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Title: Kinematic viscosity studies for medium-speed CI engine fuel blends.

Year: 2018

Version: Publisher's PDF

Please cite the original version:

Sirviö, K., Niemi, S., Help, R., Heikkilä, S., & Hiltunen, E., (2018). Kinematic viscosity studies for medium-speed CI engine fuel blends. *Agronomy Research* 16 (S1), 1247–1256. https://doi.org/10.15159/AR.18.088

Kinematic viscosity studies for medium-speed CI engine fuel blends

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Abstract. Engine-driven power plants, run by diesel fuel or gas, will be needed for peaking power to keep the electricity grids stable when the production of renewable electricity, e.g. utilizing wind or solar power, is increased.

The choice of the alternative, renewable fuels for engine-driven power plants and marine applications is at the moment quite narrow. The amount of renewables of all liquid fuels is at present less than 2%. Biodiesels, FAMEs, have been studied for long time and apparently, despite of the problems they may have, they are still in the great interest. One important increment to the category of alternatives is fuels that are produced from e.g. oil wastes, i.e., recycled fuels. They are not renewable, but recycling of potential energy raw materials is still one step forward in increasing the suitable and more sustainable options.

To utilize the blends in medium-speed engines for power production, accurate knowledge of the physical and chemical properties of fuel blends is very important for the optimization of engine performance. The determination of the fuel kinematic viscosity is needed to create proper fuel atomization. The injection viscosity affects directly the combustion efficiency and the engine power. Consequently, this study focused on measuring kinematic viscosity curves for seven fuel blends, as well as the neat fuels used for blending. The temperature range was 10–90 °C. The fuels used for blending were rapeseed methyl ester, animal-fat based methyl ester, hydro-treated vegetable oil, light fuel oil and marine gas oil produced from recycled lubricating oils.

Key words: Fuel viscosity, viscosity curve, alternative fuels, fuel blends, power plant, renewable energy.

INTRODUCTION

In future energy systems, an increasing amount of renewable energy production, e.g. wind or solar power, will be installed. Due to the intermittent electricity production of those new plants, more emphasis should be put on peaking power to keep the electricity grids stable all the time. Hydro power is the best way to adjust the electricity supply so that the frequency and voltage of the electricity grid remain at a required level. Hydro power is not, though, obtainable everywhere.

Engine-driven power plants, run by liquid fuel or gas, will also be needed for peaking and regulation power generation. They are particularly suitable for this purpose because the plants can be started, loaded and stopped very quickl. (Franck & Hägglund, 2013). They can also be feasible to ensure energy security in rural areas. To increase the share of renewable energy, new liquid and gaseous fuels produced from biomass,

residues or waste should, however, be found for engine-driven power plants. These alternative fuels are also needed for marine applications. Together with energy production, in marine industry, the need for cleaner fuels is the most prompt. In 2012, marine sector was responsible for approximately 2% of global emissions, when total greenhouse gas or CO_2 emissions were considered (European Parliament, 2015). Shipping is also one of the most important sources of black carbon in the Arctic sea areas (Quinn et al. 2011). Also the emission legislation in maritime is becoming stricter. Many ship operators cannot yet meet these new regulations. The possibilities they have to meet the limitations, is installing exhaust after treatment equipment or switching to low-sulphur diesel or residual, or other alternative fuels (Lahtinen, 2106). The alternative fuels may reduce engine emissions below mandated limits. For these reasons, the alternative fuels industry has grown dramatically for both liquid and gaseous fuels. (McGill et al. 2013)

By now, the price of the alternative fuel options has not been competitive with cheap fossil fuels. Still, alternative, local and cost-effective fuels are needed in many regions around the world to increase the self-sufficiency of the energy generation. The independence of imported energy will be emphasized during the coming decades, especially in the countryside. Gases form one option, but the availability of gas is varying and in some areas it is very limited. In the future, thus, various liquid fuel options will play an important role in flexible power generation as well as in marine and heavy-duty applications.

