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COMPARISON OF EFFECTS CAUSED BY UTILIZING RAPESEED OIL AS A FUEL FOR A MODERN AND AN OLDER DESIGN DIESEL ENGINE – PART B: EXHAUST EMISSIONS

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Abstract
Non-esterified vegetable oils produced from local crops are increasingly used as a renewable fuel for compression ignition engines, widely used in mobile machinery. While much experience and data is available for older engines with mechanical injection pumps, use of vegetable oils in modern engines with Common Rail injection is more scarce. This paper compares the performance of a Zetor 1505 tractor engine with mechanical inline injection pump and a Cummins ISBe4 engine with Common Rail system when powered by diesel fuel and heated-fuel grade rapeseed oil. An overall decrease in the emissions of hydrocarbons, carbon monoxide and total particle volume was observed, while other effects were dependent on engine rpm and load, and are reported on.

1. INTRODUCTION

The interest in renewable energy resources is currently increasing, driven by the concerns about finite fossil fuel reserves, energy independence, energy security, and greenhouse gas emissions contributing to global climate changes. Finding of replacement fuels for diesel (compression ignition) engines, a widely used propulsion source in transportation and various machinery, is part of the transition to renewable, locally produced energy supply. For diesel engines, first-generation liquid biofuels, vegetable oils in their pure, non-esterified form, and methylesters of vegetable oils, called FAME (fatty acid methylesters) or biodiesel, are among the most practical and widely used alternative fuels. Biodiesel is already a widely accepted fuel, produced from soybean, rapeseed, canola, palm and other oils, recycled cooking oil, with a review given in [1-3].

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Non-esterified vegetable oils, chemically n-alkyl-triglycerols of fatty acids, typically used as a feedstock for biodiesel production, are also used directly as a fuel. The history of combusting vegetable oils in diesel engines dates back to the very early experiments by Rudolf Diesel [4]. Later, about one hundred years ago, oil crops from colonies in tropical regions were considered as diesel engine fuels [5]. The discovery and massive coming of petroleum based fuels which were less expensive and readily available, has quenched these efforts, which were, however, periodically returned to during fuel shortages. During the World War II fuel shortages, jatropha oil was successfully used in Madagascar, Cape Verde Islands and Benin [6]. Vegetable oils are commonly used in agricultural machinery in Austria and Germany and other places throughout the world. In most current applications, vegetable oils are heated prior to their introduction into the diesel injection system. This is done partially to allow for the fuel to be utilized in cold weather, but primarily in order to reduce their viscosity to levels typical for cold diesel fuel. The desired fuel oil temperature appears to be over 60ºC [7-8], with not much improvement being gained by higher temperatures. Majority of the engines powered by vegetable oil are operated in dual-fuel mode, with diesel fuel being used to start and warm up the engine, and again for the flushing of the fuel system prior to the engine shutdown [9].

Most of the previous studies were, however, done on classical mechanically driven injection pumps, where the amount of the fuel injected is determined primarily by the volume of the fuel metered into the delivery chamber. With this type of injection pumps, higher viscosity of vegetable oils is compensated by a combination of higher fuel temperature and higher injection pressures, with little changes in the volume of the fuel delivered [10,11]. The Common Rail technology, increasingly used first on road vehicles and then throughout many other diesel engine applications, utilizes a different system of metering, where the amount of the fuel delivered depends on the fuel pressure and the length of the time of the opening of the injector, and on fuel properties such as viscosity.

The motivation of this paper is to contrast the effects of utilizing heated fuel-grade rapeseed oil, as a representative of non-esterified vegetable oils, on the performance and emissions of a "traditional" diesel engine with a mechanical inline injection pump against those of a "modern" diesel engine with electronic controls and Common Rail fuel injection system, and to highlight the differences in behaviour changes induced by using of rapeseed oil between the two engine types. Due to the overwhelming volume of experimental data and the complexity of the issue, this paper is limited to the discussion on the effects on exhaust emissions; the effects on the fuel injection system and on the combustion are reported and discussed in a companion paper.

