Effect of the stator tooth thickness on flow characteristics of high shear mixer

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Abstract. Due to the complexity of flow field in high shear mixer, it is very difficult to measure the flow field in full three-dimensional. CFD simulation has become a powerful means in mixer research. In this study, large eddy simulation (LES) was used to simulate the single-phase flow field of a pilot scale in-line high shear mixer with ultra-fine teeth. The research results show that with the increase of the stator tooth thickness, the turbulence intensity and eddy current intensity around the outermost stator increase slightly, and the shear rate area with a larger value change slightly. This means that the stator tooth thickness has a slight effect on the flow field. These results provide important guidance for the design and optimization of high shear mixer structure.

1. Introduction

In recent years, high shear mixers have been widely used in the chemical, petroleum, pharmaceutical and food industries due to the characteristics of high linear velocity at the end of the rotor, high shear rate, and high energy dissipation rate near the shear head [1]. Compared with batch high-shear equipment, in-line high-shear mixer has the advantages of continuous operation, convenient automatic control and large processing capacity, which is suitable for large-scale applications. The size of particles, droplets or bubbles produced by the high-shear mixer is closely related to the size of the stator and rotor slots.

Through experiments and numerical simulation, various attempts have been made to the flow characteristics and power consumption of the shear mixer. Padron (2001) [2] studied the flow characteristics and power consumption of different components of intermittent high shear mixer, and found that the power criterion has nothing to do with the Reynolds number in the turbulent flow, and the power criterion is inversely proportional to the Reynolds number in the laminar flow. The research results show that the power number P0 in the laminar flow has nothing to do with the configuration of the stator, and the power criterion in the turbulent flow is constant and related to the stator structure. Doucet et al. (2005) [3] also reached a similar conclusion. In the past few years, people have proposed different models to expand batch and in-line high shear mixer. Schönstedt et al. (2015) [4] proposed a new model to improve power consumption in in-line high shear mixer to achieve high precision.

The design of the high shear mixer is very complicated. Due to the high shear rate, the flow within the high shear mixer is very complicated, which makes it more difficult to understand the flow and mixing characteristics on an industrial scale. Computational fluid dynamics (CFD) is a popular tool for analyzing the flow field in a mixing tank, and it takes less time. These tools are powerful, have fewer
restrictions on operating conditions, can understand design parameters, and perform diagnosis at a lower cost.

Oezcan-taskin et al. [5] used the standard k-ε turbulence model to study the flow and power characteristics of three high shear mixers. Utomo et al. [6] used the CFD simulation method to study the effect of the stator geometry on the power consumption characteristics of the high shear mixer. The simulation results show that the power factor Po is directly proportional to the flow through the stator opening. Xu et al. [7] used the large eddy simulation (LES) method of CFD to study the flow characteristics of the high shear mixers with ultrafine teeth. Qin et al. [8] used the CFD method to study the effect of different number of holes on the flow characteristics under the same stator opening area. Zhang et al. [9] studied the influence of the distance between the rotor teeth and the base and the stator rotor shear gap width on the flow characteristics of the in-line high shear mixer.

At present, there is no literature report on the effect of the stator tooth thickness on its flow field pattern and power consumption characteristics for in-line high shear mixer with ultrafine tooth. In this paper, the large eddy simulation method is used to simulate the single-phase flow field in the high-shear mixer (in-line high shear mixer with pilot-scale specifications, double-ring ultrafine tooth stator-rotor tooth structure, in which the stator is a back-bent helical tooth structure) by CFD. Based on the torque obtained from the simulation, the power consumption characteristics of the in-line-type high-shear mixer were predicted, and compared with the power consumption model parameters reported in the literature. Finally, the verified CFD model is used to study the stator tooth thickness and its flow field pattern, including its velocity vector distribution and shear rate distribution.

2. Simulation method

2.1. The geometry of the in-line high shear mixer

As discussed by Xu et al. (2014) and Zhang et al. (2017)[7,9], using a pilot-scale mixer (FLUKOVR, FDX1/60), the stator and rotor of the mixer adopts ultrafine tooth structure, in which the rotor is double ring straight teeth, 52 teeth per turn, with a tooth gap of 1 mm; the stator is a double ring, 15° back-bent helical tooth structure, with 30 teeth per turn, with a tooth gap of 2 mm.

