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CFD analysis of flow pattern and power consumption for viscous fluids in in-line high shear mixers

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ABSTRACT

In-line high shear mixers (HSMs) with ultrafine teeth are useful to intensify mixing and dispersive process with viscous fluids. However, the relationships among the flow pattern, the power consumption and design parameters are not understood deeply yet, which hindered the further equipment optimization and scale-up. In this article, the effects of two important structural parameters, tip-to-base clearance and shear gap width, on flow pattern and power consumption of HSM were explored by CFD simulation. The LES and laminar model in turbulent and laminar flow regime were used respectively in CFD simulation with Newtonian and non-Newtonian fluids. The results indicate that with the increase of tip-to-base clearance and shear gap width, the velocity and strain rate in mixing head reduce significantly while the area of dead zone increased. The power number constant K_p and K_s of the standard in-line HSM predicted by CFD simulation agree well with the experimental data with acceptable error. The correlations of the predicted K_p and K_s of all designs which show their linear relationship with the tip-to-base clearance in axial direction $f/(f+h)$ and power function with shear gap width in radial direction g/D. These results provide the guidance on process development and scale-up of in-line HSM with the ultrafine teeth for viscous fluids.

1. Introduction

In recent years, the high shear mixers (HSMs) have a promising application in chemical, petroleum, pharmaceutical and food industries to intensify the operations, involving mixing, dispersion, dissolution, deagglomeration and emulsification with the characteristics of high rotor tip speed, high strain rate, and highly localized energy dissipation rate near the mixing head (Atiemo-Obeng and Calabrese 2004; Zhang et al., 2012). Some of the chemical and the pharmaceutical processes, particularly for food and cosmetics processes, often involve with the mixing viscous fluids including non-Newtonian fluids with the shear-thinning characteristic (Shekhar and Jayanti 2003; Thakur et al., 2004; Wang et al., 2014; Bourne and Studer, 1992). However, there are no open literatures on quantitative engineering design principles of in-line HSMs to improve the performance of operation system particularly associated with non-Newtonian fluids besides the basic suggestions of maintaining the geometry similarity during scale-up (Utomo et al., 2008; Hall et al., 2011; Schoenstedt et al., 2015). In most industrial HSMs based on constant tip speed and shear gap width, equivalent to constant nomial shear rate in the shear gap (Atiemo-Obeng and Calabrese, 2004). Therefore, in order to put forward wide applications of HSMs, it is urgent to study the influences of critical structural parameters on the flow pattern and power consumption, and to explore a quantitative method for the evaluation of the mixing performance for viscous fluids.

Cooke et al. (2012) proposed that the power number *Po* of in-line HSM for Newtonian fluids in the laminar is inversely proportional to *Re*, namely $K_p = PoRe$. The constant K_p depends on the equipment structure. For turbulent regime, the power number of in-line HSMs

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Nomenclature

D	Outer swept diameter of the rotor, mm
e	Row of rotor and stator teeth, dimensionless
f	Tip-to-base clearance, mm
g	Shear gap width, mm
h	The height of teeth of rotor or stator, mm
H	The height of mixing head, mm
i	Inner, dimensionless
k	Consistency index, Pa s^{n}
k_1	Constant, dimensionless
K_p	Coefficient of proportionality between Po and 1/Re, dimensionless
K_s	Shear rate constant, dimensionless
K_{pn}	Coefficient of proportionality between Po and 1/Re_{pl}, dimensionless
o	Outer, dimensionless
n	Power-law index, dimensionless
N	Rotational speed, s^{-1}
P_{shaft}	Shaft power, W
P_T	Tank power term, W
P_F	Flow rate power term, W
P_L	Losses power term, W
P_{fluid}	Net delivered power to fluid, W
Po_z	Power number at zero flow rate, dimensionless
Po	Power number, dimensionless
Q_M	Mass flow rate, kg/s
Q	Volumetric flow rate, m^3/s
T	The period of revolution, s

Greek symbols

τ	Stress tensor, Pa
$\dot{\gamma}$	The average shear rate, s^{-1}
μ_a	Apparent viscosity of fluids, Pa s
ε	Turbulent dissipation rate, $m^2\,s^{-3}$
ρ	Density, kg/m^3

Abbreviations

CFD	Computational fluid dynamics
EXP	Experimental results
HSM	High shear mixer
LES	Large eddy simulation
MRF	Multiple reference frame
RANS	Reynolds-averaged Navier–Stokes
SIMPLE	Semi-implicit method for pressure linked equations

is the sum of a constant and the flow term. For non-Newtonian fluids, the Metzner–Otto method (Metzner and Otto 1957) were used for the expression of apparent viscosity, and the introduced constant K_s is called as the shear rate constant depending on the geometrical parameters as with K_p. Therefore, The constant K_p and K_s can be used as the index for scale-up and optimized of in-line HSMs with viscous fluids.

