Methanol-HVO blends for efficient low-temperature combustion: analytical research on fuel properties

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Abstract. Next-generation low-temperature combustion (LTC) engines can accommodate ultra-high efficiency with near-zero NOx and PM emissions. Reaction kinetics is the governing mechanism in LTC. Onboard fuel reactivity control is, thus, becoming an interesting concept that ultimately provides pathways toward a fully fuel-flexible engine. No matter the technical realisation - in-cylinder blending or pre-blending/emulsification - the reactivity control requires fuels with complementary properties. Methanol and hydrotreated vegetable oil (HVO) seem to be one of the most promising, yet under-studied combination for LTC engines. They are both renewable and can be mixed together. Methanol's high knock resistance and large latent heat of evaporation enable a wide engine load range, with a propensity to reduce NOx emissions and mitigate thermal or mechanical stress. The same properties on the other hand require highly reactive fuel to enable the mixture to self-ignite controllably in LTC conditions. HVO is amongst the most reactive renewable alternatives and its clean paraffinic structure further mitigates particle matter formation. - Importantly, in pre-blending HVO emulsification can resolve the lubricity issues of methanol. In this paper, the aim was to study the engine-relevant properties of HVO-methanol fuel blends. The analysed properties were the distillation properties, density, kinematic viscosity, cetane index, and flash point. Based on the results, the suitability of the chosen blend shares for LTC concepts was evaluated.

Key words: CI engines, fuel blending, HVO, LTC, methanol.

INTRODUCTION

Coordinated fuel-engine research aims to find cleaner, renewable fuels that maximise powertrain efficiency at the lowest-possible emissions. The transportation sector needs to develop solutions to diminish the negative impact on the environment and the climate.

Alcohols are one fuel class that can potentially serve as a carbon-neutral fuel source for internal combustion engines (Gainey et al., 2021). Alcohols together with second and third-generation biofuels, such as renewable diesel, are sustainable and effective options for reducing emissions. Methanol is an established fuel alternative in the marine sector (Wärtsilä, 2023). One of its advantages is the ability to store it onboard in liquid form at ambient temperature and atmospheric pressure. Burning methanol causes only low

pollutant emissions. Methanol can be produced 100% renewable, utilising renewable hydrogen and captured CO_2. However, short-chain alcohols, like methanol, are easily flammable and toxic for humans (Ming & Chen, 2021).

Hydrotreated Vegetable Oil (HVO), is renewable diesel made from raw materials such as used cooking oil, animal fat from food industry waste, or crude tall oil, a residue of pulp production. In certain compression ignition (CI) engines, HVO causes less greenhouse gas (GHG) emissions over the fuel's life cycle when compared with fossil diesel. Good quality HVO is compatible with all CI engines (Niemi et al. 2016; Spoof-Tuomi et al., 2021; Hunicz et al., 2022).

Conventional diesel and spark ignition (SI) engines are at their turning point, where instantly stricter emission regulations with the improvement of fuel economy are demanded. The legislative emission levels can be still achieved with exhaust aftertreatment systems, but that increases powertrain costs and system complexity. Due to the above-mentioned reasons, advanced combustion concepts incorporating alternative fuels have awakened great interest among researchers. (Yin et al., 2023) Advanced combustion strategies aim to lower the combustion temperature. (Jääskeläinen, 2019) The strategies are called as low-temperature combustion (LTC) technologies. HVO-methanol blends seem to be promising but yet under-studied combination for LTC engines.

There are single-, dual- and tri-fuel LTC implementations. Homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI) are examples of single-fuel concepts. Reactivity-controlled compression ignition (RCCI) is a very promising dual-fuel LTC technology. LTC concepts, regardless of realisation, are shown to cut down smoke and NOx emissions, as well as particulate matter emissions. This is achieved by globally lean operation with near-homogeneous fuel/air mixture in low cylinder temperature conditions (Gainey et al., 2021). The primary difference lies in the controllability of the combustion process. In RCCI the combustion phenomenon is controlled by fuel reactivity stratification, whereas in HCCI and PCCI thermal stratification has the main control capability (Vasudev et al., 2022).

