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Simple and Multiple Water Fuel Emulsions Preparation in Helical Flow

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Abstract

This paper presents a method of simple and multiple water fuel emulsions preparation in a liquid-liquid contactor with Couette-Taylor flow (CTF contactor). This method concerns the integration of the CTF contactor with diesel engines for the injection of just-prepared emulsions. Stable simple O/W and multiple O/W/O emulsions, both with quite narrow drop size distribution, have been prepared. The strong influence of operating conditions in the CTF contactor on mean drop size of the dispersed phase was observed. Simple and multiple emulsions were considered as an alternative diesel fuel for improving engine performance and emissions characteristics.

Key words: Simple and multiple emulsions, Couette-Taylor flow.

Introduction

Diesel engines represent one of the most economical power sources; however, gases and particulate matter (PM) emitted during combustion are major air pollutants. The efforts of researchers are focused on approaches that reduce pollutants in the combustion zone.

Recently, water-oil emulsion has been considered and tested to improve combustion efficiency. There has been some basic research concerning the effects of water emulsions on exhaust emissions. Results show that both NO_x and PM can be reduced significantly, as well as fuel consumption (Park et al., 2001; Lin and Wang, 2003; Abu-Zaid, 2004). Emulsions are thermodynamically unstable dispersions of 2 or more immiscible liquids, which are kinetically stabilized by an adsorbed film at the liquid-liquid interface. Common stabilizers include polymeric or low molar mass surfactants. The liquid phases of partially wetted nm-size particles are effective stabilizers. There are simple and multiple types of emulsions. Examples of simple emulsions are oil in water (O/W type) and water in oil (W/O type). Multiple emulsions are composed of 3 phases: an inner and outer phase separated by a dispersed phase. Three-phase emulsions are denoted as O/W/O (oil in water in oil) and W/O/W (water in oil in water). The commonly used techniques for preparing emulsions are based on mechanical agitation. For stable emulsions formulation, we proposed the liquid-liquid contactor with Couette-Taylor flow.

Couette-Taylor flow (CTF) occurs in an annular space with a rotating inner cylinder. This is a steady-state flow consisting of axial Poiseuille flow and rotating Couette flow, respectively, with axisymmetric Taylor vortices. CTF flow, also referred to as helical, is a rare flow variation combining intense local mixing with a limited axial dispersion due to hydrodynamic flow instability (vortices) taking place in the CTF reactor. Problems of mixing and dispersion effects have been previously described (Kataoka et al., 1995; Desmet et al., 1996).

The Couette-Taylor Flow reactor is characterized by:

- intense local mixing with a limited axial dispersion of the phases

- high values of the volumetric mass transfer
- high values of heat and mass transfer coefficients at the outer cylindrical shell
- a constant gas substrate concentration along the tubular length of the membrane reactor
- independence of the residence time of the mixing intensity
- a possibility to be applied when the ratio of the volumetric flow rates of both phases (gas/liquid or liquid-1/liquid-2) is extremely small.

The authors have investigated mass transfer and hydrodynamics in the two-phase gas-liquid (Wronski et al., 1999; Dluska et al., 2001; Hubacz and Wronski, 2004) and liquid-liquid (Hubacz and Wronski, 2003; Wronski et al., 2003) systems in the membrane and gap of Couette-Taylor flow reactors.

The experiments indicated high values of the volumetric mass transfer coefficients in a gas-liquid system ($k_La = 1 \div 10^{-1}s^{-1}$), and in a liquid-liquid system, the overall mass transfer coefficients are an order of $K_La = 10^{-2}s^{-1}$. A specific interfacial area measured in the CTF two-phase reactor is 10^3 m^2 m^{-3} (Dluska et al., 2004; Wronski et al., 2005), and is an order of magnitude higher than those typical for a stirred tank reactor.

Recently, the above-mentioned properties of the helical flow have resulted in a significantly increased interest in those types of reactors in different processes, especially in multiphase systems.

