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Effects of geometry and flow rate on secondary flow and the mixing process in static mixers—A numerical study

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Abstract

A method based on computational fluid dynamics (CFD) for the characterization of static mixers using the Z factor, helicity and the rate of striation thinning is presented. These measures were found to be well-suited for the characterization of static mixers as they reflect the pressure drop, the formation of secondary flow, i.e. vortices, and their effect on the mixing process. Two commercial static mixers, the Kenics KM and Lightnin Series 45, have been characterized. In the mixers investigated, secondary flow is formed in the flow at the element intersections and due to the curvature of the mixer elements. The intensity of the vortices is higher in the Lightnin than the Kenics mixer due to edges in the middle of the Lightnin mixer elements. The formation of vortices affects the Z factor by an increase in the power requirement, and the rate of striation thinning by an increase in the stretching of the striations. The formation of vortices was observed at a Reynolds number of 10 in both mixers with aspect ratios of 1.5. However, the intensity of the vortices was greater in the Lightnin than the Kenics mixer, which was observed in not only the magnitude of the helicity, but also the Z factor, rate of striation thinning and the distribution of striation thickness.

The distribution in striation thickness is shifted towards thin striations as the flow rate is increased from below to above the Reynolds numbers of which vortices were first observed, but some striations still pass the mixer elements almost unaffected, which can be seen in the skewness of the distribution of the striation thickness, which shifts from being negative to positive.

Keywords: Static mixer; Rate of striation thinning; Secondary flow; Computational fluid dynamics; Particle tracking; Laminar flow

1. Introduction

Mixing is a common unit operation in a large number of processes, and it is used in many different applications where a defined degree of homogeneity of a fluid is desired. Common mixing devices are dynamic mixers for agitated tanks in batch operations and static mixers for inline mixing in continuous operations (Myers et al., 1997). Some of the advantages of static mixers over dynamic mixers are that they have no moving parts, small space requirements, low or no maintenance cost and a short residence time. Static mixers are available for different working conditions, i.e. laminar, transitional and turbulent flow regimes. Regardless of the flow regime in which the mixer is working, it is important to use optimally designed mixing systems to obtain a product that meets the requirements at the lowest production costs. To design optimal mixer geometries, appropriate tools are needed to characterize the flow conditions and their influence on the mixing process.

A static mixer designed for laminar flow conditions is usually composed of a number of mixer elements, each rotated 90° relative to the previous one. The mixer elements are designed to split the flow into two or more streams, rotate them and then recombine them. Static mixers have been on the market for about 50 years and yet they have not been well characterized due to the complexity of the flow structure inside them. Previous studies on static mixers, mainly the Kenics KM (Bakker et al., 2000; Byrde and Sawley, 1999; Chen, 1973; Fourcade et al., 2001; Grace, 1971; Hobbs and Muzzio, 1997, 1998a,b; Hobbs et al., 1998; Jaffer and Wood, 1998; Joshi et al., 1995; Pahl and Muschelknautz, 1982; Rauline et al.,

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1998; Ujhidy et al., 2003; Wilkinson and Cliff, 1977) and the Sulzer SMX mixer (Fradette et al., 1998; Pahl and Muschelknautz, 1982; Rauline et al., 1998; Visser et al., 1999; Zalc et al., 2002), have focused on several characteristics, e.g. residence time distribution, pressure drop and stretching rate. Residence time distributions and pressure drop have been characterized experimentally (Chen, 1973; Grace, 1971; Pahl and Muschelknautz, 1982; Wilkinson and Cliff, 1977) as well as numerically (Byrde and Sawley, 1999; Hobbs and Muzzio, 1997, 1998b; Joshi et al., 1995; Rauline et al., 1998; Visser et al., 1999; Zalc et al., 2002). As computer resources became more readily available, computational fluid dynamics (CFD) proved to be a useful means of gaining insight into the mixing process in static mixers.

Secondary flow, i.e. any additional structures in the flow besides the primary ones that follow the curvature of the mixer elements, is of interest when characterizing a mixer. In previous studies on the Kenics KM static mixer, vortices have been reported to occur at flow rates above certain Reynolds numbers (*Re*) (Jaffer and Wood, 1998; Ujhidy et al., 2003). For a given geometry, this critical Reynolds number is dependent on the aspect ratio (length-to-diameter ratio) of the elements, i.e. short elements lead to a low critical Reynolds number. The reason why these vortices appear has not been fully investigated. The Dean number, the ratio between the centripetal and inertial forces, has been used to predict the transition to a flow with secondary flow in a Kenics KM static mixer (Ujhidy et al., 2003). This is, however, not a good measure of secondary flow in other mixer geometries where the secondary flow may be caused by factors other than the curvature of the elements.

