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Influence of Biodiesel Fuel on the Combustion and Emission Formation in a Direct Injection (DI) Diesel Engine

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This paper studies the influence of biodiesel fuel on the combustion and emission formation of two different direct-injected diesel engines, both employing different combustion processes. The research was focused on determining the influence of the specific combustion process on measurement results to ascertain if a generalization of the results is possible or whether they have to be interpreted as specific for specific engines. Standard D2 diesel fuel and commercial 100% biodiesel fuel were used. Tests were executed using both fuels under the same conditions, and exhaust emissions and engine performance were measured and compared. In-cylinder pressure was also acquired, and the rate of heat release curves were computed by means of a zero-dimensional, one-zone combustion model. Some macroparameters of the combustion process were obtained from the heat-release-rate curves. The results obtained for both engines showed that findings regarding the influence of biodiesel fuel on the combustion process and emission formation could not be generalized and had to be interpreted as specific for the particular engine.

Introduction

Methyl esters of vegetable oils, known as biodiesel, are attracting increasing interest because of their low environmental impact and their potential as an alternative fuel. The consumption of biodiesel fuel is growing from year to year. It is stimulated by the rising price of crude oil, the striving of individual countries to reduce their dependence on imported energy sources, and the implementation of the Kyoto protocol directives for the reduction of global emissions from greenhouse gases.[1] Biodiesel is used for the propulsion of road and off-road vehicles in 5−10% blends with D2-diesel fuel; however, 100% biodiesel fuel is already sold at petrol stations in some EU countries, such as Austria and Germany.

Because of the high viscosity of raw vegetable oils, a process called transesterification is used for the production of biodiesel fuel, the characteristics of which are very similar to those of D2 fuel (Table 1). No modifications of a fuel injection system nor combustion process are therefore necessary when the D2 fuel is replaced by biodiesel fuel. The combustion process and emission formation however are altered because of the different compositions of both fuels. The low sulfur content of biodiesel fuel reduces particulate matter (PM) emissions, particularly PM associated with sulfates.[2] Also, sulfur-sensitive exhaust gas aftertreatment may be used to reduce other emissions from the exhaust gas.[3] Biodiesel contains more than 10 wt % oxygen, and the addition of oxygen-containing hydrocarbons to diesel fuel shows significant potential in reducing particulate emissions.[4,5] Furthermore, oxygen content reduces CO and unburned hydrocarbon (HC) emissions.[6] However, enhanced combustion performances may intensify combustion and accelerate NO_x formation, thus increasing its emissions. An extensive literature review proves that findings on the influence of biodiesel fuel on engine combustion and emissions cannot be generalized. Combustion-chamber geometry, the fuel injection process, combustible mixture formation with pre-ignition and ignition processes, and engine load may significantly influence combustion and emission formation and lead to a conclusion that deviates from commonly accepted norms. Some authors[6,7] report very high increases of NO_x emissions, the reduction of CO, and unburned HC emissions when using biodiesel fuel, while others have experienced just moderate increases of NO_x emissions with unchanged CO and HC emissions[2,8] or even a reduction in all emissions.[10,11] These somehow contradictory conclusions are caused by the nonuniformity of engine testing. These tests were performed on different engines using different

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(1) Markovic-Hribernik, T. Activities and instruments to control greenhouse gas emissions: The case of Slovenia. STIQE: Proceedings of the 6th International Conference on Linking Systems Thinking, Innovation, Quality, Entrepreneurship, and Environment, Maribor, Slovenia, 2002; pp 65−74.

(2) Alam, M.; Song, J.; Acharya, R.; Boehman, A. Combustion and emissions performance of low sulfur, ultra low sulfur and biodiesel blends in a DI diesel engine. SAE paper 2004-01-3024.

(3) Cowlely, L. T.; Shadling, R. J.; Doyon, J. The influence of composition and properties of diesel fuel on particulate emissions from diesel engines. SAE paper 932732.

(4) Miyamoto, N.; Ogawa, H.; Nurun, N.; Obata, K.; Arima, T. Smokeless, low NO_x, high thermal efficiency, and low noise diesel combustion with oxygenated agents as main fuel. SAE paper 980506.

(5) Giacomo, N. D.; Beatrice, C.; Bertoli, C. Diesel combustion improvements by the use of oxygenated synthetic fuels. SAE paper 972972.

(6) Nabi, M. N.; Shahadat, M. M. Z.; Rahman, M. S.; Beg, M. R. A. Behavior of diesel combustion and exhaust emission with neat diesel fuel and diesel-biodiesel blends. SAE paper 2004-01-3034.

(7) Sanatore, A.; Cardone, M.; Rocco, V.; Prati, M. V. A comparative analysis of combustion process in DI diesel engine fueled with biodiesel and diesel fuel. SAE paper 2000-01-0691.

(8) May, H.; Hattingen, U.; Theobald, J.; Weidmann, K.; Koenig, A. Untersuchung des Betriebs und Abgasemissiosverhaltens eines Dieselmotors mit Oxidationskatalysator. *Motortech. Z.* **1998**, *59*, 112−123.

(9) Tritthart, P.; Zelenka, P. Vegetable oils and alcohols−Additive fuels for diesel engines. SAE paper 905112.

(10) Hribernik, A. The influence of biodiesel fuel on injection, combustion, emissions, and performance of direct-injected diesel engine. *J. Mech. Eng.* **2006**, *52*, 3−14.

