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Performance and Exhaust Emissions of an Indirect-Injection (IDI) Diesel Engine When Using Waste Cooking Oil as Fuel

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A study was carried out on the influence of waste cooking oil (WCO) and its blends with D2 fuel on the performance, exhaust emissions, combustion and fuel injection processes of an indirect injected diesel engine. Tests were carried out using different fuels, under the same conditions. Exhaust emissions and engine performance were measured and compared. Combustion chamber pressure was also acquired, and the rate of heat-release curves were computed by means of a zero-dimensional one-zone combustion model. Some macro-parameters of the combustion process were obtained from the heat-release-rate curves. The injection system was separated from the engine and tested on a special test bench. The injected fuel quantity was measured, and the injection pressure and injector needle lift time history were acquired. The injection-rate curves were then computed, and some macro-parameters of the injection process were obtained and analyzed.

Introduction

Waste cooking oils (WCOs) are generated locally, wherever food is cooked or fried in oil. Restaurant waste oils and rendered animal fats are less expensive than food-grade canola and soybean oil.[1] Currently, all of these waste oils are sold commercially as animal feed. However, since 2002, the European Union (EU) has enforced a ban on feeding these mixtures to animals, because, during frying, many harmful compounds are formed and, if the WCO is used as an additive to feeding mixtures for domestic animals, it can result in the return of harmful compounds back into the food chain via animal meat.[2] Hence, WCO must be disposed of safely or used in a way that is not harmful to human beings. The amount of WCO generated per year in any given country is enormous, although it varies depending upon the use of vegetable oil. An estimate of the potential amount of WCO collected in the EU[3] is between 700 000 and 1 000 000 tons/year. WCO estimates in the U.S. range from 1.2 billion to 3 billion gallons a year.[4] In Japan, nearly 400 000−600 000 tons of WCO are generated annually.[5] According to Shlegemilch and Markovic,[6] 3000 tons/year of WCO could be collected in Slovenia.

The disposal of WCO is problematic, because disposal methods may contaminate environmental water. Many developed countries have set policies that penalize the disposal of waste oil through water drainage.[7] The use of WCO for energy production is one of the better ways to use it efficiently and economically.

Similar to vegetable oils, WCO boasts great promise as an alternative fuel for diesel engines because of the very significant fact that they are a renewable energy source and would emit substantially less greenhouse gases.[8] High viscosity and poor volatility are the major limitations of vegetable oils for their use as a fuel in diesel engines. The high molecular weight and chemical structure of vegetable oils contribute to their high viscosity.

The high viscosity of vegetable oils deteriorates the atomization, evaporation, and air−fuel mixture formation characteristics, leading to improper combustion and higher smoke emissions. The high viscosity of vegetable oils also creates operational problems, such as difficulty in starting the engine, unreliable ignition, and deterioration in thermal efficiency. For long-term use, durability problems, such as nozzle coking, carbon deposition in different parts of the engine, and lubricating oil dilution, arise.[9,10] The methods adopted to decrease the viscosity of vegetable oils are (i) preheating, (ii) mixing with other fuels, and (iii) conversion to biodiesel.[11−13]

Previous literature[14−17] has shown that a large amount of work has gone into evaluating the conversion of WCO to biodiesel. The use of biodiesel as a fuel for compression ignition engines has many environmental advantages; however, the production of biodiesel involves the use of a toxic, flammable liquid (methanol) and caustic compounds, such as sodium hydroxide or potassium hydroxide. The use of neat WCO constitutes the

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Table 1. Test Engine Specifications

engine	4-stroke, indirect-injected diesel engine JP Golf 1.6 D
number of cylinders	4
total displacement (ccm)	1590
compression ratio	23.5
rated torque (N m)/engine speed (rpm)	104/2000
rated power (kW)/engine speed (rpm)	40/4800
fueling	
fuel injection pump	distributor type FI pump BOSCH VE
injector	throttling pintle nozzle
pump advance	20 °CA

application of a waste byproduct, which other than filtration, does not require further postprocessing, and should be considered as an advantageous approach. This is different from the conversion of a triglyceride first to biodiesel via transesterification, only to then consume the material as fuel. The process of transesterification requires an extra step from raw material to fuel. This uses energy in the form of labor and process heat and requires at least a small processing plant. The approach taken in this paper is the filtration of the fuel source to remove particulate matter followed by its direct use in the diesel engine.