2. EXPERIMENTAL

The "traditional" engine was represented by a Zetor 1505, four cylinder in-line turbocharged tractor engine with bore/stroke 105/120 mm, displacement 4,16 dm^3, maximum torque of 525 Nm at 1300-1500 rpm and rated power of 90kW at 2200 rpm with a wastegated turbocharger, intercooling, exhaust gas recirculation, and a Motorpal inline fuel injection pump, meeting the EU Stage IIIA non-road engine standards with EGR. EGR was disabled in the tests reported here. The details of this engine, instrumentation, and test procedures are given in [11].

The "modern" engine was represented by a Cummins ISBe4, in-line, four cylinder, turbocharged with waste gate control, intake air cooling, bore/stroke of 107/124mm, displacement 4,50 dm^3, maximum torque of 700 Nm at 1300-1800 rpm, and maximum power of 136 kW at 2500 rpm. This engine is equipped with Bosch second generation Common Rail fuel system with controlled by ECU, and meets EU Euro IV standards when equipped with a SCR NO_x reduction system (which was not used in the tests reported here). The details of this engine, instrumentation and test procedures are given in [12].

Both engines were equipped with a heated secondary auxiliary fuel system, consisting of a heated fuel tank, supply pump, heated fuel filter and isolated fuel line, which allows for switching between diesel fuel and heated vegetable oil. Switching between these branches is provided by two three-way valves, one for switching supply branch is placed before in-line injection pump (Zetor) or high pressure pump for common rail system (Cummins), and second valve installed on the fuel return line.

The engines were operated on EU highway diesel fuel (EN 590) purchased at a local fueling station (ETK, Liberec, Czech Republic) and locally produced fuel-grade (DIN 51605) rapeseed oil (Fabio Product, Holín, Czech Republic) with a lower heating value of 36,9 MJ/kg (RO).

Both engines were coupled with Schenck Dynabar water-brake dynamometers and were run without any exhaust gas aftertreatment systems.

The engines were tested in steady-state operating conditions primarily corresponding to the operating points prescribed in the ISO-8178 non-road engine test (Zetor engine, see Table 1) and the ESC test (Cummins engine, see Table 2). Additional tests were run at other selected regimes. Maximum torque tests were run in a dynamic progression of rpm at a rate of 8 rpm per second.

Point no.	1	2	3	4	5	6	7	8
Speed [rpm]	2200 (max. power rpm)				1480 (max. torque rpm)			780 (idle)
% load	100	75	50	10	100	75	50	0
Weight factor	0,15	0,15	0,15	0,10	0,10	0,10	0,10	0,15

Table 1: *Regimes of eight-point ISO 8178 test cycle*

Point no.	1	2	3	4	5	6	7	8	9	10	11	12	13
Speed [rpm]	Idle	1500	1900	1900	1500	1500	1500	1900	1900	2300	2300	2300	2300
% load	0	100	50	75	50	75	25	100	25	100	25	75	50
Weight factor	0,15	0,08	0,10	0,10	0,05	0,05	0,05	0,09	0,10	0,08	0,05	0,05	0,05

Table 2: *Regimes of thirteen-point ESC test cycle*

The concentrations of the following gaseous pollutants were measured in undiluted exhaust gas: hydrocarbons (HC) by heated flame ionization detector (FID, Hartmann & Braun, Germany), carbon monoxide (CO) by non-dispersive infra red analyzer (Horiba, Japan), nitrogen oxides (NO_x) by chemiluminiscence analyzer (Horiba, Japan), carbon dioxide (CO_2) by infra red analyzer (Uras, Hartmann & Braun, Germany) and oxygen by paramagnetic analyzer.