The purpose of this study was to investigate liquid-liquid Couette-Taylor flow contactor preparation of stable simple and multiple water fuel emulsions. The ability to improve diesel engine performance with water-emulsified fuel has been known for some time. This paper presents a new method of emulsions preparation. Usually, fuel is injected into the engine from storage tanks. Emulsions from tanks include surfactants for stability. During combustion, surfactants generate new undesirable emissions. This paper proposes the integration of the CTF contactor with diesel engines for the injection of just-prepared emulsions. This is possible due to the small dimensions of the CTF contactor. In this case, a small concentration of surfactant can be used or not. Water fuel emulsions were used as an alternative fuel to improve diesel engine performance.

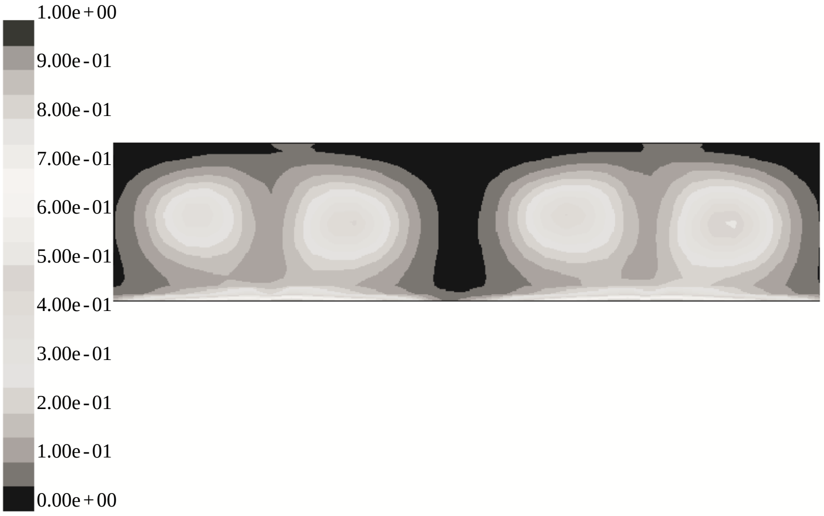
Liquid-liquid Couette-Taylor flow patterns

The hydrodynamics of the liquid-liquid Couette-Taylor flow were investigated and presented in a paper by Hubacz and Wronski (2003). The authors described characteristic flow structure and proposed a map of flow patterns. However, a numerical simulation seems to be essential for a better understanding of the features of the flow. Preliminary numerical simulation (Dluska et al., 2005) revealed a strong influence of the diameter of the drops on flow structure. When the interfacial tension value is sufficiently high (i.e. relatively large drop diameter), the lighter phase tendency was to the center of the vortices (Figure 1).

Thus, the vortex structure could be easily distinguished because the lower volume fraction of the second phase was observed at the inflow border between the vortices. However, a higher value of the volume provoked a more homogeneous flow structure and the pairs of vortices were no longer visible. A lower value of the interfacial tension resulted in smaller diameter droplets, and the flow became more homogeneous (Figure 2).

This agreed quite well with the results presented in the paper by Dluska et al. (2005). In this work, a two-dimensional simulation of the helical liquid-liquid two-phase and single-phase flows in the concentric annuli were based on calculations of parameters such as velocity, kinetic energy, and dissipation rate of turbulent kinetic energy. The results of numerical calculations have been obtained using FLUENT 6.0 and adopting the RNG k-ε or RMS method for a single-phase flow, and the Eulerian model and RNG k-ε for two-phase flow.

