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Engine performance and exhaust emission characteristics of paraffinic diesel fuel in a model diesel engine

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Abstract

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The article deals with verification of a diesel fuel and two fuel mixtures blends with different amounts of the biocomponent using the model single-cylinder engine without the additional equipment for treatment of exhaust gases. This combustion diesel engine served for measuring the performance characteristics of the model single-cylinder engine and the individual emission components in order to assess the use of these blends of liquid paraffinic diesel fuel in practice and to meet current and forthcoming European legislation and to fulfil the commitments by 2020. A detailed chemical analysis was performed in case of all the tested paraffinic diesel fuels.

Keywords: combustion engine; renewable blending component; hydrotreated vegetable oil; engine performance; laboratory test

The compression ignition engines use diesel as a fuel according to the standard EN 590:2013 (Automotive fuels – Diesel – Requirements and test methods) that reduces the content of Fatty acid methyl esters (FAME) to 7% (V/V). The following fuels are used as well FAME EN 14214:2012 (Liquid petroleum products – Fatty acid methyl esters (FAME) for use in diesel engines and heating applications – Requirements and test methods) (2012+A1) at 100% concentration: high FAME diesel fuel (B20 and B30) according to the standard EN 16709:2015 (Automotive fuels – High FAME diesel fuel (B20 and B30) – Requirements and test methods.), diesel fuels blends containing FAME B30 according to the standard ČSN 65 6508:2013 (Automotive fuels – Diesel fuel blends containing Fatty acid methyl esters (FAME) – Requirements and test methods.).

One of the possible alternatives to meet the required reduction of CO_2 greenhouse gas emission is the use of paraffinic diesel fuel from synthesis or hydrotreatment (synthesized hydrocarbons), including hydrotreated vegetable oil (HVO), hydroprocessed esters and fatty acids (HEFAs), Fischer-Tropsch biomass to liquid (FT-BtL), gas to liquid (GtL) and power to liquid (PtL). It is possible to use them separately or add them to diesel in such amount so that the final mixture complies with the requirements of the standard EN 590:2013. As there is no manufacturing capacity in the Czech Republic, the imported raw materials would be used in the initial period. The manufacturing capacity is currently considered in the Czech Republic. The operating test to produce diesel with HVO was performed in the end of 2016 in the company Česká rafinérská a.s.

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The issue of production and use of HVO/HEFAS is widely discussed at an international level (Reinhardt et al. 2006; Murtonen et al. 2009; Mäkinen et al. 2011; Erkkilä et al. 2011a; McKone et al. 2011; Naumann et al. 2016). Commercially, the hydrogenation process for processing vegetable oils is operated by the company Neste Oil and their products are labelled NExBTL (Nylund et al. 2011; Naumann et al. 2016). Raw materials used for production of hydrotreated vegetable oil are the palm oil, spent vegetable oils and waste animal fats. The possibility to use the algae oil has been verified recently and the use of microbial oil is currently being investigated. The quality requirements for these paraffin-based fuels intended for compression ignition engines with regard to their needs are recorded in the technical specification of the standard EN 15940:2016 (Automotive fuels – Paraffinic diesel fuel from synthesis or hydro treatment – Requirements and test methods.). More than 98% of this fuel consists of paraffins, max. 1% consists of aromatics and max. 0.1% consists of polyaromatics and olefins. The elimination of oxygen from triacylglycerols (TAG) by means of the catalyst in a hydrogen atmosphere at elevated temperatures makes it possible to produce a mixture of synthetic alkanes. Unlike the process of transesterification, the triacylglycerols make it possible to process materials with high content of free fatty acids (Hancsok et al. 2007; Mikulec et al. 2010; Lapuerta et al. 2011). HVO/HEFAs are characterized by lower density and viscosity in comparison with fossil fuel and biodiesel. The products have ultra-low sulphur content, high cetane number and high net calorific value, which is suitable for the combustion engines (Mikkonen et al. 2012). With regard to the above presented qualitative indicators, using HVO/HEFAs and their mixtures with diesel and FAME results in significant savings of GHG emissions (Aatola et al. 2009*)*. The results of HVO/HEFA evaluation for different driving concepts and fuels for agricultural tractors are described by Ettl et al. 2014.

MATERIALS AND METHODS

Based on the previous experience and particularly on the Regulation No. 49 issued by the UN/ECE regarding the effect of HVO and its blends on the performance parameters of the engines, and also based on the results of measurement of the monitored emissions of exhaust gases, the fuels that were used for tests and measurements in the laboratory single-cylinder engine were the diesel fuel which meets EN 590 such as standard and base fuel, mixture of 30% of HVO biofuel with standard diesel fuel which meets the standard EN ISO 590 and neat 100% HVO biofuel HVO100 (Table 1).

