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On the fate of uncombusted non-esterified vegetable oil in a diesel engine

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Background

Non-esterified vegetable oils are emerging as a popular fuel for diesel engines worldwide. They can be readily produced from a variety of local feedstocks with low energy input (20-30% of energy in fuel). Relatively high viscosity of vegetable oils, along with relatively high boiling points, often lead to deteriorated combustion and increased emissions of particulate matter at idle and low rpm and loads. Another concern is engine lubricating oil degradation due to dilution with vegetable oil which does not evaporate and under high temperature, mixing with air and presence of metal wear particles undergoes oligomerization. Another concern is formation of oily / carbonaceous deposits within the engine. The experience with the use of vegetable oil varies, the data and reports from the users are not consistent. Best cases are co-generation units, more problematic are road vehicles.

Goal

To establish a link between poor combustion, high emissions, formation of deposits in the engine, and degradation of engine lubricating oil in a production diesel engine operated on non-esterified fuel-grade rapeseed oil.

Experimental

A Zetor 1505 turbodiesel tractor engine (525 Nm @ 1480 rpm, 90 kW @ 2200 rpm) was tested in the departmental laboratory on a Schenck Dynabar D-630 water brake dynamometer. The engine was powered alternately by diesel fuel and by heated fuel-grade rapeseed oil (FabioProduct, Holín, Czech Republic). Indicated in-cylinder pressures, emissions of HC, CO, NO_x, CO_2, PM by gravimetric method, and PM size distributions were measured.

Periodically, samples of engine lubricating oil (mineral oil Paramo M7ADS III) were extracted from the pressurized oil gallery through a port installed at the oil pressure sensor. The engine was shut down, and rotated by the starter. Approx. 50 ml was taken (and returned to the oil pan) to flush the line, after which a sample was collected. Concentrations of rapeseed oil in engine lubricating oil were measured by an FTIR spectrometer, calibrated with known mixtures prepared from fresh lubricating oil and fuel. Oil analysis was performed by Jaroslav Černý from the Department of Petroleum Technology and Alternative Fuels at the Institute of Chemical Technology at Prague. Also, glow plugs were periodically removed and inspected for deposits.

It has been observed that the „combustion quality“ worsened with (1) cold engine, (2) cold fuel, (3) low rpm and load. Therefore, two extreme conditions were selected: „COLD IDLE“ (cold start and idle with cold fuel) and „WARM LOAD“ (50-100% load per ISO-8178 C-1 test with fuel at 60-90 ºC at injection pump inlet).

Results

	COLD IDLE	WARM LOAD
Onset of Combustion	Delayed vs. diesel	Comparable to diesel
Fuel Consumption	2,7 kg/h → 1,8 kg/h (diesel: 0,65 kg/h, idle on RO immediately after load: 0,8 kg/h)	Corresponds to lower heat content and higher density of RO; similar thermal efficiency
Exhaust emissions	HC+PM 20-30 g/h (> 1% of fuel) Up to order of magnitude higher PM, HC, CO vs. diesel fuel <u>Additional 400-600 g/h leaked out of the exhaust as liquid (GC analysis: mostly uncombusted fuel)</u>	HC+PM 14 g/h (<0,1% of fuel) vs. diesel: PM -67%, HC -47%, CO -48%, NOx +10%
Rapeseed oil penetration into lubricating oil	563 g/h (approx. 30% of fuel consumed from the tank)	9-10 g/h (0,10-0,15 g/kWh, approx 0,05% of fuel used)
Deposits	Oily and carbonaceous deposits on all surfaces, rapeseed oil leaking out of the exhaust system	Minimal, except in dead space between injector tips and engine head, and on cylinder wall above top ring
After transition from load to idle or from idle to load	Idle after loaded operation: Combustion delay increases, emissions gradually deteriorate, deposits form	Combustion and emissions improve, deposits in the exhaust system are emitted, fuel deposited in lubricating oil remains.

