Structural Optimization and Energy-Saving Study of a Dynamic Inline Mixer for High-Viscosity Fluids

Abstract

To address industrial challenges in the mixing of high-viscosity fluids（>50 Pa·s）, including high energy consumption, low mixing efficiency, and the tendency to form dead zones, this study investigates a multistage rotor–stator mixer. By combining computational fluid dynamics (CFD) simulations with experimental validation, the effects of operating and structural parameters on mixing performance were systematically evaluated.The study focused on the pre-distribution mechanism of the distributor and the effect of straight blades in enhancing circumferential mixing. An integrated optimization scheme was developed, incorporating an X1 rectangular distributor, optimized shear gaps, and a 16Y-4P composite rotor. Results show that, at a low rotational speed of 3.33 $r \cdot s^{-1}$, the addition of the X1 distributor significantly improved the mixing index with only a slight increase in power consumption. Under operating conditions of 6.67 $r \cdot s^{-1}$, the optimized 16Y-4P configuration demonstrated excellent mixing performance and significantly improved energy efficiency compared with a conventional 20-stage rotor–stator structureThis study provides a solid theoretical basis and supporting data for the iterative development and industrial scale-up design of FLUKO high-viscosity mixing equipment.

Keywords: Multistage Rotor–Stator Mixer; Structural Optimization; Computational Fluid Dynamics (CFD); High-Viscosity Fluids; Mixing Index; Power Consumption

1 Introduction

High-viscosity fluid mixing is a critical unit operation in fine chemicals, polymer materials, new-energy batteries, and food and pharmaceutical processing. Multistage rotor–stator mixers are widely used for the continuous mixing of high-viscosity materials because of their narrow shear gaps, large-diameter rotors, effective self-cleaning capability, and minimal dead zones. However, their high manufacturing cost and energy consumption remain significant limitations.This study aims to improve mixing performance under high-viscosity operating conditions through structural optimization, without a significant increase in energy consumption, while balancing high throughput with low power consumption.

Based on the chemical machinery research platform at Tianjin University, this study uses numerical simulation to investigate the stretching, folding, and displacement mechanisms of fluids under high-viscosity laminar-flow conditions. Through structural innovation, it aims to overcome the energy-efficiency limitations of existing equipment.

2 Numerical Simulation Methodology and Experimental Validation

2.1 Geometric Modeling and Mesh Generation

A typical multistage rotor–stator structure was selected as the baseline model (Baseline T1). To explore the potential for structural optimization, 24 distributor models incorporating sector-shaped and rectangular channels were developed, together with a composite rotor model (16Y-4P) consisting of straight blades and shear teeth. An unstructured mesh was used for the computational domain. Following mesh-independence verification, the model without a distributor employed 20.8 million cells, while the models with distributors employed 20.5 million cells to ensure computational accuracy.

2.2 Simulation Setup

Considering the flow characteristics of high-viscosity fluids, the normalized Reynolds number was set to Re* < 0.02, and a laminar-flow model was applied. The multiple reference frame (MRF) method was used to model rotor rotation. The working medium was a high-viscosity fluid with a density of 1,500 kg·m^{-3}, including Newtonian fluids (1–200 Pa·s) and power-law non-Newtonian fluids (n = 0.6–1.0).

2.3 Model Validation

To verify the engineering applicability of the simulation results, a 3D-printed structural model of the rotor–stator assembly was fabricated. A torque sensor was used to collect shaft power data in real time, with corn syrup serving as the test medium. The results showed that the mean deviation between CFD predictions and experimental values was 6.7%, with a maximum deviation of 17.2%, demonstrating that this simulation approach can guide the scale-up and design optimization of Industrial equipment.

Simulated Rotor–Stator Structure

3 Results and Discussion

3.1 Performance Analysis Under Baseline Conditions (Without a Distributor)

The study of the standard T1 model showed the following::

- **Flow Rate and Rotational Speed**: At ten times the standard processing capacity (residence time: 1.1 s), increasing the rotational speed to 16.67 $r \cdot s^{-1}$ resulted in a high mixing index, but power consumption surged to tens of thousands of watts. Simply increasing rotational speed is therefore not an economical or efficient solution.

