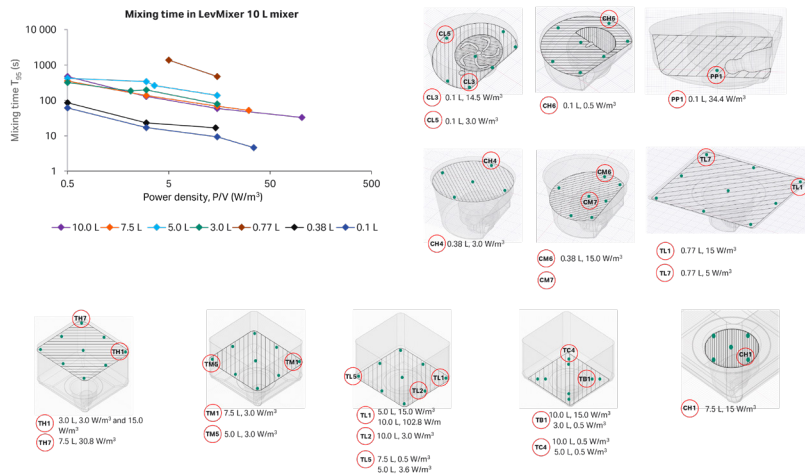


Fig 13. Trendlines showing the slowest T_{95} mixing times and the locations of the regions with the slowest mixing for each volume, analyzed at four different levels of P/V . The tank shape depicted in the figure serves as a reference image for illustrating the probe map and does not represent the actual volume.

COMPARISON OF ACTUAL EXPERIMENTS AND CFD SIMULATIONS

The mixing time values predicted by CFD were compared with experimental results for fluids of 2.67 cP and 25 cP viscosity, as shown graphically in Figure 14.

- Overall, CFD predictions closely align with experimental observations at higher power densities (P/V) of 3.0 W/m^3 and 15.0 W/m^3 , as well as under no-vortex agitation, across all tested volumes.
- At lower P/V (0.5 W/m^3), discrepancies were observed: In the 10 L and 5 L vessels with 2.67 cP fluid, experimental results indicated slower mixing times compared to CFD predictions.
- CFD analysis confirmed that homogeneity was achieved for all tested fill volumes and agitation conditions, reinforcing the robustness of the mixing performance across the operating range.

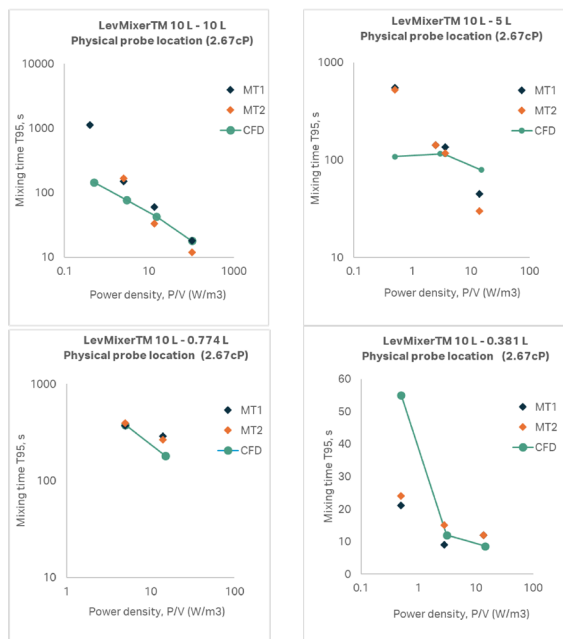


Fig 14. Comparison of CFD predicted mixing time vs actual experiments at various fill volumes.

Velocity contour

The velocity contours for all fill volumes of the 10 L systems under no-vortex agitation are presented in Figure 15.

- To enhance visualization, the velocity scale in all contour plots is capped at 0.5 m/s. Areas closest to the impeller show significantly higher velocities, while velocity gradually decreases with distance from the impeller.
- This pattern reflects the natural dissipation of kinetic energy as the fluid moves outward.

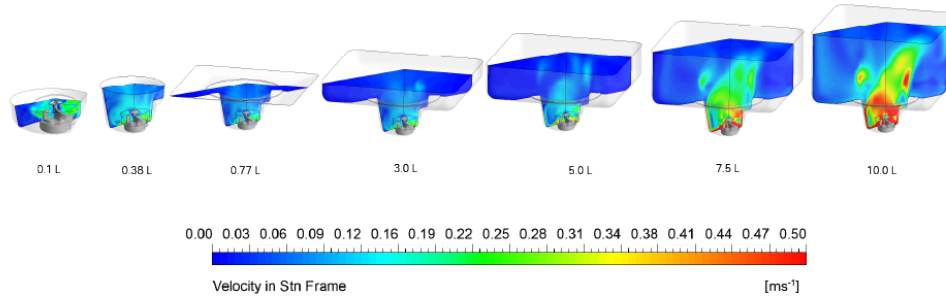


Fig 15. Velocity contours at mid- and cross-sectional planes for each volume at no vortex agitation.

