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EXPERIMENTAL INVESTIGATION OF THE COMBUSTION OF VEGETABLE OILS IN DIESEL ENGINE AT LOW ENGINE LOADS

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Abstract

Vegetable oils are being increasingly used as fuel in diesel engines in passenger vehicles, with various results. One of the associated problems is excessive emissions of organic compounds at very low engine loads.

Aside from an undesirable increase in emissions, such compounds also contribute to the formation of deposits in the engine and in the catalytic reactor. In this study, a typical turbodiesel engine, adapted for operation on vegetable oils, was fitted with fast-response in-cylinder pressure measurement system. The engine was operated on an engine dynamometer at low loads typical for urban driving at several coolant and fuel temperatures. Results will be presented and discussed.

Engine and rapeseed oil fuelling system setup, comparison of combustion timing of diesel fuel and rapeseed oil, indicated in-cylinder pressure for diesel fuel and rapeseed oil for different speeds and loads, indicated in-cylinder pressure at original and modified injection timing, comparison of NO_x *and* CO_2 *concentrations at original injection timing, emissions from rapeseed oil relative to diesel fuel at different speeds and loads, effect of injection timing optimization on peak indicated pressure, effect of injection timing optimization on* NO_x *and CO concentrations, Brake-specific fuel consumption, are presented in the paper.*

Keywords: *vegetable oils, diesel fuels, in-cylinder pressure measurement system, combustion engines, emissions*

1. Introduction

Internal combustion engines are the prime mover of the world, being utilized in most motorized transportation vehicles as well as mobile machinery used in construction, agriculture, and other sectors. They are powered primarily by liquid petroleum based fuels. Due to the increasing demand for petroleum, its finite and substantially depleted supply, and political instability in many petroleum producing regions, the real price of petroleum is expected to escalate in the years to come. Aside from the real price, the use of petroleum is associated with various external costs, associated with reliance on imports, effects of imports on trade balance, petroleum-related military costs, air pollution and its effects on human health and on the environment, greenhouse gas emissions and their effects on increases in damages caused by weather and climatic anomalies, and other. Replacement of petroleum by other sources of energy for mobile machinery is therefore one of the top priorities for the next years and decades.

Alongside developments in new propulsion technologies such as fuel cells, advanced batteries and other electric energy storage media, compression ignition engines, powered by liquid fuels, are likely to continue to be utilized, due their superior energy conversion efficiency, power to weight ratio, reliability and economy, and due to the high energy density and practical handling and storage of liquid fuels. Liquid fuels will also be popular as replacement fuels for existing engines, some with lifetime on the order of decades.

The first non-petroleum fuels were plant oils, the use of which dates back to the very origins of the diesel engine, and which were investigated during and after the petroleum crisis in late 1970's.

The utilization of plant oils was, however, found to be problematic, causing the formation of deposits on the injectors and within the combustion chamber, and resulting in increased emissions, poor performance, and eventually premature failure of injectors, injector pump and other components or the entire engine [7, 8].

Plant oils and animal fats are therefore currently utilized mostly in their “modified” version, as alkyl-esters (typically methyl-esters) of fatty acids, often termed “biodiesel”. A variety of other “synthetic” liquid fuels produced from organic material by thermal depolymerisation, gas-to-liquid conversion, Fischer-Tropsch synthesis, and other processes are being investigated, as well as their counterparts made from other fossil fuels such as coals and natural gas.

In the recent years, improvements in technology have brought a renewed interest in the utilization of unmodified vegetable oils (and in fewer cases animal fats). The practices vary, but it appears that the most common approach is to use vegetable oil in a dual-fuel system. The engine is started and warmed up on ordinary fuel, then operated on heated vegetable oil, and run again on ordinary fuel before the shutdown in order to purge the fuel injection system. The heating of the oil is accomplished by engine coolant, by electric heaters, or both.

The primary purpose of the heating of the oil is to reduce its kinematic viscosity, which is, at room temperature, typically more than an order of magnitude higher compared to diesel fuel [5]. The secondary purpose is to retain the oil in liquid form, which is important especially when utilizing high melting point fuels such as used frying oil or animal fats, or when operating at cold ambient temperatures. Another effect of heating of the vegetable oil is a decrease of its ignition delay [12].

The reasons for utilizing conventional fuel for start-up, warm-up and shutdown are several-fold. The most cited one is to allow for the vegetable oil to reach its proper temperature, which is difficult to achieve without the waste heat from the engine or relatively large amounts of electrical power. Another reason is to avoid poor combustion of vegetable oil resulting from its cooling prior to the injector tip, or from its cooling or lower combustion temperatures due to lower temperatures of the combustion chamber surfaces. Another possible reason is to avoid aging of the oil within the fuel injection system [9].

Another technological advance was the continuous improvement of diesel fuel injection systems and engine designs, especially increases in injection pressures and improvements in fuel atomization and mixing, which has resulted in a substantial decrease in the emissions of incomplete combustion products – hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM).

The mentioned changes appear to have reduced or prevented the engine damage within the short term (tens of hours), but the long-term effects remain uncertain.

The deposit formation is believed to stem from incomplete combustion of the fuel. High viscosity is believed to lead to larger droplet diameters [1], which, in combination with higher boiling points of the fuel fractions compared to diesel fuel, will result in an increase in combustion delay [12,13] and slower combustion and lower thermal efficiency [13]. These observations were, however, made on engines with HC concentrations on the order of hundreds of ppm. Commenting on new engines, however, Elsbett [16] claims shorter ignition delay. This is supported by claims of decrease in ignition delay both with increasing fuel temperature [12] and increasing fuel injection pressure [13].

The ignition delay is inversely correlated with cetane number. The cetane number for diesel fuel is 40-50 in North America and 50-55 in Europe [1], the minimum required is 40 in USA (standard ASTM D975) and 51 in the EU (standard EN590). The cetane number of rapeseed oil is 40-50 [2], 40 [1], 37.6 [6]. Cetane number is of rapeseed oil is higher if the oil is heated [12].

Formation of the deposits is also a function of the fuel characteristics, namely the presence of double bonds in the fatty acids of which vegetable oil is composed [9].

Operation of large stationary engines on heated vegetable oil was reported to be without problems in one case [11], but periodic removal of deposits was needed in another case [4].

Operation of hundreds of private automobiles and of several commercial long-haul trucks on vegetable oil resulted in no problems attributed directly to vegetable oil for tens to hundreds of thousands of kilometres [3], but few engines have accumulated the equivalent of their real-world useful life. Manufacturers of diesel fuel injection systems and diesel engines generally do not approve of the use of vegetable oil due to the formation of the deposits, leading to premature failures of the injection pumps, injectors, piston rings, and, in cases, entire engines [17].