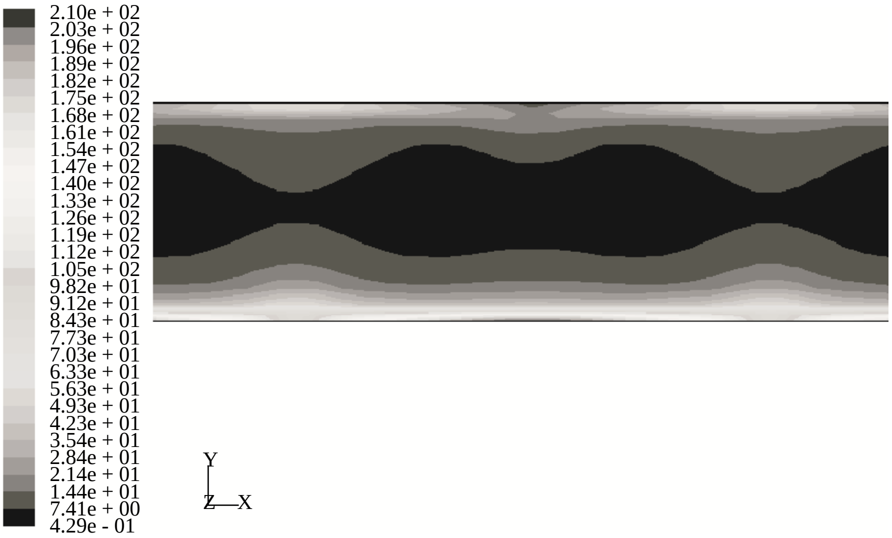
The RMS turbulent model seems to be more suitable for this purpose where the narrow gap and values of the angular Reynolds number, which are not very high, are encountered. However, this model is not available for two-phase simulation. The hydrodynamic parameters were calculated for the concentric gap of $d = 5.25$ mm, where the inner cylinder radius equals $R_1 = 0.0185$ m and $d/L = 40$, and where L is the length of the gap. For both single- and two-phase systems, the rotational speed of the internal cylinder equals $\omega = 104.7$, 209.4, or 261.8 1/s (rotational frequency $n = 1000$, 2000, 2500 rpm) and axial mean fluid velocity equals $u = 0.062$ m/s. The two-phase simulations were carried out for liquid-liquid (liquid 1: water; liquid 2: mineral oil) systems with the properties: ρ_1 =998 kg/m^3, $\mu_1 = 1$ cP, ρ_2 =840 kg/m^3, and μ_2=3.73 cP, and content of water phase



Contours of Volume fraction of phase-2 (Time = 4.8653e + 01) Mar 11, 2003

FLUENT 6.0 (axi, swirl, dp, segregated, eulerian, mgke, unsteady)

Figure 1. Structure of the flow in liquid–liquid Couette-Taylor flow with the mean value of the dispersed phase volume fraction equal to 0.17: a) vortex easily visible because of the phase separation (diameter of the dispersed phase drops $d_p = 0.0004$ m); b) homogeneous flow - small phase separation ($d_p = 0.0001$ m).



Contours of Turbulent Dissipation Rate (Epsilon) (m^2/s^3) (Time = 6.0974e + 00) Jun 16, 2005

FLUENT 6.2 (axi, swirl, dp, segregated, RSM, unsteady)

Figure 2. Contours of dissipation of the turbulent kinetic energy in the single-phase flow for $\omega = 261.8$ 1/s. In the picture, one pair of the Taylor vortices is shown.

10%. The former experimental investigation of liquid-liquid emulsification done in the same condition of the flow revealed that the oil was a continuous phase. Hence, the single-phase simulations were carried out only for oil. The two-phase numerical simulations require an assumption about the drop diameter of the dispersed phase. They were estimated experimentally and average values of the diameters of the water phase were used in our computation (Table 1).

Table 1. The average diameter of water phase dispersed in oil.

ω [1/s]	Average drop diameter $d_{p,m}$ [μm]	The most probable drop diameter [μm]
104.7	10.66	12.96
209.4	10.95	12.19
261.8	7.39	9.13

The results of the simulation suggest that flow structure is homogeneous in such flow conditions and it agrees well with earlier results (Dluska et al., 2005). During the numerical simulations, the local values of ε were obtained. We then estimated the range of the most probable values of ε in the flow (Table 2).

Table 2. The range of the most probable values of ε in the flow [m^2/s^3].

ω [1/s]	Single-phase		Two-phase
	RNG k-ε	RSM	RNG k-ε
104.7		0.50-0.66	0.004-0.50
209.4	1.18-1.41	2.32-3.27	0.362-24.43
261.8	3.67-4.00	4.14-6.01	0.910-118

The example of the distribution of ε in the gap is shown in Figure 2 for $\omega = 261.8$ 1/s. In the middle of the gap, the value of ε is lower than 7 m^2/s^3, but in the region closer to the walls, the value of ε could be several times higher.