Table 1 – Main dimensions of the experimental in-line HSM.

Structures	Dimensions (mm)
Outer rotor diameter	59.5
Inner rotor diameter	47
Number of rotor teeth	52
Outer stator diameter	66
Inner stator diameter	53.5
Number of stator teeth	30
Shear gap width	0.5
Teeth tip-to-base clearance	1
Diameter of the mixing chamber	90
Inlet tube diameter	25
Outlet tube diameter	20

Computational fluid dynamics (CFD) has been considered as a powerful and less time-consuming tool for designing reactors associated with flow field details (Razzak et al., 2008; Feng et al., 2012). Shekhar and Jayand (2003) simulated the flow pattern and power consumption of a close-clearance anchor agitator with viscous fluids. It is found that the power constant K_p and the shear rate constant K_s were depended on the radial clearance ratio c/T, which was according to the experimental correlation of Ayazi Shamlou and Edward (1989). Thakur et al. (2004) measured the power consumption of flat-bladed impellers and concluded that the constant K_p was a function of impeller length and shear gap size while the shear constant K_s depended on the gap dimension; meanwhile Vial et al. (2015) adopted CFD simulation to study the hydrodynamic behavior and obtained the relationship correlation of K_p and K_s that was the function of rotor length L_e and shear gap size in laminar regime. Mardaru et al. (2012) and Souidi et al. (2012) studied the narrow annular gap equipped with right-across paddle impellers by CFD simulation and experiments, and they reported that the impellers angle and shear gap size had a great effect on flow pattern and power consumption. Wu et al. (2014) investigated the strain rate distribution in turbulent and laminar regimes of multistage rotor–stator mixers, and developed the correlation of K_p and K_s with the axial gap and radial clearance by CFD simulation based on the preliminary experimental research by Kroezen et al. (1988). For the in-line teethed or the blade-screen configuration HSMs, so far there are no reports on the variations of flow pattern and power consumption resulted in changing key structure parameters including the tip-to-base clearance in axial direction and the shear gap width in radial direction, which are important to design and scale-up the in-line HSMs.

Previously, CFD simulation of HSMs in turbulent regime mostly adopted the standard k-ε turbulence model (Utomo et al., 2009; Jasinska et al., 2013, 2015; Wu et al., 2014) or the improved Reynolds-averaged Navier–Stokes (RANS) model (Ozcan-Taskin et al., 2011; Vial et al., 2015). Owing to the complex flow in HSMs, these models cannot provide accurate estimation of the streamline curvature and rotation, wall-bounded flow as well as locally anisotropic turbulent flows. Our previous work (Xu et al., 2014) simulated a pilot-scale in-line HSM with ultrafine teeth using the large eddy simulation (LES) model (Zhang et al., 2008; Li et al., 2011; Tabib et al., 2012; Dhakal et al., 2014). It was proved that the LES model can provide better prediction of velocity profile and power consumption than the standard k-ε turbulence model, in combination with experimental measurements. Moreover, the LES combined species transport model was successfully applied for the simulation of residence time distribution so as to study the backmixing performance of in-line ultrafine-teeth HSMs (Xu et al., 2013).

In this paper, the standard pilot scale HSM was simulated via the LES and laminar model in turbulent and laminar flow regime, which were also validated by power experiment. Other designs were simulated to investigate the effect of key structural parameters on flow pattern and power consumption of HSMs with Newtonian and shear-thinning power-law fluids. The constants of K_p and K_s were respectively correlated with the tip-to-base clearance in axial direction and the shear gap width in radial direction. These quantitative results are fundamental for the design and scale-up of in-line ultrafine-teeth HSM with viscous fluids.

2. Experimental procedure

2.1. *In-line HSM with ultrafine teeth configuration*

Table 1 shows the main dimensions of the experimental in-line HSM (shown in Fig. 1), a pilot-scale unit provided by FLUKO (Shanghai, China). The rotor includes two rows of 52 straight teeth with 1 mm slots, while the stator consists of two rows of