Recent studies of exhaust emissions of automobiles operated on vegetable oil show that the emissions of HC, CO and PM are, compared to diesel fuel, either generally higher [10], or at least higher during idle and low-load operation [15]. It should be, however, noted that all of these were relatively small passenger car engines which were generally tuned to achieve low NOx emissions, at the expense of higher HC, CO and PM emissions and fuel economy. Higher HC emissions were also reported by recent laboratory measurements [12,13], but the engines used in both studies exhibited, when operated on diesel fuel, HC emissions in hundreds of ppmC levels, which would be unacceptable for modern engines.

Further improvements are claimed to be possible by advancing fuel injection timing [12, 13], by increasing fuel injector opening pressure [5, 13], or by an alteration of both [5]. As the engines must maintain their emissions characteristics while operating on diesel fuel, such modifications might not be feasible, and might even not be necessary with modern engines [3].

This paper describes an experimental laboratory investigation of the combustion of heated rapeseed oil in a four-cylinder mechanically controlled direct-injection turbocharged diesel engine, typical of medium duty delivery trucks operated in urban areas. The engine was installed on an engine dynamometer and operated on both ultra-low sulphur EU specification diesel fuel and on virgin rapeseed oil. The focus of the work was on indication of the combustion chamber pressures at various engine speed / torque combinations, both with original and advanced injection timings. Other measurements included emissions, fuel consumption, turbocharger boost pressure, and exhaust temperature.

2. Experimental

In this study, a AVIA D 422.100 direct-injection turbocharged compression ignition engine with a mechanically controlled Bosch VE series rotary injection pump was installed on a Schenck Dynabar water brake engine dynamometer. The engine has a displacement of 3.92 litters, a 17.5:1 compression ratio, rated power of 98 kW (131 hp) at 2400 rpm and maximum torque of 565 Nm (413 ft-lb.) at 1200 rpm. This engine is typical for medium duty (gross weight on the order of several tons) delivery trucks.

To allow for investigation of combustion processes, two ports were drilled into the cylinder head to allow for insertion of pressure sensor and camera into the #4 cylinder (closest to the flywheel). To allow for variations of the injection timing, the fuel injection pump was fitted with a manual on-the-fly adjustment of the injection timing advance. No other changes were made to the injection pump or to the high pressure part of the fuelling system including the injectors.

The engine was operated on ultra-low sulphur diesel fuel (EN 590) and on cold-pressed virgin rapeseed oil. The oil was designed for the rapeseed methyl ester manufacture, and was obtained from a local producer (KL Oil, Litany, Jilin district, Czech Republic). Methyl ester produced from this oil has met the EU biodiesel standards. As various oil contaminants have primarily long-term effects, no chemical analysis was done on the rapeseed oil. Ordinary Aral DTT 15W-40 mineral oil was used as engine lubricant. Fresh oil, oil filter and fuel filters were used for the test.

To allow for operation on heated vegetable oil, a secondary fuelling system was installed, with mechanical quarter-turn three-way valves on fuel supply and return lines, and dedicated fuel filters with a hand-operated pump for each fuel. Additional valves were installed to allow for manual purge of the vegetable oil supply branch, and for diversion of return fuel into a separate container for a short period after fuel switching in order to avoid mixing of the fuels in the tanks. Vegetable oil was contained in a 27-liter thermostatically controlled heated tank. The filter and the fuel supply lines up to the fuel injection pump inlet (including the three-way valve) were insulated. A photograph of the fuelling system is shown in figure 1.

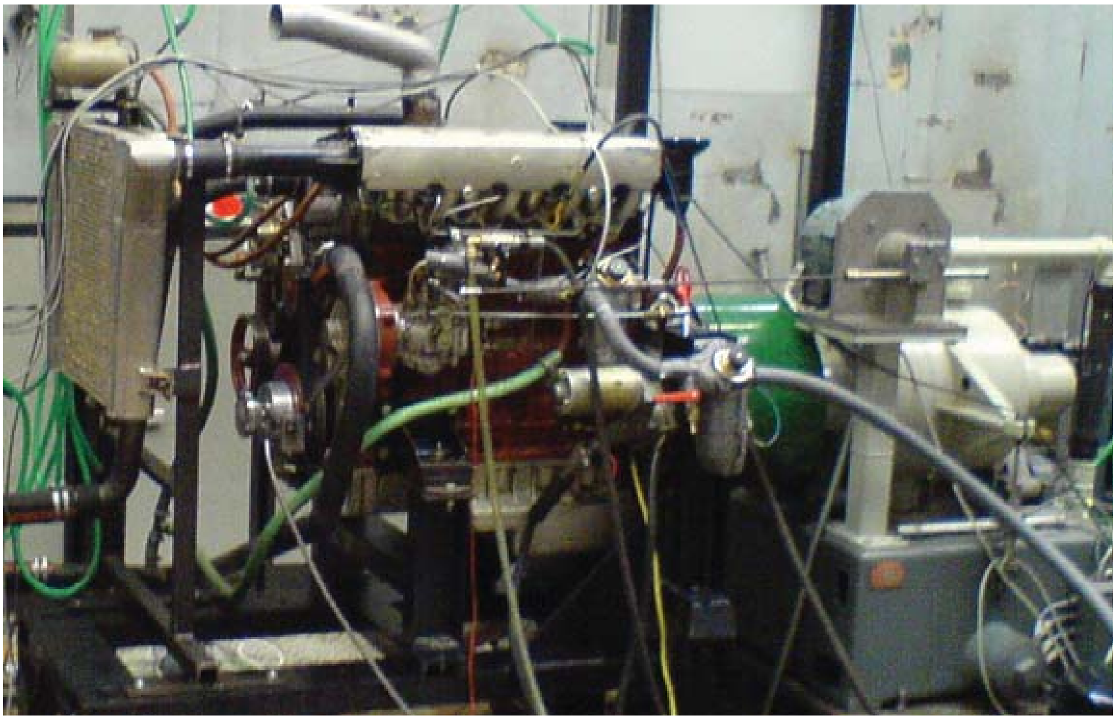

Fig. 1. Engine and rapeseed oil fuelling system setup

Fuel temperature was measured with a thermistor approx. 20 cm upstream of the fuel injection pump inlet, and was several degrees C lower than the thermostat set point on the tank. The rapeseed oil temperature was in the range of 70-75 C (160-165 F), except for short excursions to approx. 65 C during replenishment of fuel in the tank. This range was selected to mimic efficient heating of the fuel with engine coolant, which was, at the engine head and at the radiator inlet, in the 80-85 C (175-185 F) range during hot-stabilized operation.

The engine was warmed up and shut down on diesel fuel. As extended idling is known to lead to formation of deposits within the engine and within the exhaust system and to have effects on emissions during subsequent operation [14], notably on vegetable oil, the engine was not idled except for a short period after start and during investigations at the idle conditions. During final stage of warm-up, fuel switching, and delays throughout the tests, the engine was kept at a moderate load of 200 Nm at 1200 rpm.