The particle emissions measurements were conducted on samples taken from the laboratory main exhaust duct, which was used as an improvised full-flow dilution tunnel with dilution ratio ranging from about 10-15:1 at full load to 80-100:1 at idle. This approach is described in detail in a separate paper given at this conference.

From this tunnel, samples for gravimetric measurements and toxicological assays were facilitated by high-volume samplers (Digitel, Switzerland) on 150 mm diameter Teflon membrane filters; these assays and their results were reported in [13].

The particle size distribution spectra were measured by an Engine Exhaust Particle Sizer^{TM} (EEPS, Model 3090, TSI, St Paul, MN, USA), which was preceeded by an improvised secondary dilution consisting of the injection of metered amount (MassTrak, Sierra Instruments, California, USA) of HEPA filtered ambient air in the sample inlet of the EEPS to achieve a secondary dilution ratio of 3:1 to 6:1.

3. RESULTS

The summary data for both engines are given in Table 3. The particle size distribution spectra are given in Figure 1, the differences between the fuel, expressed as the difference between emissions during rapeseed oil (RO) operation relative to diesel operation, are given in Figure 2 for gaseous pollutants and in Figure 3 for total particle volume and number concentrations.

	Zetor 1505 – NRSC test			Cummins ISBe4 – ESC test		
	Diesel fuel [g·kWh^{-1}]	Rapeseed oil [g·kWh^{-1}]	RO vs. diesel [%]	Diesel fuel [g·kWh^{-1}]	Rapeseed oil [g·kWh^{-1}]	RO vs. diesel [%]
HC	0,219	0,095	-57%	0,034	0,019	-44%
CO	1,17	1,15	-2%	0,73	0,63	-15%
NO_x	5,03	5,34	+6%	11,24	11,65	+4%
PM [13]	0,185	0,202	+9%	0,031	0,024	-22%

Table 3: *Summary values for NRSC (Zetor) and ESC (Cummins) tests.*

	Zetor 1505 – NRSC test				Cummins ISBe4 – ESC test			
mode	rpm	BMEP [MPa]	PM count diesel	PM count RO	rpm	BMEP [MPa]	PM count diesel	PM count RO
1	2200	1,00	2,54E+06	1,13E+06	800	0,01	3,75E+04	1,07E+05
2	2200	0,75	1,73E+06	2,05E+06	1500	1,68	1,46E+06	8,94E+05
3	2200	0,50	1,35E+06	1,96E+06	1900	0,92	1,56E+05	1,11E+06
4	2200	0,10	1,14E+06	1,56E+06	1900	1,38	2,91E+05	9,75E+05
5	1480	1,36	1,63E+06	7,46E+05	1500	0,97	9,92E+04	6,36E+05
6	1480	1,02	1,54E+06	8,92E+05	1500	1,45	2,98E+05	4,01E+05
7	1480	0,68	1,13E+06	1,29E+06	1500	0,47	7,27E+04	7,54E+05
8	780	0,00	6,93E+05	1,28E+06	1900	1,64	6,83E+05	7,51E+05
9					1900	0,46	1,27E+05	1,65E+06
10					2300	1,41	1,10E+06	8,18E+05
11					2300	0,39	3,21E+05	1,93E+06
12					2300	1,17	9,77E+05	7,71E+05
13					2300	0,78	7,24E+05	8,54E+05