HCCI is based on mixing preheated fuel with intake air or by early injection within compression stroke. The fuel/air mix auto-ignites simultaneously at several local regions creating high cylinder pressure rise rate (PRR). The PRR is too rapid and the concept lacks control for the start of combustion (SOC) (Chaudhari & Deshmukh, 2019). Thus, HCCI combustion requires extreme focus on the fuel, the gas exchange system and engine mechanical design creating complex and demanding technology (Vasudev et al., 2022). Although HCCI has shown high-efficiency and low-emission capabilities, its operating range is significantly limited compared to SI or diesel combustion due to its lack of heat release control mechanism (Gainey et al., 2021).

In PCCI, the start of fuel injection and the start of combustion are coupled to reduce rapid PRR. PCCI combustion can be achieved with various techniques, e.g. by advancing or retarding injection timing, using multiple injection strategies, increasing fuel injection pressure, injecting portion of the fuel during the intake or recompression stroke, using extensive exhaust gas recirculation (EGR), or reducing engine compression ratio (CR). (d'Ambrosio & Ferrari, 2015; Jain et al., 2017; Park et al., 2019; Singh et al., 2020; Pradeep & Anand, 2022; Lu et al., 2023).

In PCCI and HCCI, fuels can be pre-blended to achieve autoignition at a desired location. For instance, addition of low-reactivity fuel, such as methanol, is used to

increase ignition delay and fasten up fuel evaporation creating better fuel/air mixing. Additionally, alcohols have a high cooling potential that can be used to control the start of combustion in PCCI concept (Chaudhari & Deshmukh, 2019; Gainey, 2021; Vasudev et al., 2022).

Generally, single-fuel LTC concepts suffer from the fact that wide-range mixture control is too slow to enable in-cycle combustion control (airpath control and pre-blending). The available fast control mechanism like mixture stratification in PCCI or so-called negative valve overlap (NVO) fuel reforming (Hunicz et al., 2020) offer a limited span of control. Instead, dual-fuel (DF) engine technology enables achieving controllable LTC in real-world conditions. In RCCI, the mixture reactivity is adjusted by fuel allocation and fuel properties, and controlled by injection strategy and the fuel/air mixture formation (Yin et al., 2023). High-reactivity fuel is directly injected into the cylinder containing an almost homogenous mixture of air, residuals, and low-reactivity fuel. Early injections at narrow umbrella angles create fuel-reactivity stratification of a partially premixed charge before auto-ignition.

The above LTC methods offer an in-cylinder approach to either meet the strict emission standards fully or lower the performance demands required from the aftertreatment systems. LTC methods have also shown an improved fuel economy compared to conventional diesel combustion. In LTC mode, the operating temperature is lowered by operating the engine with high dilution rates, with an excess air ratio (λ) higher than 2 or with high EGR (Jääskeläinen, 2019). At higher engine loads, the LTC mode may not work and the operation range is narrow, i.e., higher fraction of EGR supply may not be useful in fabrication engines. Achieving LTC by dual fuel, multiple injections, and negative valve overlapping strategies also raise the costs of the system. Other challenges may be unburned hydrocarbon emissions and unstable control of the start of combustion and during the load transient phases (Krishnamootrhi et al., 2019).

The performance and emissions of LTC engines are heavily dependent on fuel properties. The most important characteristic of fuels is related to their capability to mix with air and to the mixture ignitability.

Fuel volatility plays an important role in this and it is measured by analysing fuel distillation properties. The more volatile the fuel is, the more easily it will vaporise and mix with air (Jääskeläinen, 2019). The volatility of the fuel is further studied by measuring its boiling point. A lower boiling point refers to high overall volatility. The distillation curve shows the vaporisation of fuels with respect to the temperature. The volatility of alcohols is higher than it is for conventional diesel fuels. Higher volatility fuels are suitable for port fuel injection. These fuels evaporate at lower temperatures and the air-fuel mixture is homogeneous (Krishnamoorthi et al., 2019).