Pressures within the combustion chamber were measured in real-time by an Indimeter 619 (AVL, Austria) using an uncooled transducer GU21D (AVL, Austria). At each mode, pressures from 150 subsequent cycles were measured.

Concentrations of CO, CO_2 and NO_x were measured by standard laboratory techniques (CO – NDIR analyzer, VIA 510, Horiba; NO_x – chemiluminiscent analyzer NGA 2000, Rosemount Analytical, USA; CO2 - NDIR analyzer URAS 3E, Hartmann & Brown, Germany).

The engine was operated at steady-state conditions at various combinations of engine speed and load, first on diesel fuel, then on rapeseed oil.

The indicated pressure diagrams were continuously examined, and regimes where injection timing was deemed less than optimal were noted. These modes were then repeated on rapeseed oil, with injection timing manually adjusted to achieve optimum efficiency on rapeseed oil at each mode. The same modes were then repeated on diesel fuel, with timing identical to the timing used with rapeseed oil for that mode.

3. Results

The engine operated comparably on both fuels, without perceptible changes in noise, smoothness of operation, and “hardness” of the characteristic diesel combustion “knock”.

The engine rpm, torque, power, brake-specific fuel consumption, emissions concentrations, indicated mean effective pressure and its variance, maximum indicated pressure and its variance, and crankshaft angle at which 5, 10, 50 and 90 percent of heat energy of the fuel were released, are shown in Table 1, first for original and then for modified optimized injection timing.

Tab. 1. Summary of test results

	Engine	Torque	Power	BMEP	BSFC	EGT	NOX	CO	CO2	IMEP	VAR IMEP	PMAX	VAR Pmax	AQ0	AI5%	AI10%	AI50%	AI90%
	rpm	(Nm)	(kW)	(kPa)	(g/kWh)	°C	ppm	ppm	%	bar	%	bar	%	° ATDC	° ATDC	° ATDC	° ATDC	° ATDC
Diesel fuel - original timing	828	0	0	0	N/A	298	359	93	2.03	2.19	3.90	51.43	1.52	-4.17	1.47	1.73	6.98	23.62
	1000	50	5	160	309	243	430	98	3.24	3.90	4.19	60.83	2.23	-5.93	2.40	2.76	7.22	26.05
	1000	100	10	320	**	254	506	88	4.79	5.76	2.41	66.22	1.19	-5.90	2.47	2.94	9.04	30.07
	1200	50	6	160	386	173	263	108	2.95	3.98	1.87	62.15	3.06	-6.01	3.92	4.29	8.54	27.86
	1200	100	13	320	279	223	352	92	4.42	5.75	0.96	68.29	2.06	-5.95	3.67	4.09	9.64	31.40
	1200	200	25	641	242	348	457	288	7.30	9.34	1.02	79.13	1.31	-6.85	3.35	4.15	12.35	39.80
	1200	300	38	961	232	496	632	991	9.78	13.46	**	117.11	**	**	**	**	**	**
	1200	400	50	1282	245	628	660	2595	12.14	16.79	1.17	107.67	3.88	**	**	**	**	**
	1600	100	17	320	286	248	335	83	4.20	5.96	1.46	68.34	1.85	-6.43	6.21	6.69	13.01	30.96
	1600	200	34	641	239	346	490	80	6.36	9.63	1.10	80.11	0.91	-6.79	5.83	6.81	15.14	36.87
	1600	300	50	961	235	450	577	97	8.21	13.34	1.22	92.44	0.74	-6.84	6.31	8.15	17.59	42.23
	1600	400	67	1282	227	533	843	243	9.92	17.11	0.94	121.93	0.68	-6.83	3.53	5.13	16.22	45.04
	1600	470	79	1506	244	665	798	755	12.57	20.39	0.66	129.33	0.68	-6.77	3.66	5.46	18.95	50.10
	2000	100	21	320	312	312	469	45	4.38	6.84	1.50	73.30	0.82	-7.25	6.08	7.29	15.42	32.99
	2000	200	42	641	252	356	358	48	5.95	10.51	1.66	84.53	0.72	-7.88	7.08	9.09	17.87	38.46
	2000	300	63	961	247	466	484	49	7.91	14.46	1.53	103.27	1.64	-8.19	6.52	8.47	18.71	42.79
	2000	400	84	1282	243	614	735	440	10.57	18.27	0.92	135.02	0.57	-8.20	2.01	3.78	16.13	47.14
Rapeseed oil - original timing	828	0	0	0	N/A	320	288	91	2.17	1.99	7.64	48.50	1.77	-4.46	2.16	2.44	7.51	24.41
	1000	50	5	160	364	235	262	174	3.36	3.73	4.74	56.70	1.66	-5.30	3.56	3.96	8.87	27.28
	1000	100	10	320	302	253	302	160	5.04	5.53	1.51	64.09	1.24	-5.68	3.55	4.01	9.95	32.10
	1200	50	6	160	433	224	202	243	3.20	3.81	4.83	57.21	2.83	-5.54	5.06	5.38	10.00	27.46
	1200	100	13	320	315	257	280	158	4.95	5.83	1.53	64.49	2.25	-5.95	4.81	5.24	11.36	32.68
	1200	200	25	641	276	369	355	343	7.75	9.25	1.34	75.52	0.91	-6.18	4.35	5.14	13.50	41.53
	1200	300	38	961	267	487	423	991	10.19	13.03	1.06	87.97	0.61	-6.38	4.43	5.88	15.83	44.95
	1300	520	71	1666	265	669	447	1845	14.02	20.66	0.77	114.33	0.64	-6.52	5.59	7.41	20.10	48.91
	1600	100	17	320	333	325	274	77	4.70	5.55	1.85	64.49	1.38	**	6.39	7.05	14.02	33.02
	1600	200	34	641	275	388	341	82	6.99	9.67	1.53	77.76	0.86	-6.54	6.46	7.86	16.18	39.42
	1600	300	50	961	**	458	397	60	8.70	13.39	1.42	90.56	0.63	-6.65	7.01	8.79	18.62	43.90
	1600	400	67	1282	263	552	567	154	10.63	17.15	1.01	112.08	1.82	-6.53	5.08	6.77	18.23	45.51
	1600	470	79	1506	267	654	556	321	12.95	20.08	0.58	115.85	1.67	-6.59	5.62	7.52	21.12	50.50
	2000	100	21	320	340	257	183	61	4.24	6.87	1.65	75.29	1.62	-7.54	7.88	8.62	16.78	34.98
	2000	200	42	641	287	359	309	49	6.13	10.57	2.31	83.89	0.95	-7.69	7.59	9.58	18.46	38.99
	2000	300	63	961	**	456	498	46	8.12	14.41	1.32	104.67	2.56	-8.05	6.29	8.14	18.44	42.61
	2000	400	84	1282	274	618	675	191	11.08	18.20	1.02	126.29	3.21	-8.23	3.41	5.24	17.99	47.85
Diesel fuel modified timing	828	0	0	0	N/A	**	184.02	106	1.77	2.242	3.7	55.046	1.937	-3.075	0.038	0.257	5.262	22.807
	1000	50	5	160	**	193	322.64	79	3.11	3.917	1.851	65.167	2.22	-4.71	0.675	0.995	4.95	25.685
	1000	100	10	320	**	128	425.81	80	4.99	6	1.117	69.857	0.946	-4.627	0.502	0.985	7.887	30.373
	1200	200	25	641	217	402	568.62	447	7.77	9.581	1.192	90.089	0.687	-4.767	-0.928	0.078	9.383	38.425
	1600	100	17	320	265	266	382.29	56	4.37	6.238	1.765	77.226	1.365	-5.225	1.435	1.97	9.533	29.303
	2000	100	21	320	290	257	297.62	48	4.05	6.835	1.389	81.463	1.313	-6.918	3.382	4.197	12.617	31.11
Rapeseed oil modified timing	828	0	0	0	N/A	123	93	472	1.78	2.095	13.067	51.335	3.075	-2.912	1.43	1.728	6.307	23.347
	1000	50	5	160	**	**	248	273	3.15	3.81	3.825	60.746	1.517	-3.107	1.587	1.957	6.933	26.368
	1000	100	10	320	282	218	353	166	4.84	5.585	1.849	67.532	0.851	-3.458	1.243	1.655	7.923	29.347
	1200	100	13	320	315	263	446	110	4.99	5.828	1.965	70.555	1.674	-3.325	-0.135	0.278	7.915	30.098
	1200	200	25	641	280	388	492	468	8.25	9.792	1.319	87.895	0.739	-4.587	-0.372	0.632	9.963	39.045
	1600	100	17	320	308	272	367	77	4.65	5.865	2.077	73.164	1.166	-4.955	1.923	2.487	10.378	30.893
	2000	100	21	320	**	**	332	49	4.37	6.913	2.597	80.072	0.743	-6.968	3.702	5.052	13.035	31.922