Table 4: *Particle number concentrations in diluted exhaust.*

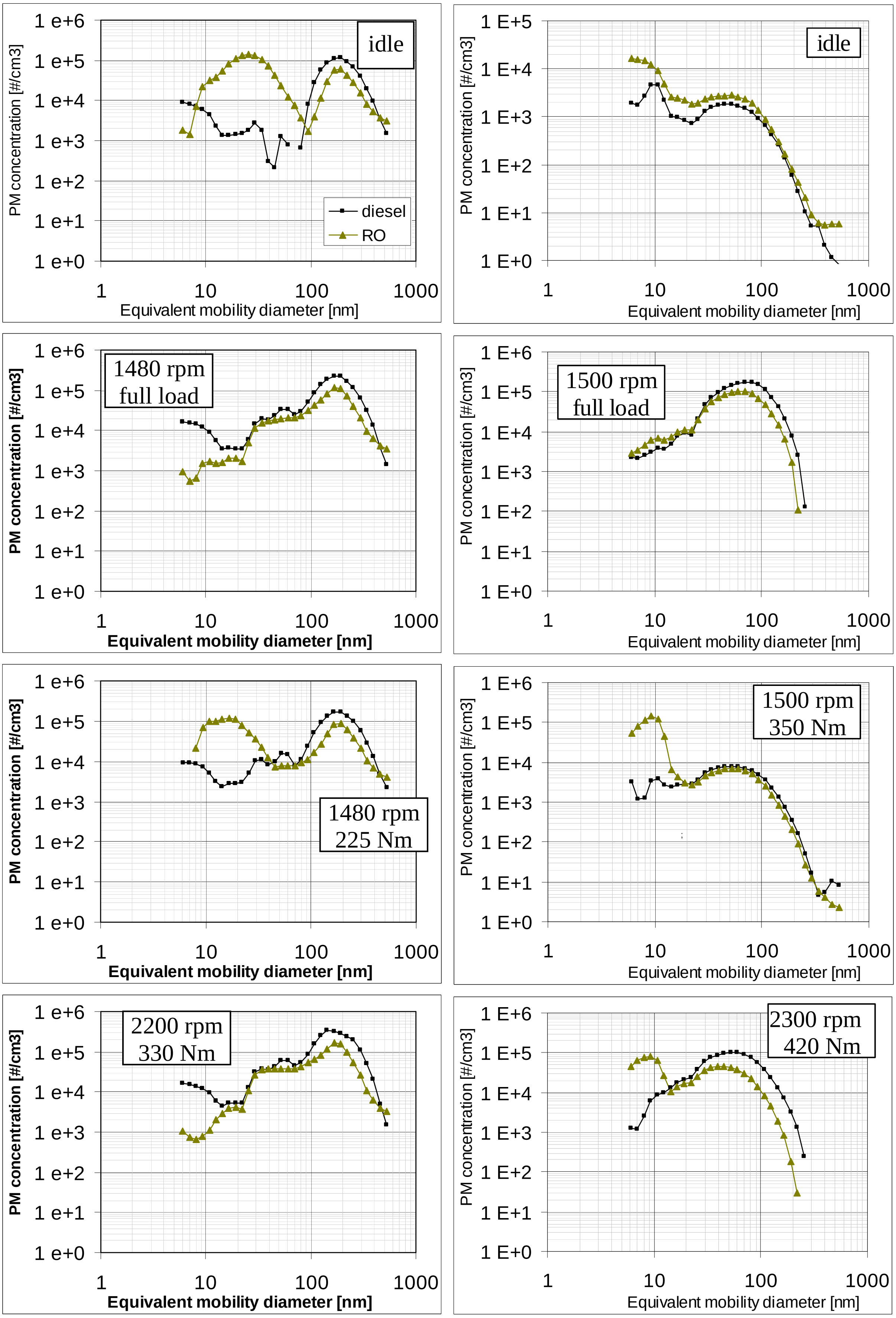

Figure 1: *Size distribution spectra of particles in the diluted exhaust during operation of Zetor (left) and Cummins (right) engines on diesel fuel and heated rapeseed oil.*