It would be interesting to compare the size of the dispersed phase with the Kolmogoroff microscale. The estimation of the Kolmogoroff micro-length scale was based on the value of the dissipation rate of turbulent kinetic energy:

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{0.25} \tag{1}$$

where η is the Kolmogoroff microscale, ν is the kinematic viscosity, and ε is the dissipation of the turbulent kinetic energy. The most probable values of η are shown in Table 3.

From our results, it is clear that the size of the Kolmogoroff microscale is bigger than the drop diameters in the emulsion produced in such a condition of the flow (see Table 1).

Similar investigations concerning the flocculation process with a Couette-Taylor flow apparatus were published by Coufort et al. (2005). The authors found that the size of the most probable floc diameter was the same as the most probable Kolmogoroff microscale. However, the size of their apparatus (cylinders diameter) was bigger than ours. Hence, the value of the turbulent dissipation rate in their apparatus was lower than in ours for a similar value of the rotational Reynolds number.

Table 3. The range of the most probable values of η in the flow [μm].

ω [1/s]	Single-phase		Two-phase
	RNG k-ε	RSM	RNG k-ε
104.7		107.5-115.2	115.2-385.3
209.4	88.91-93.00	72.05-78.51	43.58-124.9
261.8	68.51-70.00	61.88-67.92	29.40-99.20

Preparation of W/O and O/W/O emulsions in a helical flow experiment and results

In the present study, we used the Couette-Taylor flow (CTF) contactor in the liquid-liquid system (Figure 3). The purpose of this experimental study was to investigate the emulsions' properties, such as stability, mean drops size, and drop size distribution under different operating conditions in the Couette-Taylor flow contactor.

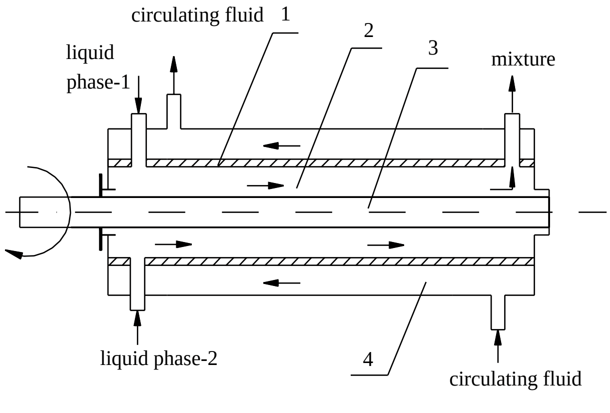


Figure 3. Liquid-liquid Couette-Taylor flow contactor 1-outer cylinder, 2-concentric gap, 3-inner cylinder (rotor), 4-casing for circulating fluid.

The operating conditions included the rotational frequency of the inner cylinder (n = 500-3000 rpm), the gap size (d = 1.5, 2.5, 5.0, and 5.25 mm), the content of water (φ = 10%-40%), the concentration of surfactant (C_R = 0.5-3% wt.), and the mass flow rate of oil and water phases (W = 10-100 kg/h). The composition of the emulsions was rape oil or diesel oil, and water with hydrophilic surfactant.

Both liquid phases, oil and water with hydrophilic surfactant, were introduced at the inlet cross section of the CTF contactor. After steady state was achieved in the CTF contactor, emulsion samples were collected. The emulsions were observed with the system microscope, an Olympus BX-60, connected to an Olympus digital camera. Drops sizes were determined using Image Pro Plus 4.5 imaging software. Stability of the emulsions was determined by visual observation with time drop sizing measurements, as well as conductivity measurements. In the experiments, 6-month-old emulsions, which maintained constant drop size throughout the study period, were prepared. The influence of the concentration of water in emulsion and surfactant on mean drop size is presented in Figures 4-7.

The effect of water content on mean drop size of emulsions was optimal at φ = 15%-25% (Figures 4 and 5).

