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EVALUATION OF THE IMPACT OF TEMPERATURE VARIATIONS IN SELECTED FUELS ON THEIR ATOMIZATION IN INTERNAL COMBUSTION ENGINES WITH COMMON RAIL INJECTION SYSTEMS

The first part of this paper presents an evaluation of the rheology of three fuel types for compression ignition engines, i.e. a conventional fuel grade and two biofuel grades, each with rapeseed oil. The analysis completed for this work has uncovered that a clear relationships exist between fuel temperature, density and viscosity. The second part of this paper is a determination of stream parameters of the analyzed fuels injected into a specially designed metering chamber via a common rail injection system. The third and last part of this paper is an evaluation of the microstructure of rapeseed stream by division of the stream into contours of different light reflectivity values corresponding to different fuel concentrations within the stream.

Keywords: common rail, FAME, temperature, density, viscosity, diesel fuel, rapeseed oil, fuel injection

1. INTRODUCTION

A current trend in the automotive industry is to reduce the emission levels of toxic and harmful compounds by reducing fuel consumption. Compression ignition engines are fed with diesel oil or diesel fuel, a product of crude oil distillation and a non-renewable energy source [Triphati et al. 2016] The consequences of non-renewable energy source consumption have become a point of interest of the scientific community, and many research centers currently work on solutions to replace petroleum-derived fuels with alternative fuels from renewable energy sources.

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Thanks to it ready availability, one of the most promising materials to produce alternative fuels are oil plants, such as rapeseed, corn or soy. The oil produced from the plants alone can be used to fuel compression ignition engines. Due to the stringent emission limits imposed on modern engines, precision injection systems must be used that are, unfortunately, very sensitive to fuel quality [Allocca et al. 2014], [Szlachta 2002]. Due to the differing physical properties that change the fuel injection parameters, use of crude oils is problematic, especially in engines with common rail injection systems. Plant oils are thus subjected to transesterification, a process which produces fuel with properties very similar to conventional fuel grades [Imran et al. 2013]. An essential task to facilitate proper and long-lasting operation of common rail engines on alternative fuels is to determine the properties biofuels exhibit at different temperatures and the effect of the temperature-dependent properties on the fuel atomization process.

2. DETERMINATION OF PROPERTIES OF FUELS

Viscosity and density are the prime characteristics which differentiate rapeseed biofuels from diesel oil. The kinematic viscosity of rapeseed oil at the temperature t_{fuel} = 20 °C ten-odd times higher than the kinematic viscosity of diesel oil at the same temperature. Esterified fuels are less disproportionate to diesel oil. Both parameters largely depend on temperature variations. The variations of viscosity and density in the function of temperature were measured prior to attempting testing at the fuel stream and temperature change recording rig.

Three basic fuel grades were admitted for the measurements, including mixtures of biofuels and diesel fuel. The percentage ratio of each fuel grade in specific mixtures was 25%, 50% and 75%. The measured liquid temperature was increased in 20 °C increments from 20 to 80 °C. The measurements were also made at 25 °C

Fuel viscosity ν_{fuel} was examined with an Engler viscometer; fuel density ρ_{fuel} was determined with aerometers. Each fuel grade was measured three times. The viscosity measurement results in seconds were averaged and converted to viscosity. The result was expressed in Engler degrees [°E]. The conventional units were converted into kinematic viscosity ν_{fuel} [mm^2/s] with an approximate relationship:

$$\nu_{fuel} = 7{,}6 \cdot {}^{\circ}\mathrm{E} \qquad \text{for } {}^{\circ}\mathrm{E} \geq 7 \tag{1}$$

$$\nu_{fuel} = 7{,}6 \cdot {}^{\circ}\mathrm{E} \left(1 - \frac{1}{{}^{\circ}\mathrm{E}^3}\right) \qquad \text{for } {}^{\circ}\mathrm{E} < 7 \tag{2}$$

The graphical representation of measurement results are shown in Fig. 1 and 2.