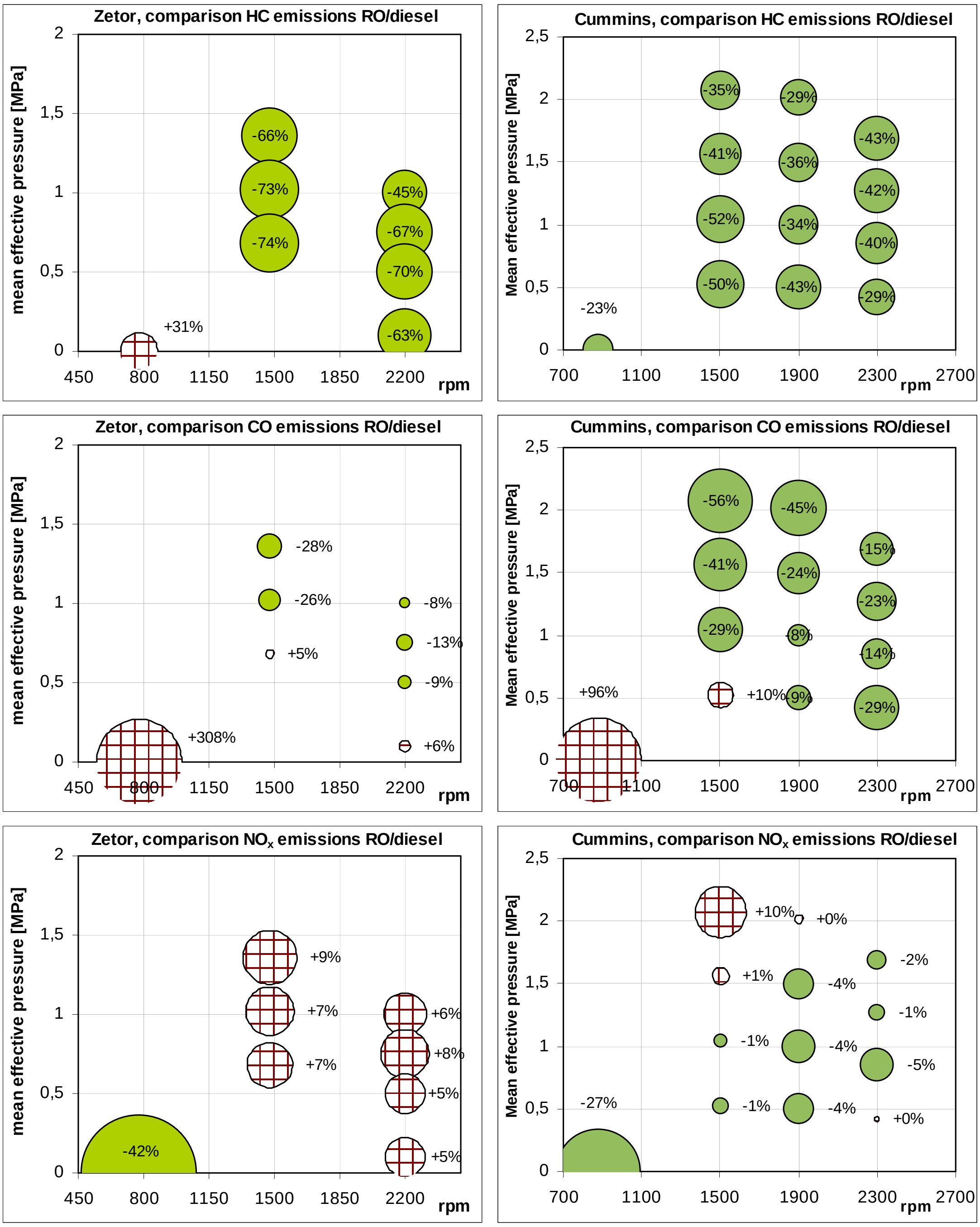

Figure 2: *Emissions of HC (top), CO (middle) and NOx (bottom) during operation on heated rapeseed oil compared to the emissions during diesel fuel operation on the Zetor (left) and Cummins (right) engine.*