- **Structural Parameters**: Increasing the number of mixing stages improved mixing performance, but with diminishing marginal benefits. Rotor–stator tooth number and tooth angle had relatively limited effects on the mixing index, while directly affecting power consumption.

- **Correlation Development**: Dimensionless correlations were established by fitting the mixing index and power consumption as functions of flow rate, rotational speed, and number of stages.

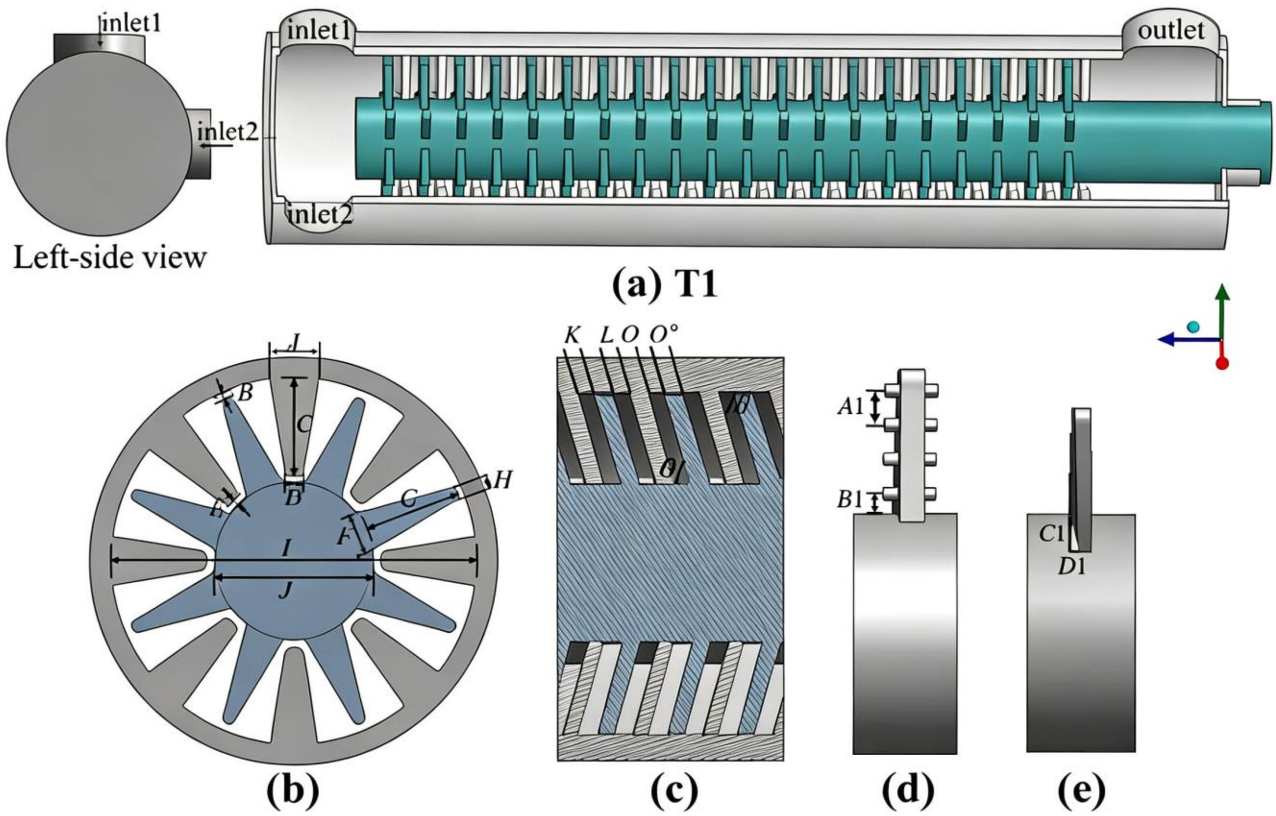


Fig. 2-1 (1) Multistage rotor-stator mixer with 8-teeth rotor-stator in the absence of the distributor(T1);(b) Radial section ofT1;(c-e) Different rotor-stator structures.