The experimental compression ignition single-cylinder AVL engine, type 5402.088 installed in the set „AVL Compact Single Cylinder Test Bed“ was chosen for testing the impact of fuels. This engine was not equipped with any device for treatment of exhaust gases (such as the oxidation catalyst, particulate filter, or recirculation of exhaust gases into the combustion chamber – EGR). In order to improve the repeatability of the measurement, the external device AVL 577 was used in the set serving to maintain constant pressure and temperature of the oil and the coolant. Therefore, the engine had dry crankcase and did not have its own pump for the oil and the coolant. The device AVL 515 prepares the air that is sucked into the engine. This device maintains constant filling pressure and temperature of the intake air. The external compressor serves as the source of pressure. The exhaust is equipped with the stilling container with volume of ca 60 l behind which there is proportionally electronically controlled throttle controlling backpressure in the exhaust. This system allows considerably independent adjustment of the filling and exhaust pressure. All samples were taken from the exhaust pipe of the engine. Basic parameters of the experimental compression ignition engine, the dynamometer and the accessories are shown in Table 2. Description of the used measuring device is shown in Table 3.

Altogether twelve combinations of revolutions and engine loads were selected by qualified judgement for the measurement in order to cover the most commonly used operating points of the engine. These points were selected on the basis of the 13-points cycle WHSC (World Harmonized Stationary Cycle) consisting of stable operating modes covering the whole working range of revolutions and engine loads. The first and the last point is the idle run that is contained twice in the test. The points for the cycle were selected on the basis of the measured external rotation speed characteristics of the experimental single-cylinder engine, within the possibilities of mechanical parts and the engine control unit. Since it is the engine with

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Table 1. Physical and chemical properties of the tested fuels

Property	Unit	Diesel EN 590 temperate, climates	Diesel	Fuel sample Diesel blends 30 % ($V\cdot V^{-1}$) HVO	Neat 100% HVO	Paraffinic diesel fuel EN 15940 temperate, climates
Start of distillation	°C	–	177.2	183.7	187.9	–
Distillation						
at 250°C recovered	% (V/V)	< 65	40.1	30.6	2.8	< 65
at 350°C recovered	% (V/V)	min. 85	96.9	–	–	min. 85
95% (V/V) recovered at	°C	max. 360	343.7	326.6	291.0	max. 360
Total distillation volume	% (V/V)	–	98.3	99.9	98.1	–
End of distillation	°C	–	350.2	344.9	298.1	–
Flash point in closed cap	°C	above 55	67.5	68.0	69	above 55
CFPP	°C	< (+5 to –20)	–24	–27	–39	< (+5 to –20)
Cloud point	°C	–	–7	–11	–34	–
Polycyclic aromatic hydrocarbons	% ($m\cdot m^{-1}$)	max. 8.0	5.0	3.6	< 0.1	max. 1.1
Fatty acid methyl esters content	% (V/V)	max. 7.0	6.3	4.6	< 0.3	max. 7.0
HVO content	% (V/V)		–	30.4	> 99.7	
Water content	$mg\cdot kg^{-1}$	max. 200	50	40	30	max. 200
Sulphur content	$mg\cdot kg^{-1}$	max. 10.0	8.5	6.1	< 3.0	max. 5.0
Ash content	% ($m\cdot m^{-1}$)	max. 0.01	< 0.001	< 0.001	< 0.001	max. 0.010
Total contamination	$mg\cdot kg^{-1}$	max. 24	< 6.0	< 6.0	< 6.0	max. 24
Carbon residue on 10% Distillation residue	% ($m\cdot m^{-1}$)	max. 0.30	0.03	0.01	0.01	max. 0.30
Copper strip corrosion	rating	class 1	class 1	class 1	class 1	class 1
Lubricity, wear scar diameter (wsd) at 60°C	μm	max. 460	178	195	423	max. 460
Viscosity at 40°C	$mm^2\cdot s^{-1}$	2.000–4.500	2.621	2.650	2.855	2.000–4.500
Total insoluble sediment	$g\cdot m^{-3}$	–	1.0	1.0	1.0	–
Oxidation stability Rancimat (110°C)	h	min. 20.0	20,1	20,1	57.2	min. 20
Oxidation stability PetroOxy	min	–	96.3	96.5	67.8	–
Cetane number	–	min. 51	51.1	55.1	74.9	min. 70
Cetane index	–	min. 46	49.6	59.6	91.6	–
Density at 15°C	$kg\cdot m^{-3}$	820-845	840.1	822.1	779.6	765.0–800.0
Net calorific value	$MJ\cdot kg^{-1}$	–	43,11	43,36	44,04	–