The overall effect of the rapeseed oil, per summary data in Table 3, is, compared to diesel fuel, a reduction in HC by approximately one half, a small reduction in CO, a 4-6% increase in NO_x, and a relatively small but uncertain change in total particle mass (see discussion). The particle size distribution spectra show an overall increase in the nucleation mode (units to lower tens of nanometers) and a moderate decrease in the accumulation mode (generally high tens to hundreds of nanometers); as a result, large differences in particle number and smaller differences in particle volume were observed. The effects are heavily dependent on engine rpm and load, with notably idle being different from the remaining data, as demonstrated in Figures 1, 2 and 3. At idle, the NO_x emissions have decreased by 42% (Zetor) and 27% (Cummins), while CO emissions have increased by 308% (Zetor) and 96% (Cummins), and particle number has increased by 85% (Zetor) and 186% (Cummins). The effects on the HC and total particle volume was non-uniform, with a 31% increase in HC and 46% decrease in particle volume on Zetor, and a 23% decrease in HC and 56% increase in particle volume for Cummins.

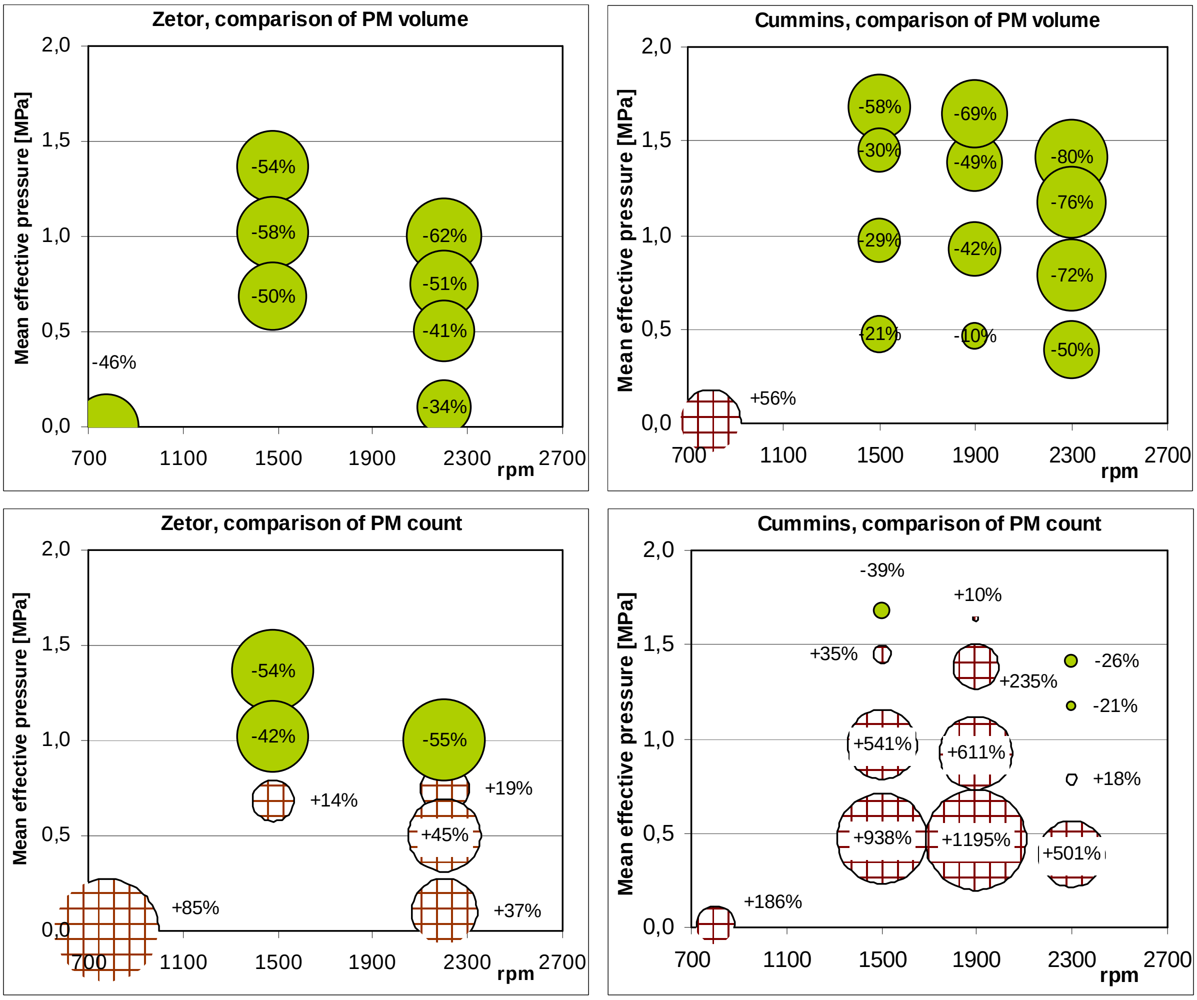

Figure 3: *Comparison of the total volume (top) and total number (bottom) of particles emitted during operation on heated rapeseed oil compared to the emissions during diesel fuel operation on the Zetor (left) and Cummins (right) engine.*

4. DISCUSSION

As it has been suggested in previous studies, a bifurcation in the data, where the effects are different at low rpm and loads and throughout the rest of the engine operating map, has been observed for both engines.

At moderate and higher rpm and loads, very little difference has been observed in the course of the combustion (see Part A of this work in these proceedings). One of the small differences is the effective advancement of the fuel injection timing on the Zetor engine with inline injection pump, caused by higher bulk modulus and higher density of rapeseed oil (RO) compared to diesel fuel, and thus higher speed of the propagation of the pressure wave. This effect is non-existent for a Common Rail engine, and might help explain why NOx might have, in most modes, been slightly higher on the Zetor engine (advancement of the injection timing) but not on the Cummins engine. Chemical structure of the RO – about one tenth of oxygen by mass and lack of aromatics – might have contributed to lower HC, CO and PM emissions. At the same time, higher "distillation temperature" of rapeseed