The rates of release of fuel energy were determined by comparing the indicated pressures with the engine running to the pressures observed on a motored engine. The crankshaft positions at which the first release of energy was observed, and the positions at which 5, 10 and 90% of fuel energy was released, are plotted in Figure 2. Each point represents an rpm/torque combination, with position on the X and Y axis describing crankshaft angles in degrees after top dead centre (ATDC), respectively, in order to allow for visual comparison between the fuels. The position at which 5, 10, 50 and 90% of fuel energy is released is for the original timing delayed by 1.0±0.6, 1.0±0.6, 1.2±0.6 and 1.1±0.9, respectively, for rapeseed oil compared to diesel fuel. All of these differences were evaluated using Student’s t-test (two-tailed, paired data) and were found to be statistically significant ($p < 0.001$). For modified timing, significant differences ($p < 0.01$) of 0.6±0.5 and 0.8±0.4 were found for 5 and 10%, respectively.

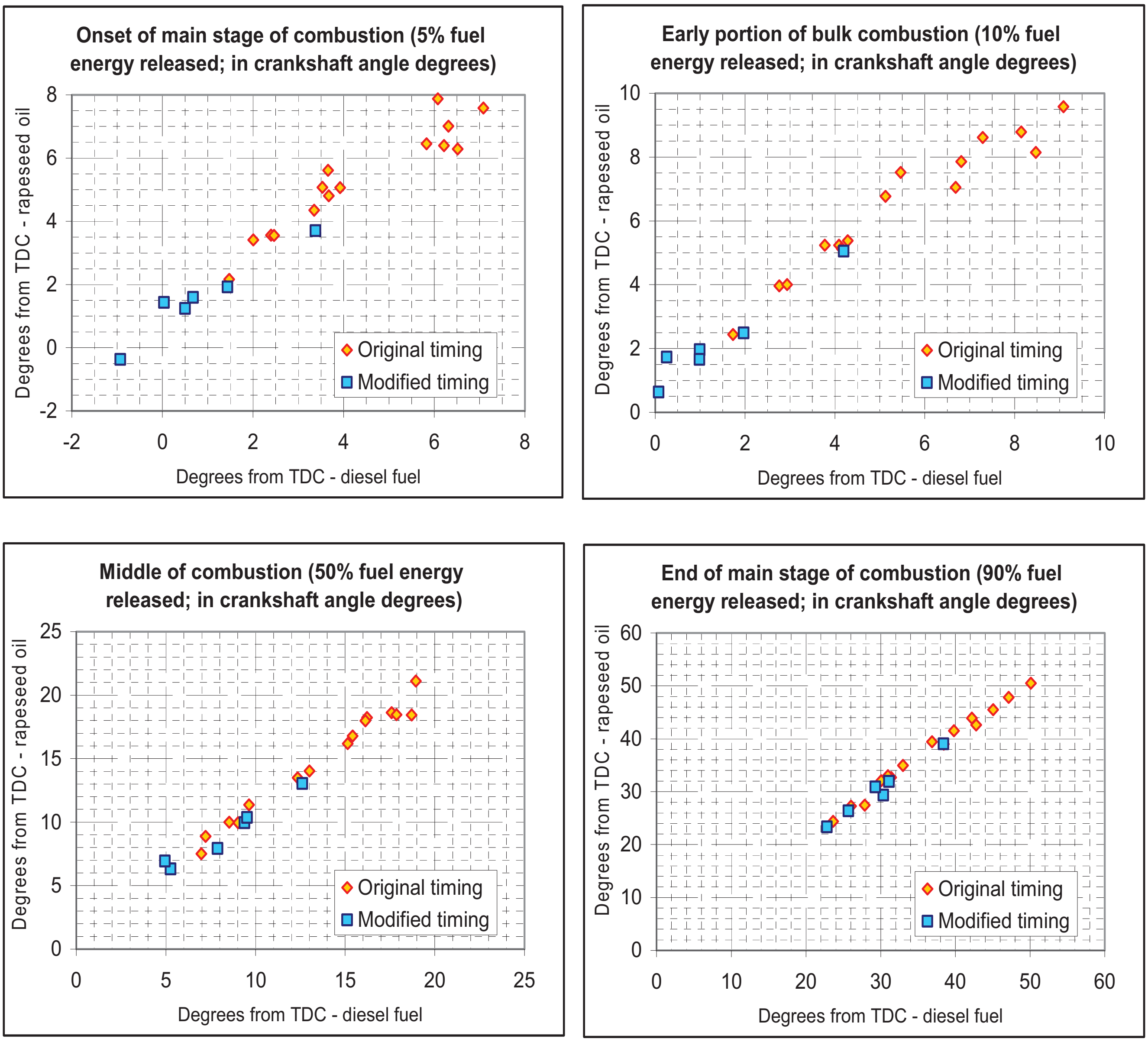

Fig. 2. Comparison of combustion timing of diesel fuel and rapeseed oil

In-cylinder pressures for 1200 rpm, 50 Nm are plotted for ten consecutive cycles in figure 3. Upper portion of the figure shows the entire pressure diagram, lower portion shows a detail of the ignition and combustion stage. Diesel fuel results are plotted on the left, rapeseed oil on the right.