Kolmogorov eddy

The Kolmogorov eddy size defines the smallest scale of turbulence in fluid flow. If the Kolmogorov eddy size is smaller than the biological entity, it is likely to be damaged by turbulence (1). The calculation method is provided earlier in Equation 4. For visualization, contour plots were limited to eddy sizes between 1 μm and 1000 μm . These plots reveal that:

- The smallest eddies occur near the impeller blades.
- Minimum eddy size observed was 10.3 μm —much larger than typical biological molecules or nanoscopic systems of interest (e.g., monoclonal antibodies, viruses, recombinant proteins).
- Away from the impeller, eddy sizes increase significantly, suggesting that shear forces are unlikely to cause aggregation or denaturation of these entities (1,2).

The minimum Kolmogorov eddy size is plotted in Figure 16, with corresponding values listed in Table 7 in the appendix. Figure 17 shows contour plots of the Kolmogorov eddy size for the fill volume under no-vortex agitation.

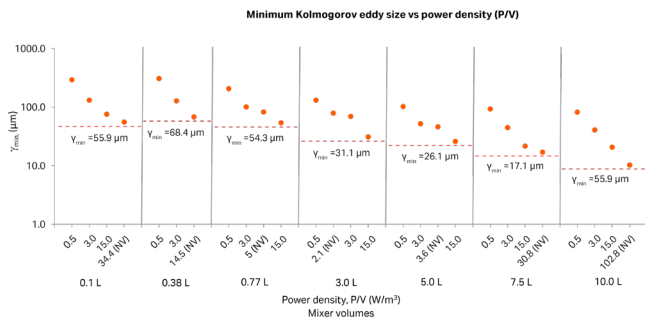


Fig 16. Kolmogorov eddy size with respect to power density (P/V) for each volume, analyzed at four different power densities (P/V).

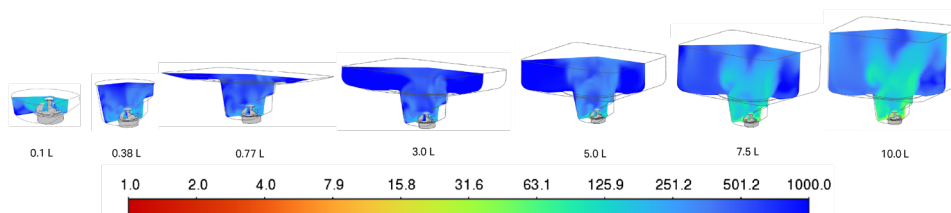


Fig 17. Kolmogorov eddy contours at mid- and cross-sectional planes for each volume at no vortex agitation.

Shear rate

- Shear rate analysis shows that values increase significantly at fill volumes above 5 L. For visualization purposes, the contour plots were limited to a maximum shear rate of 200 s^{-1} .
- These plots indicate that regions of elevated shear are concentrated near the impeller blades. The highest shear rate recorded was 598.2 s^{-1} in the 10 L fill volume operating at 1000 rpm. Despite this, shear-induced protein damage is considered highly unlikely, as literature reports negligible aggregation even at shear rates exceeding 101 s^{-1} (3).
- To provide further insight, Figure 18 illustrates how the average shear rate in the impeller zone varies with power density (P/V) across different volumes, analyzed at four power density levels.
- Figure 19 complements this by showing shear rate contours at both the mid-plane and cross-section for each volume under no-vortex agitation.

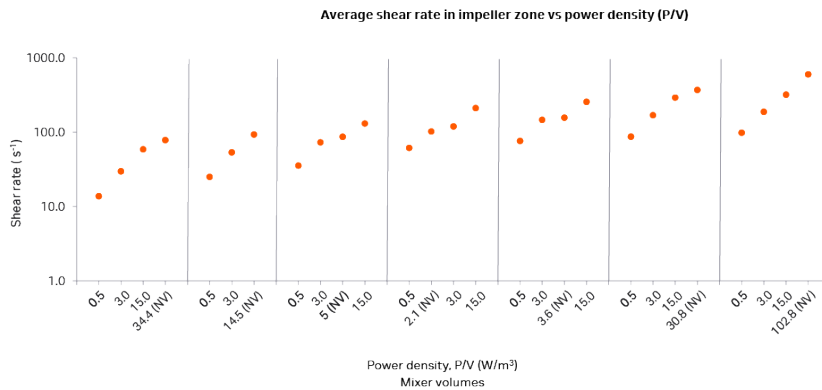


Fig 18. Average shear rate in impeller zone with respect to power density (P/V) for each volume, analyzed at four different P/V .