Table 2-1 Variables of multistage rotor-stator mixer with 8-teeth rotor-stator and different rotor-stator.

Variable	*A*	*B*	*C*	*D*	*E*	*F*
Value/m	0.0109	0.0015	0.0212	0.0040	0.0015	0.0091
Variable	*G*	*H*	*I*	*J*	*K*	*L*
Value/m	0.0212	0.0026	0.0804	0.0350	0.0046	0.0040
Variable	*O*	*Q**	*A*1	*B*1	*C*1	*D*1
Value/m	0.0031	0.0035	0.0050	0.0030	0.0091	0.0020

3.2 Study of the Distributor Enhancement Mechanism

Optimization of the equipment inlet structure was one of the core aspects of this study。

- **Pre-Distribution Effect**： Simulations showed that the distributor enables preliminary mixing of the feed before it enters the rotor–stator shear zone, thereby improving the mixing index and substantially shortening the subsequent homogenization path.

- **Optimal Structural Design**: A comparison between sector-shaped and rectangular channels showed that the X1 distributor with rectangular channels delivered the best performance. At a low rotational speed of 3.33 $r·s^{-1}$, the X1-T1 configuration achieved a mixing index of approximately 0.8, approaching the performance of the baseline model at 13.33 $r{\cdot}s^{-1}$, while consuming less than half the power. This indicates that efficient mixing can be achieved using a low-speed, high-torque motor configuration, significantly reducing both equipment procurement and operating costs.