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Table 1. Comparison of the Physical and Chemical Properties of Biodiesel and D2 Fuels[9]

	D2	biodiesel
density at 15 °C (kg/m^3)	845	865
viscosity at 40 °C (mm^2/s)	2.5	4.3
calorific value (MJ/kg)	42.6	37.3
cetane index	46	>49
composition		
mass fraction C	0.860	0.7750
mass fraction H	0.134	0.1210
mass fraction S	0.003	0.0001
mass fraction O		0.1040
stehiometric air−fuel ratio	14.5	12.4

combustion-chamber geometry. The fuel injection systems and even fuel injection strategies were different too. Some were optimized just for D2, and others were optimized just for biodiesel fuel.

Two sets of measurements were performed to establish how much influence different test conditions have on engine emission characteristics when operating with biodiesel fuel. In the first set of measurements, the turbocharged diesel engine TAM BF4L515C was used, while the natural aspirated diesel engine MAN D2566 MUM was applied in the second set of tests. Both test engine specifications are given in Table 2. Although both engines have similar geometry (bore and stroke), some important characteristics differ significantly. The TAM engine is equipped with a Bosch P-type in-line injection pump, which delivers fuel with maximum pressure up to 80 MPa. Four-hole injectors ensure very good fuel atomization, which is injected into the shallow Ω-shaped combustion chamber placed asymmetrically in the piston crown. High-intensity air swirl induced by a tangentially shaped intake valve channel enables fast evaporation of highly atomized fuel and fast mixing of fuel vapors with air, thus preventing impingement of fuel into the walls of the combustion chamber. The MAN engine uses a Bosch in-line injection pump type A. The injection pressure does not exceed 50 MPa. A single-hole injector nozzle is used, which injects fuel in the form of a compact jet against the wall of a spherical centrally positioned piston bowl. The fuel forms a film that vaporizes and forms a very intense mixture with the swirling combustion-chamber air as it passes. The air swirl with a very high intensity is necessary in this so-called M-system combustion process.

When both engines are compared from the point of view of fuel injection, mixture formation, and combustion processes, it can be concluded that they differ significantly. In a TAM engine, there is an equal influence of preburn physical and chemical reactions on the combustion process, while the physical processes of fuel film evaporation and fuel vapor−air mixing dominate any combustion in a MAN engine over chemical kinetic processes. There are some other differences between both test engines that should also be mentioned. The TAM engine is turbocharged and air-cooled, while the MAN engine is naturally aspirated and water-cooled, which assures a lower influence of engine speed on the amount of trapped fresh air, excess of fresh air, and in-cylinder conditions during the combustion delay interval.

The results of this experimental investigation into the influence of biodiesel fuel on the combustion processes and

(11) Yamane, K.; Ueta, A.; Shimamoto, Y. Influence of physical and chemical properties of biodisel fuel on injection, combustion, and exhaust emission characteristics in a DI−CI engine. The Fifth International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines (COMODIA), Nagoya, Japan, July 1−4, 2001; pp 402−409.

Table 2. TAM BF4L515C and MAN D2566 MUM Test Engine Specifications

engine	TAM BF4L515C four stroke	MAN D2566 MUM four stroke
gas-exchange process	turbocharged engine	naturally aspirated engine
cooling	air cooling	water cooling
combustion process	multihole nozzle combustion process	M system
number of cylinders	4	6
bore × stroke	125 × 145 mm	125 × 155 mm
total displacement	7117 ccm	11 413 ccm
compression ratio	15.8	17.5
fuelling	direct injection	direct injection
fuel pump	BOSCH PES6P120A72	BOSCH PES6A95D410LS2542
nozzle	BOSCH DLLA 148S	BOSCH DLLA 5S834
nozzle holes	4 × Φ = 0.375 mm	1 × Φ = 0.68 mm
injection timing	16 ^{0}CA	23 ^{0}CA

emission formations in both test engines are presented in the following paper. To consider any possible differences in fuel injection strategies, often neglected by some authors, the injection system setup was purposely optimized for the application of D2 fuel in a MAN engine and for the application of biodiesel fuel in a TAM engine.

Influence of Biodiesel on the Fuel Injection Process

The injection system was tested on a Friedman−Maier-type 12H100_h test bench for conventional fuel injection pumps. The pressure−time histories in the high-pressure line close to the high-pressure pump and close to the fuel injector were acquired together with the injector needle lift trace, and the injected fuel quantity was measured. These results were presented in the previous papers of the authors.[10,12] In ref 12, the investigation details of the BOSCH PES6A95D410LS2542 in-line fuel injection pump of the MAN engine are given, and ref 10 presents the research into the BOSCH PES6P120A72 in-line fuel injection pump of a TAM engine. The conclusions were similar for both fuel injection pumps, and they are therefore briefly presented. The injected fuel quantity per cycle was higher for biodiesel fuel especially at higher engine speeds, where the volumetric amount of injected biodiesel fuel exceeded the injected D2 fuel quantity by up to 4%. The injection duration was longer for biodiesel fuel because of an earlier needle lift and a shorter injection delay. The basic injection parameters however differed only a little. The differences were almost within the measurement of uncertainty. The dynamic parameters also proved this. The injector needle lift trace at low engine speed was almost identical for both fuels, while at maximum engine speed, a shorter injection delay was observed for biodiesel fuel and the injector needle opened earlier as with D2 fuel. The injector needle closure was identical for both fuels. The pressure−time history in the high-pressure line close to the injector was also similar, although 4−7% higher maximum pressure was observed for biodiesel fuel. It can be concluded therefore that the operation of the injection system did not change significantly when D2 fuel was replaced by biodiesel fuel, and no alteration in the injection system setup was necessary when the operation conditions, especially the fuel temperature, remained within tolerances.

(12) Kegl, B.; Hribernik, A. Experimental analysis of injection characteristics using biodiesel fuel. *Energy Fuels* **2006**, *20*, 2239−2248.

