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Blending of miscible liquids with different densities and viscosities in static mixers

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HIGHLIGHTS

- The turbulent blending of two miscible liquids in static mixers is investigated.
- RANS-based CFD simulations are adopted for the analysis.
- The effect of densities and viscosities differences is considered.
- The mixedness level is found to be a function of the Richardson number.
- Intensity, scale and rate of change of segregation are calculated.

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ABSTRACT

The homogenization of two liquids of different densities and viscosities in a pipeline equipped with a corrugated plate SMV static mixer is investigated by RANS-based CFD simulations. The blending effectiveness of the mixer is compared at different Richardson numbers and viscosity ratios for equal Reynolds numbers. The mixedness level is found to be a function of the Richardson number. As a result, depending on the pipeline scale, equal density differences require a different number of pipe diameters for the achievement of the same level of homogenization. The dynamic viscosity differences give rise to less marked effects, unless back-mixing becomes significant. Besides the coefficient of variation of the scalar concentration, which is often adopted as a measure of the intensity of segregation in turbulent static mixers, novel definitions of the scale and of the rate of change of segregation are proposed, in order to add deeper insight into the evaluation of the mixing features.

1. Introduction

Static mixers are often adopted as an alternative to dynamic agitators in a variety of industrial operations in chemical and process engineering. They are expected to play an increasingly important role considering the interest of industry to move towards continuous processes (Ghanem et al., 2014). The selection of the static mixing design depends mainly on the specific task and on the flow regime of the process. Similarly to mechanical agitators, general design rules for static mixers are not available (Paglianti and Montante, 2013), due to the complex fluid dynamic characteristics of each mixing device. Overall, extensive data and correlations can be found on pressure drops, at least for the most widespread designs of static mixer (Thakur et al., 2003), while the flow features and the mixing mechanisms have been investigated in a less wide number of works (Marshall and Bakker, 2004).

As for the adoption of static mixers for turbulent flows, that is the case considered in this work, advantages in industrial applications have been highlighted in a broad range of operations, from coagulation and disinfection in wastewater and water treatments (Jones et al., 2002), to emulsification (Theron and Sauze, 2011), heat transfer (Rakoczy et al., 2011), oxygen mass transfer in aerobic bioreactors (Ugwu et al., 2002), synthesis of pharmaceuticals (Brechtelsbauer and Ricard, 2001) and gas–liquid dispersions (Rabha et al., 2015). Amongst the different design options for turbulent flows, corrugated plate mixers are still very attractive, particularly in large diameter ducts and pipes where mixing

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length is limited (Etchells and Meyer, 2004). For this reason, an SMV type mixer has been considered in this investigation.

Computational Fluid Dynamics (CFD) simulations are virtually able to provide detailed information on the mixing effectiveness of static mixers and they are being increasingly adopted for the design, the optimization and the selection of operating conditions. Amongst others, successful simulations of HEV static mixers based on the solution of the Reynolds Averaged Navier–Stokes (RANS) equations have been presented by Mohand Kaci et al. (2009), who reported accurate flow field predictions either with the standard k–ε turbulence models and the more advanced Reynolds stress model. Following Bałdyga et al. (1997), they suggested to evaluate the mixing efficiency of the insert based on the dissipation of turbulence kinetic energy as compared with empty pipelines. The same computational method was recently applied to the optimization of the geometrical configuration of HEV tab arrangements in heat exchangers/reactors by Habchi et al. (2010). They examined the macro-, meso- and micro-mixing features of the inserts based on the predictions of residence time distribution, turbulent kinetic energy and dissipation of turbulent kinetic energy, respectively. CFD based investigations on turbulent mixing using a Kenics mixer led to analyze the specific features of the transient behavior of the single phase flow moving from laminar to turbulent regimes (van Wageningen et al., 2004), to propose a novel correlations for the pressure drops calculations (Kumar et al., 2008) and to predict the distribution of the local turbulent energy dissipation rate and of the droplet size distribution in turbulent liquid–liquid dispersions (Jaworski et al., 2007). Recently, Coroneo et al. (2012) have evaluated the capability of RANS simulations in predicting the main fluid dynamic characteristics in a pipeline equipped with an SMV static mixer element. The validation of the CFD model was performed by the comparison of the simulations' results with literature LDA mean velocity profiles (Karoui et al., 1997) and LIF tracer concentration data (Karoui et al., 1998).