oil (in reality, rapeseed oil is more likely to form gaseous products via thermal degradation than via phase change), together with higher viscosity leading to poorer atomisation, may lead to larger quantities of unburned fuel in the exhaust, which, given its distillation curve, and the smaller quantities of elemental carbon (soot particles), might result in much higher counts of nanoparticles, most likely droplets of uncombusted fuel. This leads to lower particle volume emissions (and particle mass, assuming comparable densities), but given the increase in nanoparticles being higher by count than the decrease in the larger particles (which account for bulk of the volume), the particle number concentrations decrease only at higher loads, while increase at moderate to lower loads. The increase in the particle count is higher for Cummins than for Zetor, however, the Cummins engine has markedly lower emissions (in the average, nearly an order of magnitude) than Zetor. Also, on the Cummins engine, the increase in particle count with decreasing engine load starts at higher loads, and the peak concentrations of the nucleation mode particles (nanoparticles) are shifted towards lower particle diameter, compared to the Zetor engine.

At low rpm and loads, the combustion of rapeseed oil is becoming more problematic, with longer ignition delay and slower heat release (see data and detailed discussion in Part A, see also yet more detailed discussion in [11,12]) resulting in later combustion with lower peak temperatures, a likely explanation of lower NO_x at idle for both engines (27% and 42%), and less complete combustion, with increase in the amount of unburned fuel, as demonstrated by a marked increase in CO (see Figure 2), over one order of magnitude increase in nanoparticles (see Figure 1), and a likely increase in the total volatile organic matter, which is distributed between gaseous and particle phase.

At all modes, given the different distillation curves, unburned RO is more likely to be in particle phase than unburned diesel fuel; this is consistent with observation (see Table 3 and Figures 2 and 3) that the reduction in HC was higher than the reduction (if any) of particle mass (Table 3) and volume (Figures 1 and 3). Also, considering that gaseous HC are measured at 191 ºC in undiluted exhaust and particles at tens of ºC after dilution, and thus a portion of the organic compounds might be accounted for twice, both as HC and as PM, while another portion might not be accounted for at all, HC and PM data should be interpreted carefully.