Indicated pressures at other points are shown graphically in figure 4.

To achieve optimal thermal efficiency of the engine, it is typically desirable for the onset of the rise in the in-cylinder pressure to occur immediately after TDC. As this was not the case with low-load operation, injection timing was experimentally adjusted. The adjustment was smaller for lower rpm (idle and 1000) and higher for higher rpm, resulting in changes in the onset of combustion of approx. 1 degree at idle to approx. 5 degrees at 1600 rpm and 100 Nm. The effect of the modified timing on indicated in-cylinder pressures is shown in Figure 5; numerical values are shown in the lower part of Table 1, along with emissions concentrations and other parameters.

Another statistically significant changes ($p < 0.001$) were in concentrations of NO_x (which were generally lower for rapeseed oil than for diesel fuel) and CO_2 (which were consistently higher) for original timing (changes were not significant for adjusted timing), shown in figure 6. Changes in CO varied depending on engine speed and load. Relative differences in CO and NO_x emissions are shown in figure 7.

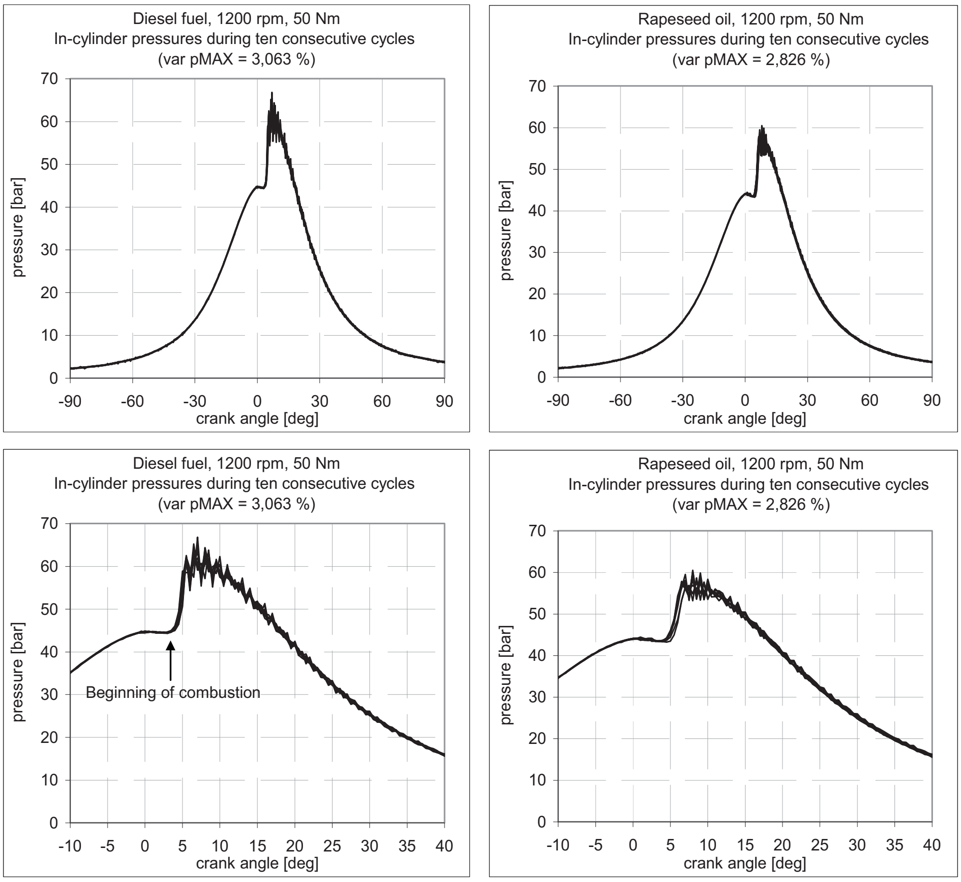

Fig. 3. Indicated in-cylinder pressure for diesel fuel (left) and rapeseed oil (right) for 1200 rpm, 50 Nm