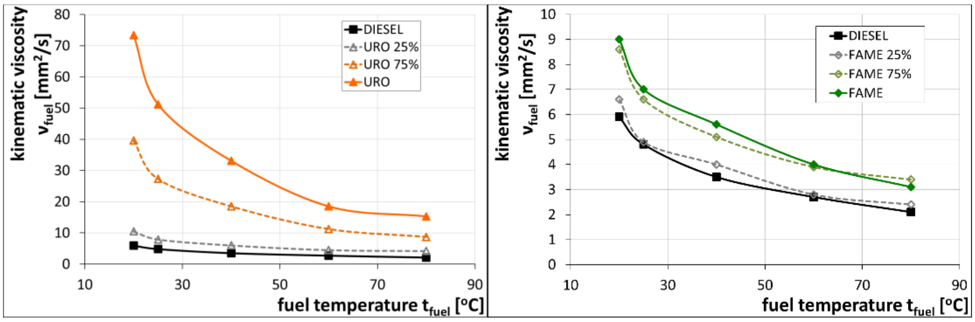

Fig. 1. Kinematic viscosity ν_{fuel} [mm^2/s] vs. temperature t_{fuel} [^{o}C] for various ratios of DF and URO, and DF and FAME.

The fuel viscosity curves (Fig. 1) show that the tested fuel viscosity decreased inversely to temperature. Out of the three basic fuel grades, the highest viscosity was displayed by crude rapeseed oil (URO), followed by rapeseed oil fatty acid methyl esters (FAME). The lowest viscosity was displayed by diesel oil. A solution to the high disproportion between the listed fuel grades is to apply mixtures of conventional fuel and biofuel.

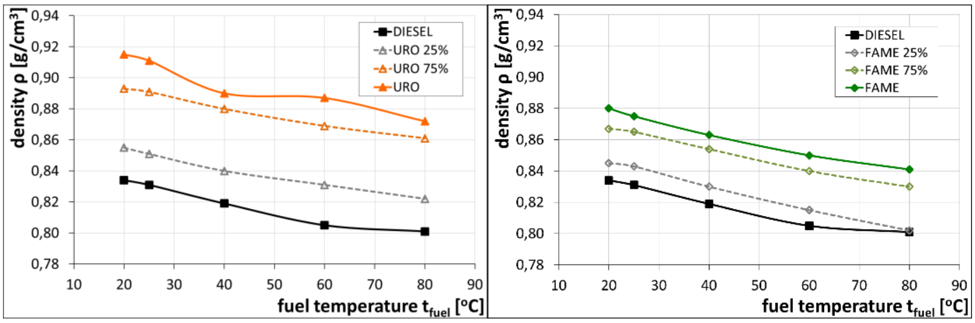

Fig. 2. Density ρ_{fuel} [g/cm^3] vs. temperature t_{fuel} [^{o}C] for various ratios of DF and URO, and DF and FAME

The density curves (Fig. 2) show that not unlike viscosity, the parameter gradually decreased as temperature increased. URO had the highest density of all three fuel grades. The percentage disproportion between the three basic fuel grades was as not significant as in kinematic viscosity. However, the difference between FAME and DF was again lower than the difference of DF and URO.

The measurements prove that temperature has a critical and essential significance to viscosity and density. It is then valid to assume that the phenomenon affects the quality of rapeseed oil fuel atomization. Given the results discussed in this section, it was decided to analyze the effect of temperature in three basic fuel types on the macro and microstructural parameters of the appliedstreams.

3. DETERMINATION OF FUEL STREAM PARAMETERS

This test was done on a test rig (Fig. 3) comprising the EVS (Engine Video System) 513D made by AVL, and Control CR, an electronic control system for the common rail test setup. The test rig facilitated temperature adjustment of fuels in use, a critical feature given the differences in viscosity. For the purpose of measurement, the atomization and output of fuel from an injector located in a chamber open to ambient environmental conditions was recorded.

