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Numerical study of liquid-liquid mixing in helical pipes

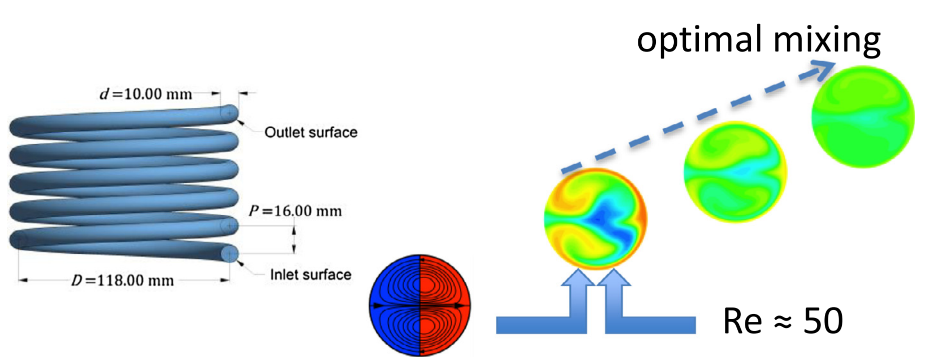
M. Mansour [a], Z. Liu [a], G. Janiga [a], K.D.P. Nigam [b], K. Sundmacher [c], D. Thévenin [a], K. Zähringer [a,*]

[a] Lab. of Fluid Dynamics & Technical Flows, Univ. of Magdeburg "Otto von Guericke", 39106 Magdeburg, Germany
[b] Indian Institute of Technology – Delhi, New Delhi 110016, India
[c] Lab. of Systems Process Engineering, Univ. of Magdeburg "Otto von Guericke", 39106 Magdeburg, Germany

HIGHLIGHTS

- Optimal liquid-liquid mixing conditions are investigated numerically in a helical pipe.
- Considering a wide range of relevant Reynolds numbers Re and Schmidt numbers Sc.
- An initially vertical liquid-liquid interface leads to the highest mixing efficiency.
- Two values of the Reynolds number are found that lead to best mixing conditions.
- From those two, Re $\simeq$ 50 leads to a lower pressure drop, and is thus recommended.

GRAPHICAL ABSTRACT



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ABSTRACT

The flow characteristics and the mixing performance of two miscible liquids in helical pipes have been studied numerically by computational fluid dynamics (CFD). The scalar transport technique is employed to quantify species mixing between the two fluids. The focus of the present study is set on investigating the optimal mixing behavior as a function of different parameters. The study is carried out for a wide range of relevant Schmidt and Reynolds numbers for laminar flow conditions. The Reynolds number (Re) and Schmidt number (Sc) have been varied from 5 to 10^4, and from 10 to 10^5, respectively. The model is first validated against experimental data from the literature. The effect of the inlet configuration is then examined; a vertical liquid interface at the inlet lead to the highest mixing efficiency. For low values of the Reynolds number, the results show that the mixing efficiency is reduced with increasing Schmidt number, until an asymptotic behavior is reached for very high Sc. For high values of the Reynolds number, increasing Schmidt number is observed to have only a minor influence on the mixing coefficient. The Reynolds number is found to have a more complex impact on mixing efficiency. Nevertheless, two optimal values of the Reynolds number can be found that lead to best mixing conditions in the laminar regime for a given length of the helical pipe. Though both values depend on the available length of the helix, they are typically found around Re $\approx$ 50 and Re $\approx$ 1000.

1. Introduction

Mixing of liquids is a critical process for many applications in chemical industry, nuclear energy, or pharmaceutical industry (Mandal et al., 2011a; Koutsky and Adler, 1964), to cite a few.

* Corresponding author.
E-mail addresses: michael.mansour@ovgu.de (M. Mansour), zhixin.liu@st.ovgu.de (Z. Liu), janiga@ovgu.de (G. Janiga), drkdpn@gmail.com (K.D.P. Nigam), kai.sundmacher@ovgu.de (K. Sundmacher), thevenin@ovgu.de (D. Thévenin), katharina.zaehringer@ovgu.de (K. Zähringer).

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Nomenclature

a	pipe radius [m]
D	coil diameter [m]
d	pipe diameter [m]
D_{ab}	mass diffusivity [m^2/s]
L	coil length [m]
M_c	mixing coefficient
n	number of turns
P	coil pitch [mm]
Δp	static pressure drop [Pa]
r	radial coordinate [m]
Re	Reynolds number, Re$= (\rho U d)/\mu$
Sc	Schmidt number, Sc$= \mu/(\rho\ D_{ab})$
U	velocity [m s^{-1}]
U_∞	surface average velocity [m s^{-1}]

Greek symbols

Γ	diffusion coefficient
δ	curvature ratio of the coil, $\delta = d/D$
θ	coil angle (measured from the inlet surface of the coil) [^{o}]
μ	dynamic viscosity [Pa s]
ρ	density [kg m^{-3}]
ϕ	angle between the inlet liquid interface and the horizontal axis [$^\circ$]
Φ	mass fraction