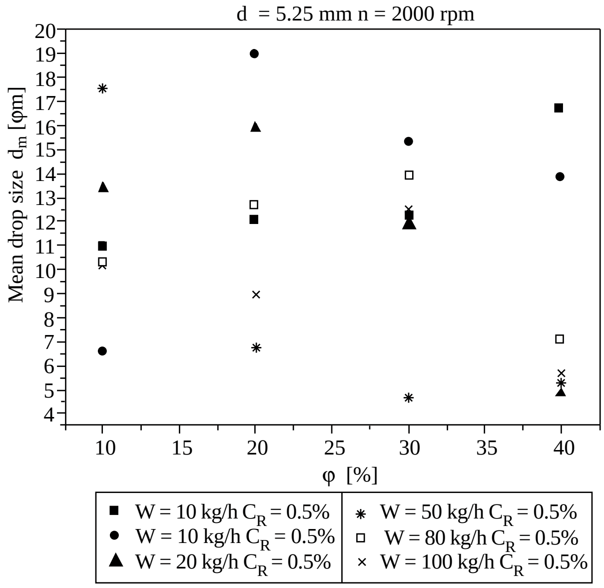


Figure 4. Variation of mean drop diameter with changing water content in emulsion.

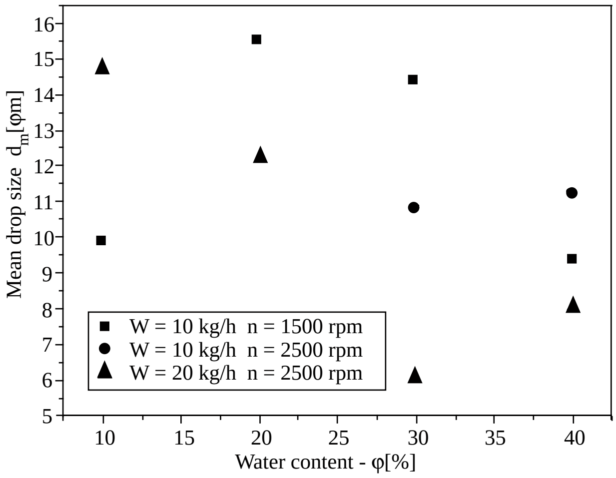


Figure 5. Variation of mean drop diameter with changing water content in emulsion.

As previously reported (Lin and Wang, 2003; Abu-Zaid, 2004), the most suitable water percentage for engine performance is about 20%. In our experiments, optimum water content corresponds with the emulsions structure, which depends on operating conditions, and is determined by size of the dispersed phase and the size of the drops. The larger mean diameter of the drops resulting from an increase in the volumetric flow of emulsion is quite evident due to shorter residence time (Figure 6). Increased surfactant concentration results in smaller mean drop diameter, which is due to the mechanism of the surfactant (Figure 7). Selected results of simple types of emulsions prepared in the liquid-liquid Couette-Taylor flow contactor are presented in Figures 8-11.

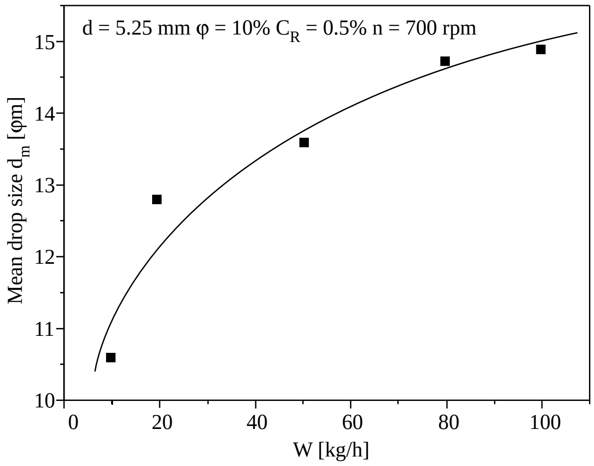


Figure 6. Variation of mean drop diameter with changing mass flow rate of emulsion.

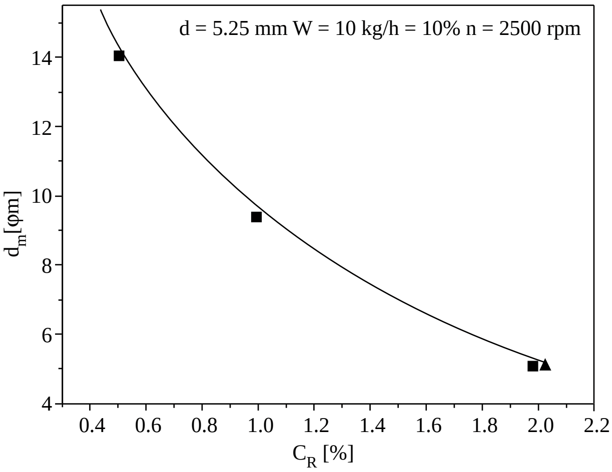


Figure 7. Variation of mean drop diameter with changing surfactant concentration.

