MICROMIXING STUDIES IN LOW-FREQUENCY ROTATING MAGNETIC FIELD PROBED VIA VILLERMAUX-DUSHMAN REACTION

Shahab Boroun, Faical Larachi*
Université Laval – Québec
Canada, QC G1V 0A6

Abstract

Micromixing has been the subject of numerous research efforts in the context of chemical reaction engineering to elucidate the impact of mixing on the conversion and selectivity of chemical reactions. In this contribution, we present the *first* report on micromixing based on magnetic field assisted mixing of paramagnetic fluids with a magnetic nanofluid. We also present a new class of mixing tools with a mechanism based on nanostirring of non-interacting uniformly dispersed magnetic nanoparticles (MNPs) in a carrier fluid subject to an external rotating magnetic field (RMF). Mixing and micromixing features are investigated using the Villermaux-Dushman reaction probe. Experiments are conducted in a T-type microfluidic device and conventional magnetic fields to investigate mixing and micromixing features. Experimental results reveal superior impact of RMF in both mixing and micromixing features in comparison to static (SMF) and low-frequency oscillating (OMF) magnetic fields.

Keywords

Micromixing; rotating magnetic field; nanofluid

Introduction

Mixing with the aid of MNPs is of great potential in chemical reaction engineering. Besides the possibility of targeted manipulation of MNPs in an external magnetic field for the purposes of mixing, actuation and intensification of mass and heat transport, a variety of magnetic materials is being developed to function as adsorbents or (bio)catalysts. Accordingly, there is a serious motivation among researchers to develop feasible and efficient mixing processes based on magnetic fields and magnetic material interactions. In addition, the broad and thoroughly studied concept of mixing at molecular scale, i.e., micromixing, and its deep influence on the selectivity and conversion of chemical reactions entails thorough investigations of new mixing methods from the micromixing standpoint. Despite an extensive body of research in the realm of magnetic-field assisted mixing, this concept still lacks knowledge of the micromixing features activated by the MNP/magnetic field association. This shortcoming becomes more marked when planning extension of magnetic mixing toward reaction engineering.

We report in this contribution, the *first* micromixing study in a mixing process between a paramagnetic fluid and a magnetic nanofluid using a T-type microfluidic mixer in which the well-known Villermaux-Dushman set[1] is implemented to decipher the reaction micromixing features. Although complete mixedness levels are achievable by previously studied SMF and OMF at proper operating conditions, we demonstrate that these methods are not suitable for micromixing applications. We further introduce low-frequency rotating magnetic fields as a promising tool with enhanced mixing and micromixing characteristics.

* E-mail address: Faical.Larachi@gch.ulaval.ca

Experimental

The mixing device used in the experiments consists of a 1-mm-ID capillary tube connected to a T-junction and a pair of electrical conductivity electrodes for detection. The mixing device is inserted inside the bore of a magnet that produces uniform static, oscillating and rotating magnetic fields with adjustable intensities and frequencies. Magnetic field vector in all aforementioned types is normal to flow direction.

For evaluation of mixing efficiency, diluted nitric acid solution and sodium hydroxide solution seeded with magnetic nanoparticles are fed separately from two branches of the T-junction. The reduction of electrical conductivity as a result of acid-base neutralization is constantly measured and a mixing efficiency based on the measured conductivity is defined as

$$\text{Mixing efficiency } (\alpha) = \frac{\kappa_{\max} - \kappa_{measured}}{\kappa_{\max} - \kappa_{\min}} \qquad (1)$$

where κ_{max} and κ_{min} are the average conductivities, respectively, at complete segregation and perfectly mixed conditions.

For micromixing studies, fast reaction of iodine dismutation (V-D reaction) and the instantaneous neutralization by protons of borate anions were conducted simultaneously in the microtube. Protons were fed from one side and the rest of reactants and MNPs were fed from the other side of the T-junction. Triiodide, I_3^-, as the product of V-D reaction is determined by UV-vis spectrophotometry. To interpret the experimental I_3^- concentration, the micromixing model of interaction by exchange with the mean was used to convert triiodide concentration into a micromixing time.

Results

Figure 1 illustrates the mixing efficiencies in three types of magnetic fields at almost equal magnetic field intensities (~31 kA/m). Mass percent of MNPs in basic solution was 5 % in all experiments. The associated Reynolds number is *ca*. 10 to ensure laminar flow inside the microtube. It can be seen that at equal magnetic field intensities, RMF exhibits superior performance as compared to the other types of magnetic fields. Unlike the mixing mechanism in SMF and OMF, dominated by the Kelvin body force experienced by the magnetic fluid, the exceptional mixing efficiency in the presence of RMF at low frequency (75 Hz) cannot merely be attributed to such a magnetic body force. As a matter of fact, the exerted magnetic torque on MNPs brings these latter into a rotational state which gives rise to a mixing mechanism based a *nano-stirring effect* of the rotating MNPs.

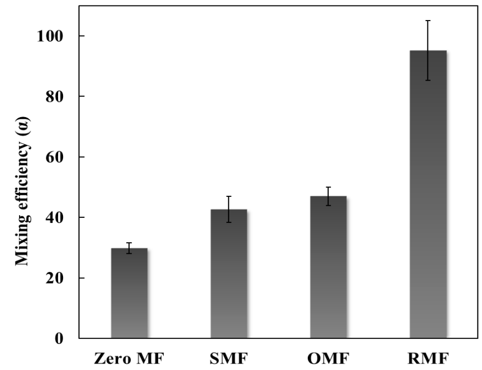

Figure 1. Mixing efficiencies at low Re numbers in the absence and presence of various types of magnetic fields.

Moreover, mixing subtended by such nano-stirring mechanism was investigated for its micromixing aspects. At very low Re number, *i.e.*, *O*(1), where the mixing efficiency at the microchannel exit is 100% for all types of magnetic fields, the micromixing feature is notably different. As can be seen in Figure 2, by application of RMF, the micromixing time is 2 to 3 orders of magnitude briefer than pure diffusional mixing and mixing under the action of SMF and OMF, respectively.

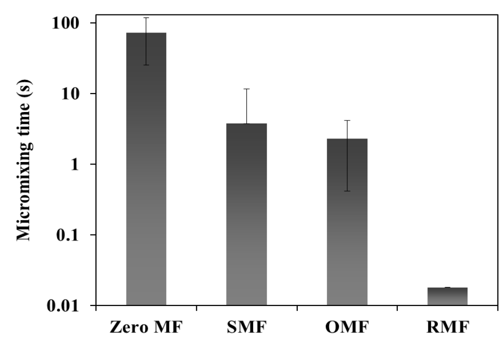

Figure 2. Calculated micromixing times based on results of V-D probe in the absence and presence of various types of magnetic fields

Conclusion

We presented the first report on application of RMF for mixing and micromixing studies for fluid phase homogenization of magnetic and non-magnetic fluids. The results reveal superior performance of RMF in comparison to previously studied SMF and OMF for mixing and micromixing.

References

1 Commenge, J. M., Falk, L., (2011). Villermaux-Dushman protocol for experimental characterization of micromixers. *Chem. Eng. Process.*, *50*, 979.