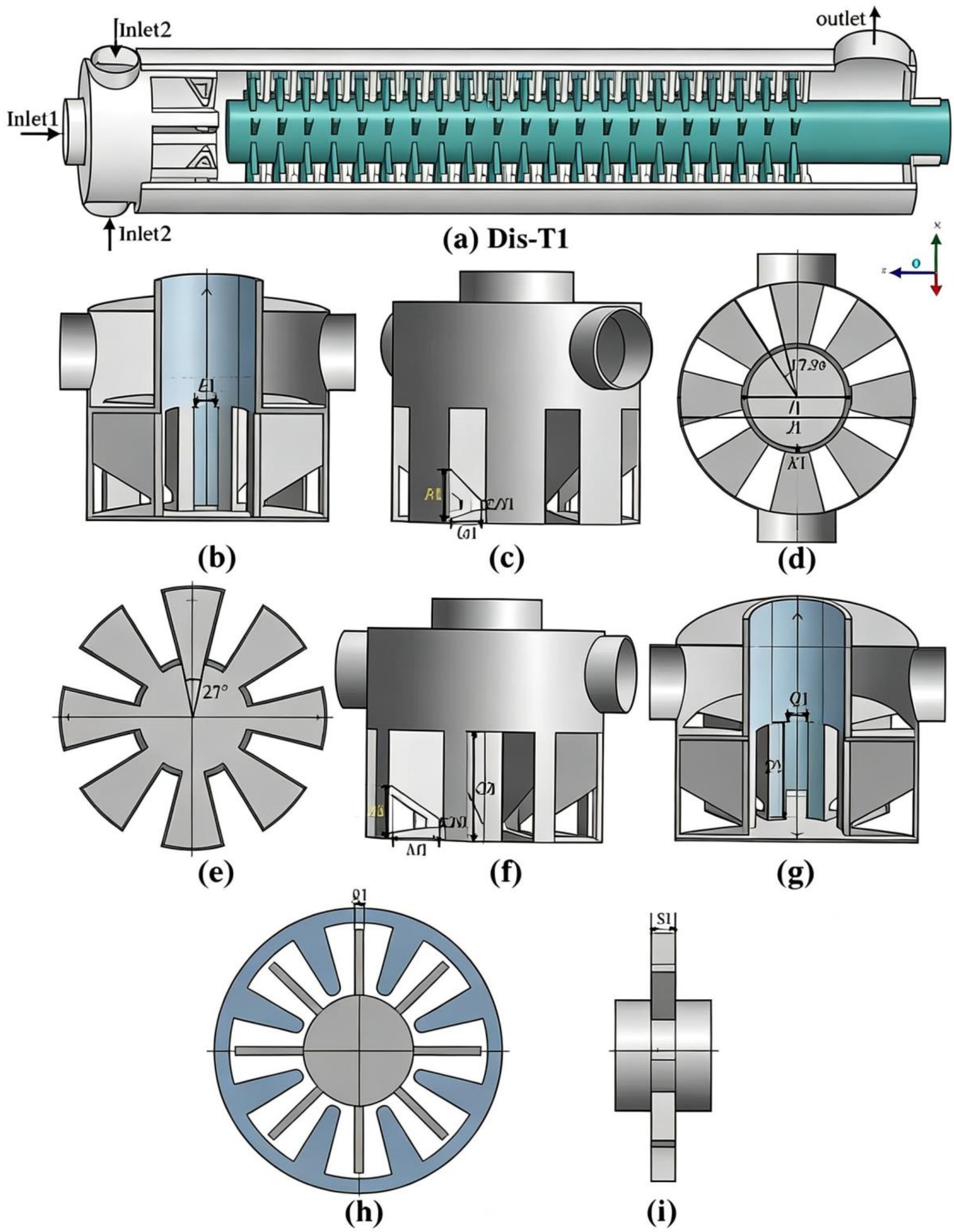


Figure 2-2 (a) Eight-stage multistage rotor-stator mixer with a distributor (Dis-T1); (b-e) distributor structure with sector-shaped channels; (d, f, g) distributor structure with rectangular channels; (h, i) straight-blade structure (b, g: axial sectional views; d, e: radial sectional views).

3.3 Optimization of the FLUKO 16Y-4P Composite Rotor

To further improve performance, a composite rotor (16Y-4P), combining shear teeth and straight blades, was developed based on the X1 distributor:

- **Shear-Gap Optimization**: Appropriately increasing the shear gap not only reduced pressure drop and torque, but also extended material residence time, resulting in a corresponding improvement in the mixing index.

- **Effect of Straight Blades**: Four stages of straight blades were introduced to enhance circumferential circulation, addressing the issue of good radial mixing but circumferential stratification in high-viscosity fluids.

- **Final Performance**: Under operating conditions of 6.67 $r \cdot s^{-1}$, the 16Y-4P model achieved an excellent mixing index while maintaining power consumption below 5 kW. Compared with the 20-stage baseline model, it delivered a higher mixing standard with substantial energy savings.