Alcohols have, however, far lower reactivity than diesels and therefore 100% methanol cannot be used as a substitute fuel in compression ignition engines without hardware changes (Krishnamoorthi et al., 2019; Zhu et al., 2023).

Instead, renewable diesel (RD) fuel is highly inflammable, very prone to auto-ignition, making it an attractive alternative for LTC. It has a very high cetane number (CN), usually above 70 (Pirjola et al., 2019). Generally, the ignition of fuel is based on the chemical kinetic characteristics when the fuel is mixed with air. The CN describes the (diesel-like) fuel's ignitability (Heywood, 2018). A high CN may cause the fuel to auto-ignite easily after fuel injection. Auto-ignition is determined by chemical kinetics, which depends on the pressure and temperature development, mixture strength, and the

chemical composition of the fuel. High-CN fuels will auto-ignite very quickly before the fuel and air are mixed sufficiently.

In LTC concepts, fuel-air mixing is accelerated and the chemical reaction is slowed down. Auto-ignition occurs after the fuel and air are better mixed and soot levels can be reduced, if soot-forming highly-reactive fuel is used instead of clean RD fuel. NOx levels decrease by reducing combustion temperature by running lean, highly-premixed, and using EGR (Kalghatgi et al., 2006).

Kinematic viscosity affects the fuel spray pattern and the spray's tip penetration. Density effects the kinematic viscosity. If the density is high, the spray pattern is narrow and the spray tip penetration is long. Low-density fuel has lower mass of fuel supply for the volume of fuel injection. Together with alcohols lower density and lower energy content properties (compared to diesel) for example fuel injection timing is increased to achieve same in-cylinder energy (Krishnamoorthi et al., 2019). Low-viscosity fuels produce smaller droplets and therefore the spray formation is good and the droplets atomisation is smooth. Fuels with lower viscosity and surface tension, compared to higher viscosity fuels, lead to faster combustion due to better fuel/air mixing caused by smaller droplet sizes and faster vaporisation characteristics (Lee et al., 2012; Chen et al., 2013; Maurya & Agarwal, 2014). Alcohols' low fuel density with low viscosity, in LTC, improve fuel atomisation resulting better fuel/air mixing and improved combustion. Advanced injection timing in LTC methods, provide even more time for fuel/air mixing (Kumar & Saravanan, 2016).

In this paper, the aim was to find out the engine-relevant properties of HVO-methanol fuel blends. The measured properties were the distillation properties, density, kinematic viscosity, cetane index, and flash point. Based on the results, the suitability of the chosen blend shares for low-temperature combustion concepts was analysed.

MATERIALS AND METHODS

Fuels
The six fuels studied in this research were: (1) methanol, (2) HVO, (3) 5/95% (MeOH5) mixture of methanol and HVO, (4) 20/80% (MeOH20) mixture of methanol and HVO, (5) 30/70% (MeOH30) mixture of methanol and HVO, (6) 50/50% (MeOH50) mixture of methanol and HVO. The blend shares were calculated based on the energy basis. The lower heating values used for calculations were 44 MJ kg^{-1} for HVO and 20 MJ kg^{-1} for methanol. Methanol was a product of Merck KGaA, analysis grade, purchased from VWR, Finland. As methanol has a clearly defined chemical makeup, its LHV was obtained from the literature (Lampinen, 2009). HVO was Neste MY renewable diesel, purchased from Neste filling station, Vaasa, Finland, and its LHV was obtained from the manufacturer's data (Neste, 2023).

Density and Kinematic viscosity
The density and the kinematic viscosity were measured by SVM 3000 viscometer, and the measurement was produced according to Standard ASTM D7042. The measurement is based on torque and speed measurements. The device calculates the dynamic viscosity from the rotor speed. The device also has a density-measuring cell that employs an oscillating U-tube principle. The kinematic viscosity is calculated automatically based on these measurements (Novotny-Farkas et al., 2010).

Distillation curve

The distillation curve was measured by OptiPMD Automatic Distillation equipment, and the measurement was produced according to Standard ASTM D7345, except MeOH results were made based on manufacturer's method for alcohols. A distillation curve shows the transition from liquid to vapor with respect to temperature (Kalghatgi, 2014).