unconventional drive of additional equipment and thus passive resistance (the crankshaft of the measured model single-cylinder engine serves as a drive for two balance shafts, the pump of coolant and lubricating oil is driven externally, the high-pressure injection pump is driven by the fully-dimensional engine), the value of indicated mean effective pressure in the cylinder was used for interpretation of the load. All presented energy and emission parameters of the AVL engine, type 5402.088 are thus related to the indicated performance. The construction of external rotation speed characteristics of the experimental single-cylinder engine is shown in Fig. 1.

The cycle was modified to reach necessary stabilization of the measured values in each point. In

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Table 2. Parameters of the experimental compression ignition single-cylinder AVL engine, type 5402.088, dynamometer and accessories

Bore / piston stroke, compression ratio	85 × 90 mm, 16:1 (max. combustion pressure 150 bar)
Max. engine speed Max. dynamometer speed Nominal moment/dynamometer performance	4,200 min^{-1} 8,000 min^{-1} 180 Nm (0–3000 min^{-1}) / 58 kW (3000–8,000 min^{-1})
Fuel injection	BOSCH Common Rail (max. injection pressure 1,800 bar)
Injection control unit	Open control unit AVL RPEMS + calibration SW/HW ETAS INCA v 7.0
Cooling/heating of oil and coolant temperature of coolant temperature of lubricating oil	AVL 577 – unit for supply and treatment of coolant and lubricating oil adjustable in range 35–120°C adjustable in range 35–110°C
Preparation of intake air temperature of intake air pressure of intake air	AVL 515 – supercharging unit, preparation of intake air adjustable in range 30–120°C adjustable in range 1–4 bar absolutely

Table 3. Measuring device used for the experimental compression ignition single-cylinder AVL engine, type 5402.088

Description	Designation	Measuring range	Accuracy
Fuel balance	AVL 733	0–500 g	± (0.12–4%)
Indication of rapidly changing pressures	AVL INDIMODUL /INDICOM		
Charge amplifier	AVL micro IFEM	10 Hz–1 kHz	+ 0.5 up – 0.25%
Cylinder pressure sensor	AVL GU22C	0–250 bar	± 0.3% FSO
Emissions devices			
Analyzer of gaseous components in raw undiluted exhaust gases	AVL AMA i60 CO CO_2 HC NO O_2	 0–10% V/V 0–20% V/V 0–20,000 ppm V/V 0–9,000 ppm V/V 0–23 % V/V	 ± 0.01% V/V ± 0.1% V/V ± 1 ppm V/V ± 1 ppm V/V 0.01 %V/V
Smoke	AVL 415SE	0–10 FSN	± 0.01 %
Opacity	AVL 439	0–100 HSU	± 0.1 %
Gravimetric sampling of particulates	AVL 472 Smart Sampler		
Counting number of particles	AVL PC 489	0–10,000 #/cm^3	± 10 %
Weight	Sartorius CP2P-F	0–500 mg	± 0.001 mg

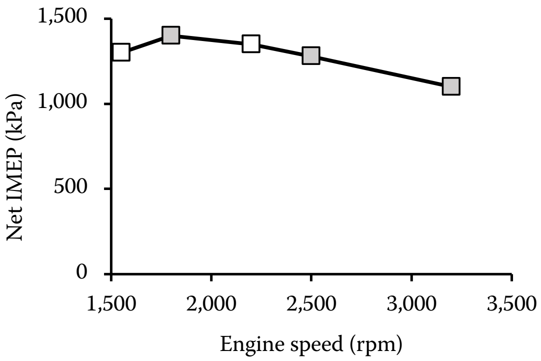

Fig. 1. External rotation speed characteristics of the experimental compression ignition single-cylinder AVL engine, type 5402.088
Net IMEP – Net indicated mean effective pressure integrated over the cycle – 720°

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Table 4. Definition of operating points of the WHSC cycle using the experimental compression ignition single-cylinder AVL engine, type 5402.088