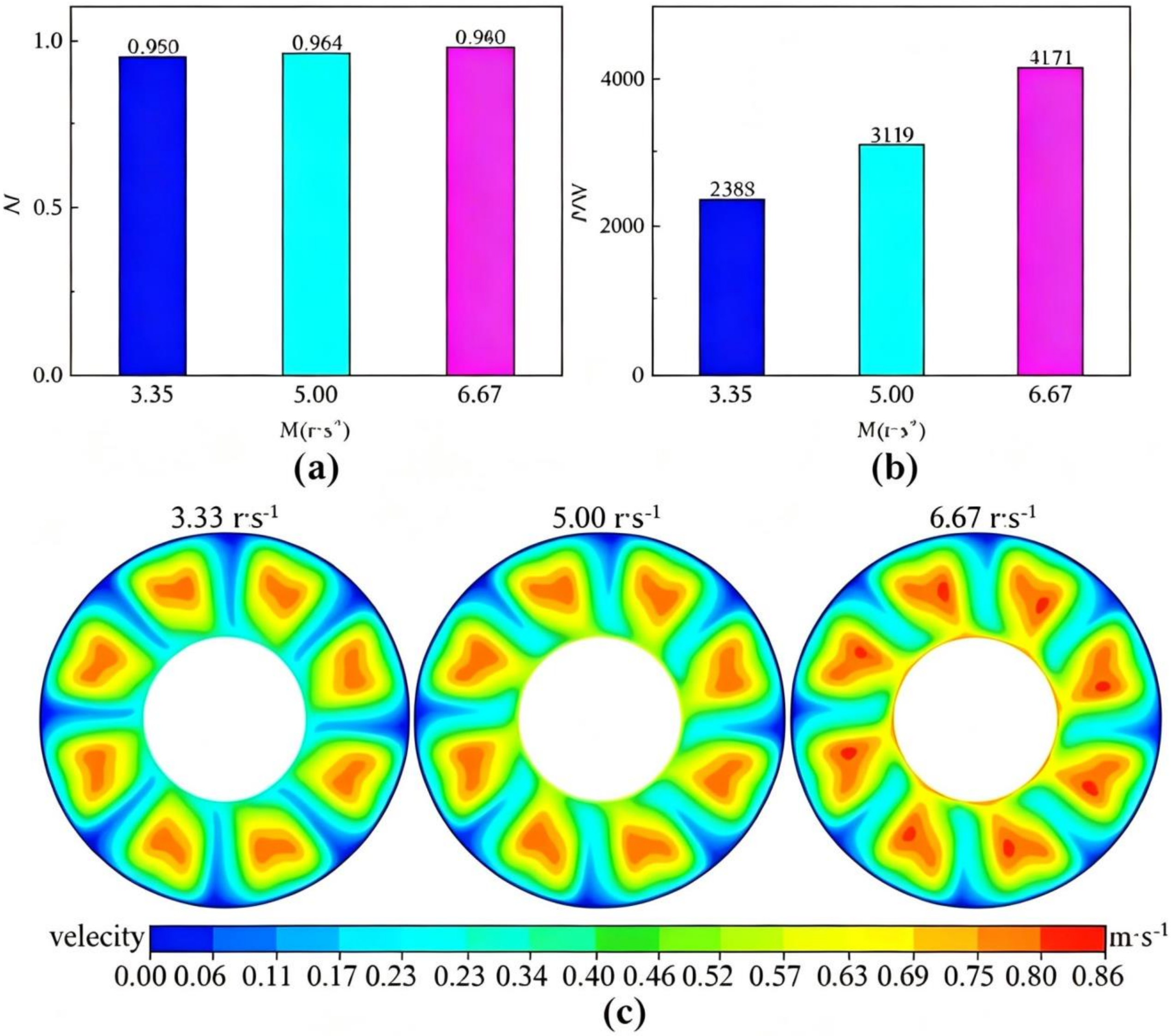


Figure 4-9 At different rotational speeds, (a) outlet mixing index and (b) power consumption of the 16Y-4P mixer; (c) velocity contours of the x-y cross-section 0.002 m downstream of the fourth-stage stator (total inlet flow rate: 14.1×10^{-4} $m^3 \cdot s^{-1}$; equal inlet flow rates).

3.4 Operational Flexibility and Material Compatibility

The optimized model demonstrated excellent adaptability for engineering applications:

- **Strong Flow-Rate Ratio Adaptability:** The mixing index showed minimal variation when the inlet flow-rate ratio changed within the operating range, making the mixer suitable for processes with unstable feed rates.

- **Broad Material Compatibility:** The mixer delivered excellent performance with Newtonian fluids having viscosities of 1–200 Pa·s, as well as shear-thinning non-Newtonian fluids. It is particularly well suited to current application requirements for lithium-ion battery slurries, polymer solutions, food products, and similar materials.

4. Engineering Significance and Practical Applications

1. Theoretical Contribution: This study reveals the synergistic mechanism between feed pre-distribution and circumferential intensification by straight blades in the laminar mixing of high-viscosity fluids. It also provides a theoretical model for the scale-up design of multistage rotor–stator mixers.

