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Laminar mixing of shear thinning fluids in a SMX static mixer

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Abstract

Flow and mixing of power-law fluids in a standard SMX static mixer were simulated using computational fluid dynamics (CFD). Results showed that shear thinning reduces the ratio of pressure drop in the static mixer to pressure drop in empty tube as compared to Newtonian fluids. The correlations for pressure drop and friction factor were obtained at $Re_{MR} \leqslant 100$. The friction factor is a function of both Reynolds number and power-law index. A proper apparent strain rate, area-weighted average strain rate on the solid surface in mixing section, was proposed to calculate pressure drop for a non-Newtonian fluid. Particle tracking showed that shear thinning fluids exhibit better mixing quality, lower pressure drop and higher mixing efficiency as compared to a Newtonian fluid in the SMX static mixer.

Keywords: Laminar flow; Mixing; SMX static mixer; Non-Newtonian fluids; Computational fluid dynamics

1. Introduction

Static mixers are applied for continuous laminar mixing of viscous liquids in many chemical industry applications, such as: polymer processing, polymerization reactions, food processing, paints, pharmaceuticals, and water treatment. Static mixers usually consist of a number of identical motionless mixing elements placed in a pipe or channel. The elements are usually rotated 90° relative to the neighboring elements as this periodic change in the geometry of static mixers produces reorientation and distribution of the fluids. The SMX static mixer is an important class of static mixers used in these applications.

The mixing elements of SMX static mixer consist of crossed bars at a 45° angle with the axis of the pipe. Each element is rotated 90° with respect to the previous element. A standard SMX mixing element has eight cross-bars and an aspect ratio of length to pipe diameter of $l/D = 1$. SMX static mixers are observed to exhibit a fast mixing rate and relatively modest pressure drop. The flow in the SMX static mixer is laminar when the Reynolds number is less than 420 (Hirech et al., 2003).

Previous experimental work has studied pressure drop, concentration distributions and striation thickness in SMX static mixers for Newtonian fluids. The ratio k of the pressure drop ΔP_{SM} in the SMX mixer to the pressure drop ΔP_0 in empty tube is constant at low Reynolds number (Streiff, 1979; Pahl and Muschelknautz, 1982; Allocca, 1982). Godfrey (1985) summarized the relationship between the various parameters for Newtonian fluids:

$$k = \frac{\Delta P_{SM}}{\Delta P_0} = \frac{(Ne\,Re)_{SM}}{(Ne\,Re)_0} = \frac{\varphi_{SM} Re}{\varphi_0 Re} \tag{1}$$

i.e.,

$$k = \frac{\Delta P_{SM}}{\Delta P_0} = \frac{(Ne\,Re)_{SM}}{32} = \frac{\varphi_{SM} Re}{64} \tag{2}$$

in which φ is the friction factor, $Ne = \varphi/2$ is Newton number, $Re = DV\rho/\mu$ is Reynolds number based on the diameter of the empty tube. Subscripts 0 and SM represent empty tube and static mixer, respectively. Here φ_0 and φ_{SM} are defined as

$$\varphi_0 = \frac{2\Delta P_0}{\rho V^2}\frac{D}{L}, \tag{3}$$

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$$\varphi_{SM} = \frac{2\Delta P_{SM}}{\rho V^2}\frac{D}{L}. \quad (4)$$

For laminar flow in a round pipe, $\varphi_0 Re = 64$. The pressure drop for a Newtonian fluid in a static mixer can be written as (Allocca, 1982)

$$\Delta P_{SM} = k\Delta P_0 = \frac{4}{\pi} Ne\,Re \frac{\mu Q}{D^3}\frac{L}{D}, \quad (5)$$

where $Ne\,Re$ is a constant depending on the geometry of static mixers, μ is viscosity of fluid, Q is volumetric flow rate. Generally, for standard SMX static mixers, $Ne\,Re \approx 1200$ or $k \approx 37.5$. Allocca (1982) found $Ne\,Re = 1237$ in a SMX static mixer.

Several experimental correlations of friction factor in Sulzer SMX mixers with large aspect ratio ($l/D > 1$) were reported for shear thinning fluids (Langer et al., 1987; Shah and Kale, 1991; Li et al., 1997). In addition, Langer et al. (1987) found that viscoelasticity increases the friction factor in static mixers. Experiments also showed that viscoelasticity of liquids strongly decreases mixing quality and increases pressure drop in a Ross ISG static mixer when $Re > 0.01$ (Langer and Werner, 1996).