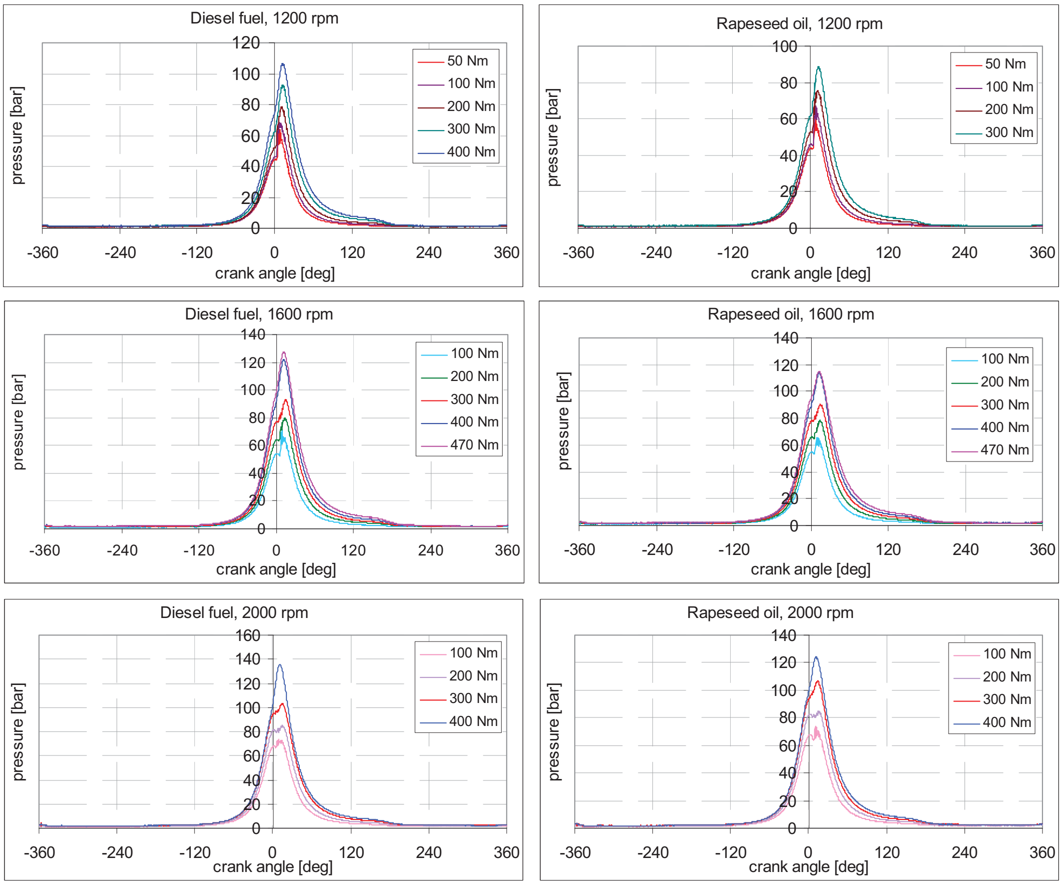

Fig. 4. Indicated pressure traces for different speeds and loads

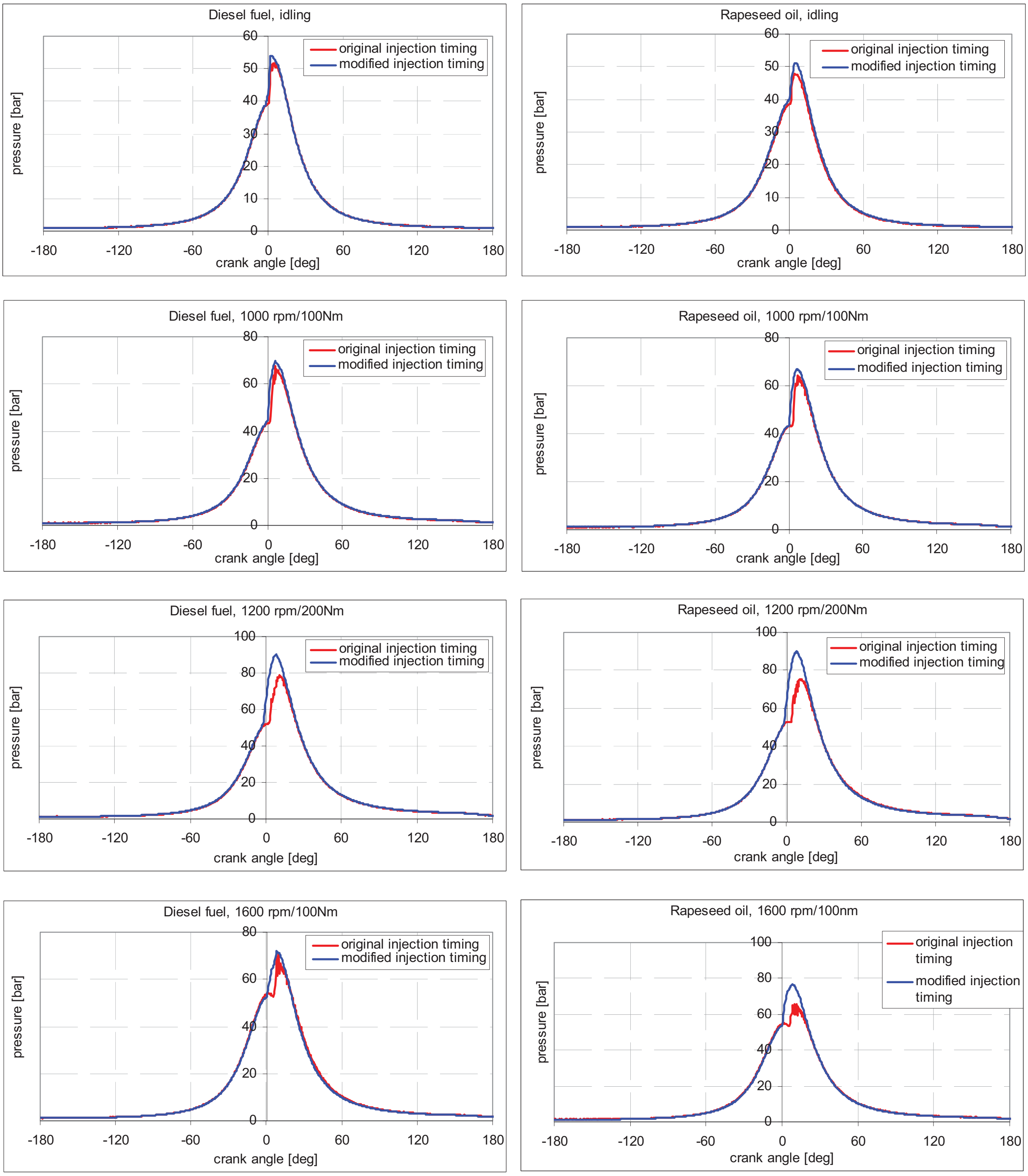

Fig. 5. Indicated in-cylinder pressure at original and modified injection timing

The effects of the change of injection timing on peak combustion pressures and on emissions at individual modes are shown in Figures 8 and 9, respectively.

The fuel economy for the original timing, as determined from the decay in the total mass of the fuel tank, is shown in figure 10, and shows a statistically significant ($p < 0.001$) increase in mass fuel consumption rates for rapeseed oil compared to diesel fuel. The overall increase, determined by a linear regression, is 13%. The fuel consumption determined by this method was found to be inconsistent, due to air in fuel return lines, and was not reported for all modes. Insufficient amount of reliable data was available for fuel consumption at modified timing.

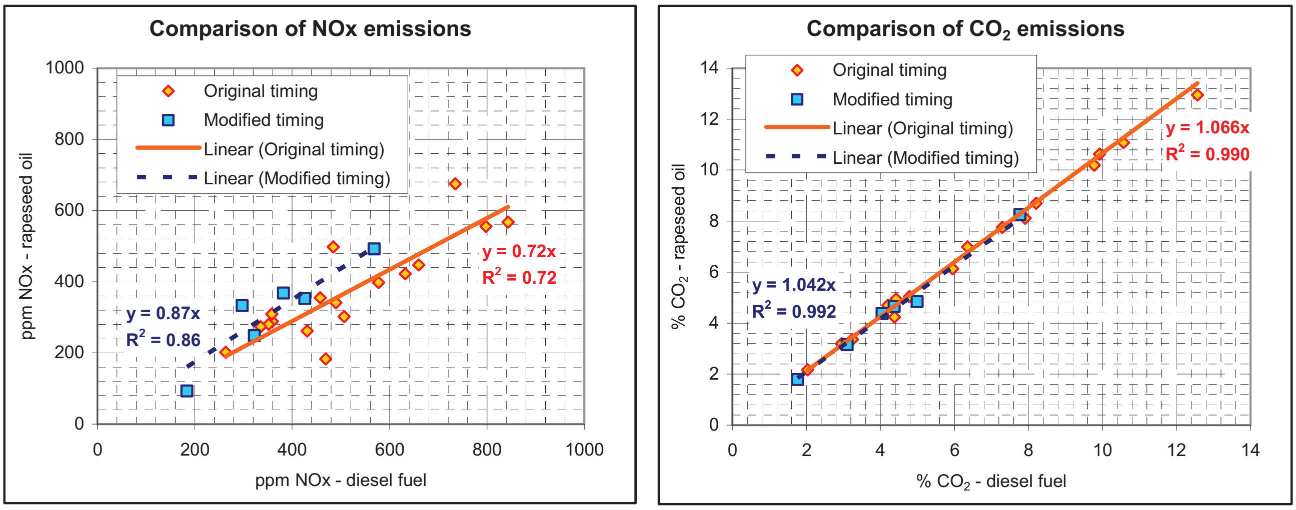

Fig. 6. Comparison of NO_x *and* CO_2 *concentrations at original injection timing*

