XLII. INTERNATIONAL SCIENTIFIC CONFERENCE
OF CZECH AND SLOVAK UNIVERSITY DEPARTMENTS
AND INSTITUTIONS DEALING WITH THE RESEARCH
OF COMBUSTION ENGINES

SEPTEMBER 8 - 9, 2011 – ZILINA, SLOVAKIA
UNIVERSITY OF ZILINA
DEPARTMENT OF AUTOMOTIVE TECHNOLOGY

COMPARISON OF EFFECTS CAUSED BY UTILIZING RAPESEED OIL AS A FUEL FOR A MODERN AND AN OLDER DESIGN DIESEL ENGINE – PART A: FUELING, COMBUSTION AND PERFORMANCE

Martin Pechout[1], Michal Vojtíšek[2]

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. Both engines performed well at moderate and higher loads, with a minor decrease in maximum torque, while combustion timing changes were observed at low loads. Fuel injection and combustion pressures and timing and maximum torque 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].

[1] Martin Pechout, Department of Vehicles and Engines, Faculty of Mechanical Engineering, Technical university of Liberec, Studentská 2, 461 17 Liberec I, Czech Republic, martin.pechout@tul.cz
[2] Michal Vojtíšek, Department of Vehicles and Engines, Faculty of Mechanical Engineering, Technical university of Liberec, Studentská 2, 461 17 Liberec I, Czech Republic, michal.vojtisek@tul.cz

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, the effects on the fuel injection system and on the combustion are reported on here, while the emissions are 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 dm3, 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. 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 dm3, 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 4 standards when equipped with a SCR NO_x reduction system. 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*

Dynamic in-cylinder pressure measurements were provided by piezoelectric sensor (GU 21D, AVL, Graz, Austria) on the 1st cylinder of the Zetor engine and 2nd cylinder of the Cummins engine, and by an optomechanical sensor (AutoPSI, Optrand, Michigan, USA) on the 4th cylinder of the Zetor engine. Dynamic fuel pressures in the supply lines of the mentioned cylinders were measured with a piezoelectric sensor (Model 4067, Kistler, Switzerland). These measurements were done for fifty consecutive working cycles and mean values were reported.

3. RESULTS

The torque curves, run with rpm increasing from 1000 to maximum at a rate of 8 rpm per second, are given in Figure 1. On the Zetor engine, the torque on rapeseed oil was, compared to diesel fuel, less than 10% lower from 1300 to 2200 rpm, with a minimum of about 6% around 1800 rpm. At lower and higher rpm, the differences were higher. On the Cummins engine, the maximum torque was lower by 11%, with the difference being remarkably constnt from 1350 to 2300 rpm.

On both engines, peak torque has dropped by up to 50% below 1300 rpm. The suspected reason for this difference was the correction of fuel delivery rates based on the intake manifold pressure. For this reason, the intake manifold pressures (turbocharger boost pressures) are reported on in Figure 2. The differences between diesel fuel and rapeseed oil are small except for full load at lower rpm, where considerable differences were observed. The differences along the maximum torque curve were generally higher for the Cummins engine.