Sometimes Eq. (5) is used to calculate the pressure drop for a non-Newtonian fluid by replacing μ with an apparent viscosity μ_{app} at an apparent strain rate $\dot{\gamma}_{app}$. For standard SMX static mixers, $\dot{\gamma}_{app} = 64V/D$ is recommended (Streiff et al., 1999).

Many computational studies have been done, for laminar flow and mixing of Newtonian fluids in static mixers, using finite element and finite volume models. Static mixers produce a multitude of striation layers in laminar flow. A very fine mesh for a computational simulation is necessary to get a good representation of the concentration field, but this requires substantial computer resources. Particle tracking is often used to visualize mixing performance because numerical diffusion in a pseudoconcentration method to track changes in mixing quality displays much faster mixing than the real physical diffusion in laminar flow (Bakker and Laroche, 1993; Fleischli et al., 1997). Fleischli et al. (1997) simulated the velocity fields and concentration fields in both Kenics and SMX static mixers. They found that the results from particle tracking show much better agreement with concentration measurements than those obtained from solving mass transfer equation in the same grid. Rauline et al. (1998, 2000) simulated the velocity fields for creeping flow conditions in Kenics, Inliner, LPD, Cleveland, SMX and ISG static mixers. Pressure drop, extensional efficiency, stretching, mean shear rate and the coefficient of variation in the particle distribution were used to compare the performance of the static mixers. The SMX mixer is the most efficient among the six mixers studied. Fourcade et al. (2001) simulated mixing in a Kenics static mixer and an SMX static mixer. They defined an average rate of striation thinning to describe the mixing performance in static mixers. They used laser LIF experiments to qualitatively verify the computational striation patterns. Recently, Zalc et al. (2002, 2003) simulated the flow and mixing in an SMX static mixer at several values of Reynolds number. Their simulations showed that lower Reynolds number flow condition shows better mixing efficiency and centerline injection is better than off-center injection. They found the pressure drop ratio at $Re \leqslant 10$ is constant and it increases quickly with increasing Re when $Re > 10$.

So far only a few CFD studies have involved non-Newtonian fluids in static mixers. Avalosse and Crochet (1997) simulated laminar flow and mixing of a power-law liquid in a Kenics static mixer. Wünsch and Böhme (2000) simulated mixing processes of a power-law liquid in an SMX static mixer in a square channel. Both works applied the shear thinning liquid with power-law index of 0.4. They found that shear thinning has no important influence on the mixture quality in the mixing process, although the velocity field is different from that of the Newtonian fluid.

Several experimental works (Langer et al., 1987; Shah and Kale, 1991; Li et al., 1997) studied the pressure drop of non-Newtonian fluids in long SMX mixers with aspect ratio from 1.25 to 1.75 (also known as SMXL type static mixers). Some correlations of friction factor did not include non-Newtonian property due to the limited range of shear thinning in the non-Newtonian fluids (Langer et al., 1987; Li et al., 1997). The effect of non-Newtonian fluids on pressure drop and mixing for a standard SMX static mixer ($l/D = 1$) in a round tube has not been reported in publications.

In this paper, we examine the effect of shear thinning of non-Newtonian fluids on pressure drop and mixing in the standard SMX mixer. The pressure drop ratio and friction factor, from a CFD simulation, are studied with changing power-law index. A proper apparent strain rate is proposed to calculate pressure drop for non-Newtonian fluid using Eq. (5) as a basis.

2. Computational method

The standard SMX mixer element studied in this work has eight cross-bars, a diameter of 52 mm and cross-bar thickness of 2 mm. The aspect ratio l/D is 1. The cross-bar width next to the tube wall is 8 mm, while the other cross-bars are 6 mm in width.

Three-dimensional simulations of the steady laminar flows of incompressible fluid in the SMX static mixer were carried out using the commercial CFD software FLUENT 5 (Fluent Inc.). The mesh geometry with four mixing elements (Fig. 1) was produced using GAMBIT (Fluent Inc.). The z-axis is the axis of the tube, with the origin at the beginning of the first mixer element, and its direction is the same as the predominant flow direction. The inlet section and outlet section are two empty tubes of $2D$ length, to provide a developmental flow length consistent with the inlet and outlet boundary conditions. A fully developed flow velocity profile is applied to the inlet of the mixer and the no slip boundary condition is applied on the tube walls and mixer element surfaces. A constant pressure outlet condition ($P = 0$) is used. The mesh has a total of 2,217,698 tetrahedral elements, and 433,463 nodes with a nominal cell size of 1 mm in mixer section, and 2 mm in inlet and outlet sections.

Most polymer melts and solutions exhibit shear-thinning behavior during flow. The power-law model used to capture shear thinning behavior is given by

$$\mu = m\dot{\gamma}^{n-1} \quad (6)$$