Generally, curved pipes show improved performance regarding key processes like mixing, heat transfer, and mass transfer (Jokiel et al., 2017; Rennie and Raghavan, 2005; Moulin et al., 1996; Abdalla, 1994). Using a helical pipe for mixing liquids may show noticeable advantages compared to using a stirrer, since this is a robust solution (no moving parts), needs no additional power source, and has a compact structure. Therefore, lower maintenance and energy consumption are usually required compared to active mixers. Additionally, mixing in helical pipes can also take place efficiently in the laminar regime, avoiding energy losses associated with the generation of turbulence. Indeed, the existence of counter-rotating vortices, as a secondary flow in helical pipes, is mainly responsible for the improved mixing characteristics. Dean (Dean, 1927, 1928) showed that these vortices are arising due to the unbalanced centrifugal forces exerted on the flow. Consequently, helical pipes have improved radial mixing and residence time distributions. However, the flow in helical pipes involves typically a higher pressure drop when compared to a straight pipe of the same length (Ito, 1959; Mishra and Gupta, 1979; Ju et al., 2001).

Different applications rely on different mixing processes, involving different phases (e.g., gas/liquid, solid/liquid, liquid/liquid, three-phase systems…). Many studies aimed at enhancing solid/liquid mixing to obtain a higher conversion rate in chemical reactors by minimizing axial dispersion (Koutsky and Adler, 1964; Saxena and Nigam, 1983; Villermaux, 1985; Leclerc et al., 1987; Palazoglu and Sandeep, 2004). In most of these investigations, the main goal was to narrow the residence time distribution (RTD) of the particles. Several techniques were used to improve the mixing characteristics, starting from simple geometrical changes, such as non-circular cross-sectional curved pipes (Jiang et al., 2004; Liu et al., 2000; Schönfeld and Hardt, 2004; Vanka et al., 2004), contraction-expansion helical pipes (Dong and Shufen, 2014; Liang and Zhang, 2014), modified flow paths (Lasbet et al., 2007), and ending with complex, chaotic configurations (Mandal et al., 2011a, 2011b; Kurt et al., 2015; Tohidi et al., 2015; Alam and Kim, 2012). Acharya et al. (1992) and Castelain et al. (2000, 1997) studied the mixing in a chaotic system constructed from several segments of bends and compared it to regular helical pipes. A considerable enhancement of the mixing was observed in the chaotic systems due to the variation of the centrifugal force direction. However, such chaotic systems show a very complex geometry, might not be suitable for practical applications, and usually lead to considerable pressure losses.

Another interesting geometry is the coiled flow inverter (CFI), which was constructed based on helically-coiled tube structures. The CFI was first introduced by Saxena and Nigam (Saxena and Nigam, 1984) and works based on the principle of complete flow inversion by "bending of helical coils" in order to cause multiple flow inversions. The configuration of the CFI is built by installing 90^o bends at regular length intervals in a helically-coiled tube geometry. It was proven by several studies that the CFI shows enhanced mixing properties compared to simple helical pipes (Mandal et al., 2011b; Saxena and Nigam, 1984; Kumar et al., 2007; Mridha and Nigam, 2008a, 2008b). However, the mixing performance of a CFI with only one or two flow inversions is very close to the simple, straight helical pipe (Mridha and Nigam, 2008b). Therefore, several flow inversions are required to achieve a considerable enhancement of the mixing performance of a CFI over helical pipes, leading unfortunately to a noticeably increased pressure drop.

The mixing properties of liquid-liquid flows in helical pipes have received less attention in the scientific literature (Mandal et al., 2011a; Vashisth et al., 2008). Vanka et al. (2004) performed a numerical study to compare the mixing performance between curved and straight channels, considering the effects of Reynolds (Re) and Schmidt (Sc) numbers, where:

$$\mathrm{Re} = \frac{\rho U d}{\mu}, \tag{1}$$

$$\mathrm{Sc} = \frac{\mu}{\rho D_{ab}}, \tag{2}$$

In these equations, ρ is the density of the fluid, U is the average velocity, d is the pipe diameter, μ is the dynamic viscosity of the fluid, and D_{ab} is the mass diffusivity from the first fluid into the second fluid. Vanka et al. (2004) showed that the mixing in curved channels is dramatically more efficient than in a straight channel. Additionally, the mixing was found to be better in both channels at low Sc-numbers. However, at higher Reynolds numbers the mixing was improved in the curved channel, while mixing efficiency was reduced in the straight pipe. Kumar et al. (2006) performed another numerical investigation to compare mixing of miscible liquids in helical pipes and straight pipes. Likewise, they showed that the mixing efficiency in helical pipes is generally much better than in straight pipes, and confirmed the findings by Vanka et al. (2004). Additionally, they discussed the effect of the coil curvature ratio ($\delta = d/D$), whereby higher $\delta = d/D$-ratios resulted in improved mixing due to the increased centrifugal effects. However, all these studies were limited to very low Reynolds numbers (Re $\leq$ 100) and low Schmidt numbers (Sc $\leq$ 1 000).

Therefore, the focus of the current paper is to further investigate the mixing characteristics of two miscible liquids in a coiled helical pipe with extended flow conditions, for noticeably higher Reynolds numbers ranging from 5 to 10^4, and for Schmidt numbers ranging