Biodiesels, FAMEs, have been studied for long time and apparently, despite of the problems they may have, they are still in the great interest. However, the FAMEs are not the only option in the category of alternatives (Bae & Kim, 2016). One important increment to the category is fuels that are produced from e.g. oil wastes, i.e., recycled fuels. They are not renewable, but recycling of potential energy raw materials is still one step forward in increasing the suitable and more sustainable options. This fuel category has been paid attention to in the latest years. Still, even larger amount of waste oils should be collected and utilized as fuel or other recycling products (Maceiras et al., 2017). Waste oils are hazardous to health because they contain Sulphur, oxidized compounds, hydrocarbons, metals (Cr, Pb) as toxicants (Nerín et al., 2000). For this reason, it is important to upgrade the waste oils and remove these toxicants at the same process.

Renewable diesels, like hydrotreated vegetable oils, HVOs, are produced from triglycerides through hydro processing. The raw material for these fuels can also be something else than vegetable oils, e.g. animal fats or forest residues, and for this reason the name renewable diesel fuel is said to be more suitable. HVOs are used for all kind of engine applications but in Finland these fuels are good-quality fuels and they fulfill the standard requirements set for automotive use. In addition, HVOs are practically Sulphur free and they reduce both greenhouse gas emissions and local emissions, such as NOx and particles (Laurikko et al., 2014; Niemi et al., 2016). Only exception may be the density, which is usually slightly lower than the lower limit of the Standard EN 590. The outcome of the high quality is that they are rather expensive.

Currently, the commercial choice of the alternative, renewable fuels is quite narrow. There are several alternatives but the price and volumes are limiting the distribution. Worldwide, the amount of renewables in all liquid fuels is at present less than 2%. One realistic way to improve the amount of renewables, to fulfill the 27% target set in the EU climate & energy framework, is to blend renewables with fossil fuels. The

renewables should still be produced in a sustainable way and the best options for biofuel production are non-edible oils and fats as well as residues and wastes. FAME is commonly blended into petroleum diesel before use, e.g. from 2 V-% (B2) to 20 V-% concentration (B20). The blend fraction of 20 V-% is becoming more common as the targets set for increasing renewable energy are aspired. The other blend options have also proven to be feasible. Lapuerta et al. have studied the properties of HVO together with low-Sulphuric fossil diesel (Lapuerta et al., 2011). MGO-FAME blend seems also be a good option for marine application based on its analysis results (Sirviö et al., 2018).

To utilize the blends in medium-speed engines for power production, accurate knowledge of the physical and chemical properties, such as kinematic viscosity, of fuel blends is very important, especially for the optimization of the engine performance. Fuel blending may inflict operating complications. The fuel blend needs to be stable and compatible with engine, lubricant and other fuels. In CI engines, fuel blending may cause, e.g., carbon deposition, lubricating oil dilution, piston ring sticking and injector nozzle choking (Patel et al., 2016).

The viscosity affects directly the combustion efficiency and engine power. The fuel kinematic viscosity is an important factor when targeting at proper fuel atomization. The atomization of the fuel into droplets ensures large surface area which again ensures the sufficient evaporation after fuel injection on the combustion chamber. In case the injection strategy of an engine is not optimum in terms of the kinematic viscosity, insufficient evaporation causes unburned hydrocarbon emissions (Heywood, 1988). The changes in viscosity cause instant changes in engine operation also in other parts except combustion chamber. Too viscous fuel increases pumping losses in the injection system and the injection pressure at the pump end may increase when conventional in-line pumps are adopted. All this may cause disruptions in the combustion process and poor combustion leads to e.g. increased hydrocarbon and soot emissions. On the other hand, a too low viscosity may cause the injection pump to seize. Too low viscosity may also produce leakage at the injection pump and injector tips. This affects the pressure and delivered volume at the injector and may cause fuel leakage into the cylinder late during expansion (Guibet, 1999; Kalghatgi, 2014). High viscosity can also increase emissions, mainly unburned hydrocarbons, by increasing the droplet size from the nozzle, which again affects the combustion process (Neste Oil, 2007).

This study concentrated on the determination of the kinematic viscosity curves for seven fuel blends, as well as the neat fuels used for blending, at a temperature range of 10–90 °C. The fuels used for blending were rapeseed methyl ester, animal-fat based methyl ester, hydrotreated vegetable oil, light fuel oil and marine gas oil produced from recycled lubricating oils. The animal-fat based methyl ester was also produced from residue, originating from fur industry. The aim was to examine the differences in kinematic viscosity of the studied blends. This study produces useful basic information for the engine injection designers in terms of engines fuel flexibility as the optimum injection temperature will be adjusted based on the viscosity curve.