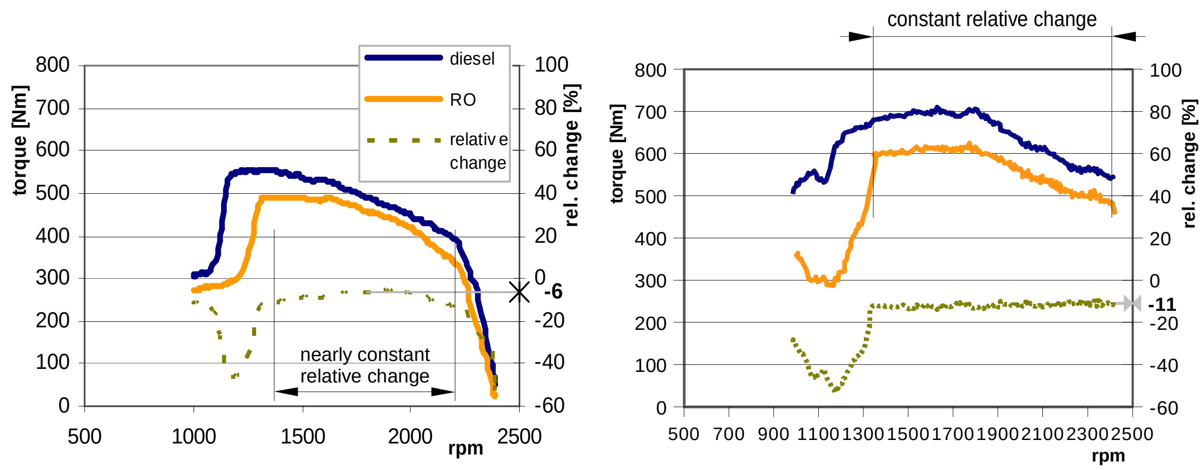

Figure 1: *Comparison of torque curves for both engines (Zetor on left, Cummins on right) during operation on diesel and heated fuel-grade rapeseed oil*

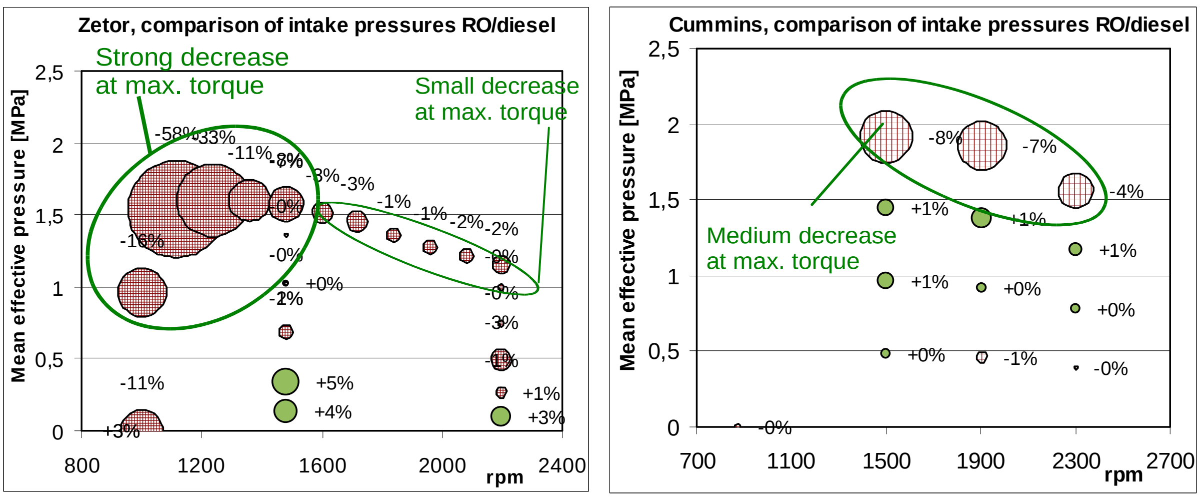

Figure 2: *Intake manifold pressures comparison*

The fuel pressures in the fuel injection line before the 1st cylinder on the Zetor engine and the 2nd cylinder on the Cummins engine are given in Figure 3.

