Chemical Engineering & Processing: Process Intensification 124 (2018) 1–10

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Process intensification in a chaotic SMX static mixer to achieve an energy-efficient mixing operation of non-newtonian fluids

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A R T I C L E I N F O

Keywords:
SMX static mixer
Computational fluid dynamics (CFD)
Yield-pseudoplastic fluids
Electrical resistance tomography (ERT)
Mixing intensification

A B S T R A C T

The purpose of this novel research was to intensify the mixing performance in a chaotic SMX static mixer at the lower primary flow rates of a yield pseudoplastic fluid. Since lower primary flow rates require less power consumption, this study enlightens the energy-efficient mixing in a chaotic SMX static mixer through the intensification of fluid deformation. Electrical resistance tomography (ERT) and computational fluid dynamics (CFD) techniques were utilized to achieve the objectives of this work. The CFD flow model was validated using the ERT tomograms, experimental pressure drop data, the secondary fluid concentration profile, and the mixing index. The species model was used to study the distribution of the secondary fluid concentration in the primary fluid. The effect of the secondary-to-primary velocity ratio on the degree of fluid deformation caused by the secondary fluid was investigated. The Newtonian secondary fluid (water) deformed the yield-pseudoplastic primary fluid more effectively than the non-Newtonian secondary fluid (0.5 wt% xanthan gum solution). Our results revealed that a more uniform radial dispersion of the secondary fluid in the primary fluid was attained through the intensification of fluid deformation at a higher secondary-to-primary velocity ratio.

1. Introduction

Mixing of highly viscous non-Newtonian fluids in a laminar flow regime is a common practice in polymer industry. The distribution of copolymer composition is dependent on the degree of mixing. Since the non-Newtonian fluid viscosity is a function of shear rate, the extreme viscosity gradients can lead to a non-ideal mixing. Intensification of momentum and mass transfer is required in order to enhance the fluid mixing. The use of the turbulent flow is not always feasible since the mixing of highly viscous fluids requires considerable amount of power [1].

Shearer [2] studied streamline mixing in three flow geometries (a stacked array of the helical flighted ducts, an assembly of the rotating blades, and an assembly of the planetary rollers) for the mixing of highly viscous liquids. The large patches of liquids become smaller as the mixing progresses due to the successive subdivision and redistribution of flow streamlines induced by the flow geometries [2].

Another alternative solution is the chaotic advection, which allows the fluids to stretch and to fold. Chaotic mixing helps achieve an exponential growth of the total interface length in time by stretching and folding [3]. In order to understand the fluid dynamics of fluorescence dye under chaotic flow, the lamellar structure was analyzed by Muzzio et al. [4]. The wide distribution of striation thickness was attributed to different rates of stretching at different location. As the magnitude of fluid stretching increased, the exposure of interfacial area for diffusion increased [4].

Static mixers such as Kenics and SMX are known to exhibit chaotic behaviour [5,6]. Meijer et al. [7] investigated the optimal interface stretching of fluid in different types of static mixer geometry. It was concluded that static mixers with few blades are most energy efficient. However, the static mixer using cross bars *X* design (i.e. SMX) outperformed all other static mixer design criteria. Rauline et al. [8] numerically investigated and compared the performances of six static mixers (e.g. Kenics, Inliner, LPD, Cleveland, SMX and ISG). The comparison among the six static mixers revealed that the SMX static mixer was the most superior. Mixing efficiency of one SMX element was equivalent to two or three Kenics mixing element [9]. Zalc et al. [10] studied the mixing characteristic of the SMX static mixer for the Newtonian fluid flow at Reynolds number less than 100. This numerical study considered the mixing of two streams with similar physical properties of glycerine. The Lagrangian particle tracking method was employed to evaluate the mixing performance of the SMX static mixer,

Abbreviations: 2D, two-dimensions; 3D, three-dimensions; DAS, data acquisition system; ERT, electrical resistance tomography; CFD, computational fluid dynamics; SIMPLE, semi-implicit method for pressure-linked equation; PRESTO, pressure staggering option; HPCVL, high performance computing virtual laboratory

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https://doi.org/10.1016/j.cep.2017.11.018
Received 21 July 2017; Received in revised form 25 November 2017; Accepted 25 November 2017
0255-2701/

Nomenclature

Notation

CoV	Coefficient of variance (Dimensionless)
C_i	Local concentration measurement (kg/m^3)
$\overline{C}$	Average concentration (kg/m^3)
D	Diameter of the pipe (m)
K	Consistency index (Pa.s^n)
K'	Consistency index for local power law parameters (Pa.s^n)
ID	Internal diameter (m)
L/D	Length/Diameter (Dimensionless)
n	Flow behaviour index (Dimensionless)
n'	Flow behaviour index for local power law parameters (Dimensionless)
np	Total number of pixels for each tomography plane
N	Number of electrodes per plane
r	Radial coordinate (m)
t	Time (s)
v	Axial velocity (m/s)
wt%	Weight percent (Dimensionless)
Re_{MR}	Reynolds number (Dimensionless)
w	Local mass fraction of secondary fluid (Dimensionless)
$\bar{v}$	Mean velocity vector (m/s)
D$_m$	Molecular diffusivity (m^2/s)

Greek letters

ρ	Density (kg/m^3)
τ_y	Yield stress (Pa)
τ_{rz}	Shear stress (Pa)
$\dot{\gamma}_{rz}$	Shear rate (s^{-1})
μ	Newtonian viscosity (kg/ms)

and the numerical and experimental pressure drop results were compared for the model validation [10]. Zalc et al. [11] conducted a detailed lagrangian analysis to characterize the chaotic mixing behaviour of the SMX static mixer using stretching field. A simple Newtonian fluid flow was considered for this simulation work.