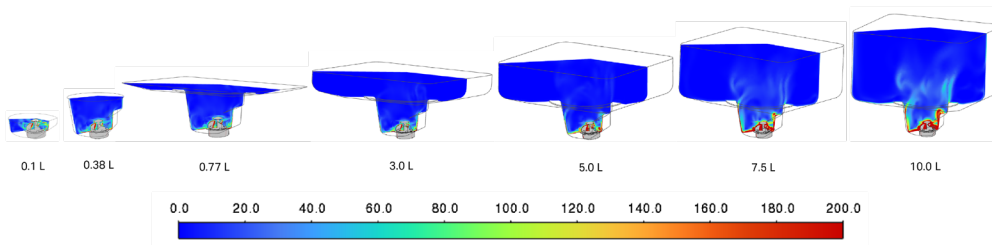


Fig 19. Shear rate contours at mid- and cross-sectional planes for each volume at no vortex agitation.

SCALABILITY

Scalable mixing strategies are critical for ensuring consistent performance across mixer tank sizes. To support scalability, approaches based on power input (P/V) and mixing time (T_{95}) are presented in this section.

These parameters are used to characterize the 10 L system relative to LevMixer 50 to 1600 L systems, enabling criterion-based comparisons across scales.

Power-input-based comparison

To achieve consistent power input across mixers, impeller speeds for the 50 to 1600 L systems were calculated at three target power-per-unit-volume (P/V) levels at 100% fill volumes using the respective power number data provided in this application note (4).

These calculated speeds were then used to estimate mixing times for each system through CFD simulations.

The results are illustrated in Figure 20, with detailed values reported in Table 8 in the appendix.

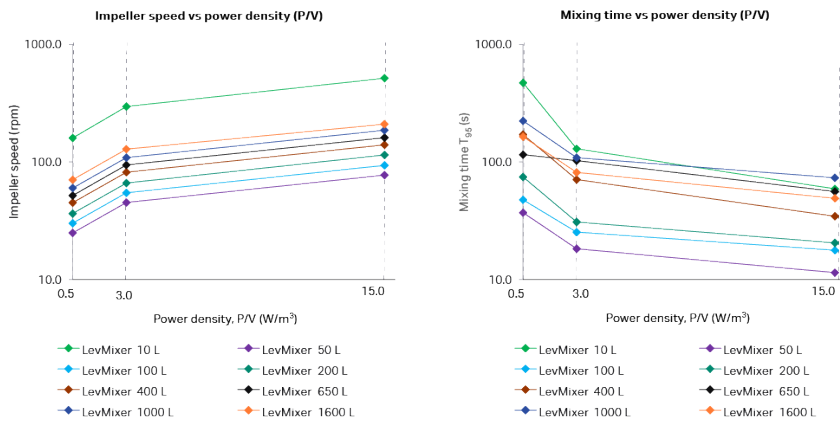


Fig 20. Power-input based comparison between LevMixer 10 to 1600 L systems at 100% fill volumes.

Mixing time-based comparison

- To achieve a target T_{95} mixing time range of 30 to 60 s, impeller speeds for the 50 to 1600 L systems at 100% fill volumes were estimated using CFD simulations.
- Results are presented graphically in Figure 21, with detailed values provided in Table 9 in the appendix.

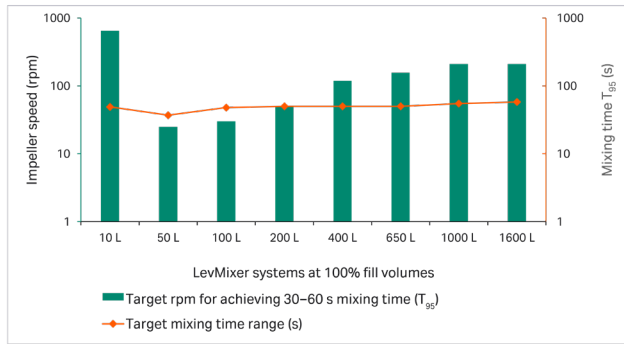


Fig 21. Mixing time-based comparison between LevMixer 10 to 1600 L systems at 100% fill volumes.