Flash point

Flash point was measured by Pensky-Martens flash point tester: PMA 5, and the measurement was produced according to Standard EN 14103. The flash point is the lowest temperature at which a volatile substance evaporates in the presence of an ignition source, forms a flammable mixture with air, and continues to burn after the trigger source is removed (Kalghatgi, 2014). The flash point of HVO was analysed in our laboratory. The flash point of methanol was from literature, the safety data sheet of methanol. Note that the most volatile fraction will always determine the flashpoint of the blend. Hence, all the analysed blends have the same flash point as methanol.

Cetane index

The cetane index is calculated based on the correlation formula of fuel's physical and chemical properties to predict the ignition quality. The method is applicable to straight-run fuels, catalytically cracked stocks, and the blends of the mentioned. (Heywood, 2018) The cetane index measurement is presented in Standard EN ISO 4264. In this study, the cetane index was analysed only for HVO.

RESULTS AND DISCUSSION

Table 1. summarises the fuels' key physical and chemical parameters. All data in the study were obtained through at least two repeated experiments.

Table 1. Fuel properties of HVO, methanol, and MeOH-HVO blends (MeOH5, MeOH20, MeOH30, MeOH50). IBP – initial boiling point. The lower heating values for methanol and HVO were received from manufacturers' data

Properties	HVO	MeOH	MeOH5	MeOH20	MeOH30	MeOH50
Kinematic viscosity at 40 °C mm^2 s^{-1}	3.14	0.55	2.90	2.64	2.26	1.25
Density at 15 °C (kg m$^{-3)}$	781.5	795.4	781.3	786.6	790.6	793.4
IBP (°C)	217	65	n/a	63	62	65
Flash point (°C)	82	9	9	9	9	9
Cetane index	93	n/a	n/a	n/a	n/a	n/a
Lower heating value (MJ kg^{-1})	44	20	n/a	n/a	n/a	n/a

The Table 1 shows that the kinematic viscosity of the MeOH-HVO blends decreases with the increase in the ratio of MeOH. The kinematic viscosity of HVO and MeOH are 3.14 mm^2 s^{-1} and 0.55 mm^2 s^{-1}, and the kinematic viscosity of MeOH-HVO blends is between 2.90 mm^2 s^{-1} and 0.55 mm^2 s^{-1}. Note that viscosity values allowing proper operation of standard common-rail direct injection systems are 1.90–6.00 mm^2 s^{-1}. (Krishnamoorthi et al., 2019). The viscosity values for HVO, including up to 30% MeOH admixtures, are in line with this range. Fuel injection system modifications may come

into consideration when MeOH content increases from 50% towards neat methanol. Increasing the viscosity of the blends by adding HVO to MeOH can help reduce the potential for leaks in high-pressure fuel systems.

The densities of HVO, MeOH and MeOH–HVO blends are between 781–796 kg m^{-3} or quite low but still in the density range of fossil fuels (750–860 kg m^{-3}) (Krishnamoorthi et al., 2019). Methanol showed a slightly higher density (795 kg m^{-3}) compared to renewable diesel (782 kg m^{-3}), Table 1. Fuel density has a direct effect on the pressure buildup in the injection system and as such affects the hydraulic injection delay. Density also affects engine power and volumetric fuel consumption (Hissa et al., 2019). Despite the higher density, the mass-based lower heating value is more than 2 times lower than HVO (Table 1). This requires roughly double the size of the fuel tank to secure comparable amount of energy as with HVO. The low heating value further implies that with a standard injection system, a methanol-operated engine might not reach its full power due to limited volumetric injection rates. Both density and LHV scale linearly between the blends within the standard deviation tolerances. This is evident in Table 1 for density. Finally, note that density has an indirect relationship with other fuel parameters such as the cetane index, viscosity, volatility, and distillation characteristics.