Wüsch and Böhme [6] numerically studied the mixing of highly viscous shear-thinning fluid in the SMX static mixer. The three-parameter Carreau model was used to characterize the rheological behaviour of the fluid studied under simulation. A hybrid method combining the Eulerian and Lagrangian view of the fluid flow was utilized in this numerical study and the analysis of the fluid dynamics revealed that the SMX static mixer was chaotic [6]. Liu et al. [12] numerically investigated the laminar mixing of shear-thinning power-law fluids in the SMX static mixer using the particle tracking method. It was found that an effective mixing quality was observed for shear thinning fluids with a lower pressure drop compared to that of Newtonian fluids.

A new design of the SMX static mixer was proposed with only 6 bar and with larger gaps between the bars. This modified design was more energy efficient compared to the original SMX design while both designs exhibited similar mixing performances [13].

Unlike the Newtonian fluids, the shear thinning fluids which exhibited some degree of elasticity deformed dramatically, resulting in an efficient mixing at the equivalent Reynolds number [14]. Groisman and Steinberg [15] discovered that viscoelastic fluids exhibit 'elastic' turbulence due to enhanced stretching of flexible long-chain polymers. Groisman and Steinberg [16] demonstrated experimentally that a low concentration of viscoelastic polyacrylamide polymer solution can be used to efficiently mix highly viscous liquids at a very low Reynolds number. Enhanced stretching of viscoelastic polyacrylamide polymer resulted in an increase in elastic stresses. The elastic instability of the polymer at low Reynolds number leads to the homogenous mixing of highly viscous liquids. Recently, Jegatheeswaran et al. [17] studied the effect of yield-pseudoplastic fluid (xanthan gum solution) rheology on the quality of mixing in the chaotic SMX static mixer using electrical resistance tomography. It was shown that the xanthan gum solution at higher concentration deformed significantly resulting in a more homogenous mixing. Knowledge of hydrodynamics is essential in order to intensify the fluid deformation and to achieve an energy efficient mixing operation.

Since limited information is available about the hydrodynamics of the yield-pseudoplastic fluid in the SMX static mixer, the intensification of mixing operation remains challenging in an industrial scale. In order to address the gap in the literature, for the first time, the economical mixing at lower primary flow rates of yield-pseudoplastic fluid was studied. Thus, the objective of this paper is to study the degree of fluid deformation caused by the secondary fluids while analyzing the quality of distributive mixing in the chaotic SMX static mixer at lower primary flow rates. Even though no reaction is considered in this research work, the concept of intensified fluid deformation can be utilized to enhance the diffusion of reactants within a highly viscous medium. From the data available in the open literature, the transport species model has never been used to simulate the fluid mixing in the static mixers. This paper also, for the first time, presents the validation for the transport species flow model of the secondary fluids in the yield-pseudoplastic primary fluid using the static mixer. The primary fluid considered in this research study was 0.5 wt% xanthan gum solution (a non-Newtonian fluid). In order to study the dispersion of the secondary fluid into the primary fluid, two different types of secondary fluids were considered: water (a Newtonian fluid) and 0.5 wt% xanthan gum solution (a non-Newtonian fluid). Both non-Newtonian secondary and primary fluids had the same rheological properties.

2. Experimental setup and procedure

The experimental set-up shown in Fig. 1 consisted of a transparent PVC pipe within which 5 SMX static mixer elements (Sulzer, Switzerland) were equally spaced. The internal pipe diameter (*ID*) and the pipe length were 0.1016 m and 2.02 m, respectively. The aspect ratio (*L/D*) of the 5 SMX static mixer was equal to 3. A pressure transmitter (Model: PX409-005DWU5 V, Omega, Canada) was used to measure the differential pressure between the pipe inlet and the pipe exit. The details of the experimental setup have been described elsewhere [17].

The working fluid was 0.5 wt% xanthan gum solution (CP Kelco, USA). The xanthan gum solution is a shear thinning fluid with yield stress and obeys the Herschel-Bulkley model [18–21].

$$\tau_{rz} = \tau_y + K(\dot{\gamma}_{rz})^n \tag{1}$$

where τ_{rz} is the shear stress, τ_y is the yield stress, $\dot{\gamma}_{rz}$ is the shear rate, and K and n are the shear rate independent constants. The rheological properties of the xanthan solution are listed in Table 1 [22]

The secondary fluid was more conductive than the primary fluid (0.5 wt% xanthan gum) as 5 wt% table salt was added to the former fluid. Electrical resistance tomography (ERT) captured the dispersion of the secondary fluid into the primary fluid based on the difference in both fluids' conductivities. The dispersion of the secondary fluid into the primary fluid occurred due to the following mechanisms: (1) bulk advection of the primary fluid, (2) chaotic advection created by the SMX static mixer element, and (3) diffusion. Since the rheological properties of xanthan gum solution can be significantly affected when the salt concentration exceeds the threshold limit, the salt concentration in xanthan gum solution was kept below the threshold level of 0.17 wt% [22]. Upon the injection of the more conductive secondary