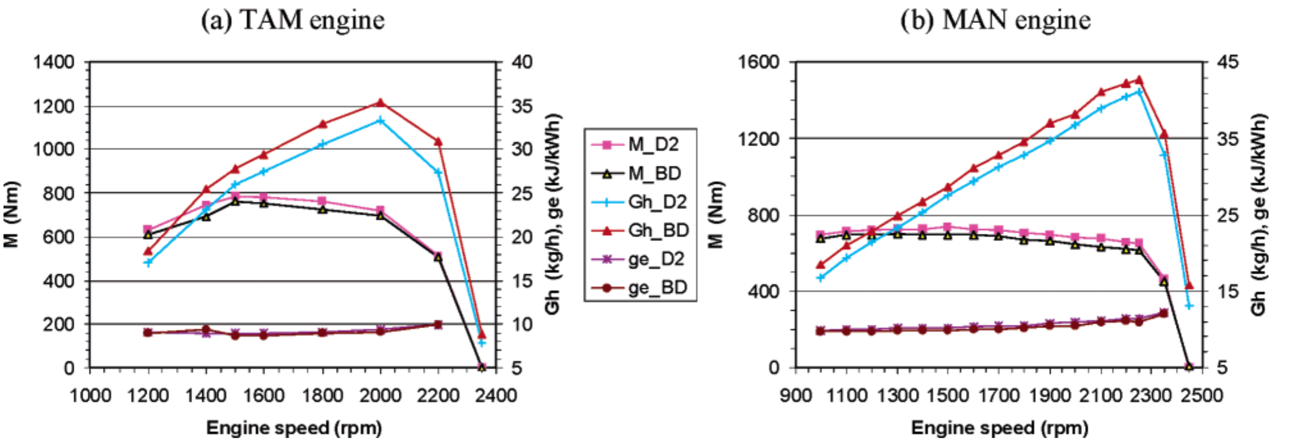

Figure 1. Comparison of the engine torque (M), fuel consumption (Gh), and brake specific energy consumption (ge) at full load for biodiesel fuel (BD) and D2 fuel in (a) TAM and (b) MAN engines.

Influence of Biodiesel on the Engine Operation and Emission Formation

Engine tests were performed on a test bed using a dynamometer that enables the measurement of engine speed and load characteristics. In addition to the basic engine operational parameters, such as engine speed, turbocharger speed, engine load, air mass flow, fuel consumption, pressure, and temperature in both intake and exhaust systems, the concentration of gaseous components and particulates in the exhaust gases was also measured. The NO_x concentration was measured using a chemiluminescence analyzer; a flame ionization detector was used for unburned HC measurements; the particulates were monitored using an AVL smoke meter; the concentration of CO was measured with a nondispersive infrared analyzer; and a ZrO_2 sensor was used for oxygen concentration measurements.

Full-Load Characteristics. The full-load characteristic is measured at the full-rack position of the fuel injection pump ("full throttle"), by gradual variation of the rotational speed of the engine. This is presented in parts a and b of Figure 1 for the TAM and MAN engines, respectively. As can be seen, the engine torque and, consequently, the engine power are lower at all engine speeds when the engine is fuelled by biodiesel fuel. This is expected because the calorific value of biodiesel fuel is 12.5% lower than that of D2 fuel (see Table 1). It also follows from Figure 1 that the biodiesel fuel consumption (Gh, parts a and b of Figure 1) is higher at the full-rack position. There are two reasons for this. First, the biodiesel fuel density is higher (see Table 1), and second, the injected fuel quantity per cycle is also higher. The reduction of engine torque and power when fuelled by biodiesel fuel is therefore not as high as 12.5% but is just 5%. At the same time, the brake-specific energy consumption (ge, parts a and b of Figure 1) remained unchanged. Therefore, it may be concluded that the engine torque and power are reduced by 5%, and the effective engine efficiency remains unchanged when D2 fuel is replaced by biodiesel fuel.

The application of biodiesel fuel does not affect the mass flow of air through the naturally aspirated engine. The equivalent air−fuel ratio in the MAN engine was therefore increased by 7% (Figure 2) because of the lower oxygen demand of biodiesel fuel. On the other hand, the equivalent air−fuel ratio increased only slightly in the turbocharged TAM engine (Figure 2). The reduction of the engine power also influenced the decrease of turbocharger speed as air mass flow by 4%, and the resulting increase of the air−fuel ratio was just 2%. Moreover, at peak torque (n = 1400 rpm), a 2% reduction of the air−fuel ratio was observed.

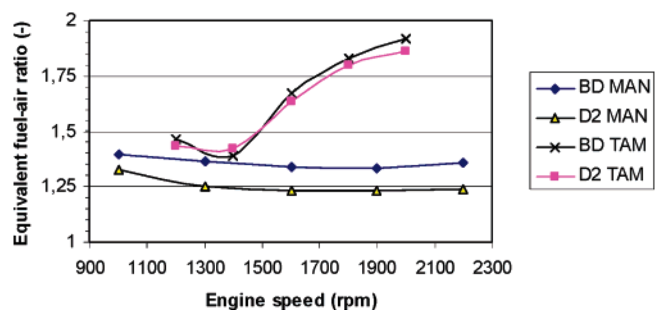

Figure 2. Influence of the applied fuel (biodiesel BD and D2) on the equivalent air−fuel ratio.