Fig. 1 shows the distillation curves of HVO, MeOH, and MeOH–HVO blends. In this research, no data were obtained for the boiling properties of MeOH5 as the boiling of this sample was too unstable. The initial boiling points of MeOH, MeOH20, MeOH30 and MeOH50 are 65 °C, 63 °C, 62 °C and 65 °C, respectively. The initial boiling point of HVO is 217 °C. The distillation behavior of all the MeOH–HVO blends is very similar. The distillation curve of MeOH differs from those of the blends only within the last 10%as the final boiling point (FBP) of MeOH is much lower. The FBP for the blends is approximately 245 °C and for MeOH it is 73 °C. The FBP of HVO is above 300 °C. The distillation properties of MeOH-HVO blends and neat MeOH are similar, because MeOH and HVO will not mix and react together, and the amount of MeOH in the blends boils out of the sample as it does in the neat MeOH sample.
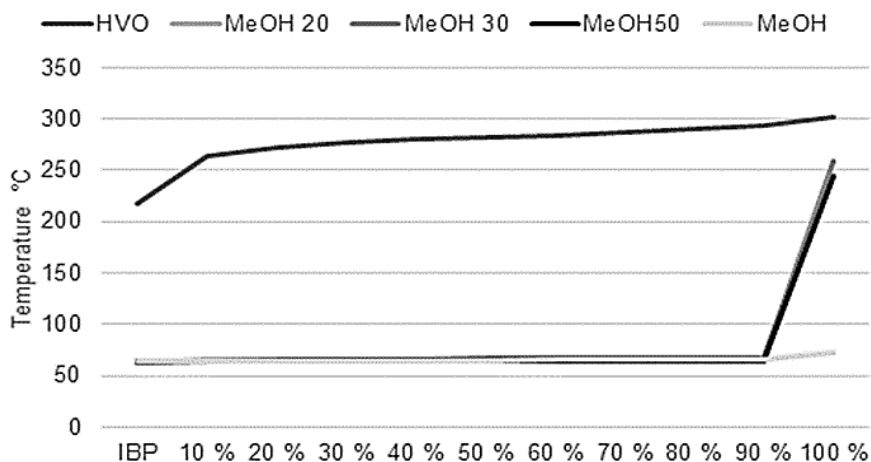

Figure 1. Distillation curves of the tested samples. MeOH05 is excluded from the analysis.

All the flash points of MeOH-HVO blends are much lower than HVO's. The flash point of HVO is 82 °C, the flash points of MeOH and MeOH–HVO blends are just 9 °C. The flash point determines the lowest temperature at which the fuel vapours form an explosive mixture with air. As such the most volatile fraction in the blend always determines this criterion. The high flammability of the fuel must be considered when storing and transferring the fuels, and pre-blending with low flash-point fuels does not solve the safety concerns.

The HVO's cetane index of 93 is an estimation. Neste states the cetane number for Neste MY to be above 80 (Neste, 2023). The calculation formula presented in the ISO 4264 standard is not suitable for HVO due to its low density, and neither for methanol or the blends. Cetane number (CN) indicates the fuel's auto-ignition property under compression. A high CN shortens ignition delay, which enhances smooth engine combustion decreasing e.g. noise and smoke emissions (Hissa et al., 2018). In future studies, the cetane number analysis based on the ISO 5165:2020 should be used for HVO and other biofuels, also the blends studied in this paper. Methanol's low cetane number of 3 (AMF, 2023) indicates poor auto-ignition capability leading to increased ignition delay. In LTC however, increased ignition delay can be used to improve fuel/air mixing with advanced injection.

It should be noted that methanol does not mix homogeneously with HVO and the stability of the blends caused challenges in measurements. Due to its higher density, methanol stratified into the bottom of the bottles. When mixed properly, the blends formed an emulsion which tended to recover into two phases after some time. According to Ghosh & Ravikrishna, surfactants, such as 1-dodecanol, could be used to stabilize the blend. The results have been promising, at least for a blend containing up to 25 wt.-% of methanol in diesel (Ghosh & Ravikrishna, 2021).