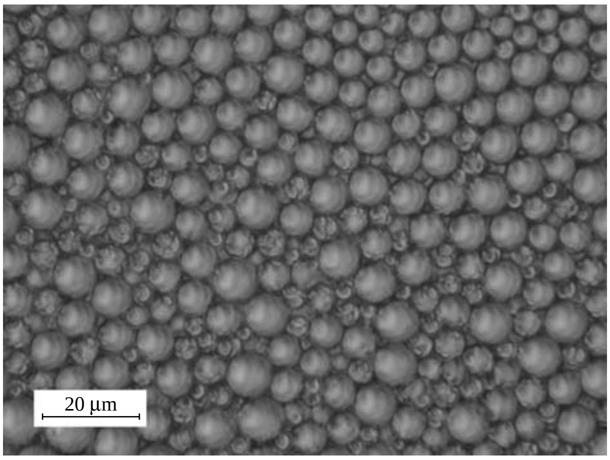


Figure 8. Simple emulsion of W/O (water in diesel oil) D = 5 mm, n = 1500 rpm, φ = 40%, W = 10 kg/h, C_R = 2% wt.

Multiple emulsions of O/W/O are presented in Figures 12 and 13. The drop size of the dispersed phase of multiple emulsions ranges from 20 to 70 μm and the inner phase drops have a diameter of 2-10 μm.

The prepared stable simple and multiple emulsions were used as a diesel fuel to determine diesel engine performance and emission characteristics (Piaseczny and Zadrag, 2005). As the water percentage in the emulsion was 15% by volume, the preliminary results of 6-cylinder diesel engine (420kW) performance indicated the reduction of NO_x by about 12% and CO by 18% (Piaseczny and Zadrag, 2006). Fuel consumption decreased by an estimated 5.7%-11%.

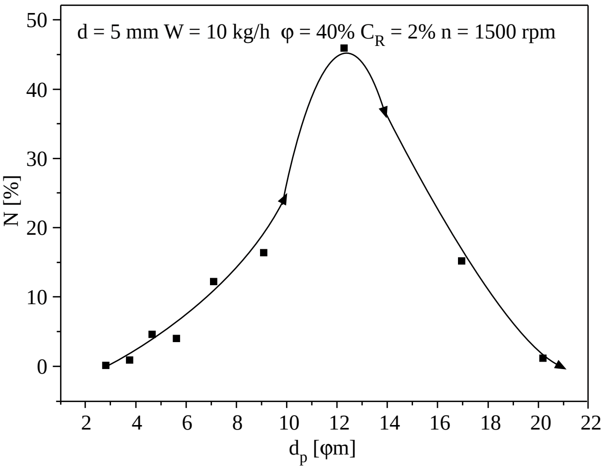


Figure 9. Drop size distribution (d_p) of the dispersed phase of a simple emulsion prepared in CTF contactor, N-content of defined size drops.

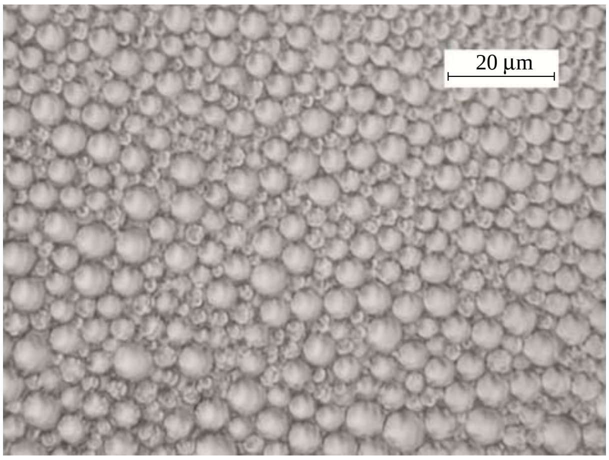


Figure 10. Simple emulsion of W/O (water in diesel oil) d = 5 mm, n = 2500 rpm, φ = 40%, W = 20 kg/h, C_R = 2% wt.