Parts a and b of Figure 3 show the influence of a particular fuel on the specific emissions of both engines. It should be noted that injection system setup was optimized for the application of D2 fuel in the MAN engine and for the application of biodiesel fuel in the TAM engine. A reduction in CO, HC, and soot emissions upon the application of biodiesel fuel containing more than 10% of oxygen is characteristic for both engines. Oxygen bonded in the biodiesel fuel reduces the deficit of oxygen within the fuel-rich regions, hinders soot formation, and accelerates the oxidation processes. In the MAN engine, soot emissions were reduced most (up to 4 times). The air−fuel ratio increased by 7%, as shown previously, and therefore exceeded the so-called soot limit. CO emissions were halved, while the already very low HC emissions remained almost unchanged. In the TAM engine, both soot and HC emissions were halved, while CO emissions decreased only moderately. With regard to NO_x emissions, both engines responded differently on the application of biodiesel fuel. Specific NO_x emissions were almost doubled in the MAN engine but were reduced in the TAM engine, which is undoubtedly the consequence of the already-mentioned specific engine setup. However, comparing engine emissions at full load may be misleading, because the application of biodiesel fuel reduces the engine load and therefore moderates any conditions for emission formation, especially NO_x emissions. The engine tests were therefore performed again under partial-load conditions

Partial-Load Characteristics. Partial-load characteristics were measured at 70% of the full load. It was possible therefore to maintain the same engine load with both fuels. Main engine operational parameters, such as engine torque and power, did not differ significantly when the D2 fuel was replaced by the

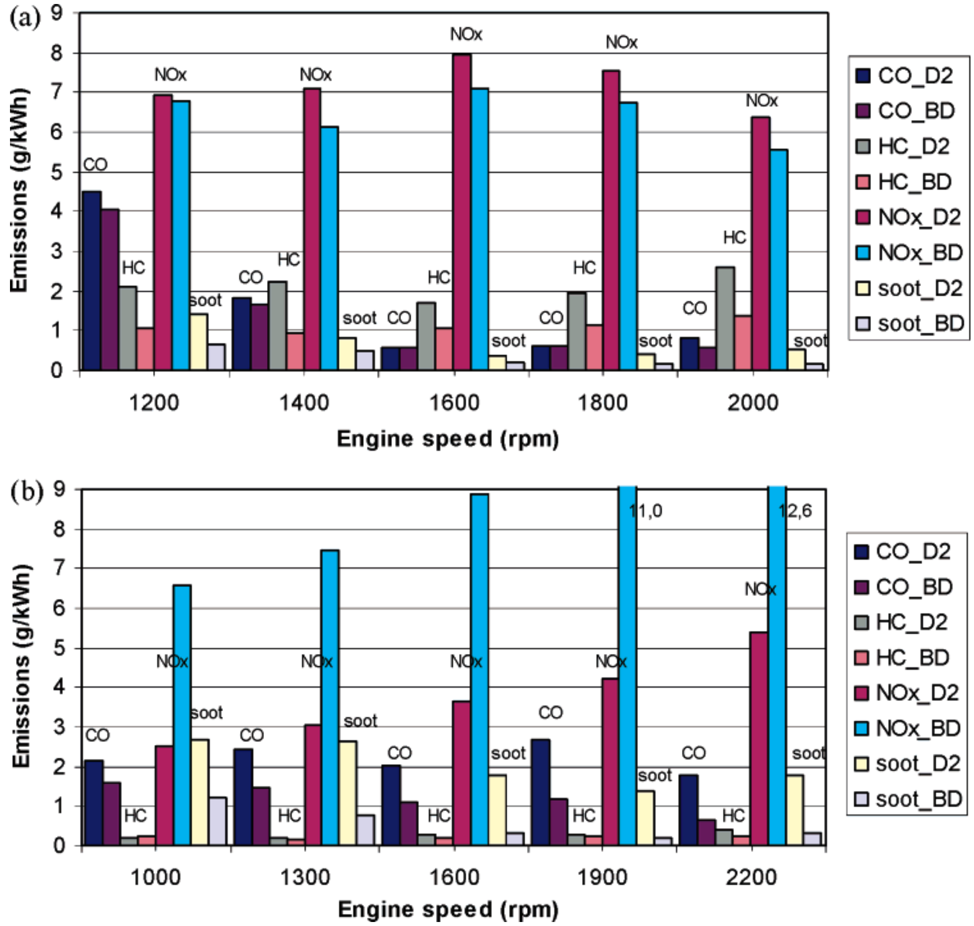

Figure 3. Comparison of specific emissions of CO, HC, NO_x, and particulate (soot) at full load for biodiesel (BD) and D2 fuel in (a) TAM and (b) MAN engines.

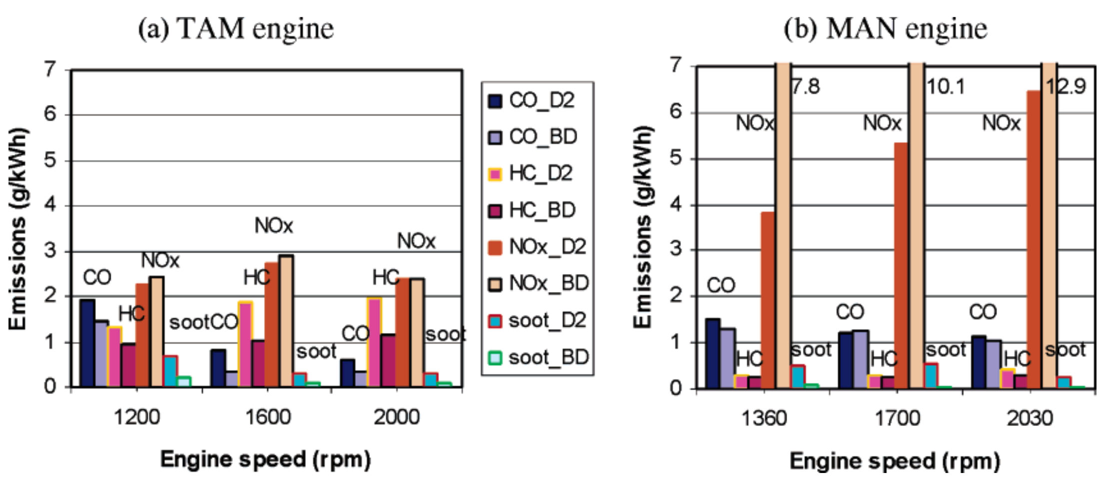

Figure 4. Comparison of specific emissions of CO, HC, NO_x, and particulate (soot) at partial load for biodiesel (BD) and D2 fuel in (a) TAM and (b) MAN engines.

