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Flow of deep eutectic solvent-simulated fuel in circular channel: Part I—flow patterns and pressure drop

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ABSTRACT

Flow patterns and pressure drop measurements in a circular 1.22 mm ID glass channel were investigated for two immiscible liquids; namely: simulated fuel and a deep eutectic solvent (DES). The effect of the inlet junction and initial channel saturation phase were studied by using two different configurations (T and cross) and two initial saturation phases (DES and fuel). Annular, drop, dispersed and plug were the major flow patterns observed, but the area covered on the map by each type varied to some extent from each other. For the T junction; plug flow was observed when the DES was the saturation phase but it did not exist when the fuel was the saturation phase. In contrast, the area covered by the drop flow increased when the fuel was introduced first. For the cross junction; the flow pattern map was dominated by annular flow while minor presence of dispersed and plug flow patterns was noticed in comparison to those reported using the T-junction. For constant fuel velocity, the pressure drop was found to increase as the DES velocity increased. On the other hand and for constant DES velocity, the pressure drop was found to fluctuate as the fuel velocity increased.

1. Introduction

One of the worldwide important issues in the refining industry is the removal of sulfuric compounds (desulfurization) from fuels due to their severe noxious impact on ecosystems and human beings to below environmental set limits (Amaral et al., 2014; Gano et al., 2015). Some of the used methods for desulfurization are prevaporation, selective adsorption, and hydrodesulfurization (HDS). HDS technology is commonly used in the industry (Xu et al., 2013). However, this technology is very costly for deep desulfurization applications since it works at high operating conditions (pressure, temperature and catalytic operation) and the utilization of hydrogen is ingrained (Gano et al., 2015). As such, an extensive research was conducted to search for more viable techniques to meet the environmental regulations for desulfurizing liquid fuels. Among the proposed techniques, extractive desulfurization using solvents (EDS) can be used effectively to remove refractive sulfur-containing compounds from liquid fuels. This technique requires low energy consumption since it operates at mild operating conditions and does not require any hydrogen consumption. However, the success in using this technique depends on the selection of efficient and environmentally benign solvents. Recent studies have shown that deep eutectic solvents (DESs) and ionic liquids (ILS) can be efficiently used for extractive desulfurization (Mjalli et al., 2014).

A DES is commonly synthesized by forming a mixture of a hydrogen bond donor (HBD) and a quaternary ammonium or phosphonium salt. Different types of salts can be used in the preparation of DESs. The complexation between the salt and the HBD through the formation of new hydrogen bonds results in considerable depression of the mixture melting point. The formed DES exhibits many similar characteristics to common ionic liquids (ILs). DESs are generally pharmaceutically tolerable concerning toxicity, biodegradability, recyclability, and have high chemical and thermal stabilities (Jibril et al., 2014; Kianpour and Azizian, 2014). In contrast to DESs, waste disposal, organic solvent

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usage and supply of heat are associated in the synthesis of ILs which increase their synthesis cost as well as their negative impact on the ecological fingerprint. All of these drawbacks of ILs make DESs better potential alternatives (Jibril et al., 2014).

DESs have wide and variable applications such as in fields of catalysis, dissolution, material chemistry, organic synthesis and electrochemistry, but they were not used in liquid–liquid extraction (LLE) applications in the same extensive rate. In recent studies, DESs were used in LLE by means of agitated vessel and packed columns with a macroporous resin (Qi et al., 2015). The limitation of using DES in LLE is linked to the high energy of mixing cost due to their relatively high viscosity. However, the high operating cost associated with this type of solvent can be overcome by conducting this separation using small or microchannels and regenerating the DES by simple distillation. In addition, conducting the process in a micro-scale contributes in enhancing the inter-phase mass transfer characteristics of the LLE process and consequently improves productivity.

Up to the authors' knowledge, there is no reported study that investigates the flow of DES in microchannel. Understanding of the flow behaviour of the two contacted liquids involved in LLE can be crucial to improve mass transfer, obtain better extraction and decrease the pressure drop in the channel. In the present work, the flow patterns and the pressure drop of a simulated fuel and tetra-*n*-butylammonium bromide-based DES were investigated in a very small glass channel. The effects of operating conditions, inlet mixing zones and initial channel saturation phases were studied. The outcome of this investigation will be used in another future study on the deep desulfurization of liquid fuel using similar type of DESs.