Discussion

The combustion of non-esterified rapeseed oil in a diesel tractor engine was heavily dependent on engine speed and load and fuel and engine temperature. Combustion deteriorated at prolonged idle and at lower rapeseed oil temperatures – onset of combustion was delayed, emissions of PM, HC and CO increased. In the extreme case of cold start and idling on non-preheated rapeseed oil, ~30% of fuel penetrated into engine lubricating oil, ~30% of fuel condensed in the exhaust (discussion: should that be considered “engine-out PM”?), oily deposits formed in the engine and exhaust. The fuel condensed in the exhaust was allowed to leak out (connections not tight), otherwise it would be emitted as HC+PM (mostly organic compounds, white smoke with characteristics „food frying“ odor) after transition to higher loads. At medium to high loads, combustion was comparable to diesel fuel, PM, HC and CO emissions were lower, < 0.1% of fuel emitted as HC+PM, ~0.05% of fuel penetrated into engine lubricating oil. Deposits were burned off and only remained on „cold“ surfaces (cylinder wall above the top ring, dead space around injector nozzle walls).

Conclusions

The results demonstrate that low rpm and loads and low rapeseed oil temperatures which lead to poor combustion and high emissions also lead to high rate of dilution of engine lubricating oil with fuel and formation of deposits. On the other hand, operation at medium and higher loads does not appear to be problematic in terms of combustion, fuel efficiency, emissions, lubricating oil dilution, or deposits. Avoiding operation on vegetable oil in problematic conditions (or resolving the problem by altered engine design) is therefore believed to resolve bulk of the issues associated with the use of non-esterified vegetable oils in diesel engines.

Acknowledgments

The tests were funded by the Czech science foundation project 101/08/1717, Optimization of combustion of vegetable oils in diesel engines. The engine was loaned by the Tractor Research Institute (Zetor Brno, Czech Republic). The oil analysis was performed by Jaroslav Černý from the Department of Petroleum Technology and Alternative Fuels of the Institute of Chemical Technology, Prague, CZ.

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Background

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- Relatively high viscosity of vegetable oils, along with relatively high boiling points, often lead to deteriorated combustion and increased emissions of particulate matter at idle and low rpm and loads.
- Another concern is engine lubricating oil degradation due to dilution with vegetable oil which does not evaporate and under high temperature, mixing with air and presence of metal wear particles undergoes oligomerization.
- Another concern is formation of oily / carbonaceous deposits within the engine.
- The experience with the use of vegetable oil varies, the data and reports from the users are not consistent. Best cases are co-generation units, more problematic are road vehicles.

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To establish a link between poor combustion, high emissions, formation of deposits in the engine, and degradation of engine lubricating oil in a production diesel engine operated on non-esterified fuel-grade rapeseed oil.

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- A Zetor 1505 turbodiesel tractor engine (525 Nm @ 1480 rpm, 90 kW @ 2200 rpm) was tested in the departmental laboratory on a Schenck Dynabar D-630 water brake dynamometer.
- The engine was powered alternately by diesel fuel and by heated fuel-grade rapeseed oil (FabioProduct, Holín, Czech Republic).
- Indicated in-cylinder pressures, emissions of HC, CO, NO_x, CO_2, PM by gravimetric method, and PM size distributions were measured.
- Concentration of rapeseed oil in engine lubricating oil was measured by an FTIR spectrometer, calibrated with known mixtures prepared from fresh lubricating oil and fuel. Oil analysis was performed by Jaroslav Černý from the Department of Petroleum Technology and Alternative Fuels at the Institute of Chemical Technology at Prague.
- „Combustion quality" worsened with (1) cold engine, (2) cold fuel, (3) low rpm and load.
- „**COLD IDLE**" (cold start and idle with cold fuel) and „**WARM LOAD**" (50-100% load per ISO-8178 C-1 test with fuel at 60-90 ºC at injection pump inlet) were selected as two extreme conditions.
- Oil samples were taken and glow plugs inspected after 30 minutes of cold idle and after 2 hours at warm load. Engine was then partially dissasembled.

Discussion

- The combustion of non-esterified rapeseed oil in a diesel tractor engine was heavily dependent on engine speed and load and fuel and engine temperature.
- Combustion deteriorated at prolonged idle and at lower rapeseed oil temperatures – onset of combustion was delayed, emissions of PM, HC and CO increased.
- In the extreme case of cold start and idling on non-preheated rapeseed oil, ~30% of fuel penetrated into engine lubricating oil, ~30% of fuel condensed in the exhaust ("engine-out PM"?), oily deposits formed in the engine and exhaust.
- The fuel condensed in the exhaust was allowed to leak out (connections not tight), otherwise it would be emitted as HC+PM (mostly organic compounds, white smoke with characteristics „food frying" odor) after transition to higher loads.
- At medium to high loads, combustion was comparable to diesel fuel, PM, HC and CO emissions were lower, < 0.1% of fuel emitted as HC+PM, ~0.05% of fuel penetrated into engine lubricating oil. Deposits were burned off and only remained on „cold" surfaces (cylinder wall above the top ring, dead space around injector nozzle walls).