MATERIALS AND METHODS

In the current study, several fuel blends were prepared for the viscosity measurements. The fuels used for blends were the following.

Rapeseed methyl ester (RME) was a product of ASG Analytik-Service Gesellschaft mbH, Germany. It contained 1,000 mg kg^{-1} of butylated hydroxytoluene (BHT) as antioxidant and it was delivered to the University of Vaasa (UV) in January, 2017. RME fulfilled the requirements of Standard EN 14214:2012 (EN 14214, 2012).

Hydrotreated vegetable oil (HVO) was a product of UPM Biofuels, Finland. It is renewable diesel based on wood and forest residues namely tall oil. HVO was delivered to the UV in February 2017.

Animal fat methyl ester (AFME) was Feora Ecofuel, a product of Ab Feora, which is located in Uusikaarlepyy, Finland. AFME was delivered to the UV in March 2017.

Light fuel oil (LFO) was a product of Oy Teboil Ab, Finland. It was low sulphuric, winter grade diesel, delivered to the UV in September 2016. LFO fulfilled the requirements of Standard EN 590:2013 (EN590, 2013).

Marine gas oil (MGO) was a product of STR Tecoil, Finland. It was marine fuel produced from recycled lubricating oils. It was delivered to the UV in September 2016.

Seven different fuel blends were prepared: RME-LFO 20:80, HVO-LFO 20:80, AFME-LFO 20:80, RME-HVO 20:80, RME-MGO 20:80, HVO-MGO 20:80, AFME-MGO 20:80. Table 1 lists the fuel blends and their blending ratios. The blends were prepared in the Fuel laboratory at the University of Vaasa.

Table 1. Fuel blends and their blending ratios.

Sample	RME (V-%)	LFO (V-%)	HVO (V-%)	AFME (V-%)	MGO (V-%)
RME-LFO	20	80			
HVO-LFO		80	20		
AFME-LFO		80		20	
RME-HVO	20		80		
RME-MGO	20				80
HVO-MGO			20		80
AFME-MGO				20	80

Kinematic viscosity

The kinematic viscosity was measured by a Stabinger SVM 3000 rotational viscometer. The measurement is based on a torque and speed measurements. The device calculates the dynamic viscosity, η (mPas), from the rotor speed by Eq. 1

$$\eta = \frac{K}{(n_2 / n_1 - 1)} \qquad (1)$$

where K is constant; n_1 is speed of the measuring rotor (mm s^{-1}); n_2 is speed of the measuring tube (mm s^{-1}).

The device also has a density measuring cell that employs an oscillating U-tube principle. The kinematic viscosity, KV (mm^2 s^{-1}), was calculated automatically based on these measurements according to Eq. 2

$$KV = \frac{\eta}{\rho} \qquad (2)$$

where η is dynamic viscosity (mPas); ρ is density (g cm^{-3}) (Novotny-Farkas et al., 2010).

The kinematic viscosity was measured as a function of temperature for all the seven blends and for all the neat fuels used for blending. The measurements were carried out

according the Standard ASTM D7042 (Anton Paar, 2012; ASTM D7042, 2016). The uncertainty was ± 0.30% for the kinematic viscosity. The dynamic viscosity was also measured, as it is a necessity to measure the kinematic viscosity. The uncertainty was ± 0.30% for the dynamic viscosity.

The device also has a density measuring cell that employs an oscillating U-tube principle. The densities were also recorded. For the density, the uncertainty was ± 0.05%.

The limitation of kinematic viscosity set in automotive fuel Standard EN 590 is 2.00–4.50 mm^2 s^{-1} and the limitation of density is 820–845 kg m^{-3} (EN 590, 2013). The limitation of kinematic viscosity set for methyl esters in EN14214 is 3.50–5.00 mm^2 s^{-1} and the limitation of density is 860–900 kg m^{-3} (EN 14214:2012, 2012). In marine fuel Standard (DMA grade) the limitation of density is maximum 890 kg m^{-3} and the limitation of kinematic viscosity is 2.00–6.00 mm^2 s^{-1}. (ISO 8217:2017, 2017)

RESULTS AND DISCUSSION

The dynamic viscosity (40 °C), kinematic viscosity (40 °C) and density (15 °C) results are presented in Table 2. The kinematic viscosities are also shown as a function of temperature in Fig. 1 for neat fuels, in Fig. 2 for the blends made of LFO, FAMEs and HVO, and in Fig. 3 for the blends made of MGO, FAMEs and HVO. The temperature range is 10–90 °C. All the obtained results are arithmetic means of at least two replicate measurements. The results of dynamic viscosity are not though examined as detailed as kinematic viscosity and density because the dynamic viscosity is not standardized property and therefore cannot be compared to the Standards.

