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Vpliv biodizla na zgorevanje in emisijske značilke dizelskih motorjev

The Influence of Biodiesel on the Combustion and Emission Characteristics of a Diesel Engine

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Rezultati raziskav vpliva biodizla in njegovih mešanic z gorivom D2 na delovanje dizelskih motorjev so si pogosto nasprotujoči. Medtem ko velja glede emisij splošna ugotovitev o zmanjšanju koncentracije saj ter zvečanju NOx, pa so si ugotovitve o emisijah nezgorelih oglikovodikov in CO pogosto nasprotujoče. Tudi poročanje o zmanjšanju emisij NOx ni redko. Vzrok za tako različne ugotovitve tiči najverjetneje v različnih razmerah raziskovanja, motorjih z različno obliko zgorevalnega prostora, različnih sistemih za vbrizg goriva in podobno. Da bi analizirali mogoče vplive, smo opravili raziskave na dveh različnih dizelskih motorjih. Izmerili smo obratovalne in emisijske značilke pri delovanju z biodizlom in gorivom D2 ter posneli indikatorske diagrame, s katerimi smo lahko analizirali potek zgorevanja. Rezultati so pokazali, da ugotovitev o vplivu biodizla na potek zgorevanja in emisijske značilke ne smemo posploševati, saj se za oba obravnavana motorja pomembno razlikujejo.

(Ključne besede: bio-goriva, zgorevanje, dizelski motorji)

The results of investigations of the influence of biodiesel fuel and its blends with D2 fuel on the operation of diesel engines are often contradictory. Although there is a common belief that the use of biodiesel reduces soot and increases NOx emissions, the findings for CO and HC emissions tend to vary from case to case. Furthermore, there are even some reports of NOx reduction when using biodiesel. These inconsistent conclusions are caused by the non-uniformity of engine testing. These tests were performed on different engines using different combustion-chamber geometries, different fuel-injection systems, etc. In order to identify and analyze some of the possible reasons we tested two different diesel engines. The operation and emission characteristics of both engines with biodiesel and D2 fuel were measured and compared, and in-cylinder pressure traces were acquired and used for the combustion analyses. 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 generalised, and had to be interpreted as being specific to the particular engine.

(Keywords: bio-fuels, combustion, diesel engine)

0 UVOD

V skladu s smernicami EU naj bi se v prometnem sektorju uporaba biogoriv do leta 2020 zvečala na kar 20 % celotne porabe goriv za pogon motornih vozil. K temu spodbujajo tako okoljski vidiki (zmanjševanje emisij toplogrednih plinov), kakor tudi doseganje večje energetske neodvisnosti članic EU. Doseganje tako visokih ciljev je mogoče z uporabo čistih biogoriv ali njihovih mešanic s običajnimi fosilnimi gorivi. Pri tem je za pogon

0 INTRODUCTION

According to EU guidelines the consumption of bio-fuels for road transportation should represent 20 % of the total fuel consumption by 2020. The use of bio-fuels will be stimulated by environmental aspects (CO_2 emission reduction), as well as by individual EU countries striving to reduce their dependence on imported energy sources. This high percentage of bio-fuels in the total fuel consumption is possible by using neat biomotornih vozil z bencinskimi motorji najprimernejši etanol, za dizelske motorje pa biodizel. Slednji se uporablja že sedaj. Največkrat s 5-odstotnim prostorninskim deležem v mešanici z gorivom D2.

Značilke biodizla, ki jih pridobimo iz rastlinskih olj in odpadnih živalskih maščob s postopkom transestrifikacije se pomembneje ne razlikujejo od značilk goriva D2, zato ga lahko brez večjih posegov uporabimo v dizelskih motorjih. Zaradi njegove nižje kurilnosti se sicer zmanjšata moč in navor motorja, vendar pa lahko njegova sestava pomembno prispeva k zmanjšanju emisij. Biodizel vsebuje dobrih 10 % kisika, zato lahko igra podobno vlogo kakor dodatki gorivu v obliki oksigentov, ki uspešno zavirajo nastanek saj ([1] in [2]). Dodatno prednost pri zmanjševanju emisije delčkov, še posebej tistega dela, ki izvira iz sulfatov, daje biodizlu majhen delež žvepla ([3] in [4]). Delež kisika v biodizlu vpliva tudi na zmanjšanje koncentracije CO in nezgorelih ogljikovodikov (HC) [5], vendar pa krepitev oksidacijskih pojavov pospeši nastajanje dušikovih oksidov NOx in povečanje njihove koncentracije v izpušnih plinih. Sprememb emisijskih značilk ob uporabi biodizla pa ne smemo posploševati, saj nanje pomembno vplivajo tudi oblika zgorevalnega prostora, postopek vbrizgavanja goriva in obremenitev motorja. Tako nekateri avtorji poročajo o znatnem zvečanju emisij NOx in zmanjšanju emisij HC ter CO ([5] in [6]), spet drugi opažajo le zmerno zvečanje NOx ob skoraj nespremenjenih emisijah HC in CO ([3] in [7]), tretji pa zasledijo celo zmanjšanje vseh emisij ([8] in [9]). Razlaga za tako neenotne rezultate raziskav se skriva v dejstvu, da so bile razmere, pri katerih so bile raziskave opravljene, pogosto precej različne.