The preheating of WCO is typically performed using waste heat from the engine or electricity. One common solution is to add an additional fuel tank for "normal" diesel fuel (D2 or biodiesel) and a three-way valve to switch between this additional tank and the main tank containing WCO. The engine is started on diesel, switched over to vegetable oil as soon as it is warmed up, and then switched back to diesel shortly before being switched off to ensure it has no vegetable oil in the engine or fuel lines when it is cold-started again. In colder climates, it is often necessary to heat the vegetable oil fuel lines and tank because it can become very viscous and even solidify. These unfavorable effects may be reduced by blending the WCO with diesel fuel, which would allow for unmodified diesel engines to be used. To analyze the operation of an unmodified diesel engine with neat D2 fuel and its blends with WCO, a series of tests were performed on a small 1.6 L, four-stroke indirect-injected diesel engine. The test engine specifications are given in Table 1. No modifications of the fuel injection system or combustion chamber design were made. The influence of a particular fuel on fuel injection, the combustion process, and emission formations were experimentally investigated, and some of the results are presented here. The injection system setup was not optimized for any particular fuel and remained unaltered throughout the tests.

Table 2. Measured Physical Properties of WCO and Its Blends with D2 Fuel

parameter	fuel: WCO	blend[a]: WCO90	blend[a]: WCO80	blend[a]: WCO70	D2[b]	biodiesel[b]
density at 15 °C (kg/m^3)	915	902	899	890	829	865
kinematic viscosity (mm^2/s)						
at 40 °C	32.3	24.8	20.7	15.4	2.5	4.3
at 100 °C	5.5					
flash point temperature (°C)	285	115	100	95	57	100
calorific value (MJ/kg)					42.6	37.3
stoichiometric air/fuel ratio					14.5	12.4

[a] Blend WCO*xy* consists of *xy* vol % of WCO and (100 − *xy*) vol % of D2 fuel. [b] See ref 18.

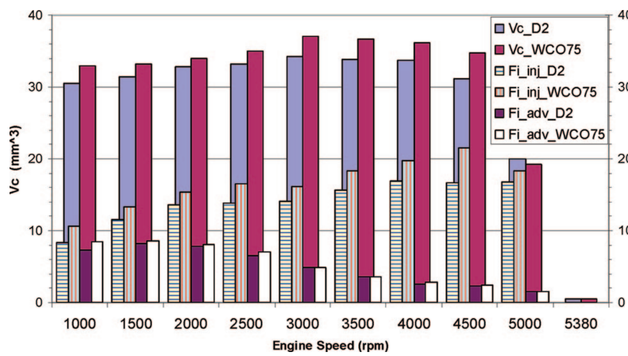

Figure 1. Injected fuel quantity per cycle (Vc), injection duration (Fi_inj), and injection advance (Fi_adv) for D2 and WCO75 at the full-rack position of a fuel injection pump and fuel temperature at 25 °C.

Characteristics of WCO

WCO collected from a small restaurant was used in our tests. The oil was first heated to 40 °C and then filtered using a 4 μm filter. The basic physical properties of the filtered WCO and its blends with D2 were then measured, and some of the results are presented in Table 2. The density of neat WCO is 12.5% higher than the density of D2 fuel, and it is then gradually reduced by blending WCO with D2. At 40 °C, the viscosity of WCO is more than 10 times higher than the viscosity of D2; however, it can be effectively reduced by either heating WCO (at 100 °C, the viscosity is 7 times lower) or by blending WCO with D2 (a more than 2 times lower density was measured for WCO blended with 30% D2). As seen in Table 2, WCO blending with an even very small amount of D2 reduces the flash point of the fuel substantially.