biodiesel fuel. The differences in air mass flow were within the measurement of uncertainty interval for naturally aspirated MAN as well as for the turbocharged TAM engine. The air−fuel ratio was again higher by approximately 3% when biodiesel fuel was used, this time for both engines, because the turbocharger operation was unaffected by engine load reduction.

Specific engine emissions at partial load are presented in Figure 4. Significant reduction in soot emissions with biodiesel fuel was again observed for the MAN engine, while CO and HC emissions remained the same (Figure 4b). Specific NO_x emissions increased by 100% and moreover attained the level of full-load emissions (Figure 3b), while all other emissions decreased with the reduction of the engine load. Quite different results were obtained for the TAM engine (Figure 4a). NO_x emissions were halved with the engine load reduction, and in contrast with the full load, the specific NO_x emissions increased by 7% with biodiesel fuel. This confirms the hypothesis that any comparison of engine emissions using different fuels should be performed under the same conditions, which is unfulfilled at full load. Specific emissions of CO, HC, and soot were also reduced with the engine load reduction, and the additional reduction of these components because of the application of biodiesel fuel was similar to the full load.

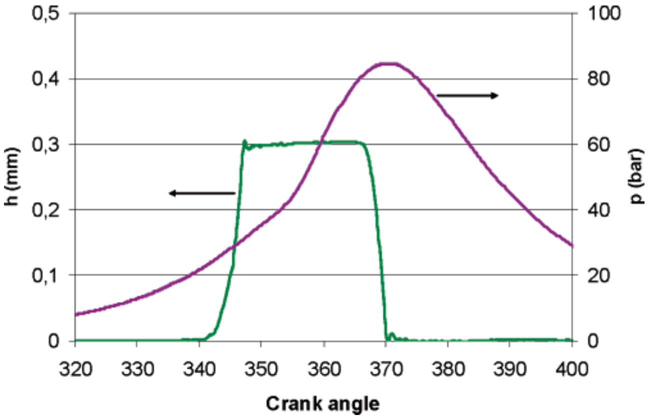

Figure 5. Measured traces of in-cylinder pressure (p) and injector needle lift (h) (biodiesel fuel, $n = 1700$ rpm, $p_e = 9$ bar) in a MAN engine.

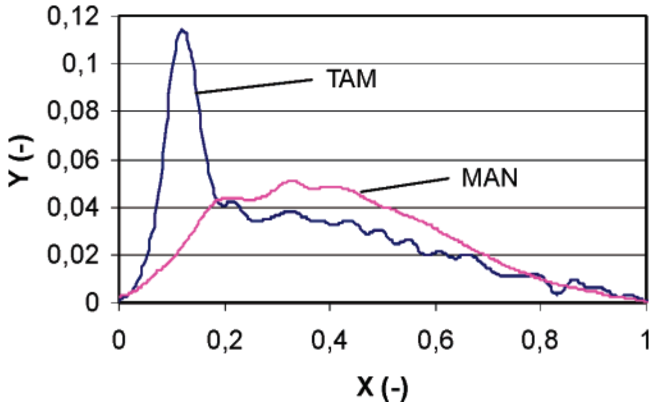

Figure 6. Comparison of nondimensional RHR curves of TAM and MAN engines for D2 fuel (x = relative combustion time, and y = relative heat release rate).

Influence of Biodiesel on the Combustion Process

The basic characteristics of the combustion process can be obtained by the computational processing of the in-cylinder pressure trace. The in-cylinder pressure− and injector needle lift−time histories were therefore acquired from the first engine cylinder. A piezoelectric sensor was placed in the combustion chamber for pressure pick up; an inductive sensor was used for needle lift measurements; and an optical encoder was applied for reference crank angle position pick up. Signals from the sensors were acquired by a computer-aided data acquisition system with a sampling rate of 100 kHz per channel. LabVIEW software was used to build the computer applications for data logging and signal processing. The characteristic in-cylinder pressure and injector needle lift trace obtained by measurements are presented in Figure 5. 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[13] was used to derive the mass- and energy-conservation equations at the cylinder. This system of two 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.

As stated in the Introduction, the combustion processes of both tested engines differ significantly. Highly atomized fuel and a fast mixing of fuel vapors with air prevent the impingement of fuel into the walls of the combustion chamber in a TAM engine. Fuel burns with the characteristic two-stage RHR (Figure 6), where the first stage corresponds to the combustion of those premixed reactants formed during ignition delay and the second stage corresponds to the diffusion combustion controlled by the rate of fuel evaporation and mixing with fresh air, i.e., the rate of combustible mixture formation. The M-system combustion process used in the MAN engine differs significantly. This wall distribution combustion system, in which the fuel is applied to the wall of the combustion chamber, makes use of the heat generated at the combustion-chamber wall and the swirling action of the air, in addition to the injection energy for mixture formation. The ignition delay is longer; however, a very small amount of premixed reactants is formed because of moderate fuel evaporation and fuel−air mixing rates. The RHR curve (Figure 6) has therefore usually only one peak and an almost unnoticeable transition from premixed to the diffusion combustion. Because of these differences, the results of RHR analysis are presented separately for each engine.