2. Product Upgrade: The proposed X1 rectangular distributor and 16Y-4P composite rotor can be directly applied to the development of FLUKO's next-generation high-viscosity mixing equipment. This solution achieves low-speed, low-power, and high-uniformity operation, addressing the energy-consumption challenge associated with high-throughput processing.

3. Practical Engineering Applications:

(1) Silicone Oil Emulsification and Polymer Dispersion

Typical applications include emulsions composed of silicone oil, water, and emulsifier, as well as dispersions of polymers and steam. Silicone-oil-based emulsions commonly have viscosities in the range of 10^5 – 10^6 cP. Conventional batch vessels may require several hours to produce a uniform emulsion, whereas dynamic mixers can achieve uniform mixing at high throughput with short residence times through continuous inline processing. The pre-distribution mechanism of the X1 distributor ensures that multiple components form alternating pre-mixed layers before entering the main shear zone, substantially shortening the subsequent homogenization path. This directly addresses common challenges in silicone oil emulsion production, such as agglomeration and uneven dispersion.

(2) Continuous Mixing for Polyurethane Foaming

Polyols and catalysts are pumped into the inline mixer by external pumps, while the blowing agent is injected upstream of the mixer inlet. Rapid, uniform mixing and initial reaction take place within the mixing chamber. This application requires precise proportional pre-distribution of multiple material streams, which is precisely the core capability of the X1 rectangular distributor. The structure offers excellent operational flexibility and is fully capable of handling multi-stream feed processes such as polyurethane foaming.

(3) Food and Shear-Sensitive Materials

Dynamic mixers also have well-established applications in the food industry:

Mayonnaise and dressings: pre-mixing of egg yolk, oil, and vinegar solution

Marshmallow aeration: egg white, sugar–water–glucose mixture, and air → fine-cell foam

Processed cheese: efficient cooking of cheese using steam

Yogurt and fruit preparations: uniform blending of fruit preparations into yogurt at 4–12 °C, including fruit pieces larger than 15 mm

Pet food: dynamic mixing of cooked meat with solid or powdered additives

Peanut butter and solids/powders: continuous mixing of pumped peanut butter with solid powders at 40–55 °C

Chocolate and nuts: continuous mixing of tempered chocolate with nuts

These materials are generally high-viscosity and shear-sensitive systems. These cases demonstrate that lower-torque drive motors and gentler shear treatment can be used, aligning well with the need to protect shear-sensitive materials in the food and pharmaceutical industries.

(4) Chemical Industry Applications

Vegetable oil + methanol/methyl ester (pre-mixing for biodiesel transesterification)Latex + vulcanizing paste + gelling agent (foam rubber)

Bitumen + polymer + acid + binder (modified bitumen)

4. Application Value: For FLUKO, these research outcomes can enhance the competitiveness of its products in high-end markets. In particular, when replacing conventional energy-intensive mixing equipment, such as double planetary mixers, the optimized solution offers clear energy-saving advantages and technological differentiation.

5 Recommendations and Outlook

Key Innovations:

- Dimensionless correlations between the mixing index (M) and power consumption (P) were established for the first time for a multistage rotor–stator mixer operating without a distributor.

- A combined optimization strategy was proposed, integrating distributor pre-distribution, enhanced circumferential mixing by straight blades, and enlarged shear gaps. This approach overcomes the energy-consumption limitations associated with simply increasing the number of stages or rotational speed.

Outlook:

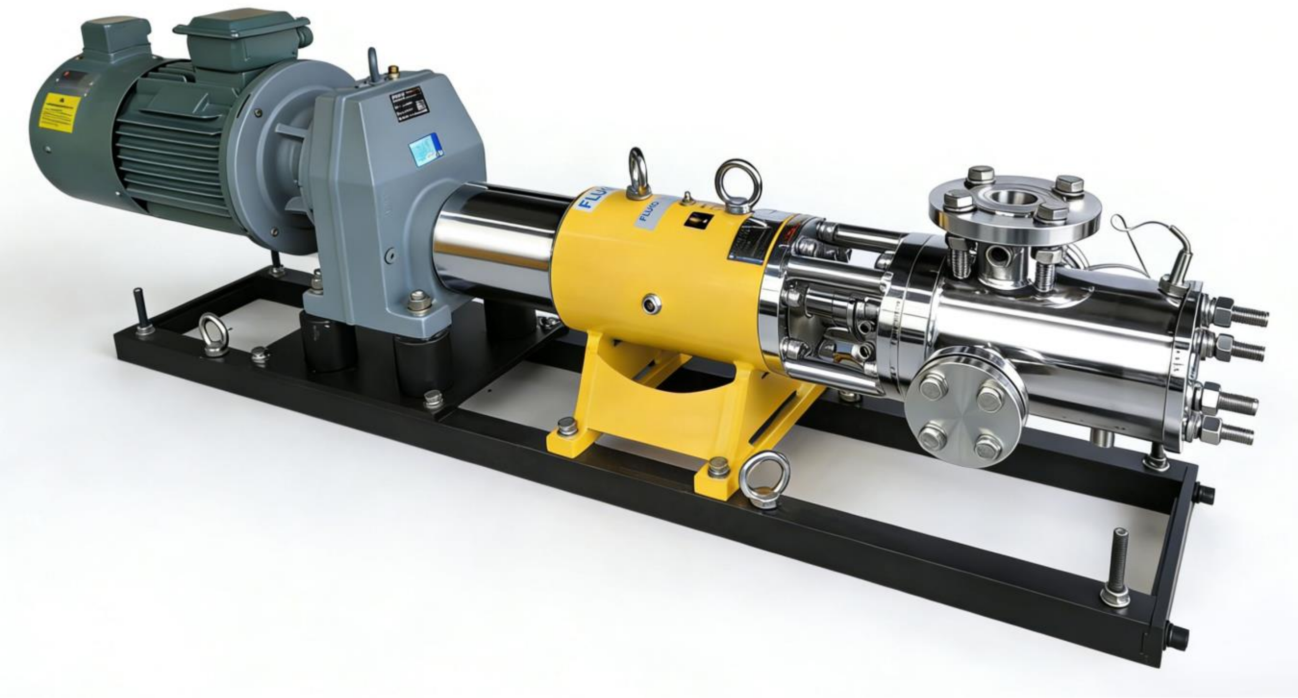
- The current study focuses only on Newtonian fluids and shear-thinning power-law fluids. Future research may be extended to more complex rheological systems, including Bingham and thixotropic fluids.
- Mixing-dominated chemical reactions and two-phase mixing processes may also be investigated to explore the potential of the mixer as a reactor.

6 Product Introduction

- The FDLS2/15, a representative model of FLUKO's FDLS2 series, is a truly low-temperature-rise, low-shear-damage dynamic inline mixing system. During mixing, the material temperature rise does not exceed 1 °C. It can process extremely shear-sensitive materials, such as foams, without causing product damage.

- The FDLS2 series is a proprietary Dynamic Inline Mixer developed by FLUKO and forms part of the company's Process Intensification Reactor and Dynamic Mixing Reactor product portfolio. It is specifically designed for the homogeneous mixing of shear-sensitive, high-viscosity liquids. It is particularly effective at uniformly incorporating additives such as flavors, colorants, and emulsifiers into high-viscosity materials including fats and chocolate, achieving complete mixing uniformity even at very low additive ratios.

- The series fills the gap left by conventional high-shear dispersing and emulsifying machines in gentle-mixing applications. It offers broad application potential in food processing, including chocolate, fats, and dairy products, as well as in the personal care, pharmaceutical, and chemical industries. It is an important part of FLUKO's Process Intensification Reactor product portfolio.



The related findings of this study were published online in May 2021 in the Chinese Journal of Chemical Engineering, under the title "Optimization of Multistage Rotor–Stator Mixer Structure for Enhanced Mixing of High-Viscosity Fluids," by Chen, Liying; Zhang, Jinli; et al.