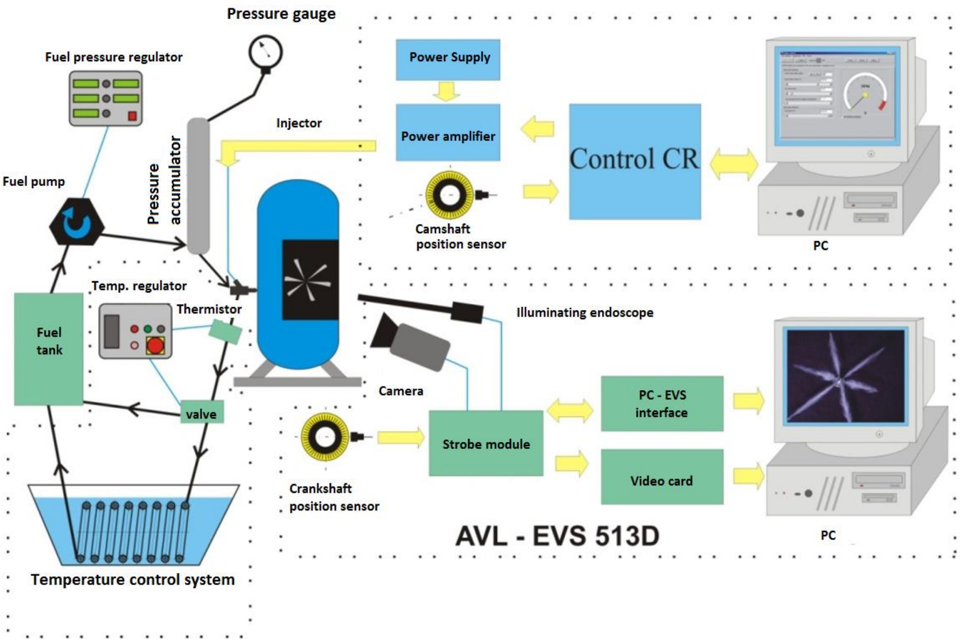

Fig. 3. Overview diagram of major components of the atomization video test rig

The fuel was injected into the chamber at P_{inj}= 40 MPa of pressure, and the test temperature for each fuel was t_{inj} = 25, 60 and 80 ^{o}C. For the sake of legibility of the plots, the results shown herein include only two temperature limit values.

Unprocessed video measurement still shots were compared prior to their digital analysis. The comparison shown in Fig. 4 presents the photographic images of diesel oil streams and rapeseed oil streams as captured at the same time, i.e. 0.5 ms from the emergence of fuel at the atomizer outlets. Hence the pressurized biofuel forcing and injection delays, as caused by physical and chemical properties, were not included. The temperature of both fuels shown in the figure was 25 and 80 ^{o}C.

The biofuel streams at the lower of the two temperatures were longer and narrower than the diesel oil streams at the same temperature. The higher range of rapeseed oil streams at the moment shown was caused by the higher viscosity, which in turn was correlated with the larger diameter of fuel droplets. The visible differences in the luminous intensity between diesel oil and the biofuel were caused by the different injection times.