Amongst the different aspects affecting the performances of static mixers, the consequences of density and viscosity differences upon miscible liquids blending are not widely established. To the best of our knowledge, they have never been systematically investigated in the field of turbulent in-line mixing. Knowledge is often limited to practical recommendations given by the manufacturer. Overall, the effect of the density ratio between the main and the secondary stream in turbulent liquid blending with motionless mixers is considered negligible for vertical orientation, unless the densiometric Froude number is lower than 20 (Etchells and Meyer, 2004). Comparatively, more investigations have been carried out on blending of liquids with different densities and viscosities in stirred tanks, by experiments and more recently by direct numerical simulations. Different conclusions on the impact of density differences have been achieved, depending on the initial conditions. When the two liquids are initially stably stratified, a different dependency of the mixing rate on the density difference was found at different ranges of the Richardson number (Rielly and Pandit, 1988). In addition, the increase of the Reynolds number above a critical value is suggested to achieve good mixing, depending on the viscosity ratio. For small amount of a secondary liquid, the location of the addition was found to affect the impact of the density differences, highlighting different regimes (Bouwmans et al., 1997); also, a different dependency of the density difference on the mixing time was found for different impeller types (Gogate and Pandit, 1999). Generally, as soon as the buoyancy forces become significant, the Richardson number has been found to clearly govern the fluid dynamic behavior together with the Reynolds number (Derksen, 2011). Unlike laminar flows (Regner et al., 2008), a weak effect of the viscosity ratio upon turbulent mixing was observed (Derksen, 2012).

The turbulent blending of two miscible liquids of equal or different densities and viscosities is analyzed in this work. The model equations and the solution methods are based on previous verification and validation analysis of the single phase flow and of the tracer homogenization dynamics in the same geometry performed by Coroneo et al. (2012).

The effect of buoyancy is assessed for variable physical properties of the two liquids and different geometrical parameters, including pipe diameter and element orientation. The effect of different viscosity ratio at constant Reynolds number is also assessed.

2. The model equations

The simulations are based on the solution of the Reynolds-Averaged conservation equations of mass, momentum and scalar concentration for incompressible, isothermal and steady-state flow of Newtonian liquids. The Reynolds stress and the Reynolds flux terms are modeled using the eddy viscosity and the eddy diffusivity hypotheses, respectively. The formulation of the equations is as follows:

$$\nabla \cdot (\rho \mathbf{U}) = 0 \tag{1}$$

$$\nabla \cdot (\rho \mathbf{U}\mathbf{U}) = -\nabla p + \nabla \cdot \left[(\mu + \mu_t)\nabla \mathbf{U}\right] + \rho \mathbf{g} \tag{2}$$

$$\nabla \cdot (\rho \mathbf{U} Y_i) = \nabla \cdot \left(\rho D_{i,m} \nabla Y_i + \frac{\mu_t}{\sigma_t}\nabla Y_i\right) \tag{3}$$

$$\rho = \frac{1}{\sum_i \frac{Y_i}{\rho_i}}; \quad \mu = \sum_i Y_i \mu_i \tag{4}$$

where $\mathbf{U}$ is the mean velocity vector, ρ_i is the density of the fluid species i, ρ the volume averaged density of the fluids, $\mathbf{g}$ is the gravity acceleration, μ_i is the viscosity of the fluid species i, μ is the mass averaged viscosity of the fluids, p is the pressure, Y_i is the mass fraction of the liquid species i, μ_t is the turbulent viscosity, σ_t is the turbulent Schmidt number and D_m is the molecular diffusivity.

The molecular diffusivity is fixed to the value of 10^{-9} m^2/s regardless of the fluid considered. Its contribution is expected to be negligible, while the overall scalar dispersion is dominated by the turbulent diffusivity. It is defined as the ratio between the turbulent viscosity, which results from the turbulence closure equations, and the turbulent Schmidt number. This last parameter is fixed at 0.7, as is commonly suggested (Hartmann et al., 2006). The adequacy of this value is confirmed by the preliminary

Fig. 1. Geometry of the computational domain.