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Experimental investigation of emulsified fuels produced with a micro-channel emulsifier: Puffing and micro-explosion analyses

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ABSTRACT

In this investigation, puffing and micro-explosion occurrence in emulsified fuels are studied. The emulsified fuels are formulated using a micro-channel emulsifier, a blend of rapeseed oil in diesel fuel as continuous phase, water as dispersed phase and Sorbitan Sesquioleate as surfactant. Several stable dispersed systems are obtained, classified as emulsions based on their optical appearance and dispersed droplet size. The dynamic viscosity measured as a function of shear rate indicated non-Newtonian behavior with a shear-thinning response for all emulsions. An increase of water percentage led to emulsified fuels with higher viscosity levels. Finally, puffing and micro-explosion occurrence was studied by placing emulsified fuel droplets on a heated plate leading to the Leidenfrost effect. The puffing occurrence is reported for all emulsified fuels tested. A sudden puffing is noted when the water ratio is increased. Conversely, the micro-explosion phenomenon only occurred in emulsions formulated without surfactant. However, an analysis conducted on a smaller emulsion droplet showed several ejected child droplets and micro-explosion. This fact denotes a strong relationship between the emulsion droplet size, water ratio and water droplet size with the occurrence of the puffing and micro-explosion phenomena.

1. Introduction

In many countries, energy is primarily produced using fossil fuels. The finite fossil fuel reserves, greenhouse gas emissions and related global warming, volatility fossil fuel prices and their influence on energy scenarios are currently worldwide problems. This situation has motivated governments, automotive industries, energy-producing industries and the scientific community around the world to search for suitable alternatives and strategies to reduce fossil fuel usage.

In this context, fresh or recycled vegetable oils and animal fats can replace fossil diesel in some applications. However, their direct use is not straightforward due to their different properties. Emulsifying these oils or fats is a promising way for obtaining an environmentally friendly fuel with proper physicochemical properties, allowing improvements on spray atomization, combustion and exhaust emissions. Emulsified fuels might be applied as alternative fuels for diesel engines, fired boilers and power plants. For this reason, several investigations have been conducted in this field [1–18].

Emulsified fuels are generally obtained applying several procedures such as mechanical stirrer, ultra or sonic device, colloid mill, membrane emulsifier and micro-channel emulsifier. Among the above-mentioned methods, the application of micro-channel emulsifiers for producing alternative fuels has not been often reported. Nevertheless, two interesting contributions in this field have been recently reported by Belkadi et al. [19,20].

Belkadi's studies [19–22] are focused on the fuel emulsifiers based on impingement of two phases using different velocity impinging flows and singularities in the micro-channels, as well as the use of one or two micro-channels. Depending on the applied flow-rates and water fraction, a strong influence on dispersed water droplets sizes was observed. Belkadi et al. [20] also pointed out that the use of a series of micro-systems is recommended when the oil phase contains no surfactant and for a high water flow rate. Regarding the dispersion process in the micro-channel, a swirl and convective flow was noted during the emulsification process [19,20].

According to Tran et al. [23] the combustion of emulsified fuel droplets is largely characterized by the difference between water and fuel volatility. The droplet is heated by convective and radiative heat

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transfer after injection in the hot compressed air within a diesel engine, and its temperature reaches the superheat limit. Inside the droplet, this is followed by a rapid bubble nucleation, and then, internal formation of vapor bubbles [23]. The vaporization of water then blows up the oil layer and thereby forms smaller oil droplets, which increase the oil droplet's surface to volume ratio [8]. This phenomenon is called "micro-explosion" [8,24].

The micro-explosion causes the secondary atomization which forms the bulk of much finer droplets [23]. Such secondary drops evaporate very quickly and are dispersed over a large volume, improving fuel/air mixing and the overall combustion efficiency [25]. This mechanism is fundamental in reducing particulate emission in the combustion of medium and heavy oils [25]. In addition, the presence of water influences the physics and chemical kinetics of combustion [26]. The vaporized water reduces the flame temperature, changes the chemical composition of the reactants, resulting in higher OH radical concentration controlling the NO formation rate and soot oxidation, and dilutes the rich zones in the combustion chamber [26].

Thus, a large scientific effort has been devoted to the experimental evaluation of the micro-explosion phenomenon [27–43]. However, the micro-explosion hypothesis has also been questioned [44]. Califano et al. [25] pointed out that the micro-explosion does not always occur, and that its occurrence depends on a number of parameters. An important factor affecting the micro-explosion could be the coalescence or phase separation of the dispersed water droplets in the continuous phase [25,27].

On the other hand, several studies [2,9,28,31–33,45,46] have reported the occurrence of a particular phenomenon (i.e. puffing or bubbling) prior to the micro-explosion phenomenon. The occurrence of puffing is also linked to the thermal effect affecting the water fraction within the emulsion, under intense heat flux. This phenomenon is not always observable, it consists in the formation of irregular bubbles of steam that perturb the free surface of the droplet [33,47].