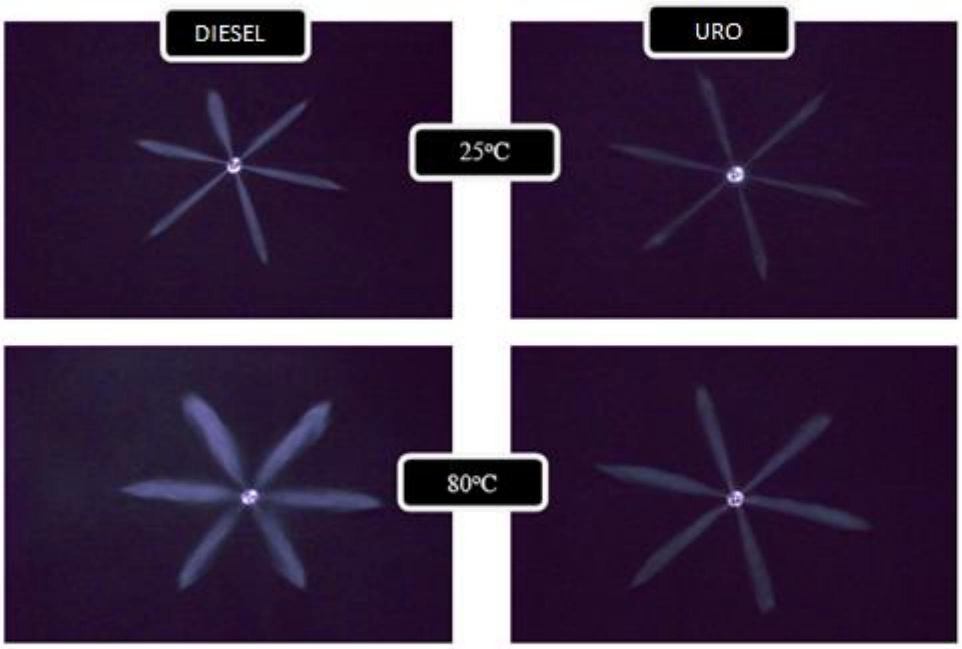

Fig. 4. Comparison of the diesel oil streams (DF, left-hand column) to the biofuel streams at different temperatures.

Heating the biofuel significantly improves the stream structure. At a comparable range, the individual stream surface area was larger than in the lower of the tested temperatures. The comparison of the UROstream atomization at 80 ^{o}C z to the DFstream atomization at the lower test temperature shows similarities in the form of the streams, where the UROstreams boast a slightly higher range. A visible improvement was shown by the diesel oil stream atomization at 80 ^{o}C. The streams were wider and larger in volume when compared both to the lower injection temperature streams and the UROstreams at the same temperature. Note that the biofuel viscosity at the higher test temperature was still higher than in the diesel oil.

A detailed analysis confirmed the dependences and made the results more precise. The comparison of the stream front ranges (Fig. 5) shows that the highest range belongs to the crude rapeseed oil at 25 ^{o}C. The streams of the conventional fuel at the same temperature boasted a lower range already in the first stages of measurement. The average stream range of DF was 8% lower than the average stream range of URO. By analogy, the difference between FAME and DF reached 5% maximum at the lower and higher temperature.

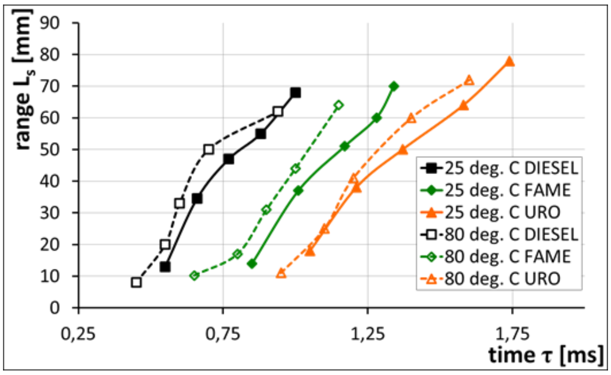

Fig. 5. Variation of stream range L_s[mm] of the studied fuel grades at different temperatures vs. fuel injection time τ [ms]

Increasing the temperature specific to the individual fuel grades in use reduced the stream range in all fuels by approximately 15%. The UROstream ranges at 80 °C were comparable to the DFstream range at 25 °C in most of the measurement points.

The streams of every fuel grade were injected much faster at higher temperatures. This is tantamount to the reduction of the unfavorable injection start delay, a distinct feature of biofuels. Viscosity was reduced when the temperature increases. During the test, the stream output was accelerated by a range from approximately 10% in URO to approximately 20% in DF. This is also evident by the comparison of the aperture angles of streams from fuels at the test temperatures (Fig. 6).