Some differences between the engines were observed in NO_x emissions, as discussed in the second paragraph of this section, and in CO emissions, where the increase at idle was higher for the Zetor engine (four-fold) than for the Cummins engine (two-fold), and the reductions at higher loads were higher for Cummins than for Zetor. It should be also noted that Cummins engine uses higher fuel injection pressures (up to nearly twice compared to Zetor), multiple injections per working cycle which can be arbitrarily timed, four valves per cylinder, and different combustion chamber design than the Zetor engine, where the injection timing is static, with no adjustments for varying rpm or load. Also, the Cummins engine uses much more advanced timing than Zetor, as it relies on SCR unit for NOx reduction, which has not been used during these tests; this alone has contributed to lower HC, CO and PM, more complete combustion, and higher NO_x. The apportionment of the differences in emissions among the differences in engine design is not an easy task and was beyond the scope of this work.

Throughout this work, no changes to the engine or its adjustment took place. On the Zetor engine, the possibility for changes is limited if the ability of the engine to run on diesel fuel, and to meet the applicable legislative requirements while doing so, is to be retained without being compromised. On the Cummins engine, however, at least a theoretical possibility of sensing what fuel the engine is running on (such as based on pressure drop across a part of the fuel system, fuel density measurements with a microsensor, or by other means) and making on-the-fly fuel-specific adjustments, exist and should be considered, even if in reality, changes to the engine control unit are reserved to larger engine manufacturers and are difficult to implement as a part of an aftermarket retrofit.

From the legislative view, the only effect of possible concern when meeting emissions standards is the slight (4-6%) increase in NO_x. On both engines, HC emissions were already low enough to meet Euro V EEV, and CO emissions low enough to meet proposed Euro VI limits (see EU Directives 2005/55/EC, 2005/78/EC, 2006/51/EC and 2008/74/EC). During the tests reported here, none of the engines met the standards for NO_x, as the EGR was disabled on the Zetor engine (as it has greatly reduced repeatability of the measurements) and SCR was not used on the Cummins engine (we did not have it). It is anticipated that the inclusion of EGR would easily lead to 20-25% reduction in NO_x needed to meet EU Stage IIIA for Zetor, and the inclusion of SCR would easily lead to about 70% reduction needed to meet Euro IV for Cummins; no reason exists for a concern about efficiency or performance of SCR with vegetable oil fueled engine, an argument supported by [10]. No problem is anticipated with total particulate mass, which has been reduced. The exceedance of the Euro IV by the Cummins engine is attributed to measurement artefacts caused by slow dilution and thus more organic particles accumulating on the filter.

5. CONCLUSIONS

The effects of utilizing heated, fuel-grade rapeseed oil as fuel on the exhaust emissions were examined for a "traditional" Zetor engine with an inline fuel injection pump and a "modern" Cummins engine with a Common Rail fuel injection system. On both engines, the emissions of HC have about halved, CO was slightly reduced, NO_x has increased by 4-6%, PM mass and volume have decreased. The effect on particle number emissions was non-uniform, with a general increase in nucleation mode nanoparticles and a general decrease in larger accumulation mode particles, with the effects on total particle number ranging from an order of magnitude increase in nanoparticle emissions at idle and lower loads, and reduction in total particle number at high loads. The increase in particle number emissions were higher for Cummins than for Zetor. The effects on the emissions depended on engine rpm and load, with larger increase in CO (more pronounced for Zetor engine) and PM and decrease in NO_x at idle. As HC and CO emissions were well below the limits, and PM emissions have decreased, the only issue possibly affecting the emissions limits is the 4-6% increase in NO_x, a difference hardly above the measurement uncertainty, that can be addressed, for example, by altering the settings of base injection timing, EGR or SCR.

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