Point	Engine speed (rev·min^{-1})	Pint (kPa)	Pairset (kPa)	EGP set (V)	Gas pedal (%)	Weighting factor (1)	Mode/AVL sampling time (s)
1	800	142	0	8	9.6	0.112	275/58.1
2	2,499	1,273	100	8.8	100	0.026	275/72.6
3	2,499	318	25	8.8	25	0.132	275/272.1
4	2,499	891	70	8.8	70	0.039	275/100.2
5	1,881	1,403	100	9	100	0.026	275/54.6
6	1,572	373	10	8.8	24	0.105	275/119.3
7	2,190	937	70	8.8	70	0.039	275/87.8
8	2,190	335	25	8.8	25	0.079	275139.1
9	2,499	637	50	8.8	50	0.066	275/156.5
10	3,117	1,097	100	8.6	100	0.026	275/90.5
11	1,881	708	50	8.8	46.4	0.105	275/194.6
12	1,881	355	20	8.8	25	0.132	275/196.6
13	800	142	0	8	9.6	0.112	275/58.1

pint – the measured value of the pressure in the combustion cylinder (kPa); pairset – set point pressure in the intake manifold of the engine (kPa); EGP set – managing set point throttle exhaust (2–10 V)

order to determine gravimetrically the weight of emitted particles, each point was provided with a weight by means of which the overall value for the cycle was calculated as a weighted average of values measured in the individual points. The calculation was done by means of software of the relevant device. This calculation includes corrections to actually reached values of dilution and time of intake through the filter. The individual points and provided weights are shown in Table 4.

RESULTS AND DISCUSSION

The summary results of the tested fuel samples in the WHSC cycle are shown in Table 5 in absolute terms and also in relative terms with regard to the referential fuel – diesel. Each listed value is evaluated as a weighted average of the test cycle. The emissions measured in the test were evaluated as follows: for gaseous components of emissions, the mass flow of the component was evaluated for each measured point in the cycle. In case of other calculations, values of emissions in wet exhaust gases were used for all components irrespective of the method of sample treatment with respect to water content. The resulting mass flow of the whole cycle was determined as a sum of coefficients of partial mass flows and weight factors. The resulting specific mass flow of the component was determined as the quotient of the absolute mass flow of the component and the medium-indicated engine performance. The medium-indicated performance in the test was weighted by the same algorithm with the same weighting factors as the emission components.

Comparison of medium-indicated engine performance (*Pi*) in the test is presented as a graph (Fig. 2). *Pi* grew by 1.38% during the measurement. The graphic presentation of results of the examined fuels shows an increase of indicated power Pi with increasing concentration of HVO in the fuel. This trend can be considered as proved due to its definite course and achieved highest difference 4.53%

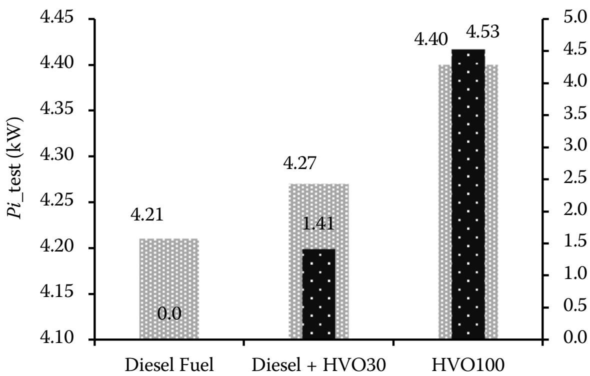

Fig. 2. Medium-indicated engine performance *Pi* and relative engine performance Δ*Pi*

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Table 5. Summary results of the tested fuel samples in the emission cycle WHSC in the experimental compression ignition single-cylinder AVL engine, type 5402.088

Fuel designation	Diesel fuel	Diesel fuel + HVO30	HVO100
HVO content (%)	0	30	100
Air temperature (°C)	20.9–22.5	18.3–22.9	23.3–23.9
Humidity (%)	20.7–23.6	28.6–37.6	25.2–26.4
Number of filter for PM	2	3	4
mCO_test (mg·kWh^{-1})	4,400	3,273	1,679
mCO_2_test (g·kWh^{-1})	580	569	559
mNO_x_test (mg·kWh^{-1})	7036	6,780	6,738
mHC_test (mg·kWh^{-1})	275	188	98
nsfc_test (g·kWh^{-1})	185.74	181.64	177.36
PN_test (#·kWh^{-1})	$1.6.10^{13}$	1.5×10^{13}	1.2×10^{13}
Opacity_test_avg (HSU)	6.3×10^{-01}	5.7×10^{-01}	4.6×10^{-01}
Smoke_test_avg (FSN)	7.3×10^{-02}	6.7×10^{-02}	5.4×10^{-02}
PM (mg·kWh^{-1})	0.106	0.052	0.021
*Pi*_test (kW)	4.214	4.273	4.405
Relative expression in relation to the referential fuel (diesel fuel)			
mCO_test (%)	0.0	–25.6	–61.8
mCO_2_test (g·kWh)	0.0	–1.8	–3.6
mNO_x_test (%)	0.0	–3.6	–4.2
mHC_test (%)	0.0	–31.5	–64.3
nsfc_test (%)	0.0	–2.2	–4.5
PN (%)	0.0	–10.5	–24.5
Opacity_test_avg (%)	0.0	–9.3	–26.9
Smoke_test_avg (%)	0.0	–7.6	–25.6
PM (%)	0.0	–50.9	–80.2
Δ *Pi*_test (%)	0.0	1.4	4.5