2. Literature review

2.1. Flow patterns

Microchannels are characterized with dimensions which lay in a range that varies from submicrons to hundreds of microns. Many materials can be used in the fabrication of microchannels. Examples are glass, polymers, silicon and metals. These materials attain many advantages because of their tiny volumes, upturn surface-to-volume ratio and short transport path (Chai et al., 2015), which lead to high rate of heat and mass transfer in any system such as the biological human body systems including kidneys and lungs (Mohammed et al., 2011).

Due to its extensive applicability to modern and advanced science and technologies, two phase flow in small and micro channels has drawn the attention of many concerns. Two phase flow is encountered in many industrial processes such as oil recovery, cosmetic production, food manufacturing, fire-fighting and nuclear power plant cooling. The relative significance of surface to volume forces raises as the dimension reduces to microscale (Cubaud et al., 2006).

Two phase flow, which is the simplest type of multiphase flow, takes place when two partially or not miscible fluids are brought in contact and subjected to pressure drop (Hessel et al., 2009). This kind of flow in general has more complexity than a single phase flow. In the single phase flow, the known forces present are inertia, pressure and viscous. The interfacial tension is an additional force that affects the two phase flow. The liquid wetting properties on the wall of the tube also has an effect on the two phase flow (Revellin et al., 2006). In general, two phase flow in small and micro channel systems have rapid mixing, high interfacial areas and minimised mass transfer restrictions (Hessel et al., 2009).

Flow in micro channels differs from the macroscopic scale because of the very small scale which makes molecular effects like wall slip more essential (Sharp and Adrian, 2004), surface tension and viscous forces become more important in comparison to inertia and buoyancy forces (Cubaud et al., 2006; Awad et al., 2014), unlike the flow in large channels which is mainly controlled by gravity and inertia effects (Yusuf et al., 2012).

Different flow patterns such as drop, plug, annular and parallel flows can be observed in small and micro channels (Tsaoulidis et al., 2013). The formation of these patterns depends on several factors such as flow rates, phase ratio, fluid properties, geometry of the channel, wettability of the system and the roughness of the channels (Tsaoulidis et al., 2013; Lin and Tavlarides, 2009; Jovanović et al., 2011). Prediction of the flow pattern or configuration is an important concern in many applications. It provides quite a few positive peculiarities in the multiphase flow systems analysis. For example, the right pressure drop method evaluation is determined by the flow pattern identification of the multiphase flow (Mukhaimer et al., 2015).

2.2. Pressure drop

Pressure drop of two-phase flow in pipes is expressed in terms of frictional loss, acceleration head, and static term due to the gravitational force (Collier and Thome, 1994; Barreto et al., 2015). Because of the interactions between the liquids and the wall of the tubes, and between both of the liquids (across the interface) in two-phase flow, the frictional pressure drop is related to the irreversible loss of energy and there is no exact theory that predicts the frictional pressure losses (Barreto et al., 2015).

Despite the importance of knowing the pressure drop for the design of a better energy transporting system, very few studies are currently available in the literature on pressure drop in liquid–liquid system (see for example, Chakrabati et al., 2005; Jovanović et al., 2011; Tsaoulidis et al., 2013; Awad and Butt, 2015).

3. Experimental set-up and procedure

3.1. Experimental set-up

Fig. 1 shows a schematic of the experimental set-up used to investigate the two phase flow of DES and fuel in microchannels. Two syringe pumps, Sage instruments syringe pump model 355 with an accuracy of ±0.5%, were used to deliver the liquids to the mixing zone. Two junctions were used as a mixing zone for the liquids those are T and cross junctions. The test channels along with the mixing junctions are made of stainless steel. A glass channel of an internal diameter (ID) of 1.22 mm and 100 mm in length was used as the test section.

The flow pattern observation was performed using a Canon EOS 1100D camera provided with a macro extension tube ring and a source of light. The camera was subjected to the last 40 mm near the outlet of the channel to ensure a full development of the flow. For the pressure drop measurements, a digital monometer with an accuracy ±0.2% was used with one of its ends connected directly to the inlet of the channel via a pressure port, while the other end was exposed to the atmosphere, since the outlet of the channel was opened to the atmosphere.

The working fluids used in this study were a simulated fuel (see Table 1 for its composition) and a deep eutectic solvent, Tetra-*n*-butylammonium bromide (TBAB): polyethylene glycol