In spite of these puffing and micro-explosion phenomena being known and reported since 1965 by Ivanov and Nefedov [45], their influence on the atomization of emulsified fuels and the effect of additional factors such as the surfactant percentage, emulsion droplet and continuous phase properties (e.g. volatility, viscosity, etc.) has not been studied thoroughly. Therefore, the scope of this investigation is to analyze the puffing and micro-explosion occurrence in emulsified fuels produced with a micro-channel emulsifier. The effect of surfactant will also be studied.

2. Materials and methods

2.1. Emulsified fuels formulation

The emulsified systems were formulated based on the range of stability reported in our previous experiments [6], using a blend of rapeseed oil in diesel fuel as continuous phase (i.e. 20% rapeseed oil and 80% diesel fuel). In the present work, additional components such as water as dispersed phase and Sorbitan Sesquioleate (Span 83) as surfactant provided by *ALDRICH* (HLB = 3 and 0.989 g/mL at 25 °C) were used. The emulsified fuels were prepared using 2% and 4% of surfactant (by volume). The physicochemical properties of diesel fuel and rapeseed oil are shown in Table 1.

Table 1
Physicochemical properties of neat fuels.

Properties	Unit	Diesel fuel	Rapeseed oil
Dynamic viscosity*	$mPa{\cdot}s$	3.5	28
Density*	g/cm^3	0.810	0.901
Water content	%	< 0.05	< 0.05

* Measured at 40 °C.

Table 2
Preparation matrix used for emulsification process using micro-channel emulsifier.

Emulsified fuel	Components (% by volume)			Flow rate (mL/min)	
	RO-Diesel	Surfactant	Water	Continuous phase	Dispersed phase
ERO1	88	2	10	225	25
ERO2	78	2	20	200	50
ERO3	68	2	30	175	75
ERO4	86	4	10	225	25
ERO5	76	4	20	200	50
ERO6	66	4	30	175	75

ERO: Emulsified rapeseed oil.

The emulsification process was conducted using a micro-channel. The emulsified fuels were prepared based on the matrices shown in Table 2. For each case, the continuous phase and surfactant were blended and stirred during 15 min (at 1000 *rpm*) as a first step, before the use of the micro-channel emulsifier. The stirrer speed was selected in order to avoid violent turbulence which promotes a negative influence on dispersed system characteristics (e.g. foam formation, viscosity and surface tension variation) as a consequence of air bubble incorporation, in agreement with Kerihuel et al. [48]. Additional systems avoiding the use of any surfactant are formulated (ERO7: emulsion with 10% of water, ERO8: emulsion with 20% of water and ERO9: emulsion with 30% of water). The aim of this formulation is to investigate the effect of surfactant, water ratio and droplet size on puffing and micro-explosion occurrence. That is why the most and less stable emulsions are going to be compared.

The experimental facilities for the emulsification process are three pistons displacement pumps (ARMEN-AP-TRIX-500-200), two weighing scales Sartorius – MSE2203 (accuracy of ± $10^{-3}\,g$) and two compact pressure transducers Gems-3100 (accuracy of ± 0.25% of full scale). The pressure sensors are connected to the emulsification loop between the pumps and the inlet of each channel. The sensors measure the relative and static pressure for each flow. Connections between the pumps and the micro-channel are made using fluoropolymer tubes with an inner diameter of 1.55 *mm* and an outer diameter of 3.125 *mm*.

The schematic diagram of the experimental set-up used for the micro-channel emulsification process is shown in Fig. 1a.The micro-channel used has an optimized geometry, which has been recently presented by Belkadi et al. [49]. Two opposite channels with different diameters were used as the inlets of each phase. The cross-section of the dispersed phase channel is reduced, compared to that of continuous phase, in order to meet the condition needed for the production of emulsified fuel. The impinging flow principle and mechanism of liquid-liquid fractionation during the emulsification process is shown in Fig. 1b.

2.2. Physicochemical characterization and measurements set up

In most cases, a way to describe the emulsified fuel's quality is to analyze its optical appearance, stability period and droplet size distribution. In this context, dispersed water droplet size has a strong influence on the deformation of the whole emulsified droplet (e.g. puffing and micro-explosion phenomena); which also affects the atomization structure and combustion process considerably. Therefore, properties such as optical appearance, stability, dispersed water droplet size and the rheological assessment of the dynamic viscosity-shear rate relationship were evaluated.

The dispersed water droplet sizes were measured through a microscope Olympus BX61. The mean values of the dispersed water droplets size were processed using the integrated Olympus Stream image analysis software. The dispersed systems were analyzed on a PolyMethylMethAcrylate (PMMA) home-made hemocytometer cell