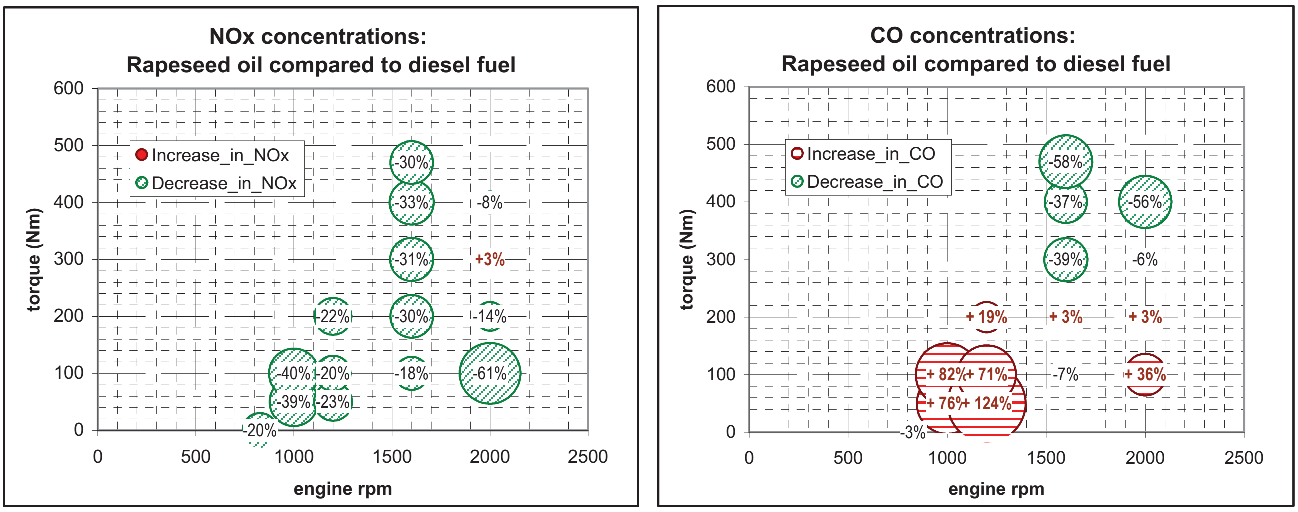

Fig. 7. Emissions from rapeseed oil relative to diesel fuel at different speeds and loads

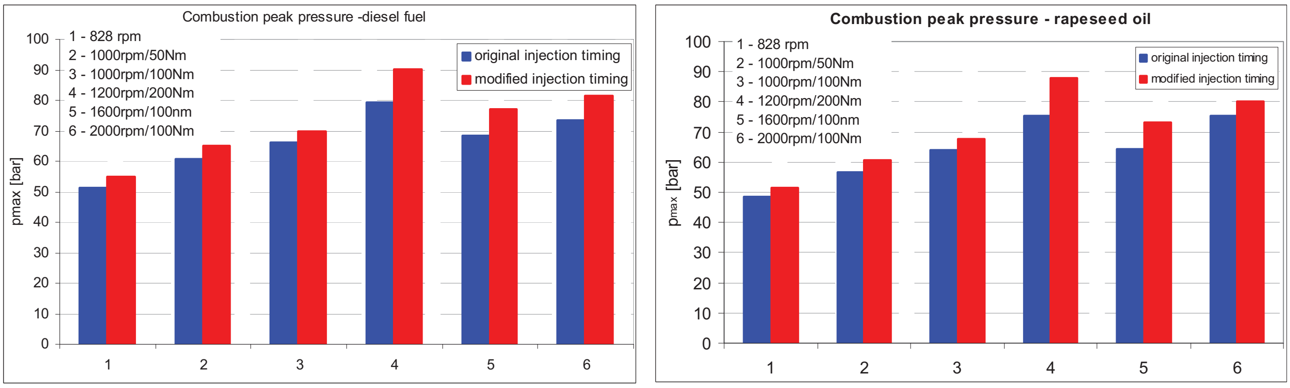

Fig. 8. Effect of injection timing optimization on peak indicated pressure (original injection timing – blue column, modified injection timing – red column)