Table 1. Different in-line high-shear mixers examined in CFD simulation

| Item | S (mm) | ST-b (mm) | T (mm) | H (mm) | D-o (mm) | D-l (mm) | D-o (mm) | D-l (mm) |
|------|--------|-----------|--------|--------|----------|----------|----------|----------|
| HSM1 | 0.5    | 1         | 2.75   | 12     | 59.5     | 47       | 66       | 53.5     |
| HSM2 | 0.5    | 1         | 2      | 12     | 58       | 47       | 63       | 52       |
| HSM3 | 0.5    | 1         | 2.5    | 12     | 59       | 47       | 65       | 53       |
| HSM4 | 0.5    | 1         | 1.5    | 12     | 61       | 47       | 65       | 53       |
| HSM5 | 0.5    | 3         | 2      | 14     | 58       | 47       | 63       | 52       |
| HSM6 | 0.5    | 3         | 2.75   | 12     | 59.5     | 47       | 66       | 53.5     |
| HSM7 | 0.5    | 3         | 3.5    | 14     | 61       | 47       | 69       | 55       |
| HSM8 | 2      | 1         | 2      | 12     | 64       | 47       | 72       | 55       |
| HSM9 | 2      | 1         | 2.75   | 12     | 65.5     | 47       | 75       | 56.5     |
| HSM10| 2      | 1         | 3.5    | 12     | 67       | 47       | 78       | 58       |

Note: D-o - outer rotor diameter; D-l - inner rotor diameter; D-o - outer stator diameter; D-l - inner stator diameter; S - shear gap width; ST-b: tip-to-base clearance; T - tooth thickness.

Table 1 show the structure of the in-line high-shear mixer in CFD simulation, and the high-shear mixer with 1mm tip-to-base clearance and 0.5 mm shear gap width in practical applications is used as the standard structure type. Other high shear mixers were used to study the effect of key structural parameters of tooth thickness on the flow field in the high-shear mixer. All high shears include double-circle stator rotors and the same tooth height, tooth width, and number of teeth. The design of the chamber is also the same.
2.2. Simulation method
All CFD calculations are simulated by ANSYS Fluent 18.0 software. In the process of simulation calculation, the LES model is used to predict the flow of the in-line high-shear mixer. The multiple reference frame (MRF) method technique was used to simulate the relative motion of the stator and rotor. In the simulation, the velocity inlet, pressure outlet, and non-slip wall coupled SIMPLE algorithm are used to solve the discretization equation, the number of meshes reaches 3.14 million to 3.82 million. All high shear mixers here only considered water (23~25°C, ρ=998.2 kg/m³, μ=1cP) as the working fluid. The standard Smagorinsky-Lilly subgrid-scale model is used for LES simulation to solve the momentum equation. The time step size is set to T/600, and other settings are default. The convergence criterion is set as the absolute residuals of all equation scales of 1×10⁻⁴, the maximum number of iterations within each iteration step are set at 20.

3. Data post-processing
The power consumption of the in-line high shear mixer is related to the speed and flow rate, so it cannot be characterized only by the stirring power number Po. Kowalski [10] proposed the power consumption model of in-line high shear mixer.

\[ P_{\text{shaft}} = P_{\text{fluid}} + P_L = P_T + P_F + P_L = P_o \rho N^3 D^5 + k_1 Q \rho N^2 D^2 + P_L \] (1)

In formula, \( P_{\text{shaft}} \) is the total energy, \( P_T \) is the power required to overcome the fluid resistance during the rotor rotation, \( P_F \) is the energy required for the fluid to flow through the mixer, \( P_L \) is energy loss, \( P_{\text{fluid}} \) is the net power, \( \rho \) is the density of the working fluid. This formula was further derived as,

\[ P_o = \frac{P_{\text{fluid}}}{\rho N^3 D^5} \] (2)

\[ P_o = P_o + k_1 \frac{Q}{\rho N D} = P_o + k_1 F_l \] (3)

Where \( P_o \) is the power number, \( P_{o0} \) is the power number under zero flow, \( F_l \) is the flow number. In this study, the linear velocity, Reynolds number Re and flow number Fl are calculated based on the outer diameter of the outer ring rotor.

4. Results and discussion
4.1. Simulation and verification
The net power of the in-line high shear mixer can be calculated from torque and speed. With water as the working fluid, the Reynolds number ranges from 2.8×10⁴ to 2.5×10⁵ in the speed range of 500~4000 rpm, which can be regarded as the complete turbulent flow. Figure 1 shows the power consumption curve of the HSM1 calculated by CFD.

![Figure 1. Power curve of in-line high shear mixer](image)

(a) speed 1000rpm, flow rate (500-2000 L/hr); (b) flow rate 500 L/hr, speed (1000-4000rpm)

Figure 1(a) shows the correlation between the power number \( P_o \) and the flow number \( F_l \) of the HSM1 under the operating speed (1000rpm) and flow rate (500~2000 L/hr) with water as the working fluid. It can be seen that the linear relationship between the power number \( P_o \) and the flow number \( F_l \) is more obvious. Figure1(b) shows the correlation between the power number \( P_o \) and the Reynolds number Re.
of the HSM1 under the operating speed (1000~4000rpm) and flow rate (500 L/hr) with water as the working fluid. When the Reynolds number Re is more than $1\times10^5$, the turbulent power number gradually approaches the constant. All CFD calculation results show that in the turbulent state, the overall law of all power consumption curves is very similar to the literature [4,5,7,9].