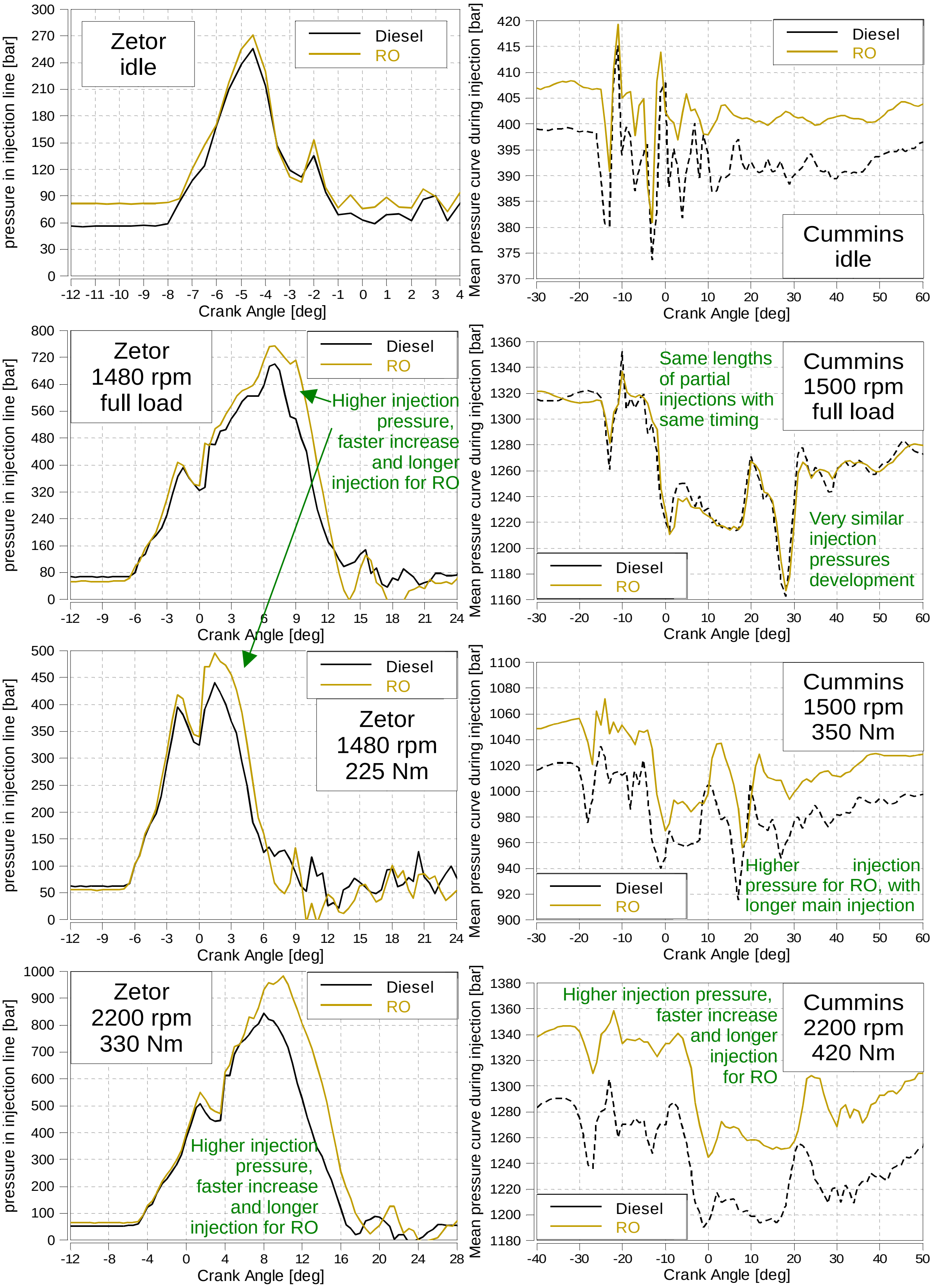

Figure 3: *Comparison of pressure before injector on Zetor and Cummins for selected regimes*

The indicated in-cylinder pressures (4th cylinder Zetor, 2nd cylinder Cummins), encoded with the crankshaft position, are reported in Figure 4. The heat release rates, calculated from the indicated pressures, are given in Figure 5.