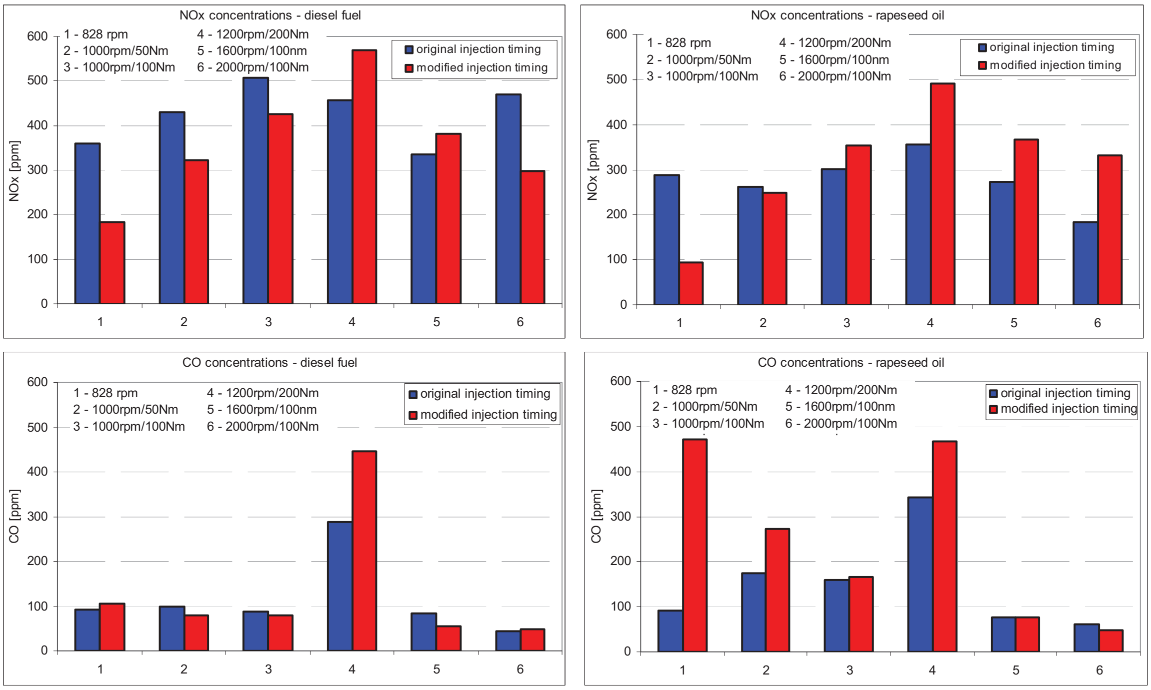

Fig. 9. Effect of injection timing optimization on NO_x and CO concentrations (original injection timing – blue column, modified injection timing – red column)

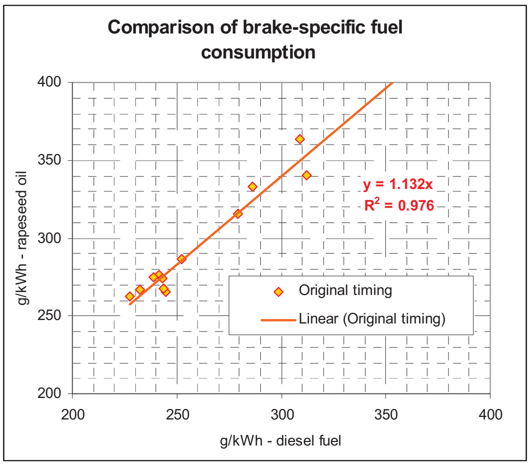

Fig. 10. Brake-specific fuel consumption

4. Discussion

Rapeseed oil has, compared to diesel fuel, lower heat content per kg, but a higher density, resulting in comparable energy content per unit of volume. As fuel is metered on a volume basis, this result, at a constant fuel delivery rate, in higher mass of rapeseed oil but equivalent heat content, being injected into the cylinder. In the case of a comparable thermal efficiency between the fuels at full torque, brake-specific fuel consumption expressed in fuel mass (kg of fuel) is therefore higher for vegetable oil, while brake-specific fuel consumptions on a volume basis, and also torque and power, are comparable. Lower torque and higher fuel consumption on a volume basis would therefore be an indicator of a reduced overall thermal efficiency.

As the intake manifold absolute pressures (MAP) were comparable for both fuels (not significantly different, with a median difference of 2 kPa), and so were engine rpm and intake air temperature, it can be assumed that the intake air flows, and hence mass exhaust flows were comparable (with the accuracy of several percent) for both fuels. Therefore, relative differences in mass exhaust emissions between the fuels at any given operating point are reasonably proportional to the relative differences in concentrations.

For rapeseed oil, CO_2 concentrations were remarkably consistently higher by 6.6% (Figure 6); at carbon contents of 77.9% for rapeseed oil and 86.6% for diesel fuel, this translates to a 18-19% increase in the mass of fuel consumed, but, at fuel densities of 0.88 (heated) to 0.92 (unheated) g/cm^3 for rapeseed oil[12] and 0.84 g/cm^3 for diesel fuel, only to a 8-13% increase in the volume of fuel consumed, depending on fuel temperature, compared to diesel fuel.

The 18-19% increase in mass fuel consumption rates is higher than the observed increase of 13%; this difference is attributed to inaccuracies in mass fuel consumption rates measurements, to the general inaccuracy of measurement, and to non-linearities within the relationships.

Measurement of maximum torques would be beneficial here, but were not reported, as the maximum torque appeared to vary with past operating history of the engine and was therefore found unreliable. Observations show comparable torques on both fuels, with torques on rapeseed oil slightly exceeding diesel torques. Also, engine was operating at 1300 rpm and 520 Nm on rapeseed oil, which is close to its full rated torque of 565 Nm (at 1200 rpm), especially considering higher than normalized intake air temperatures of 30-35 C Additional investigation into the operation at torque curve would be beneficial and is underway.

Analysis of indicated in-cylinder pressures has shown a slightly higher ignition delay for rapeseed oil, on the order of one degree of the crankshaft rotation. This difference might be attributed to the lower cetane number of rapeseed oil. The cetane number of rapeseed oil is cited as 37.6; more recent publications give a range of 40-50 but do not show at what temperatures; heated rapeseed oil had a higher cetane number. For comparison, European diesel fuel according to EN 590 has a minimum cetane number of 51. Diesel fuel in North America, on the other hand, has a minimum cetane number of 40; this would explain why a change in the injection timing might be recommended by European sources [5], but deemed unnecessary in North America [4].

CO concentrations for rapeseed oil, as compared to diesel fuel, were higher at low speeds and loads, and lower at high speeds and loads. The difference at low loads could be potentially attributed to the lower combustion efficiency of rapeseed oil at low loads (and hence lean fuel-air ratios and low combustion temperatures), and was observed, on modern vehicle engines, in other studies [10, 14, 15]. The difference at high loads could be attributed to "overfilling" of the engine on diesel fuel, but lesser degree of overfilling on rapeseed which is by nature an oxygenated fuel.

Advancing the fuel injection timing at idle (830 rpm, 0 Nm) and low rpm, low load conditions (1000 rpm, 50 and 100 Nm) has resulted, as judged by the measured CO_2 concentrations, in reduction of fuel consumption for both fuels, with resulting CO_2 concentrations being comparable for both fuels. At all points, both the mean and maximum indicated pressures were higher. Patterns in emissions data are not well understood, which might be elucidated by collection of additional data. It appears that benefits could be obtained from changes in injection timing, but it is not readily clear that these changes should be different for each fuel. Additional investigation is underway.

5. Conclusions

The study reports on laboratory testing of a 92 kW four-cylinder direct-injection mechanically controlled turbocharged diesel engine. The engine was operated on diesel fuel and on rapeseed oil heated to 70-75 C. Analysis of indicated in-cylinder pressure has shown a consistently higher beginning of combustion, by approx. 1 degree of crankshaft rotation, for rapeseed oil compared to diesel fuel. Operation on rapeseed oil resulted in a consistent but varying reduction in NOx emissions and to a very consistent increase in fuel consumption. CO emissions were higher at low load and low rpm, and lower at high loads, compared to diesel fuel.

For some modes, the fuel economy disadvantage of rapeseed oil was reduced, and fuel economy improved on both fuels, by adjusting the injection timing. This area deserves additional attention, especially in terms of the effects on exhaust emissions.

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