PM – particulate matter; WHSC – world harmonized stationary cycle; PN – particles number; HVO – hydrotreated vegetable oil; *Pi* – performance indicated

(measured fuel HVO100), i.e. higher than the achieved error of the measurement repeatability.

The following comparison of quantities measured in the test is presented as a graph (Fig. 3). At the top of the graph, there are absolute values and at the bottom there are relative increments to the referential diesel fuel. This type of graph will be used for all further presented quantities.

The comparison of net indicated specific fuel consumption (nsfc) for different fuels is shown in Fig. 3a. The graphs show a favourable effect of the increasing concentration of HVO, which causes reduction of the specific fuel consumption (sfc). This result is influenced by higher achieved indicated performance for higher concentrations of HVO, and also lower density of HVO compared to diesel.

The carbon monoxide emissions (CO) are shown in Fig. 3b. The effect of increasing concentration of HVO in the fuel is evident and its progress is continuous and clear. Concerning the WHSC test for engines of commercial vehicles, the emission standard Euro 6 sets a limit 1,500 mg·kWh^{-1} for this harmful emission. It can be assumed that a common modern engine with the system of additional treatment of exhaust gases with the oxidation catalyst for all measured fuels would successfully manage the carbon monoxide emission.

The specific emissions of carbon dioxide (CO_2) are shown in Fig. 3c. A small decrease of CO_2 concentration with increasing concentration of HVO is probably caused by different proportion of carbon in the fuel.

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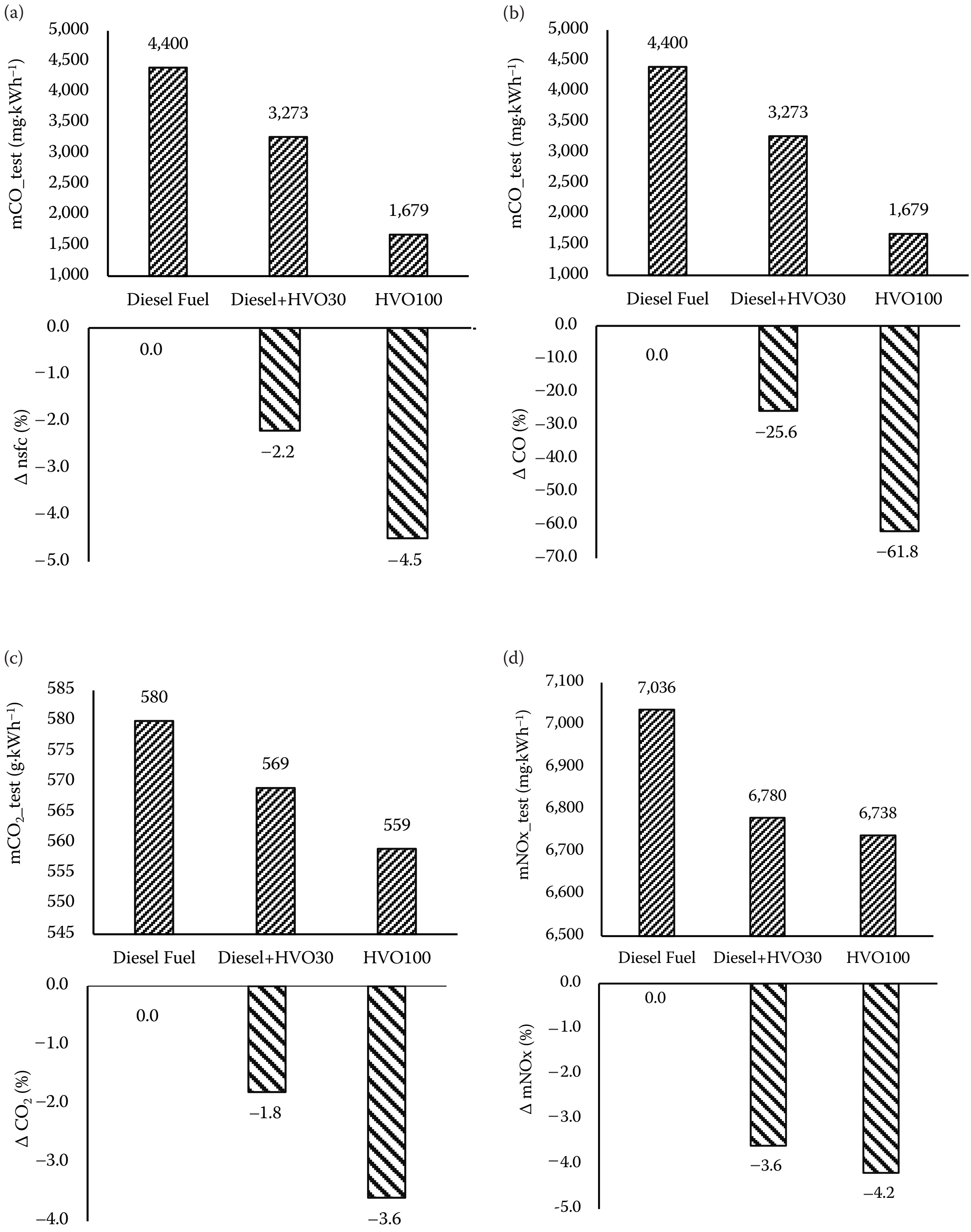