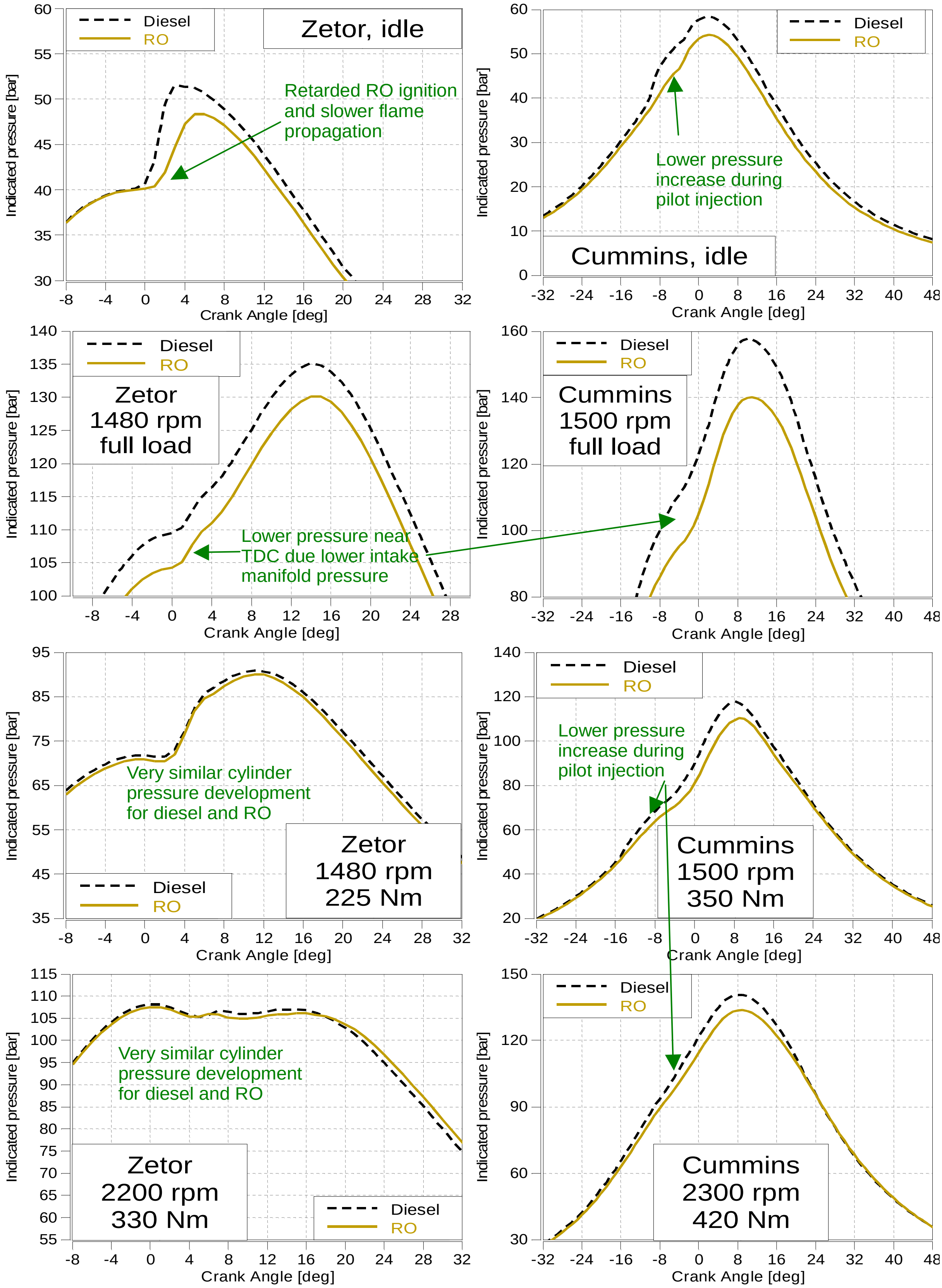

Figure 4: *Comparison of indicated pressures on Zetor and Cummins for selected regimes*