4.2. The effect of stator tooth thickness on the flow field

Figure 2 shows the velocity vector diagram of the Newtonian fluid (pure water 23~25°C, $\rho=998.2$ kg/m$^3$, $\mu=1$ cP) on the plane $z=3$ mm, $z=6$ mm under the turbulent state (N=1000 rpm, Q=500 L/h) of the high shear mixer. It can be seen from the velocity vector diagram that the in-line high shear mixer turbulent flow is very complicated, which is manifested by the self-circulating flow in the stator teeth gaps. The flow ejected from the outermost stator teeth gaps forms eddy current, and the fluid near the eddy current is drawn into the shear gap again. These phenomena are similar to the flow field characteristics of the high shear mixer in the literature [4,7,9]. Figure 2 has the following obvious characteristics: as the stator tooth thickness increases, the turbulence intensity and eddy current intensity around the outermost stator increase slightly. At the same time, the increase in eddy currents near the outermost stator is accompanied by less fluid entrainment into the shear gap.

![Figure 2. Velocity vector diagram of in-line high shear mixer](image)

Figure 2. Velocity vector diagram of in-line high shear mixer

(a1) $z=3$ mm, HSM2; (b1) $z=3$ mm, HSM3; (c1) $z=3$ mm, HSM1; (c1) $z=3$ mm, HSM4
(a2) $z=6$ mm, HSM2; (b2) $z=6$ mm, HSM3; (c2) $z=6$ mm, HSM1; (c2) $z=6$ mm, HSM4

Figure 3 shows the shear rate cloud diagram of various in-line high shear mixers on a plane $z=6$ mm with water as the working fluid, operating speed of 1000 rpm and flow rate of 500 L/hr. From figure 3(a, b, c), it is known that with the increase of the stator tooth thickness, the shear rate area with larger value changes slightly. Therefore, the stator tooth thickness has a slight influence on the shear rate distribution. From figure 3 (a, b, c) and (d, e, f), with the increase of the distance between the rotor teeth and the base, the change of the shear rate area with a larger value decreases slightly. Figure 3 (a, b, c) and (g, h, i) show that as the width of the shear gap increases, the value of the shear rate decreases significantly, and the region of the shear rate with a larger value is less obvious. Therefore, the stator tooth thickness and the distance between the rotor teeth and the base have a slight effect on the shear rate distribution, and the shear gap width is a key parameter that affects the shear rate distribution.
Figure 3. Shear rate cloud diagram of in-line high shear mixer: (a) HSM2; (b) HSM1; (c) HSM4; (d) HSM5; (e) HSM6; (f) HSM7; (g) HSM8; (h) HSM9; (i) HSM10

Figure 4. The histogram of the shear rate distribution of the in-line high-shear mixer: (a) HSM2; (b) HSM1; (c) HSM4; (d) HSM5; (e) HSM6; (f) HSM7; (g) HSM8; (h) HSM9; (i) HSM10
Figure 4 shows the histogram of the shear rate distribution of the in-line high-shear mixer in turbulent flow, with a span of 0–2×10^4 s^{-1}, divided into 100 groups. It can be seen from figure 4 that as the stator teeth thickness increases, the distribution of the low shear rate in the shear head of the high shear mixer is high. This means that its shear capacity is reduced. As the distance between the rotor teeth and the base increases, the shear rate distribution in the high shear mixer shear head decreases overall.

With the increase of the width of the shear gap, the distribution of the shear rate becomes more concentrated, and the distribution of the low shear rate in the shear head of the high shear mixer is higher, which is similar to the straight distribution of the shear rate of the in-line high shear mixer in the literature [10]. This also strongly shows that the stator tooth thickness and the distance between the rotor teeth and the base has a slight effect on the shear rate distribution, but the width of the shear gap has an important effect on the shear-force of the in-line high shear mixer.

5. Conclusions
This paper uses the CFD simulation method to study the effect of the stator tooth thickness on the flow field characteristics of the high-shear mixer in the turbulent state when water is used as the working fluid. The research results show that as the stator teeth thickness increases, the turbulence and eddy currents around the outermost stator increase slightly, and the eddy currents near the outermost stator increase with less fluid entrained into the shear gap. The maximum value of the shear gap can reach the order of 2×10^4. As the stator teeth thickness increases, the shear rate area with a larger value changes slightly, while the area with low shear rate in the high shear mixer increases slightly. This also strongly shows that the thickness of the stator teeth has a slight influence on the shear rate distribution.

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