Influence of WCO on the Fuel Injection Process

The injection system was tested on a Friedman−Maier type 12H100_h test bench for a conventional fuel injection pump. Pressure−time histories within a high-pressure line, close to the high-pressure pump and the fuel injector and the injector needle lift trace, were acquired, and measurements were taken of the injected fuel quantity. Some of the results obtained with WCO75 and D2 fuel are presented in Figure 1. As can be seen, the injected fuel quantity per cycle is higher for WCO75,

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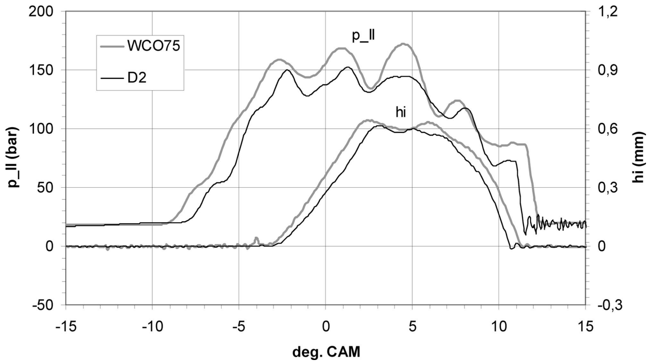

Figure 2. Comparison of injection pressure (p_II) and injector needle lift (hi) traces for WCO75 and D2 fuel at 2000 rpm, the full-rack position, and fuel temperature at 25 °C.

especially at higher engine speeds, where the volumetric amount of injected WCO75 exceeds the injected D2 fuel quantity by 10%. The injection duration (Fi_inj) is longer for WCO75 at all engine speeds, and at low engine speeds, injection starts earlier (longer injection advance Fi_adv) because of a shorter injection delay.

The comparison of injection pressure and injector needle lift traces for WCO75 and D2 fuel is presented in Figure 2. A shorter delay of injection is observed in the WCO75, and the injector needle opens 0.5 °CAM earlier than with D2 fuel. The closure of the injector needle with WCO75 is prolonged by almost 1 °CAM. The injection pressure−time history is similar for both fuels, although a 13% higher maximum pressure is observed with WCO75. Similar to the needle lift, 0.5 °CAM earlier pressure rise and 1 °CAM delayed pressure decrease are indicated. It can be concluded, therefore, that the operation of an injection system does not change significantly when D2 fuel is replaced by WCO75 and no alteration in the injection system setup is necessary when the operation conditions, especially the fuel temperature, remain within tolerance.

Influence of WCO on Engine Operation and Emission Formation

Engine tests were performed on a test bed using a dynamometer, which enabled the measuring of engine speed and load characteristics. In addition, measurements were taken of the basic engine operational parameters such as engine speed, engine load, fuel consumption, pressure and temperature in the intake and exhaust systems, and the concentration of gaseous components and particulates in the exhaust gases. The NO_x concentration was measured using a chemiluminescence analyzer; a flame ionization detector was used for unburned hydrocarbon measurement; particulates were monitored by an AVL smoke meter; concentration of CO was measured by a nondispersive infrared analyzer; and a ZrO_2 sensor was used for the oxygen concentration measurement.

Full-Load Characteristic. The full-load characteristic is measured at the full-rack position of the fuel injection pump ("full throttle"), by gradual variations of the rotational speed of the engine-dynamometer system. It is presented in Figure 3. As can be seen, the torque and, consequently, the power of the engine are almost identical for both fuels WCO75 and D2, which is surprising, because the calorific value of the WCO is approximately 13% lower than that of D2 fuel. However, this is compensated for by the higher density of WCO and increased quantity of injected fuel when WCO75 is applied. Moreover, at low engine speeds, engine torque increases with the application of WCO75. At high engine speeds, the modified operation

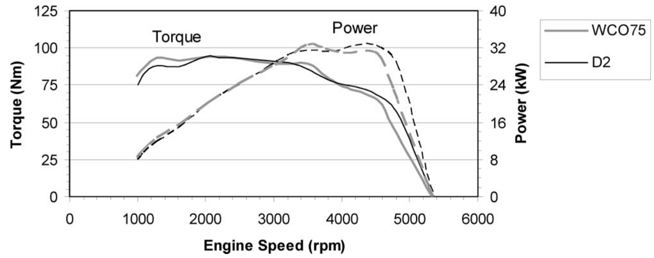

Figure 3. Comparison of engine torque and power for WCO75 and D2 fuel at full load and fuel temperature at 25 °C.