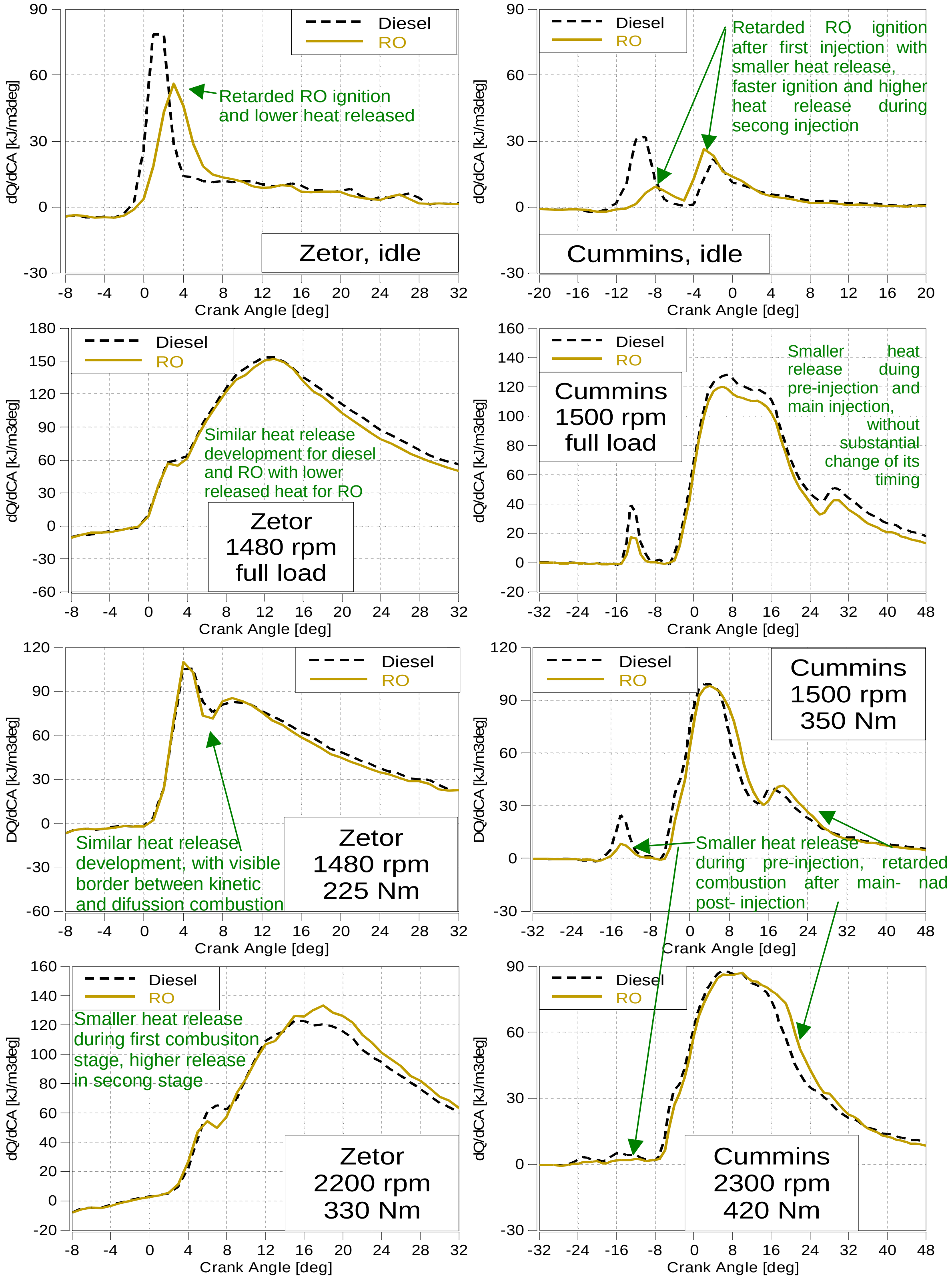

Figure 5: *Comparison of released heat on Zetor and Cummins for selected regimes*

4. DISCUSSION

The lower heating value of rapeseed oil (RO), 36,9 MJ/kg [13], is about 13% lower than the LHV of diesel fuel, 42,5 MJ/kg. The density of RO, approximately 900 kg/m^3 [13], is about 8% higher compared to 835 kg/m^3 for diesel fuel [13]. Based on these data, the volumetric energy density of RO, approximately 33,2 MJ/liter, is 6-7% lower than 35,5 MJ/liter for diesel fuel. Therefore, under a theoretical assumption of constant volume of fuel delivered per cycle and constant engine thermal efficiency on both fuels, the maximum torque during operation on RO should decrease by about 7%. The theoretical value was expected to hold for the Zetor engine, where the volume of the fuel is set by the fuel injection pump, and the higher viscosity of RO [13,14] is compensated for by a higher fuel injection pressure; an additional increase in the fuel injection pressure is due to the higher bulk modulus [14] of RO. On the Cummins engine, however, the fuel delivery is given by the opening time of the injector and the rail pressure, and was expected to be more dependent on the markedly higher viscosity of RO.