Fig. 3. Results of the WHSC cycle, indicated specific fuel consumption (a), specific emissions of CO (b), specific emissions of CO_2 (c), specific emissions of NO_x (d), specific production of HC (e), particle number emissions (PN) (f), Specific particulate matter emissions (PM) (g), opacity(h), and smoke (i)

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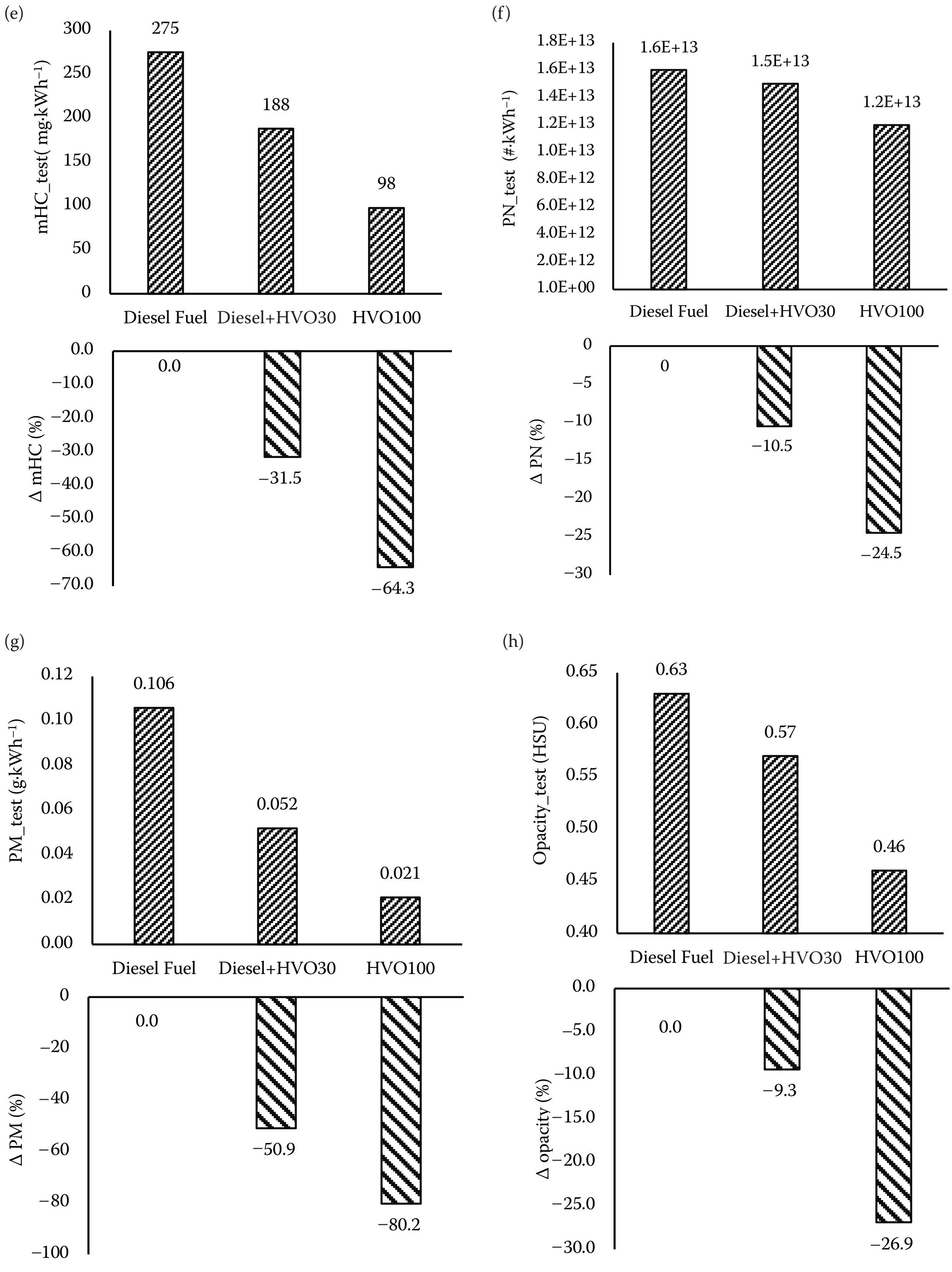