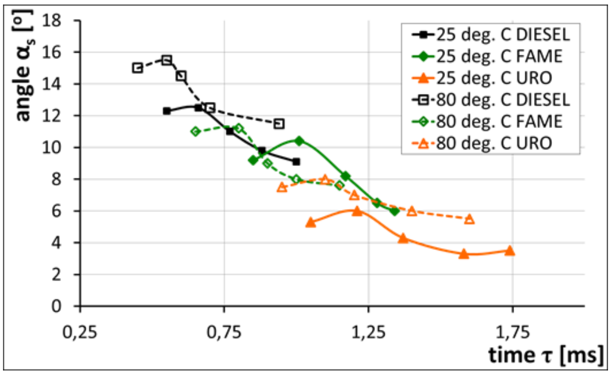

Fig. 6. Variation of aperture angle ofstream α_s[°] of the studied fuel grades at different temperatures vs. fuel injection time τ [ms]

Similar to the comparisons discussed so far, the aperture angle of stream for each fuel at the two test temperatures would become smaller while the stream propagation increased. Each reduction of aperture angle of stream was preceded by its increase in the injection initial phase. Diesel fuel gives the widest streams. The poor flash off of rapeseed oil fuel at the lower temperature reduced the aperture angle ofstream,a phenomenon most likely caused by the surface tension that was elevated at lower temperatures. The UROstreams were 50% narrower than the DFstreams on the average. Smaller differences in the aperture angle of stream were exhibited by FAME and URO at both test temperatures. The cause of reduction in the aperture angle of stream of both biofuels, and especially evident in the crude biofuel grade at lower temperatures, was its poor flash off.

The analysis of the fuel temperature impact on this macrostructural parameter reveals that the fuel curves at low temperatures have a lower amplitude, which means that the streams were narrower by a range from 15 to 35%. Hence, it is found that increasing the temperature of each fuel increases the aperture angle of stream. The aperture angles of stream of esterified biofuel at the higher test temperature are comparable to the conventional aperture angle of stream at the lower test temperature. The higher temperature of fuel also increased the stream surface areas shown in the images (Fig. 7).

The streams of the fuels injected at the higher temperature were larger. The trend was consistent across all tested fuel grades. Note that the esterified fuel streams at 80 ^{o}C were similar in volume to the diesel fuel at 25 ^{o}C. By analogy, the UROstreams at 80 ^{o}C were approximate in volume to the FAMEstreams at 25 ^{o}C. Hence the effect of temperature increase was similar to that caused by pressure increase. The modification of liquid viscosity facilitated atomization of droplets into smaller diameters. The reasons for the refined atomization include surface tension reduction by increasing the fuel temperature. Consequently, the aperture angle of stream and the surface area can be increased at a comparable stream range.

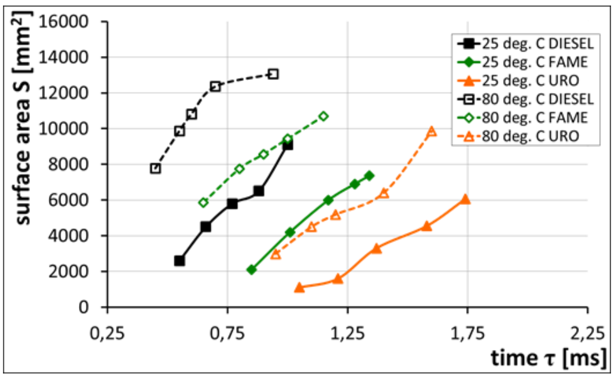

Fig. 7. Variation of stream surface area S [mm^2] of the studied fuel grades at different temperatures vs. fuel injection time τ [ms]

The last stage of the analysis of the fuel temperature effect on atomization involved a comparison between the microstructures of a single fuel grade. Rapeseed oil was chosen for this purpose and measured at two temperature values (25 and 80 ^{o}C) at the same injection time phases. Both measured streams were divided into sub-areas characterized by specific reflectivity values (luminance values) assigned to relative fuel concentrations. The curve in Fig. 8 shows a comparison made for a single injection phase. The curve is representative of the entire measurement series.