From the perspective of the results presented above, different LTC concepts can be categorized depending on the method a premixed or partially stratified fuel mixture is prepared in the combustor. HCCI embraces the LTC principle to the greatest extent by involving a completely evaporated and well-premixed fuel before combustion starts. Being a single-tank concept that favors low-reactivity fuel, usually admission with a port-fuel injection (PFI) or low-pressure direct injection system. With such constraints, methanol excels over other low-reactivity fuels. Its high-octane number combined with large volatility and high latent heat of evaporation allows operating at higher compression without knock resulting in higher indicated efficiency with very low NOx and unburned Hydrocarbon emission (Zhen & Wang, 2015). The latter is usually problematic for gasoline HCCI (Vasudev et al., 2022). At the same time, methanol's density and viscosity allow for it to be used with standard gasoline injection systems. Note, that methanol is commercially available in bulk amounts which makes it an attractive solution compared to other alternative fuels (Wärtsilä, 2023).

HCCI has been tested with diesel-like fuels (Ganesh et al., 2008; Singh & Agarwal, 2012). However, low fuel volatility requires impractically high intake air preheating (160–200 °C) to promote evaporation in PFI systems. HVO as such, has not been investigated with HCCI. With its purely paraffinic composition, it has only slightly higher volatility than diesel but its high cetane index in connection with elevated charge temperature implies the use of high EGR dilution rates to suppress premature autoignition.

Taking to account the above contradicting effects, and considering the measured properties of HVO-methanol blends, their emulsified application in PFI HCCI is possible but it is not expected to bring additional benefits from the perspective of combustion efficiency or controllability over the neat methanol-HCCI concept. With a lack of direct combustion control mechanism in HCCI, the intake thermal management must simply be optimized for the given fuel option (Kumar & Saravanan, 2016; Krishnamoorti et al., 2019).

Low volatility/high reactivity fuels like HVO generally perform well with direct injection. Premixed Charge Compression Ignition (PCCI) aims at achieving LTC assuming minimum or no modifications to conventional diesel engine platforms. From this perspective properties of HVO are fully compatible with EN590 standard for automotive diesel, yet there is limited experience with this fuel with PCCI. Hunicz et al., (2022) showed that higher volatility of HVO in connection with a high cetane Index allowed for achieving partially premixed compression ignition (a variant of PCCI on a bridge of CDC) with higher premixed share than diesel while avoiding wall wetting. Further diluting the fuel was limited with elevated CO emissions resulting from heavy EGR rates applied to mitigate pre-ignition. Although PPCI and PCCI are feasible for diesel engines, the concepts favor low-reactivity fuels as they allow higher compression ratios and better air-fuel mixing due to longer ignition delay and faster evaporation (Reitz, 2013). The same properties that make Methanol superior in HCCI would make it a favorable choice for its partially homogenous variant. The practical implementation in high-pressure injection systems is however technologically limited by its viscosity. According to Table 1, methanol's viscosity is very low (0.55 mm^2 s^{-1}) and leakage from the injector nozzle sealing and the high-pressure pump system occurs (Wärtsilä, 2023). Overcoming this requires sophisticated hydraulic sealing systems.

Blending the methanol with HVO increases the viscosity and the challenges with leakages in the engine system are reduced. According to Table 1, the MeOH30 blend has this parameter in accordance with the EN590 standard (2–4 mm^2 s^{-1}). Further analysing the destination curve of the blend (Fig. 1) in connection to lower viscosity will improve fuel-spray atomization and evaporation (Hissa et al., 2018), allowing earlier injections towards more premixed fractions in PCCI. At the same time reducing the overall cetane index (reactivity) and higher heat of evaporation of the blend will allow using less EGR to secure proper combustion onset, while minimizing NOx Emissions. Lower EGR in turn should contribute to higher indicated efficiency and provide more complete combustion (reduced CO and THC emission). The latter is further supported by the fact that methanol blends will be proportionally oxygenated with a hydroxyl group. Resulting in increased oxygen availability during combustion (Kumar & Saravanan, 2016) is particularly important for PCCI combustion with EGR dilution.

Using in-tank blends of MeOH and HVO with a ratio up to 2:5 is a feasible way to achieve superior performance in high-pressure injection PCCI systems, assuming emulsification issues are solved by additive (chemical stabilization) or applying a mixer in the feeding tank. This hypothesis has not been yet verified experimentally.