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- **The results demonstrate that low rpm and loads and low rapeseed oil temperatures which lead to poor combustion and high emissions also lead to high rate of dilution of engine lubricating oil with fuel and formation of deposits.**
- **On the other hand, operation at medium and higher loads does not appear to be problematic in terms of combustion, fuel efficiency, emissions, lubricating oil dilution, or deposits.**
- **Avoiding operation on vegetable oil in problematic conditions (or resolving the problem by altered engine design) is therefore believed to resolve bulk of the issues associated with the use of non-esterified vegetable oils in diesel engines.**

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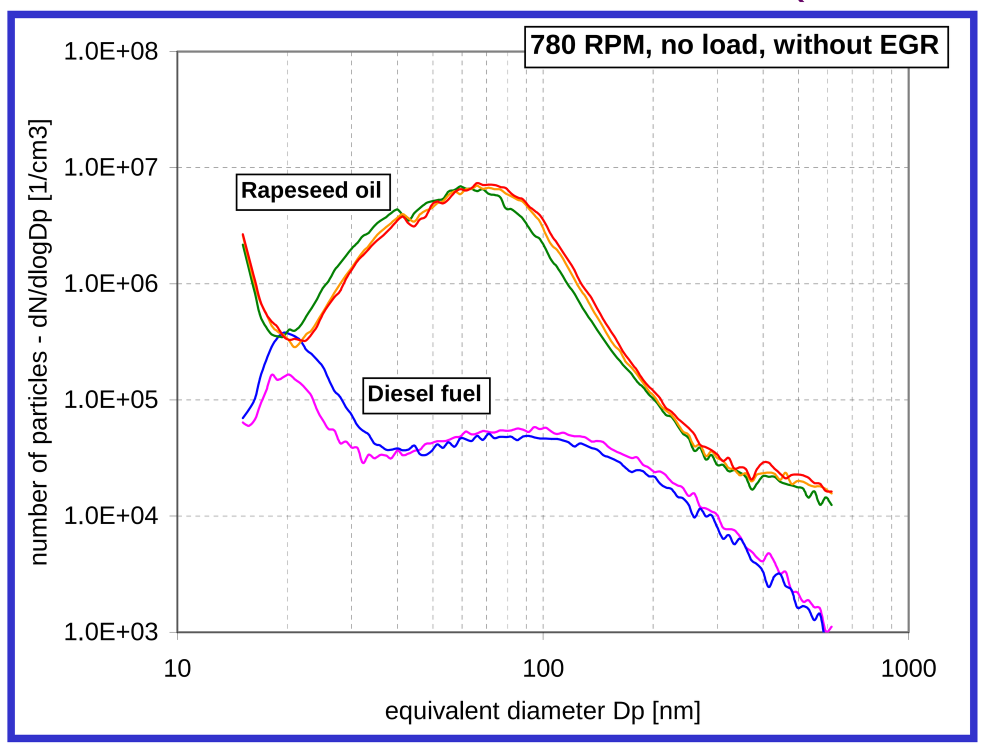
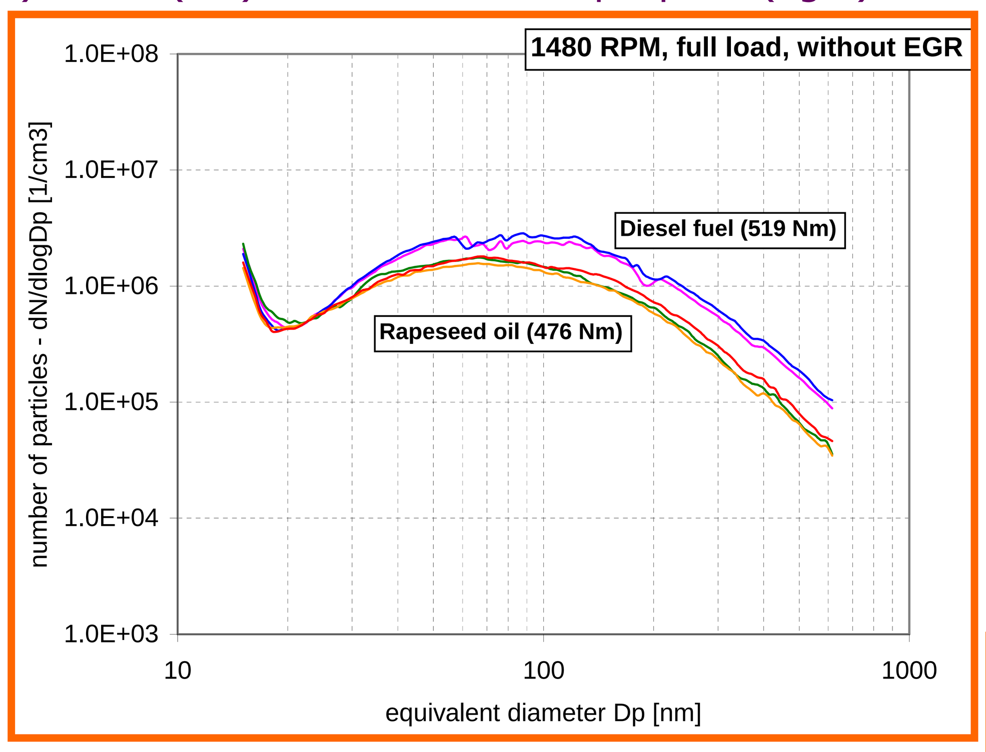
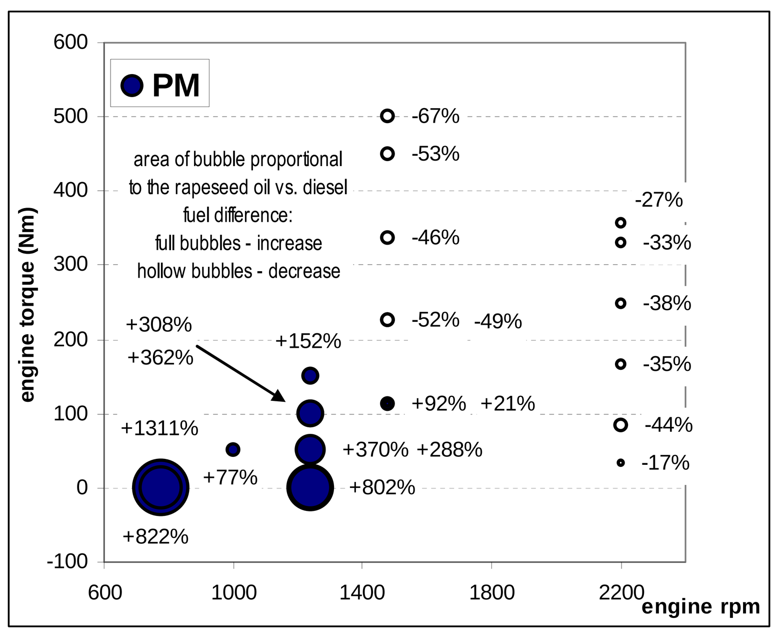
Results