Influence of Biodiesel the on Combustion Process of the MAN Engine. Four characteristic engine-operational regimes were selected for the presentation (Figure 7). Both high and low engine speed and high and low engine load operational regimes were embraced. Figure 7 shows that both fuels produce almost identical RHR curves. There is a small phase shift that corresponds to the phase shift of the injector needle lift traces. The phase shift of the injector needle lift traces increases with the engine speed and decreases with the engine load. The phase shift is 2 ^{0}CA at 2030 rpm and $p_e = 2$ bar and reduces to 0.15 ^{0}CA at 1360 rpm and $p_e = 7$ bar. The injection starts earlier with biodiesel fuel, and the injection duration is approximately 2 ^{0}CA longer at all regimes, because the amount of injected biodiesel fuel has to be 10% greater at the same engine load because of the lower calorific value of biodiesel fuel (see Table 1). The RHR curves almost completely agree at 2030 rpm and $p_e = 7$ bar. This implies that physical processes prevail during ignition delay. The ignition delay, which consists of the physical part influenced by fuel evaporation, fuel−air mixing, and mixture heating processes and the chemical part connected with ignition, is the same for both fuels. Biodiesel fuel however has a higher cetane index than D2 fuel and should accelerate combustion and reduce the ignition delay if the significance of the physical and chemical parts of the ignition delay were the same. The formation of premixed reactants is slowed during the ignition delay, because of the relatively slow-running physical processes of combustible mixture formation. The RHR curve then appears in most cases with one peak only. A double-peak RHR curve only appears at a very low load and is the most distinctive at 1360 rpm and $p_e = 2$ bar (Figure 7b). The portion of premixed combustion with biodiesel fuel is only slightly lower at this regime, and the differences in RHR for both fuels may be attributed to the measurement of uncertainty or pressure trace smoothing. It may be concluded therefore that the application of biodiesel fuel in a MAN engine, which employs a M-combustion process, does not influence the RHR. The oxygen bonded in the biodiesel fuel however creates much better conditions for a more complete oxidation of fuel molecules (therefore, lower soot, CO, and HC emissions), which increase local flame temperatures and accelerate NO_x formation.

Influence of Biodiesel on the Combustion Process of the TAM Engine. Four characteristic engine operational regimes were selected for the presentation (Figure 8), again to embrace high and low engine speed and high and low engine load operational regimes.

(13) Heywod, J. B. *Internal Combustion Engine Fundamentals*; McGraw-Hill: New York, 1988.

