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Study of two impinging flow microsystems arranged in series. Application to emulsified biofuel production

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HIGHLIGHTS

- Water-in-oil emulsion is produced using two micro-channels in series.
- Droplets size of the dispersed phase reaches 11 μm without surface active agent.
- A decrease of the average water droplet size by 40% compared to the use of single micro-system.
- Energy balance is performed.
- Flow visualization is given.

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ABSTRACT

Development of alternative fuels and improvement of their combustion is a necessity in a general context of scarcity of fossil energy resources and of environmental pollution. In particular, the use of water dispersed in biofuels is known to improve combustion quality of diesel engine and to reduce pollution in gas emissions. This work aims at contributing in the development of a compact continuous emulsifier that could be used to feed energy systems. In order to fulfil requests such as convenient size of water droplets, absence of surfactant and needed flow rates of biofuel, the association of two micro-systems in series is investigated and compared to the use of a single one. The comparison of the emulsions obtained by the different systems is made in terms of mean size and size distribution of the water droplets in the dispersion, and process energy consumption. In the absence of surfactant, depending on applied flow-rates and water fraction, the use of two micro-systems in series allows to reduce the mean size of droplets by a factor 2 to about 3. Flow phenomena which lead to water phase fragmentation are described thanks to high-speed visualization of the flows in the micro-channels.

1. Introduction

The possibility to use animal fats, vegetable oil or heavy fuel for the production of emulsified bio-fuel in the aim of an energy utilization is demonstrated [1–6]. Therefore, these energy resources could be burnt inside energy systems to transform their calorific value into heat, mechanical work or electrical energy using stationary applications like Combined Heat and Power (CHP) [6,7]. The presence of water or more precisely dispersed droplets of water plays a crucial role in the optimization of the combustion. Thermophysical phenomena are induced by the presence of these droplets, like micro-explosion which reduces the production of carbonaceous particles (soot) [8–10]. Another effect is the reduction of temperature during the combustion, due evaporation of water, which leads to a reduction of emissions of nitrogen oxides (NOx) [11–13,6,14].

Most of combustion tests using emulsified bio-fuel were conducted in the laboratory conditions [15], often with a single-cylinder engine such as in [16,17]. Many applications are developed, for examples boiler [6] or dual-fuel in compression-ignition (C.I.) engines [18]. Chen and Lee have investigated the possibility of using oily wastewater emulsified fuel in boiler. A system including a tank to pre-mix the respective aqueous and oily phases and a surface active agent, as well as a commercial micro-emulsifier was investigated to feed continuously the boiler. According to the authors, this emulsification equipment can produce 5–8 tonnes per hour of emulsified fuels [4].

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Chelemuge et al. [6] have recently investigated the use of commercial static mixers to feed continuously an industrial boiler with water in base fuel oil emulsion, using or not a surface active agent. The experiments were conducted using a single oil flow rate (91 l/h) and four different water flow rates (4–11 l/h). As an example of commercial application can be cited, the PEP-99® technology from Petroferm Fuel Company which function is to create and stabilize water-in-oil emulsions with heavy fuel oil typically burned in large industrial boilers and process heaters.

Concerning the optimal size of water droplets in the emulsion, the review of Mura et al. [19] points out that several studies converge to a value of about 5 µm. The same review mentions that a water content comprised in the range 8–30% may be convenient. It may be added that the range of water fraction available depends on the lipid phase. Then, the optimal water fraction may vary according to the composition of oil. Another aspect to consider is the use of surfactants. They are known to act favorably on the stability and then to the duration of storage of emulsions. However, they have an influence on the micro-explosion temperature and waiting time. On the other hand, the use of surfactant is not a positive point concerning the global carbon balance of the process.

Taking into account these requests, the present work investigates the use of micro-systems to produce a continuous flow rate of emulsified bio-fuel. Operating with the principle of the impinging flows, these systems are formed from micro-channels of 20 mm length machined in PMMA slab in such a way to form a cross. The channels have a square cross-section with a side dimension less than one millimeter (600 µm and 300 µm). The applied flows, through the developed micro-fluidic systems in this study, are ranged in the laminar regime.

The flow-rates of emulsions produced in this study are about 50–110 ml/min such that the residence time in the micro-channel system is less than 14 ms. The corresponding capillary numbers range in the interval 3–14 [20]; they are clearly above those listed by the scientific literature (Ca < 1.5) for the same range of dimensions of channels [21–23]. To study the feasibility of using such a device as a continuous dispersion system, this work is focused on the improvement of the design of micro-system design. The main objective is to obtain an acceptable ratio between the quality of emulsion and process energy consumption. In our previous study [20], the micro-channel designed as "300–600" and described hereafter was selected among a set of five tested micro-systems for its optimal water-in-oil dispersion. In the present contribution, the implementation of this micro-channel in a series with a second one designed as "600–600" is studied in order to explore the possibility of getting a finer water-in-oil dispersion. Experiments are mostly conducted without surfactant. The emulsions produced with respectively the micro-system "300–600" alone and the series made of micro-systems "300–600" and "600–600" are compared in terms of mean droplet size and droplet size distribution. Subsequently, the additional energy cost is discussed on the base of the surface area created. On the other hand, understanding the

Table 1
Properties of the used fluids, at 25 °C.