PM size distribution (SMPS+CPC) at idle (left) and maximum torque point (right)

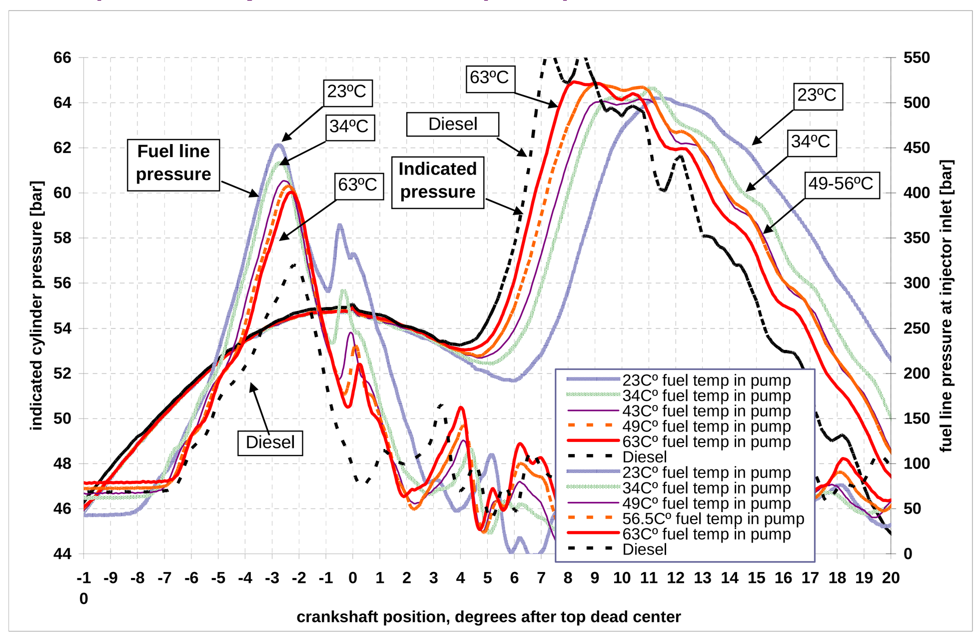


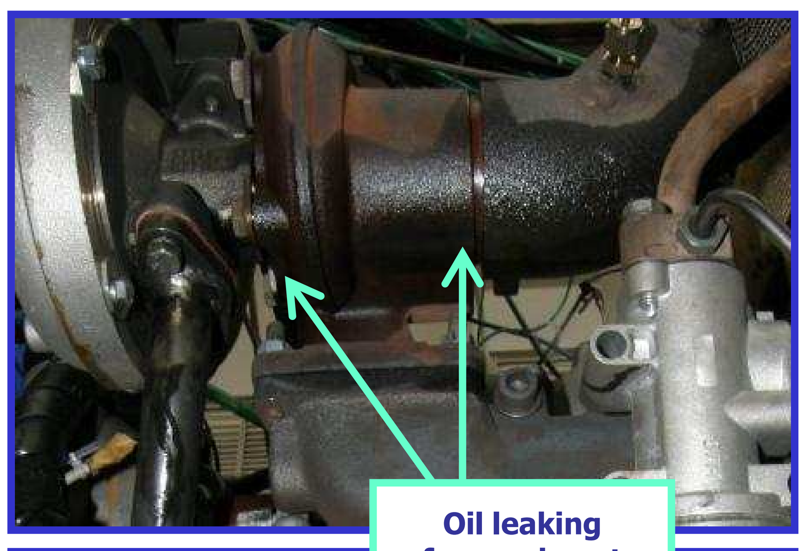


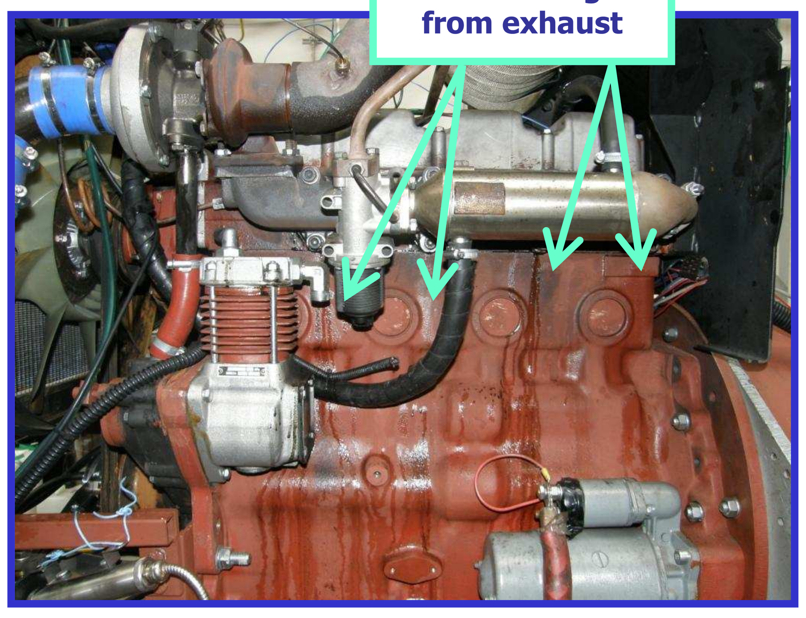
PM mass: Rapeseed oil vs. diesel fuel at selected rpm and loads (gravimetry)