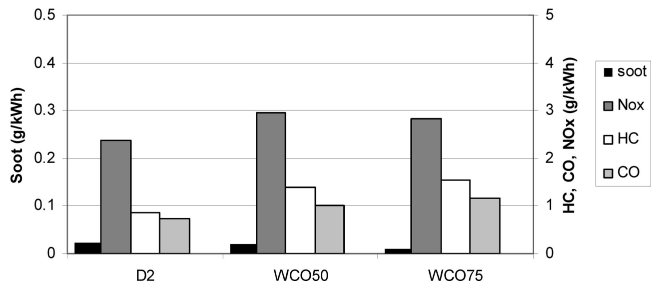

Figure 4. Comparison of specific emissions of CO, HC, NO_x, and particulate (soot) for D2 fuel and its blends with WCO at 2000 rpm and 50.5 N m and fuel temperature at 25 °C.

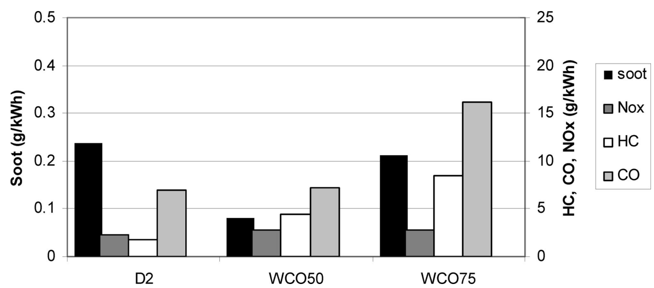

Figure 5. Comparison of specific emissions of CO, HC, NO_x, and particulate (soot) for D2 fuel and its blends with WCO at 2000 rpm and 84.5 N m and fuel temperature at 25 °C.

of a mechanical governor is observed. The governor starts to reduce injected fuel quantity earlier when WCO75 is used; thus, engine torque and power decrease faster.

Emission Characteristic at Partial Load. To avoid any difference in engine load as a result of the application of different fuels, the emission characteristics were measured at partial load. Measurements were performed at 2000 rpm (maximal torque engine speed). Three different fuels were used: WCO75, WCO50, and D2, and a constant engine torque of 50.5 and 84.5 N m, respectively, was controlled by dynamometer. The main engine operational parameters were, therefore, the same for all four fuels, which allowed for an unbiased comparison.

Specific engine emissions at 50.5 N m (approximately 60% engine load) are presented in Figure 4. CO and HC emissions increase with the portion of WCO in the fuel. A reduction in particulate emissions is observed, and the emissions of NO_x increase by 25%, with their maximum at a 50% share of WCO in the fuel (WCO50). Similar trends are also observed at 84.5 N m (an approximately 90% engine load). The results are presented in Figure 5. There is just a moderate increase of NO_x and particulate emissions in comparison to the 60% engine load results. On the other hand, a very large increase of HC and CO emissions is observed, which both grow almost exponentially with the portion of WCO in the fuel. These trends are surprisingly different from the common belief that the application of biodiesel fuel increases NO_x emissions and decreases

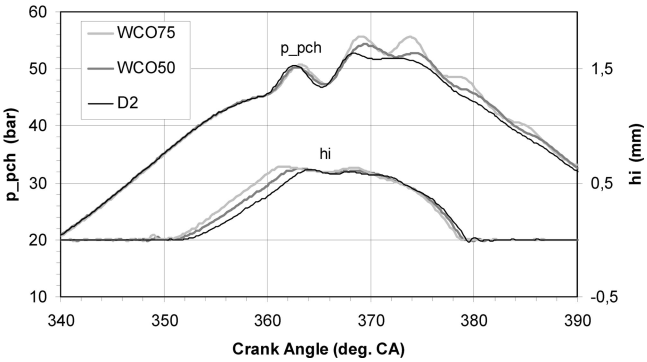

Figure 6. Comparison of injector needle lift (hi) and prechamber pressure trace (p_pch) for D2 fuel and its blends with WCO at 2000 rpm and 84.5 N m and fuel temperature at 25 °C.

all other emissions because of the high content of bonded oxygen in the fuel.[19] However, it should be noted that the two fuels differ quite significantly. Using the transesterification process, the viscosity of biodiesel is reduced to the levels of D2 fuel; thus, the atomization of injected fuel is much better, and this increases the quality of the combustible mixture formation and combustion.