On both engines, the **maximum torque** has decreased considerably at low rpm (below about 1300 rpm). This differences is attributed to the decrease in the fuel delivery as a response to lower turbocharger boost pressure, with a "spiraling loop" (less boost -> less fuel -> less boost -> ....) causing a substantial decrease until "excess" boost is available around 1300 rpm.

Above 1300 rpm, the maximum torque has decreased by 6-10% on the Zetor engine, and by a uniform 11% on the Cummins engine. The decrease in torque on the Zetor engine corresponds to, and can be attributed mostly to, the differences in volumetric energy density between the fuels, with higher viscosity and higher bulk modulus resulting in higher fuel injection pressures. The somewhat higher than theoretical (by 4%) drop in maximum torque on the Cummins engine can probably be attributed to the higher viscosity of vegetable oil and thus its different behavior in the fuel injection system. The differences in engine thermal efficiency, inferred both from the indicated pressure and fuel consumption data, were within the uncertainty of the measurement.

On the Zetor engine, the **pressures in the fuel injection line** were for RO, compared to diesel fuel, somewhat higher. The rise in the pressure was faster and was advanced by about half of a crankshaft angle degree, a natural consequence of the higher bulk modulus and higher density of RO, discussed in previous work [11]. On the Cummins engine, the pressures in the fuel injection line appear to be a function of the commanded fuel pressure in the rail, with dynamic changes resulting from the injections. At full load, the dynamic fuel injection pressures were nearly identical for both fuels. At partial loads, the fuel injection pressures were higher for RO, and exhibit signs of longer injection for RO, but these changes can be attributed to the higher volume of RO being injected to reach the desired torque to compensate lower volumetric energy density of RO. Also, on the Cummins engine at partial loads, but not at full load, the fuel pressure "dips" were delayed for RO.

On the Zetor engine, the **indicated pressures** and the **heat release rates** are comparable (with the exception of differences resulting from different turbocharger boost pressures) for diesel fuel and for rapeseed oil for all modes except idle. At idle, the onset of the combustion was delayed by about two degrees of crankshaft rotation and the rate of heat release is slower compared to diesel fuel.

On the Cummins engine, featuring two to three separate injections per cycle, the delay in the onset of the combustion following the first injection was comparable for both fuels except for idle, where it was delayed by about two degrees; after the second injection, the onset of the second wave of heat release was advanced by about one degree at idle and comparable for both fuels at remaining rpm and loads. On the Cummins engine, the heat release following the first (pilot) injection was smaller, while following the second or third injection, the heat release was higher on RO compared to diesel fuel. This was apparent in all modes, notably at idle. It therefore appears that portion of RO injected during the pilot injection has not combusted "immediately", but following the second or third injection, demonstrating a "time redistribution" of the combustion. At the same time, the relatively higher amount "uncombusted" RO from the pilot injection has accelerated the onset of the combustion of the subsequently injected dose.

It should be noted that the changes in the timing of the heat release rates are not necessarily same as the **changes in the ignition delay**. The ignition delay is the lag between the start of the injection and the onset of the combustion demonstrated by the rise in the heat release rate. On the Zetor engine, the injection timing was effectively advanced by the higher bulk modulus of RO, therefore, if the onset of the combustion for RO and diesel fuel is comparable, the ignition delay must have been increased, and if the onset of the combustion is advanced slightly, with this advance corresponding to the advance in the start of the injection, the ignition delay has not changed. Therefore, changes in ignition delay cannot be inferred solely from the indicated pressure data, but their determination requires the evaluation of the injection timing as well. In the case of both tested engines, the ignition delay appeared to be the same for both fuels, except for idle, where the ignition delay was longer for RO by one to two degrees.