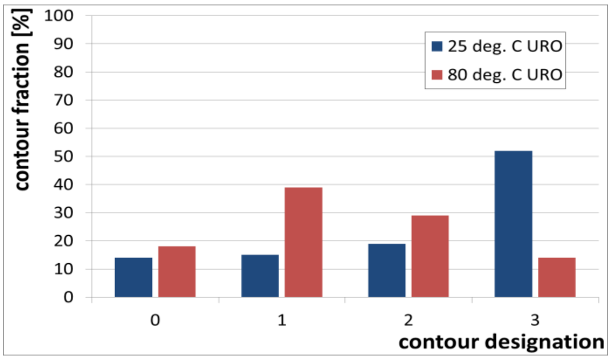

Fig. 8. Comparison of contour sizes in UROstreams at different temperatures and identical injection times

The fuel streams injected at the higher temperature were more homogeneous, as demonstrated by the approximate distribution of individual contour fractions. Contours 1 and 2 have the highest surface area. It can then be inferred that the respective droplets have smaller mean diameter values. The fraction of Contour 3, evident by its high reflectivity, was merely at 14%. The opposite is seen in fuels injected at the lower temperature, since here Contour 3 fraction was the highest. It was 52% at the measured injection time. The comparison completed on a single fuel grade permits a conclusion that the trends displayed by the fuel in question would be consistent in all other fuel grades. The analysis indicates without doubt that fuel performance is better at higher temperatures, when they are less viscous.

4. SUMMARY

To conclude the analysis, a positive effect on fuel atomization quality is evident when fuel temperature is increased. Based on reference studies it is said that the observed variations are related to the variations in physicochemical properties of fuels. The surface tension which affects the aperture angle of stream was reduced in inverse proportion to temperature. The viscosity and density of the biofuels would also decrease towards the values typical of the conventional fuel. Higher fuel temperatures increase the aperture angle of stream and stream volumes at comparable ranges. Consequently, in the comparison of the two greatly different fuel grades, the UROstreams injected at the higher temperature are similar to the DFstreams injected at the lower temperature. Similar to higher injection pressures, higher fuel temperatures facilitates accelerated initial injection of biofuels. The higher temperature fuel streams were also more uniform than the streams at 25 ^{o}C. Rapeseed oil requires careful and proper selection of temperatures. Unfavorable effects may occur in actual IC engines above certain temperature thresholds, such aspolymerization, a process favored by high fuel temperatures.

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OCENA WPŁYWU ZMIAN TEMPERATUR WYBRANYCH PALIW NA ICH ROZPYLENIE W SILNIKACH WYKORZYSTUJĄCYCH UKŁADY WTRYSKOWE TYPU COMMON RAIL

Streszczenie

W pierwszej części artykułu przedstawiono ocenę parametrów reologicznych trzech paliw stosowanych do zasilania silników o zapłonie samoczynnym – paliwa konwencjonalnego oraz

dwóch rodzajów biopaliw rzepakowych. Przeprowadzona analiza uwidoczniła istnienie wyraźnych zależności pomiędzy temperaturami paliw a ich gęstościami i lepkościami. Druga część pracy obejmuje wyznaczenie parametrów strug analizowanych paliw wtryskiwanych do specjalnie w tym celu przygotowanej komory pomiarowej przy użyciu układu wtryskowego typu commonrail. Ostatni etap dotyczy oceny mikrostruktury strugi oleju rzepakowego poprzez jej podział uwzględniający warstwice o różnym stopniu odbicia światła tj. różnym stopniu nagromadzenia paliwa w strudze.