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Continuous production of water-in-oil emulsion using micromixers

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HIGHLIGHTS

- T-shape micromixers are used at high flow rates.
- Obtained water in oil emulsions have a mean size of droplets smaller than 10 μm.
- Two sizes and geometries of channels are tested.
- Three flow configurations are implemented.
- The length of the channels has to be optimized.

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ABSTRACT

The formation of emulsions is a critical application that interests many industrial fields. Among the various interests to produce emulsions, this work focuses on the emulsification of water in fuels, in order to improve combustion and reduce emission of harmful gases. The manufacturing process of these emulsions must meet a number of constraints such as water fraction, mean droplet size, delivered flow rate and process energy consumption. Among possible techniques, this study focuses on the implementation of crossing microchannels. For this purpose, two geometries of the cross section of the channels have been tested. The implementation of several flow configurations has also been investigated. Other parameters were varied such as the variation of the ratio of flow rates of lipid phase and water, the nature and content of surfactant. In conclusion, obtaining emulsions of water in oil having a mean droplet size of about 4 μm was possible with several operating conditions. Channel geometry and flow pattern have a significant influence on the possibility of forming this type of emulsions.

1. Introduction

Continuous production of emulsions is an application that involves many areas. In particular, the burning of fuels and new sources of biofuels requires in practice to emulsify the water in the fuel. This operation allows better combustion due to the phenomenon of micro-explosion of water droplets [1] and reduces the formation of undesirable compounds such as NOx as previously shown for vegetable oils and ethanol-biodiesel mixings [2–4]. The synthesis process of these water in oil (w/o) emulsions must meet a number of constraints. In particular, for economical and environmental considerations, the use of surfactants needs to be avoided or to be minimized. Due to the poor stability in time of such emulsions, their production can consist in an in-line process which is included upstream the boiler. [5]. In the present case the expected fraction of water in the emulsion is about 10–15%, the mean droplet size has to be comprised in the range 1–10 μm and, of course, the dispersion of the size of the droplets should be narrow. Other characteristics have to be considered such as the level of the delivered flow rate of the emulsion, the energy consumption of the process, its maintainability. As an example for the emulsion flow rate to be delivered, the fuel consumption of a engine of 50 kW is about 100 mL/min.

Among the techniques available for continuous production of emulsions, those based on the formation of droplets through micro pores or membranes allow obtaining droplet sizes characterized by relatively small size distribution and by a mean size of the order 0.1–10 μm [6]. However, the cost of the membranes, the risk of clogging and the level of pressure needed for such devices are prohibitive in the present objective. In this work, simple micro mixers of the cross-type and T-type are investigated. Among the studies previously conducted on such devices, the characterization of flow regimes favouring the mixture [7,8] and production of oil in water (o/w) emulsions [9] have shown that increasing flow rates in such systems promotes mixing and, on the other hand, makes the mean droplet size decreasing. Considering to the present target, working with "high flow rates" is an advantage to exploit in the case of

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microsystems, compared to their more classical uses for obtaining for example uniform size of droplets at "low flow rates" with flow-focusing or co-flowing in particular [10,11]. Matsuyama et al. [12,13] have shown the interest of high-throughput micromixers which may be used for industrial applications. However, the generated pressure drop should not be limiting. Thus, this study focuses on preliminary calculations of pressure drop in micro channels. Then, production of emulsions is investigated by varying different criteria: size of the channels, flow configuration, flow rates of the phases, water fraction and percentage of surfactant in the continuous phase.

2. Materials and methods

2.1. Reagents and their physical characterization

Sunflower oil (Lesieur, "Coeur de tournesol") and demineralized water are used at room temperature (20 °C) as the respective continuous and dispersed phases. The density of the oil is 915 kg/m^3, its dynamic viscosity is 71 mN/m and its superficial tension is 33 mN/m. The interfacial tension between oil and water is 26 mN/m. The superficial and interfacial tensions are measured with a tensiometer (Krüss, K-12).

The rheology of emulsions is studied with a cone and plate viscometer (Paar Physica MCR 500 Anton Paar France S.A.S.). The absence of an eventual pseudoplastic-dilatant rheological behavior of the oil and emulsions was verified by measuring shear stress at variable shear rates between 25 and 1000 s^{-1}.