Fig. 3. to be continued

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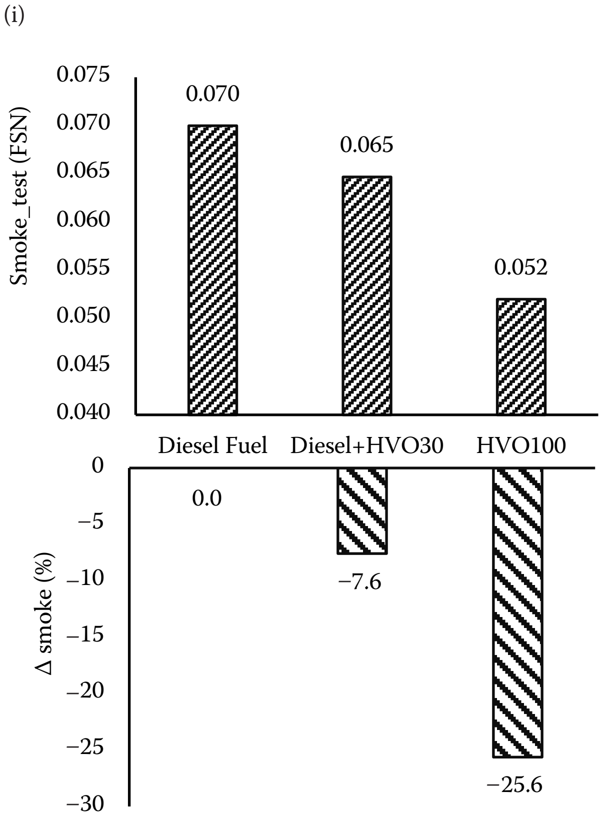

Fig. 3. to be continued

The nitrogen oxides emissions (NO_x) in the test are shown in Fig. 3d. The measured values in case of the tested fuels show a slight decrease of NO_x concentration with the increasing concentration of HVO. With regard to a less smooth progress of this dependence, it is necessary to interpret this little noticeable benefit very carefully. The achieved concentrations are also quite distant from the limits of the Euro 6 standard (400 mg·kWh^{-1}). This is in compliance with the contemporary and already generally known experience that it is virtually impossible to meet this standard without the system of selective catalytic reduction (SCR).

The emission of unburned hydrocarbons (HC) in the cycle is shown in Fig. 3e. It is evident that the presence of HVO in the fuel positively affects the emission of the particular pollutant. In case of 100% HVO, the level of the pollutant even gives a chance of reaching the limit set by the Euro 6 standard for the WHSC cycle even without the additional treatment of the exhaust gases (the limit is 130 mg·kWh^{-1}). However, the HC emissions (together with CO) are not a problematic component of the diesel exhaust gases as they can be quite successfully disposed of in the oxidation catalyst.

The graph in Fig. 3f clearly shows a positive influence of HVO on the amount of particles (PN) in the exhaust gases (measured by means of the particle counter AVL 489; AVL LIST GmbH, Austria), the progress of the trend is clear. The Euro 6 standard sets a value of 8.0 × 1,011 particles·kWh^{-1}, which is a value ca by one order higher than the measured value. This is in compliance with the contemporary need for providing the compression ignition engines with the particles filter.

The gravimetric measurement of the mass production of solid particles (PM) is summarized in Fig. 3g. It is clear that the production of gravimetrically measured emission of PM significantly reduces, in case of 100% HVO even by 80.2%. Further argumentation is in compliance with the above-mentioned description of particles formation.