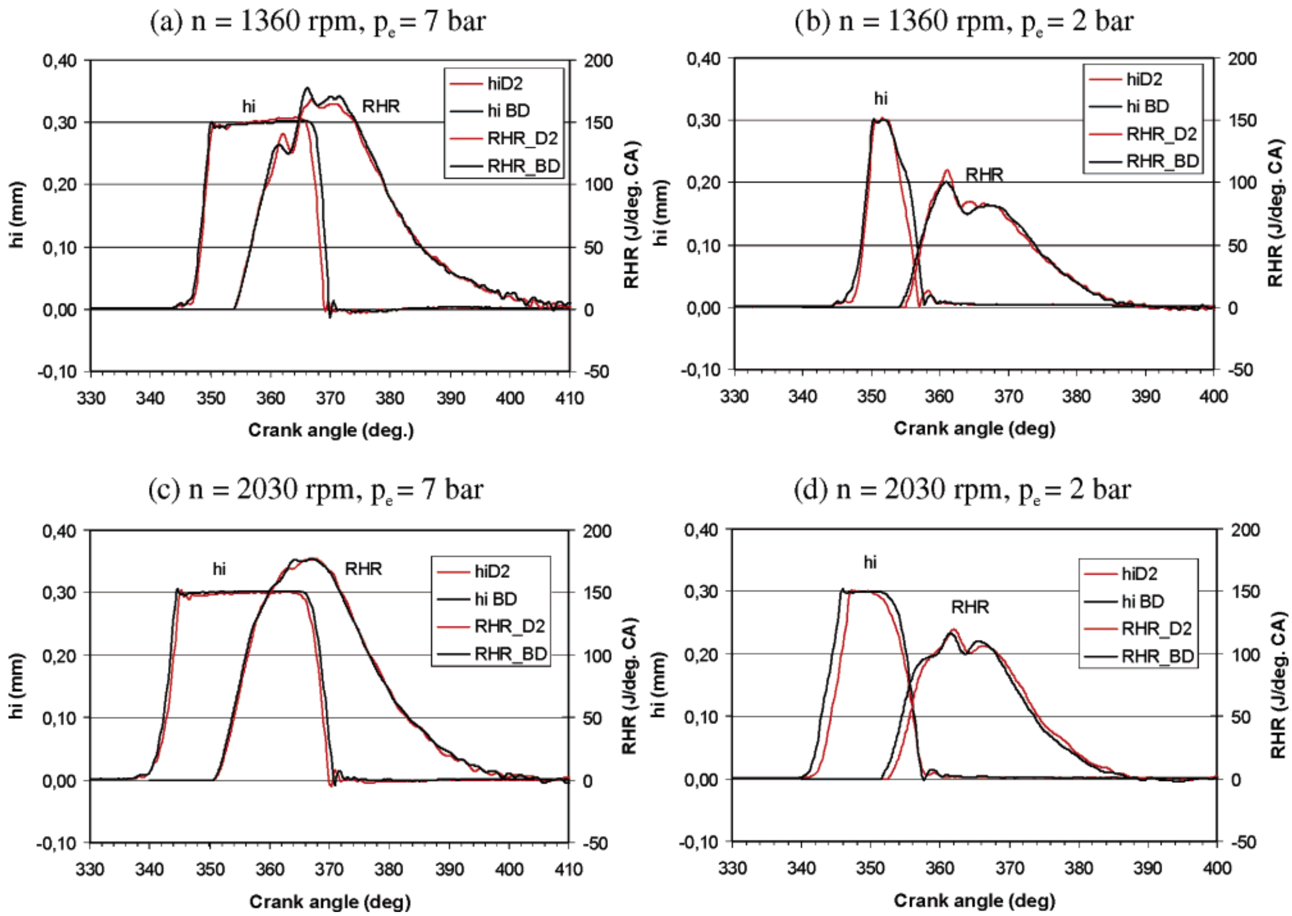

Figure 7. Comparison of the injector needle lift trace (hi) and RHR curves for biodiesel (BD) and D2 fuel in a MAN engine.

The RHR curves of the TAM engine differ substantially for different fuels in comparison with the MAN engine. In addition to the phase shift, there are distinguishable differences in the shape of the RHR curve. Moreover, the phase shift is not caused by the injector needle lift shift only but also by the reduced ignition delay of the biodiesel fuel. This implies that the chemical part of the ignition delay became more influential in the TAM engine, and therefore, the application of biodiesel fuel, which has a higher combustibility (cethane index) than D2 fuel, caused different combustion rates in the initial phase of combustion. The biodiesel fuel ignited quicker; thus, the ignition delay was shorter, and the quantity of premixed reactants decreased, which then reduced the share of fuel burned with the premixed flame and lowered the maximal rate of heat release by more than 40%. The share of combustion with the diffusion flame was therefore higher, and the combustion intensity with the diffusion flame increased.

The expressive portion of the premixed combustion with a high heat release rate is characteristic for D2 fuel at a low engine load ($p_e = 4.5$ bar; Figure 8). Premixed combustion is far less intense for the combustion of biodiesel fuel. This distinguishing difference is caused by different ignition delays of the two fuels, which are given in Table 3. The combustibility (cetane index) of biodiesel fuel is higher, and thus, its ignition delay is shorter. The quantity of premixed reactants that are formed during the ignition delay is small, and the share of fuel that burns with the premixed flame is also small; therefore, the peak rate of heat release at the beginning of combustion is much smaller. Heat-release rates are much lower for both fuels in the region of diffusion combustion following premixed combustion (Figure 8). The diffusion combustion of the biodiesel fuel is more intense at both engine loads. The explanation for this is a higher cetane index and, in particular, the lower oxygen demand of biodiesel fuel, which intensifies the formation of the combustible mixture and its combustion with the diffusion flame. Similar conclusions can be found for the high speed (2000 rpm), low load ($p_e =$ 4.5 bar) regime (Figure 8d).

The portion of premixed combustion is less explicit at high engine loads ($p_e = 9$ bar; parts a and c of Figure 8) and, for biodiesel fuel, is already hardly noticeable at high engine speed $n = 2000$ rpm (Figure 8c). Its share is reduced by 50% (Table 3) for both fuels because of the shorter ignition delay, which is characteristic for high engine loads and turbocharged engines. The reduced share of the premixed flame and its intensity have an influence on the reduction in local temperatures and decelerate NO_x formation. The increase of NO_x emissions with biodiesel fuel is therefore far from that encountered by the MAN engine. The oxygen bonded in the biodiesel fuel however aids the oxidation of fuel molecules and therefore produces lower soot, CO, and HC emissions.

The combustion process is reflected in the pressure trace during combustion. The intense combustion of premixed reactants at the beginning of D2 fuel combustion at a low engine load causes very high-pressure gradients. In-cylinder pressure increases much faster during the combustion of D2 fuel (Figure 8) and reaches its peak earlier, although the biodiesel fuel ignites earlier. Its peak is therefore closer to the top dead center and thus higher than with the combustion of biodiesel fuel (Figure 8). Higher combustion pressure gradients are also observed with the combustion of D2 fuel at high engine loads. The differences in pressure gradients however do not exceed 20%, which shows that the maximum combustion pressure gradient decreases with the engine load. The combustion pressure peak is therefore further from the top dead center, and it coincides with the second