Table 2 shows that LFO met the requirements of kinematic viscosity (2.00–4.50 mm^2 s^{-1}) and density (820–845 kg m^{-3}) set in automotive fuel Standard EN590 (EN590, 2013).

Table 2. Dynamic viscosity (40 °C), kinematic viscosity (40 °C) and density (15 °C) results for the blends and neat fuels

Sample	Dynamic viscosity, 40 °C (mPas)	Kinematic viscosity, 40 °C (mm^2 s^{-1})	Density, 15 °C (kg m^{-3})
RME-LFO	2.62	3.15	849
HVO-LFO	2.34	2.86	836
AFME-LFO	2.59	3.12	849
RME-HVO	2.49	3.08	826
RME-MGO	5.73	6.85	853
HVO-MGO	5.34	6.49	839
AFME-MGO	5.71	6.84	852
LFO	2.38	2.89	841
RME	3.92	4.48	883
AFME	3.86	4.47	880
HVO	2.28	2.87	813
MGO	6.36	7.70	843

Both FAMEs also met the limitations set for methyl esters in EN14214, which are 3.50–5.00 mm^2 s^{-1} and 860–900 kg m^{-3} (EN 14214:2012, 2012).

MGO was compared to marine fuel Standard and it met the limitation of density, as it is maximum 890 kg m^{-3} but the kinematic viscosity of MGO was above the allowed 6.00 mm^2 s^{-1} being 7.70 mm^2 s^{-1} (ISO 8217:2017, 2017).

The blends RME-LFO, AFME-LFO and RME-HVO fulfilled the requirements set for B20 in EN 16709, the standard for B20 and B30 fuels. The limitation of kinematic viscosity is 2.00–4.62 mm^2 s^{-1} and density 820–860 kg m^{-3} (EN 16709:2016).

The blend LFO-HVO can be compared to EN590 and it fulfilled the requirements set for these properties.

None of the blends, which contained MGO, fitted in the limits of kinematic viscosity set for marine fuels in Standard ISO 8217. The densities of these blends were, though, within the limits.

The kinematic viscosity of MGO was the highest within the entire temperature range. FAMEs had almost equal viscosities; the curves cannot be separated from each other in Fig. 1. LFO and HVO had the lowest viscosities and showed very similar results throughout the whole 10 to 90 °C range.
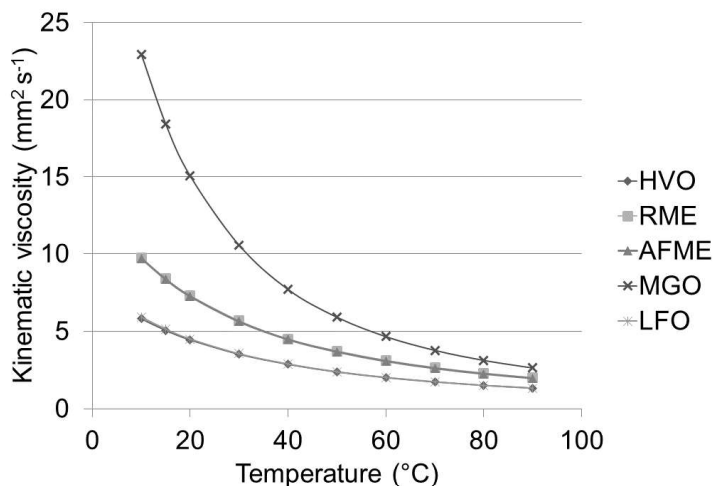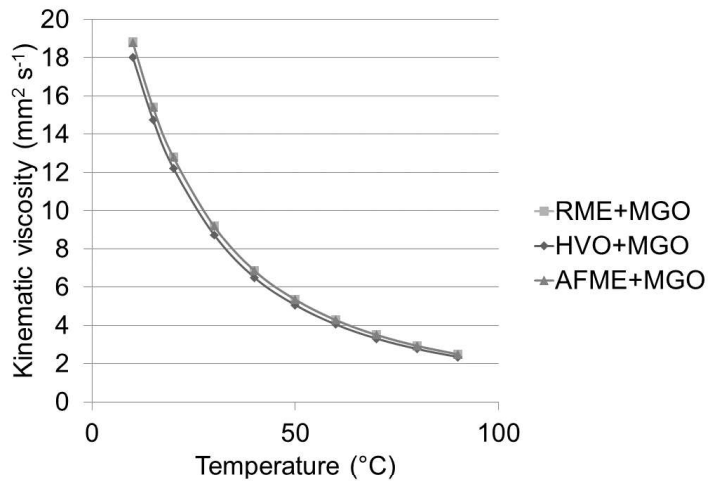