Conclusions

We evaluated the mixing performance of the LevMixer 10 L mixer through a combination of physical experiments and advanced CFD simulations. The results demonstrate that the 10 L system supports criterion-based comparison across scales under the tested operating conditions.

Key findings include:

- Vortex-free operation: Across all tested volumes and fluid viscosities, the mixer achieved no-vortex conditions at defined impeller speeds.
- Rapid and uniform mixing: At 10 L, $T_{95} = 18$ s (2.67 cP) and 33 s (25 cP) under no-vortex speeds; homogeneity achieved across all tested volumes.
- CFD validation and predictive capability: CFD predictions aligned well with experimental results at higher power densities (P/V) and under no-vortex conditions, with minor discrepancies observed at very low P/V values.
- Gentle mixing environment: CFD analysis of shear rates and Kolmogorov eddy scales confirmed that the 10 L system operates well within acceptable limits, avoiding damage to sensitive molecules such as mAbs and recombinant proteins.
- Criterion-based scale-up: The study defined comparison criteria based on power input (P/V) and mixing time (T_{95}). These criteria were evaluated at nominal volumes and support criterion-based comparison between the LevMixer 10 L and 50 to 1600 L systems, as well as *vice versa*.

RECOMMENDATIONS AND FREQUENTLY ASKED QUESTIONS (FAQ)

You can use the characterization data produced in this application note to help determine the working speed range for the different fill volumes we selected and studied.

When homogenization time is not a critical factor, we recommend operating at a lower speed without vortex formation. Conversely, selecting the highest speed that still avoids vortex formation can be considered when faster mixing is desired, provided this is balanced against the need to minimize the risk of introducing unwanted air bubbles.

In summary, the 10 L single-use mixing system combines rapid, homogeneous mixing with vortex-free operation and gentle handling of shear-sensitive products. Supported by physical experiments and CFD modeling, the results demonstrate that the 10 L system provides a well-characterized mixing performance that supports criterion-based comparison across scales for bioprocessing applications where efficiency, product integrity, and process predictability are critical.

FREQUENTLY ASKED QUESTIONS (FAQ)

Q1. Why avoid vortex formation?

A stable vortex increases air-liquid interfacial area and entrainment, which can raise aggregation risks for proteins and other shear-sensitive products. Operating below the no-vortex rpm minimizes this risk.

Q2. How is T_{95} defined and measured?

T_{95} is the time to reach 95% of the final conductivity after tracer addition and remain within $\pm 5\%$. We used a calibrated conductivity probe sampling every 3 s; each condition was run in duplicate.

Q3. Which volume was most challenging?

0.77 L showed longer T_{95} driven by shallow fluid depth and transition geometry near the container bottom. Homogeneity was still achieved; higher rpm within no-vortex boundaries helps.

Q4. How does CFD help in practice?

CFD provides power draw, P/V normalization, and mixing predictions across volumes and speeds, reducing experimental burden. It also quantitates shear and eddy scales to assess product safety.

Q5. What scaling approach should I use—P/V or T_{95} ?

Use P/V matching to keep energy input consistent across scales (good for comparability and tech transfer). Use target T_{95} when a specific mixing time is the process constraint (e.g., dissolution, inline dosing).

Q6. Are shear rates safe for proteins?

Yes. Observed max shear $\approx 598 \text{ s}^{-1}$ and eddy scales $\geq 10 \text{ }\mu\text{m}$ are well below levels generally associated with protein damage ($> 10^5 \text{ s}^{-1}$ in many reports) (1–3).

Q7. Can I expect the same results with other solutes/sensors?

Trends are robust, but absolute T_{95} may vary with sensor placement, signal response, temperature, and fluid properties. Confirm critical setpoints experimentally.