The measurement of visible smoke and the opacity evaluation is shown in Fig. 3h. The effect of HVO in the fuel is positive again, since it causes almost a proportional decrease of smoke with increasing proportion of HVO in the fuel.

Smoke was measured by means of the filter method. The courses of smoke are depicted in Fig. 3i and they are quite similar to the above-mentioned measurement of opacity and it is possible to use similar argumentation.

In earlier studies (Miers et al. 2005; Kitano et al. 2007; Larsson, Denbratt 2007*)* the results show consistently lower soot emission with GtL or FT-BtL fuel than with crude oil-based diesel fuel, whereas the reductions in NO_x emissions are not clear. In the studies in which emissions of a passenger car or passenger car-engine size are measured with GtL, there are no clear and consistent reductions in NO_x compared to crude oil-based diesel fuel. According to Erkkilä et al. (2011b) a demonstration project using NExBtL in some 300 buses in the Helsinki metropolitan area was organized in 2007–2010. Test fuels consisted of a 30% blend of NExBtL and neat (100%) NExBtL. Neat NExBtL reduced NO_x emissions by 10% and particulates by 30% compared to the conventional diesel fuel.

An average relative change of the measured emissions (CO, HC, NO_x, smoke), and volumetric and mass-based fuel consumption of the test engine ran with default injection timings is presented by Nylund et al. (2011). The test engine was a turbocharged 8.4 litre 6-cylinder 4-stroke direct in-

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jection heavy-duty diesel engine. The engine was equipped with a common-rail fuel injection system and a charge air cooler. No EGR or exhaust after-treatment device was used. Nominal power of the engine was 225kW at 2,200 rev·min^{-1}. As it can be seen from HVO and HVO 30 (EN 590-30) compared with EN 590 fuel as the reference fuel, average reductions of all emissions are clear with 100% HVO. The most significant reduction of about 35% is measured in smoke. With 100% HVO, NO_x emission is reduced about 5%. With the EN 590-30 diesel fuel, smoke is reduced about 11% but NO_x is found to be approximately the same as with the reference fuel. The changes in HC and CO emissions are not very significant in absolute terms because of the already quite low absolute values. Compared with the reference fuel, gravimetric specific fuel consumption is reduced with 100% HVO and with EN 590-30 diesel fuel because of the higher mass-based effective heating value of the HVO. Volumetric fuel consumption is increased with 100% HVO and with EN 590-30 diesel fuel because of the lower volumetric effective heating value of the HVO.

The diesel vehicle fleet in Europe is generally validated for fuels with a HFRR wear scar diameter of maximum 460 μm thus correlating to a SL-BOCLE value of > 3,500 g (Nikamjan 1999). No or low aromatic fuels do not necessarily have the same good lubrication characteristics as crude oil-based diesel fuels protecting simultaneously against wear and seizure. Some paraffinic fuels poor in "natural" seizure protection do not protect against seizure even if the WSD in the HFRR test is adjusted to < 460 μm. All lubricity additives reduce the risk of wear. However, depending on the nature of the fuel and the type and concentration of the additive used for adjusting the lack of lubricity, adequate seizure protections is not necessarily ensured by low values in the HFRR test on its own (Table 1).

CONCLUSIONS

Altogether three samples of fuels were tested in the experimental single-cylinder engine in the engine dynamometer laboratory by means of the test based on the WHSC cycle. The evaluation concerned the overall energy and emissions parameters such as specific values related to the indicated power (all values were averaged). In case of both energy and emission parameters there are evident trends concerning dependence on the measured fuel.

The proportion of HVO in the fuel had a slightly positive effect on the indicated power Pi and specific fuel consumption according to NSFC. It did not significantly affect the amount of emitted nitrogen oxides NO_x. However, it has a very positive effect on smoke and the amount of emitted particles measured according to all available methodologies. The same can be said about the emissions of carbon monoxide and hydrocarbons. From the point of view of the observed parameters, the increased proportion of HVO in the fuel had only a positive effect.

The diesel fuel high in paraffin content does not always protect fuel system components sufficiently against seizure. The lubricity requirement ensures protection against wear but not necessarily also against seizure. Appropriate seizure protection shall be provided by using suitable fuel additives or by blending of minimum 2% (V/V) of FAME. Paraffinic diesel fuel is not validated for all vehicles, thus consult the vehicle manufacturer before use.

HVO paraffinic diesel fuel can also offer a meaningful contribution to the target of increased non-petroleum and renewable content in transportation fuel pool.

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