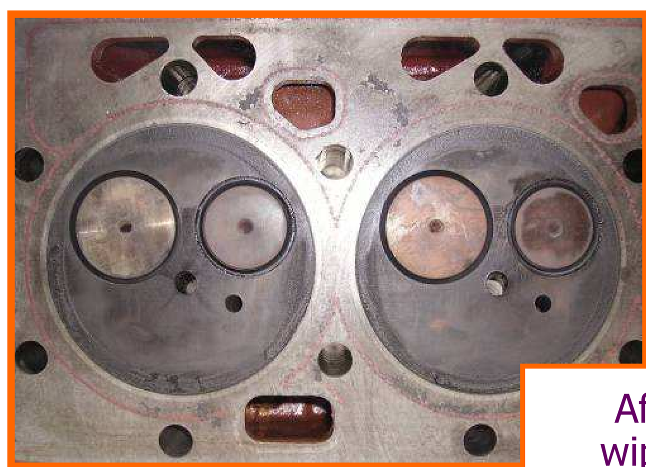


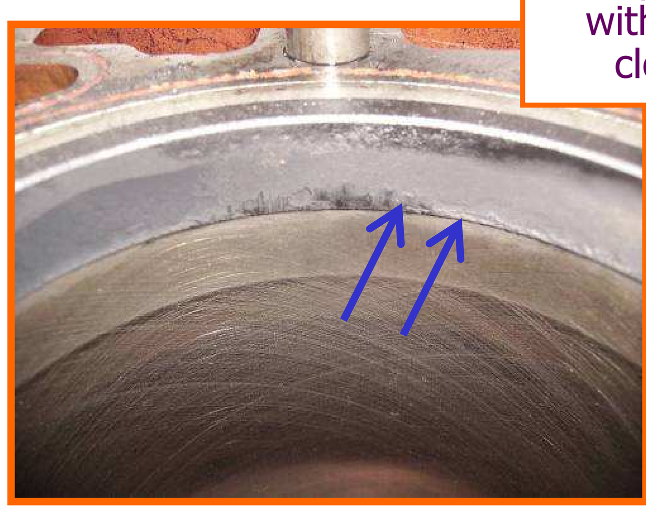
Effect of rapeseed oil temperature on fuel injection line pressures and onset of combustion (indicated pressure) at max. torque rpm and 10% load

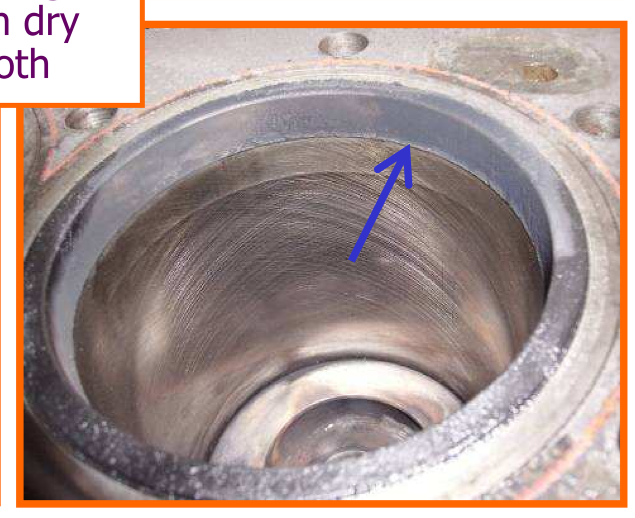












COLD IDLE (30 min)		**WARM & LOADED (2 hours)**
Delayed vs. diesel	***Onset of Combustion***	**Comparable to diesel**
2,7 kg/h → 1,8 kg/h, (diesel: 0,65 kg/h, idle on RO immediately after load: 0,8 kg/h)	***Fuel Consumption***	**Corresponds to lower heat content and higher density of RO; similar thermal efficiency**
HC+PM 20-30 g/h (> 1% of fuel) Up to order of magnitude higher PM, HC, CO vs. diesel fuel Additional 400-600 g/h leaked out of the exhaust as liquid (GC analysis: mostly uncombusted fuel)	***Exhaust emissions***	**HC+PM 14 g/h (<0,1% of fuel) vs. diesel: PM -67% HC -47% CO -48% NOx +10%**
563 g/h (approx. 30% of fuel consumed from the tank)	***Rapeseed oil penetration into lubricating oil***	**9-10 g/h (0,10-0,15 g/kWh, approx 0,05% of fuel used)**
Oily and carbonaceous deposits on all surfaces, rapeseed oil leaking out of the exhaust system	***Deposits***	**Minimal, except in dead space between injector tips and engine head, and on cylinder wall above top ring**
Idle after loaded operation: Combustion delay increases, emissions gradually deteriorate, deposits form	***After transition from load to idle or from idle to load***	**Combustion and emissions improve, deposits in the exhaust system are emitted, fuel deposited in lubricating oil remains.**