Figure 1. Kinematic viscosity as the function of temperature for the neat fuels.

The kinematic viscosities of the blends made of LFO, FAMEs and HVO were at an almost similar level throughout the temperature range, approximately from 1.3 to 6.5 mm^2 s^{-1}. The curve of HVO-LFO was slightly below the curves of FAME containing blends, as could be expected from the results of neat fuels.

The kinematic viscosity curves of the MGO blends, Fig. 3, differed from those of other blends, presented in Fig. 2. The viscosities of MGO blends varied approximately between 2.5–23 mm^2 s^{-1}. The viscosities of other blends varied from 1.3 to 6.5 mm^2 s^{-1}. As neat, the viscosity of MGO was the highest at 40 °C (7.70 mm^2 s^{-1}), and the phenomenon was the same for the MGO blends. Their viscosity was higher within the whole temperature range than it was for the other blends.
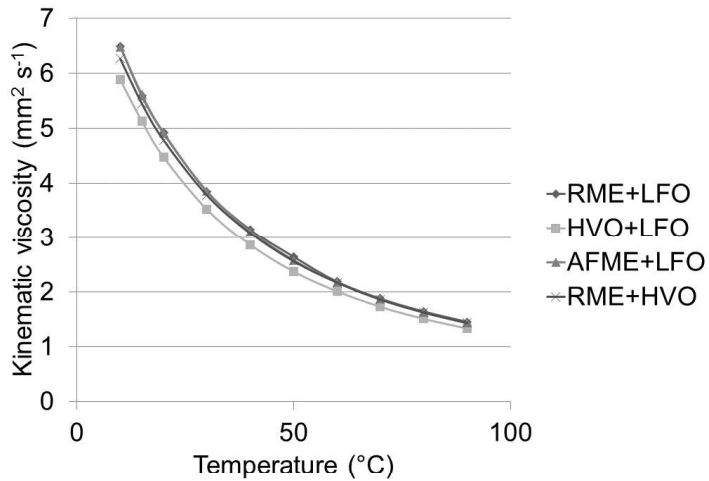
Figure 2. Kinematic viscosity as the function of temperature for the made of LFO, FAMEs and HVO.

Figure 3. Kinematic viscosity as the function of temperature for the MGO blends.

Gabiña et al. have studied a technical suitability of an alternative marine fuel, produced from automotive lubricating oil. In their study, the kinematic viscosity at 40 °C of the fuel was 20.8 mm² s⁻¹ and the density 850.3 kg m⁻³ at 15 °C. They state that the fuel must be warmed up to adjust the viscosity at the level, the injection system requires (Gabiña et al. 2016). The quality of their lubricant based fuel differs from the MGO studied here in terms of the viscosity. The kinematic viscosity curve was not measured in Gabiña et al. study. Neither were there other published results found in terms of MGO's kinematic viscosity as function of temperature.

Lapuerta et al. studied the HVO blends kinematic viscosity as a function of blends HVO content. In their study, the neat HVO had a kinematic viscosity of 2.65 mm² s⁻¹ and a density of 775.8 kg m⁻³. The LFO they used for blending, had 2.24 mm² s⁻¹ as kinematic viscosity and 843.8 kg m⁻³ as density. (Lapuerta et al., 2011) Compared to the

HVO and LFO studied in this paper, the fuels of Lapuerta et al. resulted in lower viscosities. Apparently, the fuels in the Lapuerta et al. study would also lead to lower kinematic viscosity curves than the fuels studied in this research work.