Influence of WCO on the Combustion Process

The basic characteristics of the combustion process can be obtained with a computational processing of the in-cylinder pressure trace. The combustion chamber pressure– and injector needle lift–time histories were, therefore, acquired from the first engine cylinder. A piezoelectric sensor was placed in the prechamber for pressure pick up; an inductive sensor was used for needle lift measurements; and an optical encoder was applied for the reference crank angle position pick up. Signals from the sensors were acquired by a computer-aided data acquisition system, with a sampling rate of 80 kHz per channel. LabVIEW software was used to build the computer applications for data logging and signal processing. Measured pressure traces were used for the prediction of combustion heat release rates, the so-called rate of heat release (RHR) curves. A one-zone zero-dimensional combustion model[20] was used to derive the mass- and energy-conservation equations in the cylinder and prechamber. This system of four differential equations was then numerically integrated using a personal computer. The pressure traces acquired at different partial-load engine operational conditions were processed this way, and RHR curves were obtained.

Figure 6 presents pressure–time histories and injector needle lift diagrams obtained for three different fuels: neat D2, D2 blended with 50% WCO (WCO50), and D2 blended with 75% WCO (WCO75). As can be seen from the injector needle lift diagram, injection starts faster with an increased portion of WCO in the fuel. On the other hand, the prechamber pressure rise begins almost at the same moment for all three fuels. It therefore follows that the ignition delay increases with the portion of WCO in the fuel (Table 3). This is not surprising, because the fuel atomization is worse as a result of the much higher fuel viscosity. The first part of the combustion process that takes place within the prechamber is, therefore, delayed, and higher pressure oscillations as well as higher maximum pressure indicate a much more vivid second part of the combustion

Table 3. Comparison of Ignition Delay and Combustion Duration for D2 Fuel and Its Blends with WCO at 2000 rpm and Fuel Temperature at 25 °C

	ignition delay (ms)			combustion duration (°CA)		
torque (N m)	D2	WCO50	WCO75	D2	WCO50	WCO75
50.5	0.46	0.49	0.59	45.5	44.4	42.2
84.5	0.44	0.50	0.58	67.6	66.1	67.5

process taking place in the engine cylinder. Figures 7 and 8, showing RHR diagrams, easily confirm this. There is a two-stage combustion cycle that is characteristic of the auxiliary chamber process. The fuel is ignited within the prechamber and the sudden rise in pressure pushes the fuel-rich mixture into the cylinder, where combustion proceeds. Some fluctuations in combustion intensity (RHR) are already seen for neat D2. Moderate oscillations of RHR are observed with 5 J/°CA amplitude and frequency approximately equal to 2000 Hz. An increased portion of WCO in the fuel increases the oscillation amplitude substantially, while oscillation frequency remains unchanged. Oscillation amplitude increases to 7 J/°CA for the WCO50 fuel (Figure 7) and even to 12 J/°CA for the WCO75 fuel (Figure 8). The later amplitude represents more than 30% of the RHR maximum and points to an extremely unstable combustion process. It is believed that these high-amplitude oscillations of combustion intensity do influence combustion efficiency and cause increased CO and HC emissions observed with the increased portion of WCO in the fuel.