5. CONCLUSIONS

The effects of utilizing heated, fuel-grade rapeseed oil as fuel on the performance, injection and combustion 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. The maximum torque above about 1300 rpm has decreased by 6-10% on the Zetor engine and by uniform 11% on the Cummins engine, which generally corresponds to the lower volumetric fuel density of vegetable oil. Higher differences below 1300 rpm which were likely due to the fueling rate correction for intake manifold pressure. Small changes up to one degree of crankshaft rotation were observed in the timing of the fuel injection and combustion, except for idle, where onset of the combustion was delayed by one to two degrees. On the Cummins engine, the heat release rates were smaller following the pilot injection, and larger following the main injection(s). Differences in the fuel injection pressures were attributed primarily to the lower volumetric energy density and, for the Zetor engine, higher bulk modulus of rapeseed oil. No operating problems, anomalies, or issues were identified during tens of hours of operation of each engine on heated rapeseed oil.

REFERENCES

[1] Szybist JP, Song J, Alam M, Boehman AL: Biodiesel combustion, emissions and emission control. Fuel Processing Technology, 88, 7, 2007, 679-691.

[2] Demirbas A: Importance of biodiesel as transportation fuel. Energy Policy, 35, 9, 2007, 4661-4670.

[3] Knothe G: Biodiesel and renewable diesel: A comparison. Progress in Energy and Combustion Science, 36, 3 (2010) 364-373.

[4] Diesel-Engine Management, 4th edition, Robert Bosch GmbH, 2005

[5] Knothe, G.; Van Gerpen, J.; Krahl, J. The History of Vegetable Oil-Based Diesel Fuels. The Biodiesel Handbook. Champaign: AOCS Press. 2005. Chapter 2.

[6] G.M. Gubitz, M. Mittelbach, M. Trabi, Exploitation of the tropical oil seed plant Jatropha curcas L., Bioresource Technology 67 (1999) 73–82.

[7] Labeckas, G.; Slavinskas, S.: Performance of direct-injection off-road diesel engine on rapeseed oil. Renewable Energy, 31, 6 (2006) 849-863.

[8] Bari, S.; Lim, T.H.; Yu, C.W.: Effects of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine. Renewable Energy 27 (2002) 339–351.

[9] Compilation of information at the Biofuels library, online at http://www.journeytoforever.org/biofuel_library.html

[10] Czerwinski, J.; Zimmerli Y.; Kasper, M.; Meyer, M.: A Modern HD-Diesel Engine with Rapeseed Oil, DPF and SCR. SAE Technical Paper 2008-01-1382, Society of Automotive Engineers, Warrensdale, PA, USA, 2008.

[11] Vojtíšek-Lom, M.; Blažek, J.; Dufek, M.; Fenkl, M.: Investigation of Combustion Rates and Injection and Ignition Onset of Heated Rapeseed Oil in Direct-Injection Turbodiesel Engines. SAE Technical Paper 2009-01-1914. Society of Automotive Engineers, Warrensdale, PA, USA, 2009.

[12] Vojtíšek-Lom, M.; Pechout, M.; Mazač, M.: Experimental investigation of rapeseed oil combustion in a modern common-rail diesel engine. Accepted for publication by the Society of Automotive Engineers as a technical paper 2011-24-0104.

[13] Soltic, P.; Edenhauser, D.; Thurnheer, T.; Schreiber, D.; Sankowski, A.: Experimental investigation of mineral diesel fuel, GTL fuel, RME and neat soybean and rapeseed oil combustion in a heavy duty on-road engine with exhaust gas aftertreatment. Fuel, vol. 88, 2009, 1-8.

[14] Coupland, J.N.; McClements, D.J.: Physical Properties of Liquid Edible Oils. Journal of the Americal Oil Chemists Society, 74, 1997, 1559-1564.

ACKNOWLEDGEMENT

The Zetor engine was loaned from the Tractor Research Institute in Brno, Czech Republic. The Cummins ISBe4 engine was obtained from Cummins Ltd., Darlington, England. The background research and most of the measurements were funded by the Czech Science Foundation project no. 101/08/1717, "Optimization of the combustion of vegetable oils in diesel engines". The analysis of the data reported on in here and the preparation of this manuscript were funded by the Technical University of Liberec Student Grant Program (SGS) no. 2826/115 (first author) and by the Czech Ministry of Education project 1M0568, "Josef Božek Research Center of Engine and Automotive Engineering" (second and third author), with smaller part relevant to factors affecting public health carried on within the project MEDETOX, "Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic", funded by the European Commission under the LIFE+ program.