Due to the industrial objective of this study, the prepared emulsions do not need to have a particular stability versus time because they should be made in situ and used immediately. However, in this study, the characterization of the emulsions needs a minimal stabilisation in time, and then a surfactant is added to the continuous phase. For the sake of preparation of such w/o emulsions, it is recommended to use surfactants with low HLB (hydrophilic lipophilic balance), i.e. generally 3 < HLB < 6 [14]. The non-ionic emulsifier, sorbitan sesquioleate (Span 83, Merck) is particularly interesting in the case of the ratio of the two phases involved in this study. It results from the mixing of sorbitan esters; then it contains no sulfur, no nitrogen and no aromatic hydrocarbon. The HLB value of this surfactant is 3.7. It was selected for the experiments for its ability to diminish the value of the interfacial tension between the continuous phase and the dispersed phase. Span 83 has been tested with a concentration ranging between 1% and 10% in weight in the continuous phase. The interfacial tension between oil containing a mass fraction of 1% of Span 83 and water is 9.95 mN/m; it falls to respectively 1.5 and 0.84 mN/m using 5% and 10% of Span 83 in the continuous phase. With a mass content of 0.1% of Span 83, the value of the interfacial tension with water is 22 mN/m; this value is closed to the interfacial tension between pure oil and water (26 mN/m), so this mass fraction has not been tested for the experiments. Concerning the influence of the fraction of water in our experiments, the phase inversion is observed above a small value of the fraction of water, i.e. 18.8% (Fig. 3). However, knowing that the fraction of water necessary in the emulsion is about 10–15% this phenomenon is not limiting in our case.

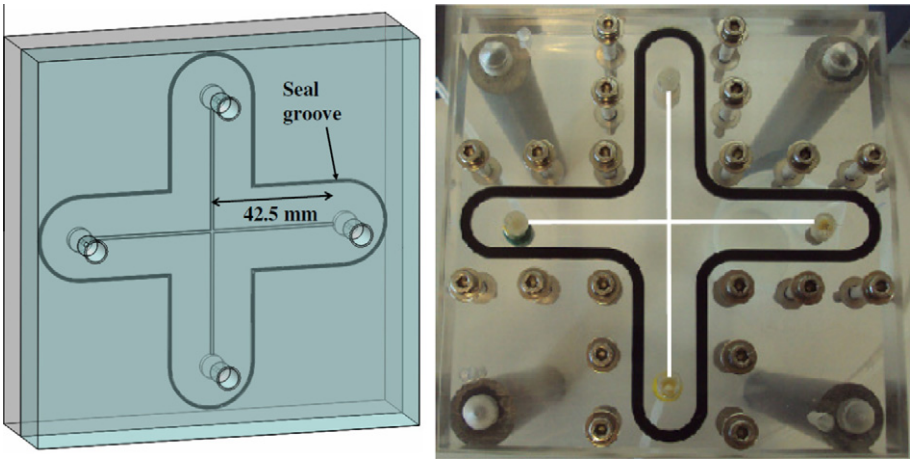

Fig. 1. On the left, sketch of the device. On the right: view of the top of the device; channels are featured with white lines to be more visible.

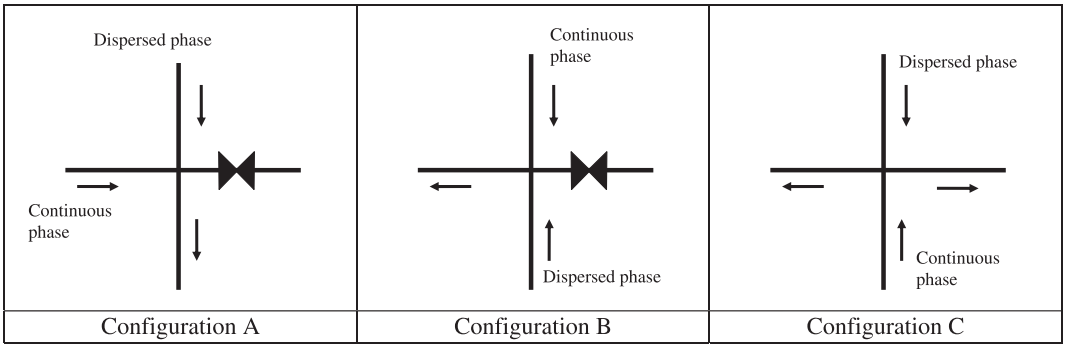

Fig. 2. Sketch of the three tested configurations.