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APPENDIX

Results of the single-phase simulations

Table 6. Results of single-phase analysis—estimation of the power number and impeller speed

LevMixer model	Volume (L)	P/V (W/m ³)	Power number	Agitation (rpm)
10	0.1	0.1	1.52	37.4
		2.9	1.19	71.7
		14.5	1.06	127.0
		34.4	0.96	175 (NV)
	0.38	0.5	1.98	52.7
		3.1	1.71	100.6
		14.5	1.54	175 (NV)
	0.77	0.6	1.88	70.84
		3.2	1.72	128.73
		5.0	1.70	150 (NV)
		15.2	1.60	222.1
	3.0	0.5	1.91	107.3
		2.1	1.73	175 (NV)
		3.0	1.69	200.0
		14.8	1.59	347.0
	5.0	0.5	1.90	127.5
		3.0	1.74	234.8
		3.6	1.73	250 (NV)
		15.0	1.66	407.3
	7.5	0.5	1.85	144.6
		3.0	1.73	269.2
		15.0	1.63	468.8
		30.8	1.59	600 (NV)
	10.0	0.5	1.84	160.0
		3.0	1.72	296.4
		14.9	1.62	515.8
		102.8	1.53	1000 (NV)

* NV = No vortex

Results of mixing time simulations

Table 7. Results of CFD mixing analysis–estimation of T_{95} mixing time

Volume(L)	P/V(W/m ³)	Power number	Agitation (rpm)	CFD average T_{95} mixing time (s)	CFD slowest T_{95} mixing time (s)	Probe location of slowest mixing	Kolmogorov eddy size (μ m)	Average shear rate in impeller zone (s ⁻¹)
0.1	0.5	1.52	37.4	25.1	34.9	CH6	294.3	13.8
	2.9	1.19	71.7	9.6	12.8	CL5	131.7	29.8
	14.5	1.06	127.0	4.5	6.2	CL3	75.8	58.9
	34.4	0.96	175.0 (NV)	4.1	4.6	PP1	55.9	78.3
0.38	0.5	1.98	52.7	59.2	67.7	CM7	307.9	25.1
	3.1	1.71	100.6	13.8	23.1	CH4	128.5	53.4
	14.5	1.54	175.0 (NV)	10.8	16.8	CM6	68.4	93.0
0.77	5.0	1.70	150.0 (NV)	494.7	1370.7	TL7	82.8	86.5
	15.2	1.60	222.1	216.3	470.5	TL1	54.3	130.9
3.0	0.5	1.91	107.3	230.2	319.4	TB1	132.0	61.6
	2.1	1.73	175.0 (NV)	88.3	184.3	TH7	79.3	102.1
	3.0	1.69	200.0	73.3	196.9	TH1	69.5	119.3
	14.8	1.59	347.0	31.1	79.2	TH1	31.1	211.0
5.0	0.5	1.90	127.5	125.6	418.1	TC4	102.7	76.3
	3.0	1.74	234.8	132.0	338.9	TM5	52.3	146.5
	3.6	1.73	250.0 (NV)	126.7	261.8	TL5	46.3	156.7
	15.0	1.66	407.3	80.7	138.1	TL1	26.1	255.3
7.5	0.5	1.85	144.6	171.9	350.7	TL5	93.5	87.0
	3.0	1.73	269.2	92.4	137.1	TM1	44.8	169.1
	15.0	1.63	468.8	50.1	68.3	CH1	21.7	291.2
	30.8	1.59	600.0 (NV)	38.4	52.2	TH1	17.1	369.1

* NV = No vortex

Power/density-based comparison

Table 8. P/V based comparison data for LevMixer 10 to 1600 L systems at 100% fill volumes

LevMixer model	Volume (L)	P/V (W/m ³)		
		0.5	3	15
		Mixing time (s) (agitation [rpm])		
10	10	471.4 (160)	129.6 (296.4)	59 (515.8)
50	50	37.1 (24.9)	18.3 (45.3)	11.5 (77.4)
100	100	47.6 (30.1)	25.3 (54.7)	17.8 (93.6)
200	200	74.5 (36.5)	30.9 (66.3)	20.5 (114.8)
400	400	171.3 (45)	71 (81.8)	34.5 (139.9)
650	650	115.5 (51.9)	102.6 (94.3)	56 (161.2)
1000	1000	223.8 (60)	108.8 (109)	73.4 (186.3)
1600	1600	163.9 (70.7)	81.5 (128.5)	49.1 (210) *

* The 1600 L system reaches a maximum P/V of 13.4 W/m³ at 210 rpm.



Mixing-time based comparison

Table 9. PMixing-time based comparison data for LevMixer 10 to 1600 L systems at 100% fill volumes

Target rpm for achieving 30– 60 s T_{95} mixing time				
LevMixer model	Volume (L)	Mixing time (s)	Agitation (rpm)	P/V (W/m ³)
10	10	49	650	29.4
50	50	37	25	0.5
100	100	48	30.1	0.5
200	200	50	49	1.2
400	400	50	118.5	9.3
650	650	50	156	13.8
1000	1000	55	210	21.6
1600	1600	58	210	13.6

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