The Lyapunov exponent gives a measure of the stretching value in the flow direction, and has been used in some studies as an indirect measure of the rate of striation thinning since it is easier to calculate than the striation thinning (Hobbs and Muzzio, 1997, 1998a,b; Hobbs et al., 1998; Rauline et al., 1998). In other studies, different methods have been used to calculate the striation thickness in order to obtain a measure of the mixing performance (Byrde and Sawley, 1999; Fourcade et al., 2001; Jaffer and Wood, 1998). The rate of striation thinning is closely related to the Lyapunov exponent, but in contrast to the Lyapunov exponent it neglects the stretching in the mean flow direction. Despite this, the rate of striation thinning will give a better understanding of the coupling between the flow pattern, the mixer geometry and the mixing process than the Lyapunov exponent, as information about the distribution of the striation thickness can be achieved as an intermediate result in the calculations.

Fourcade et al. (2001) implemented the concept of striation thinning based on the work of Ottino et al. (1979) using the following definition:

$$\alpha = -\frac{v_z}{L} \ln\left(\frac{s_{\mathrm{after}}}{s_{\mathrm{before}}}\right). \tag{1}$$

In contrast to Fourcade et al. (2001), Regner et al. (2005) used the local axial velocity in the calculations instead of an average velocity, in order to obtain a more accurate measure of the mixing process at the end of the pipe. The strength of the striation thinning method is that it reflects the physics of the mixing process well. However, the method is not suitable for investigating the mixing process for more than a few mixer elements since it is very demanding in terms of computer time, and can only be applied until the stretched striations reach a thickness of the same order as the numerical noise (Regner et al., 2005).

The aim of this study was to find a way to characterize and investigate the effects of flow rate and the geometry of the mixer elements on secondary flow and the mixing process in static mixers under laminar flow conditions by applying the method of rate of striation thinning, developed and presented by the authors in a previous paper (Regner et al., 2005). For this purpose CFD was used.

2. Methods

Two commercial static mixers were chosen for this study, namely the Kenics KM static mixer (Chemineer Inc., Dayton, OH, USA) and the Lightnin Series 45 static mixer (Lightnin mixers Ltd, Poynton, UK). Both mixers result in a helical flow structure, the Kenics KM mixer with a smooth twist and the Lightnin mixer with semi-elliptical plates connected by triangular plates forming edges past which the liquid must flow, see Fig. 1. The main difference between them is the edges in the Lightnin mixer, which will create different flow patterns and mixing performance.

2.1. Geometry and fluid properties

In the standard Lightnin mixer, with an aspect ratio of 1.5, the semi-elliptical plates are assembled at 34° and 146° to the flow axis. Each mixer element is rotated 90° relative to, and twisted in the opposite direction to, the previous one. This will cause the flow to have an altering clockwise and counter-clockwise rotation. The geometries of the Kenics KM and standard Lightnin mixer elements are described in Tables 1 and 2.

In addition to the standard configuration of the Lightnin static mixer, i.e. an aspect ratio of 1.5 and a pipe diameter of 40 mm, three other mixer configurations were investigated: two with the pipe diameter 40 mm and mixer element aspect ratios of 1.0 and 2.25, and one with a pipe diameter of 80 mm and an aspect ratio of 1.5.

The model liquid used in the simulations has the same properties as a 65% sugar solution ($\rho = 1317\,\mathrm{kg\,m^{-3}}$, $\mu = 0.1492\,\mathrm{Pa\,s}$).

2.2. Numerical methods

The simulations were performed in Fluent 6.1 (Fluent Inc., Lebanon, NH, USA). The geometries of the mixers were laid out using the grid generator Gambit 2.0.4 (Fluent Inc.), and unstructured tetrahedral meshes of the fluid volumes were constructed using TGrid (Fluent Inc.). The meshes were then exported to Fluent 6.1, where they were scaled according to the specifications in Tables 1 and 2. The meshes consisted of