Increased oscillations in combustion intensity do not influence combustion duration. It remains the same for all three fuels

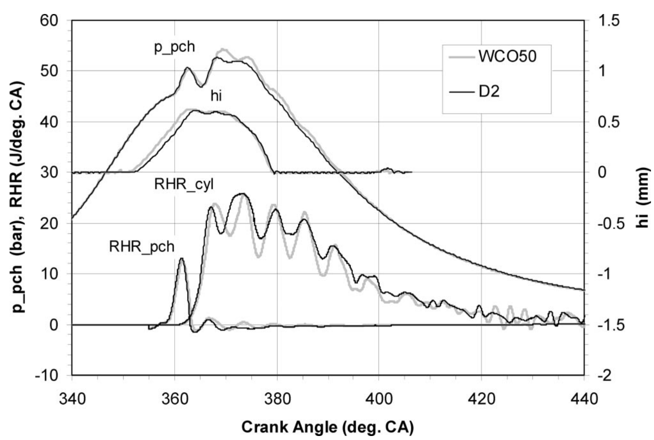

Figure 7. Comparison of RHR, injector needle lift (hi), and prechamber pressure trace (p_pch) for D2 and WCO50 fuel at 2000 rpm and 84.5 N m and fuel temperature at 25 °C.

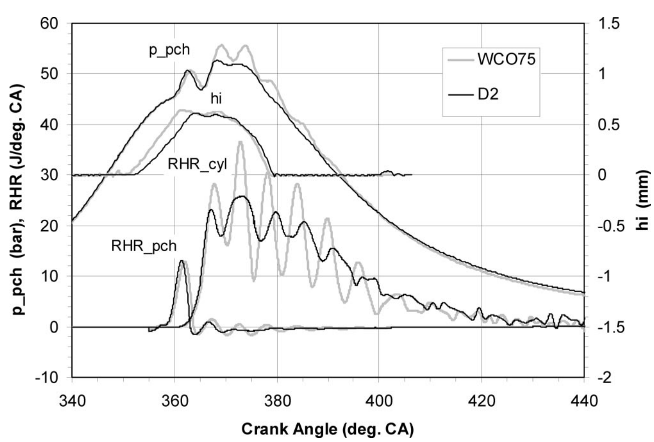

Figure 8. Comparison of RHR, injector needle lift (hi), and prechamber pressure trace (p_pch) for D2 and WCO75 fuel at 2000 rpm and 84.5 N m and fuel temperature at 25 °C.

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(Table 3). In addition, because the reduced injection delay compensates for the increased ignition delay fairly well, no injection timing alteration is necessary when D2−WCO blends are used. Although the increased injection timing advance would probably reduce very high HC and CO emissions observed for D2−WCO blends, attention should be directed to NO_x emissions, which would, in this case, increase substantially and even worsen the overall emission characteristics of the engine.

Conclusions

The paper presented the results of experimental research on the influence of WCO on fuel injection and the combustion process of diesel engines. The influence of WCO on basic engine operational parameters and emission formation was also studied and presented. The engine setup was not optimized for any particular fuel, and it remained unaltered during the tests.

No operational problems were encountered by the application of D2−WCO blends with up to 75% of WCO. The engine ran smoothly, and no reduction in output power was observed; however, the pollutant emissions increased significantly. CO and HC emissions increased by more than 300%, and a moderate NO_x increase was also detected. The RHR comparison shows that oscillations of combustion intensity increase dramatically with the amount of WCO in the fuel. This destabilizes the combustion process and causes an increase in CO and HC emissions. The application of D2−WCO blends with a higher amount of WCO is, therefore, to be avoided, unless fuel preheating is used and the engine is pretuned for the specific D2−WCO blend, as reported by Masjuki et al.[11]

The following conclusions can be made when comparing the results obtained for neat D2 fuel and its blends with WCO. (a) Fuel injection process: (1) the amount of injected fuel increases with the amount of WCO in the fuel; (2) the injection delay decreases with the amount of WCO in the fuel; and (3) the maximum injection pressure increases by up to 20% with the amount of WCO in the fuel. (b) Combustion process: (1) the ignition delay increases with the amount of WCO in the fuel; (2) the oscillations of combustion intensity increase with the amount of WCO in the fuel and destabilize the combustion process; and (3) the combustion duration is not influenced by the amount of WCO in the fuel. (c) Engine operational parameters and emissions: (1) the maximum engine power and torque remain unchanged; (2) the specific CO and HC emissions increase significantly with the level of WCO in the fuel; (3) the particulate emissions remain unchanged; and (4) NO_x emissions increase slightly with the amount of WCO in the fuel.

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