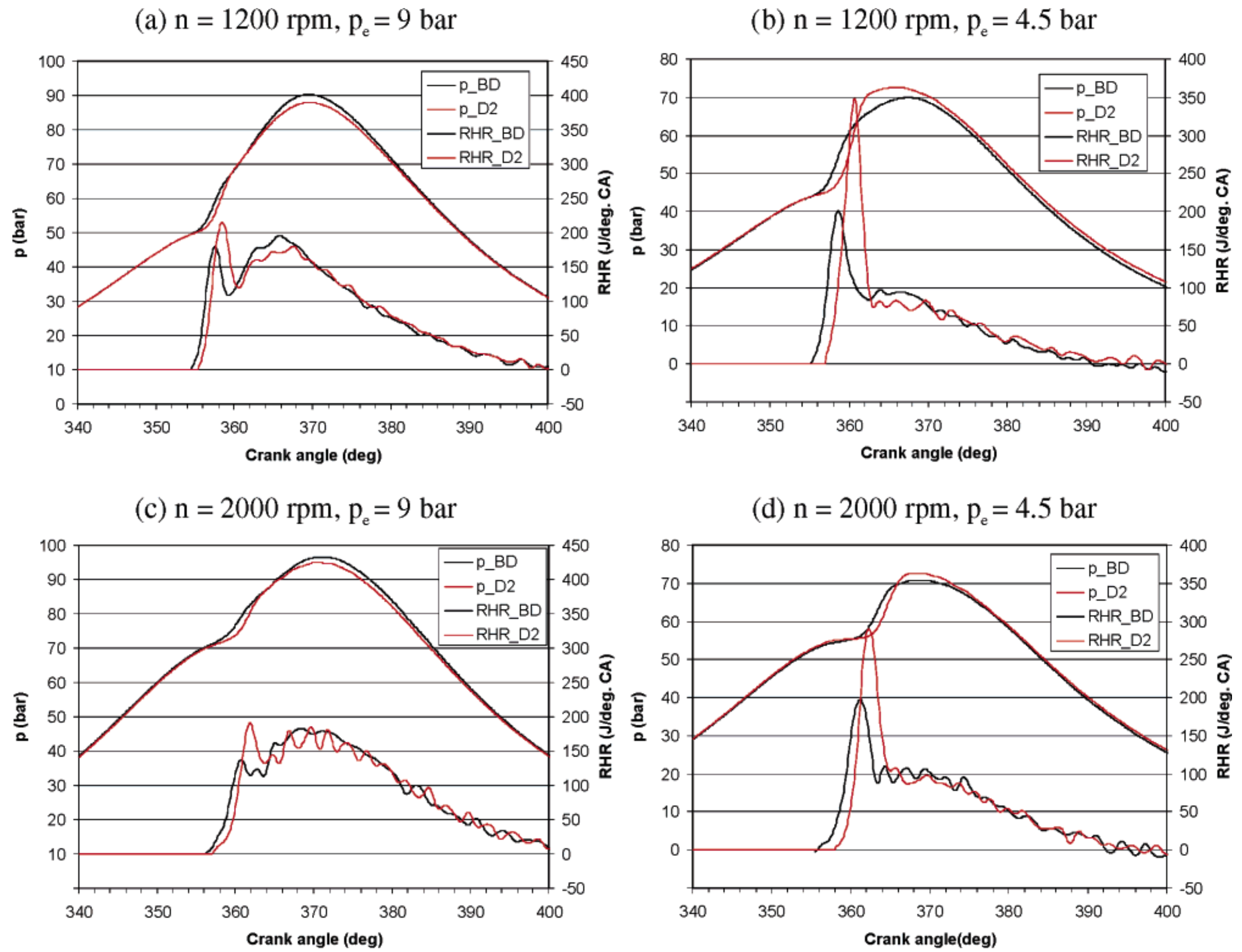

Figure 8. Comparison of the in-cylinder pressure trace and RHR curves for biodiesel (BD) and D2 fuel in a TAM engine.

Table 3. Comparison of the Ignition Delay and Share of Premixed Combustion for Biodiesel and D2 Fuel for a TAM Engine

load p_e (bar)	engine speed (rpm)	ignition delay (ms)		premixed burn (%)	
		D2	BD	D2	BD
4.5	1200	0.97	0.81	43.8	38.0
	1600	0.81	0.74	39.4	36.2
	2000	0.68	0.63	38.2	29.4
9	1200	0.75	0.62	17.3	13.5
	1600	0.69	0.61	16.6	12.5
	2000	0.62	0.57	16.1	9.7

peak of the RHR curve, which is in the region of diffusion combustion (Figure 8). In addition, because the diffusion combustion of biodiesel fuel is more intense, the maximum combustion pressure at a high engine load is higher when the D2 is replaced by biodiesel fuel.

Conclusions

This paper presents experimental results from the research into the influence of biodiesel fuel on the combustion process, emission formation, and engine operational parameters of a diesel engine. This research was performed using two different diesel engines, naturally aspirated MAN and turbocharged TAM engines, both employing different combustion processes. The research focused on determining the influence of a specific combustion process on the measurement results, to ascertain if a generalization of the results is possible or whether they have to be interpreted as specific for specific engines. The injection system setup was purposely optimized for the application of D2 fuel in the MAN engine and for the application of biodiesel fuel in the TAM engine.

The application of biodiesel fuel influences the main engine operational parameters of both engines very similarly. The following conclusions can be made for both engines: (i) maximum engine power and torque are reduced by 5%; (ii) fuel consumption at full load is increased by 8%; (iii) brake effective engine efficiency remains unchanged; and (iv) the equivalent air−fuel ratio is increased.

Combustion processes of both engines differ significantly. Because the combustion process, especially combustible mixture formation, plays a very important role, no generalization of findings can be made. Conclusions for a particular engine are as follows (1) for the M-system combustion (MAN engine): (i) physical processes prevail over chemical ones during ignition delay; and (ii) the combustion process is unaltered; RHR is almost the same for both fuels; and (2) for the multiple-hole nozzle combustion process (TAM engine): (i) the ignition delay is reduced using biodiesel fuel; (ii) the intensity of premixed combustion is reduced by up to 40% using biodiesel fuel; (iii) the intensity and share of diffusion combustion is increased using biodiesel fuel; (iv) the combustion duration is the same for both fuels; and (v) the combustion pressure gradient is reduced using biodiesel fuel, and therefore, the engine operation is smoother and quieter, especially at a low engine load.

Emissions of CO, HC, and soot are reduced under all engine operational regimes in both engines using biodiesel fuel. The reduction of soot emissions is the highest. CO emissions decrease more in the MAN engine, while HC emission reduction is higher in the TAM engine. Specific NO_x emission is doubled in the MAN engine and moreover does not decrease even at partial 70% load. In the TAM engine, specific NO_x emissions decrease at full load and increase slightly over the values for D2 fuel under equal load conditions (70% load).

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