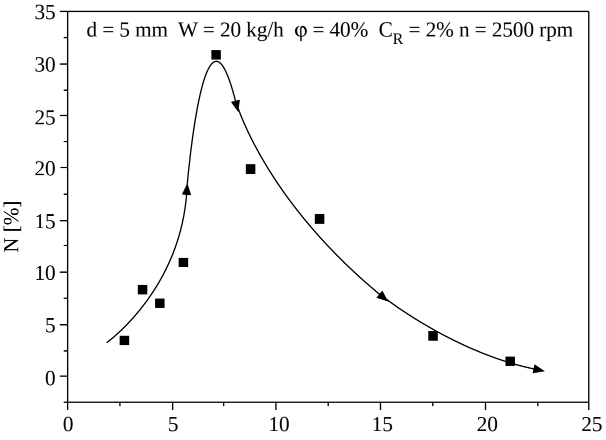


Figure 11. Drop size distribution (d_p) of the dispersed phase of a simple emulsion prepared in CTF contactor, N-content of defined size drops.

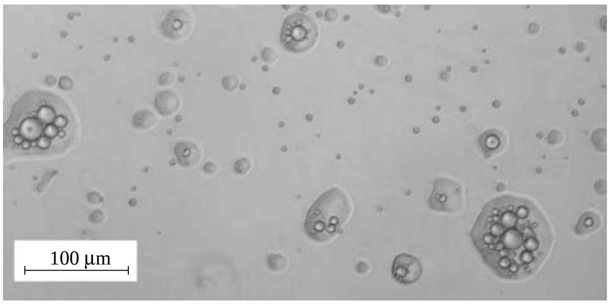


Figure 12. Multiple emulsion of O/W/O (O = mineral oil) d = 1.5 mm, W = 100 kg/h, φ = 30%, n = 2800 rpm, C_R = 2% wt.

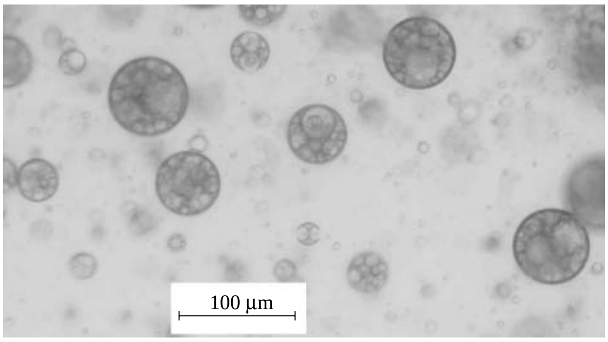


Figure 13. Multiple emulsion of O/W/O (O = vegetable oil) d = 1.5 mm, W = 11 kg/h, φ = 13%, n = 2000 rpm, C_R = 2%.

Summary

The liquid-liquid Couette-Taylor flow contactor for simple and multiple emulsions preparation via a one-step emulsification process was proposed and investigated.

The prepared emulsions are characterized by drop sizes within a narrow range, and little variation in the duration of time that drop sizes remain constant.

The mean drop size of the inner phase of multiple emulsions was ranged from
2 to 10 μm.

The results indicated a strong influence of the investigated operating conditions in the Couette-Taylor flow contactor, as well as the percentage of surfactant and water in the emulsions on the stability of drop size and drop size distribution of both simple and multiple types of emulsions.

The concept of integration of the Couette-Taylor flow contactor, due to its small dimensions, with diesel engines for injecting just-prepared emulsions was discussed. The preliminary results of the use of water fuel emulsions of W/O in diesel engine performance were cited.

Multiple emulsions of O/W/O can be considered as an alternative diesel fuel.

Nomenclature

c_R	surfactant concentration
d	annular gap width of the CTF contactor
d_m	mean drop size
d_p	drop size
$d_{p,m}$	average drop diameter
n	rotational frequency of the inner cylinder
N	content of defined size drops
W	emulsions mass flow rate
ε	dissipation of the turbulent
η	Kolmogoroff microscale
φ	content of water
ν	kinematic viscosity
ω	rotation speed of the inner cylinder

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