Liquids at 25 °C	Tap water	Sunflower oil	Span83	Butanol
γ (mN/m) Surface tension	73.5	33.7	–	24.6
$\gamma_{w/o}$ (mN/m) Interfacial tension	–	27.6	–	2
Viscosity μ (mPa s)	0.91	52.2	–	5.9
Density ρ (g/l)	998	865	989	806
HLB	–	–	3.7	–

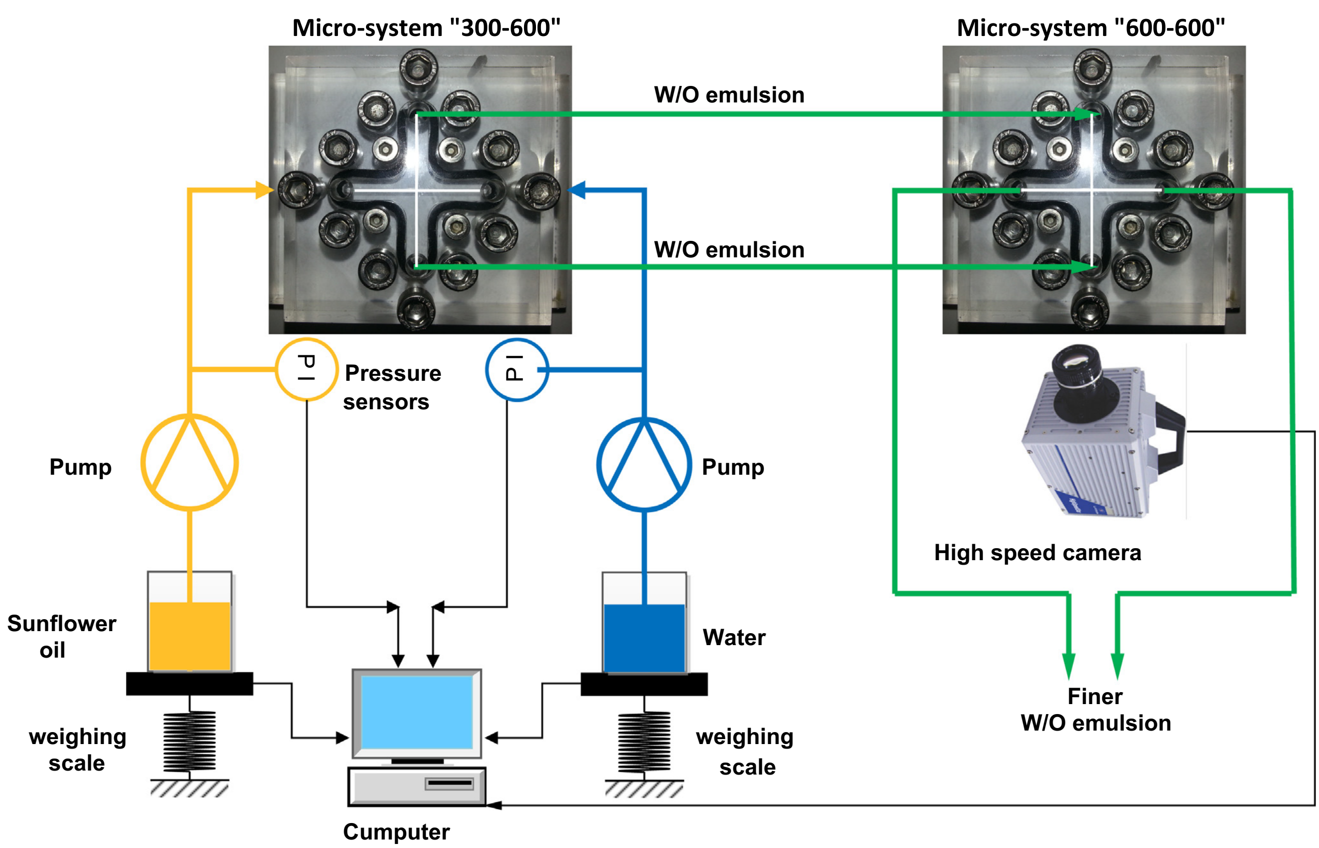

Fig. 1. Schema of series arrangement of two micro-systems "300–600" and "600–600".