As LTC favors low reactivity fuels, further increasing the share of methanol in the blend would require two separate injection systems for methanol (a low-pressure PFI or DI system) and HVO (admission using a high-pressure Common rail injection system). The dual-fuel realization of the LTC concept is referred to as RCCI. This gives the benefit of controlling fuel reactivity depending on the engine operating point. RCCI

combustion has been well studied in literature with diesel and alcohols (Benajes et al., 2015; Park et al., 2016) with some intial tests with methanol in particular (Duraisamy et al., 2020). The study revealed that a higher octane number of methanol compared to conventional low-reactivity fuels (gasoline, natural gas) allows for maintaining high engine compression ratio. This results in 8% higher efficiency compared to the baseline diesel engine platform, with near-zero NOX emissions (attribute of LTC reinforced by the cooling potential of methanol evaporation in the cylinder). This was verified experimentally for a single mid-load operating point. The low load operation was still limited with excessive THC emissions and moving towards high load was possible with EGR (to suppress high-pressurised rates) but with a trade-off on CO emissions and efficiency.

Analysing the above results implies that both issues of methanol operation in RCCI could be mitigated by using a higher cetane index fuel as an ignition promoter. HVO with its very high reactivity (cetane index 93 according to Table 1) could promote efficient low-load operation with a higher methanol blend ratio, and its more volatile nature (than diesel) allows moving towards earlier injections without wall-wetting. At high load, high cetane index allows for easier and more complete ignition with heavy EGR dilution rates.

CONCLUSIONS

The discussion of physicochemical properties of methanol-HVO blends performed in context of individual low temperature combustion technologies, allows formulating the following conclusions:

- All properties except the flash point scale linearly (within the tolerances of standard deviation) between HVO and methanol. The property is determined by the most volatile fraction (methanol), and the value of 9 °C classifies the blends as low-flashpoint fuels with their respective special storage safety concerns.

- Distillation curve remains roughly the same for all the tested blends between 100% and 50% methanol. In all samples, 90% of the fraction boils off at 50 °C (the same as for neat methanol). The maximum boiling point for all the blends is around 250 °C and is roughly 50 °C lower than for HVO.

- Viscosity of the blends remains above 1.9 mm^2 s^{-1} for the MeOH-HVO blends up to 40%. These can be used in standard high-pressure diesel injection systems without modifications after considering lubricity and emulsification issues.

- Methanol is identified as the most favourable fuel for the mono-fuel HCCI concept with port fuel injection. Despite the blends could be used in this system, their incorporation does not bring synergetic benefits in terms of performance or combustion controllability.

- MeOH-HVO blends between 30% and 50% are considered potentially superior for PCCI realized on contemporary diesel engine platforms. With viscosity-compatibility, the blends allow higher compression ratios and better air-fuel mixing due to longer ignition delay and faster evaporation enabling high-efficient fast combustion with limited EGR.

- Dual-fuel RCCI application of methanol and HVO with separate injection systems allows to build on the complementary properties of the fuels to the biggest extent

extending the high-efficiency LTC operating range. The high reactivity (cetane index) of HVO can promote efficient low-load operation with a higher methanol blend ratio, while its high volatility allows moving towards earlier injections without wall-wetting. At high load, high cetane index of HVO allows for easier and more complete mixture ignition with heavy EGR dilution rates.

- Nether of the three mentioned fuel-combustion concept combinations have been to date tested experimentally. Fundamentally from the emission/efficiency perspective, all concepts will favour high methanol ratio. HVO applied in PCCI (pre-blended) and RCCI (in-cylinder blending) allows to achieve this respectively by supporting technical compatibility of the fuel-injection system or enhancing combustion controllability.

- The conventional, legislative fuel metrics, being the focus of the present work were designed to support compatibility with conventional engine concepts. In the context of LTC, neither the Cetane nor the Octane numbers quantify the fuel reactivity properly. In that sense, developing new - dedicated metrics describing kinetic-based combustion/ignition behavior under changing mixture strength/composition conditions are required. Developing such metrics forms an important task for contemporary analytical and computational chemistry-driven fuel research.

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