According to Fig. 1, the viscosity behavour of LFO and HVO were very similar during the whole 10 to 90 °C range, varying approximately from 1.3 to 6 mm^2 s^{-1}. In terms of viscosity, these fuels are acting similarly as a function of temperature. Gong et al. had studied the suitability of HVO as a single fuel for currently available fuel injection systems. They found out that LFO and HVO fuels displayed very similar spray tip penetrations and droplet sizes. (Gong et al., 2010) Even though there are several factors affecting the injection system, the similarity in viscosity behavior is one of the most important ones. The study of Gong et al. proved the same phenomenon as the present study. The quality of HVO fuel is almost equivalent to LFO.

Corach et al. (2017) studied kinematic viscosity of soybean biodiesel and its blends with fossil diesel fuel. Their measurement temperature range was 25–45 °C. Within this range, none of the fuels from B0 to B100 resulted in above 6 mm^2 s^{-1}. This is similar to the results of FAME blends in the present study. Ramírez-Verduzco et al. (2011) studied the densities and viscosities of biodiesel blends to develop predicting models for the viscosity measurements. They measured kinematic viscosities at temperatures of 20–100 °C. The biodiesel they used was made of a mixture of vegetable oils. At 40 °C, the neat biodiesel had a kinematic viscosity of 7.03 mm^2 s^{-1} and B20 showed 3.30 mm^2 s^{-1} (Ramírez-Verduzco et al., 2011).

The biodiesels studied here had lower viscosities at the temperature of 40 °C as did the biodiesel of the Ramírez-Verduzco et al. (2011) study: AFME 4.47 and B20 of AFME, 3.12 mm^2 s^{-1}, and RME 4.48 and B20 of RME, 3.15 mm^2 s^{-1}. Even though the FAMEs studied in this study were manufactured from different raw materials, they gave similar results in the measurements. The study of Ramírez-Verduzco et al. (2011) showed that this is not the case with all FAMEs and the blends prepared from them. Yoon et al. (2008) studied the properties of soybean oil biodiesel. In their study, only B100 and B80 fuel reached the kinematic viscosity of 10 mm^2 s^{-1}. The temperature was then below 10 °C. (Yoon et al., 2008)

What needs to be taken into account is that biodiesels and HVO are mainly used in other engine applications than marine or power plant engines. According to the results of this study, all the studied blends are, however, also feasible for marine and power plant applications. As the viscosities vary or are rather low, there is need for more detailed engine design in terms of the fuel injection. The properties and feasibility of all kind of alternative fuels must be studied detailed to reach the ambitious targets for emissions reduction. One way to control the emissions is to optimize the fuel injection to ensure proper combustion in the cylinder. The fuel kinematic viscosity is an important factor when targeting at proper fuel atomization; the viscosity affects combustion. Poor atomization leads to poor combustion and higher hydrocarbon and soot emissions. Fuel flexibility is the future in engine design. It means that even if the fuel properties change, the engine will be flexible and able to run on different fuel options. The optimum injection temperature will be adjusted based on the viscosity curve. For the engine designers and operators, this study produced useful fundamental information about the behavior of fuel and fuel blends. This study also proved that there are cleaner options available for energy production and marine industry.

CONCLUSIONS

The aim of this study was to measure kinematic viscosity curves for seven fuel blends, as well as the neat fuels used for blending, within a temperature range of 10–90 °C. The fuels used for blending were rapeseed methyl ester, animal-fat based methyl ester, hydrotreated vegetable oil, light fuel oil, and marine gas oil produced from recycled lubricating oils. Based on the results, the following conclusions could be drawn:

• For MGO and the MGO blends the kinematic viscosities varied between 2.5–23 mm^2 s^{-1} at temperatures from 10 to 90 °C.

• For the blends containing LFO, FAME and HVO the kinematic viscosities varied from 1.3 to 6.5 mm^2 s^{-1} at temperatures from 10 to 90 °C.

• Even though the methyl esters studied here were produced from different raw materials, animal fat and rapeseed oil, they both and their blends with LFO behaved almost identically in the kinematic viscosity measurements.

• The studied HVO fuel showed viscosity results almost equal to LFO.

• All the studied blends proved to be feasible options for medium-speed and other CI engine fuels. The fuel injection system must only be optimized properly for different kinematic viscosities.

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