Da bi ugotovili, kolikšen je lahko vpliv različnih razmer pri raziskovanju na izmerjene emisijske značilke motorja pri delovanju z biodizlom, smo meritve izvedli na dveh različnih dizelskih motorjih TAM BF4L515C in MAN D2566 MUM. Osnovne specifikacije obeh motorjev so podane v preglednici 1. Izbrana motorja se v osnovnih geometrijskih izmerah skoraj ne razlikujeta, pomembne razlike pa so v postopku zgorevanja, načinu izmenjave delovne snovi in izvedbi hlajenja motorja.

fuels or by the application of their blends with standard fuels. Ethanol is already used as a substitute for gasoline in gasoline engines and 5 % biodiesel blends with D2 fuel are used in diesel engines.

A process called transesterification is used for the production of biodiesel, the characteristics of which are very similar to those of D2 fuel. No special engine modifications are, therefore, necessary when D2 fuel is replaced by biodiesel. Although there is a reduction of the engine's torque and power due to the lower calorific value of biodiesel, its chemical composition may significantly effect the reduction of emissions. Biodiesel contains more than 10 wt% oxygen and the addition of oxygen-containing hydrocarbons to diesel fuel has been shown to have significant potential for reducing particulate emissions ([1] and [2]). The low sulphur content of biodiesel reduces particulate emissions too, particularly the particulates associated with sulphates [3]. Also, a sulphur-sensitive exhaust-gas aftertreatment may be used to reduce other emissions from the exhaust gas [4]. The oxygen content may influence the reduction of CO and HC emissions [5], too. However, enhanced combustion performances may intensify the combustion and accelerate NOx formation, thus increasing its emissions. An extensive literature review proved that the findings on the influence of biodiesel 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 the combustion and the formation of emissions. Some authors ([5] and 6]) report very high increases of NOx emissions, the reduction of CO, and unburned HC emissions when using biodiesel fuel, while others have experienced just moderate increases in NOx emissions with unchanged CO and HC emissions ([3] and [7]), or even a reduction in all emissions ([8] and [9]). These, somehow contradictory, conclusions are caused by the non-uniformity of the engine testing.

A comprehensive study was performed in order to establish how much influence different test conditions have on the engine-emission characteristics when operating with biodiesel fuel. Two diesel engines, TAM BF4L515C and MAN D2566 MUM, were used. Both test-engine specifications are given in Table 1. Although both engines have similar geometries (bore, stroke), some important characteristics, like the combustion process, the gas-exchange process and the cooling system differ significantly.

Preglednica 1. *Podatki o testnih motorjih*
Table 1. *Test engine specifications*

motor engine	MAN D2566 MUM	TAM BF4L515C
izmenjava delovne snovi gas exchange process	sesalna izvedba naturally aspirated	tlačno polnjenje turbocharged
hlajenje cooling	vodno water cooling	zračno air cooling
zgorevalni postopek combustion process	M – postopek M - system	zgorevanje v zračnem vrtincu combustion in air swirl
število valjev number of cylinders	6	4
premer × gib bata bore × stroke	125 mm × 155 mm	125 mm × 145 mm
gibna prostornina total displacement	11413 ccm	7117 ccm
kompresijsko razmerje compression ratio	17,5	15,8
dobava goriva fueling	neposredni vbrizg direct injection	direktni vbrizg direct injection
tlačilka fuel pump	BOSCH PES6A95D410LS2542	BOSCH PES6P120A72
šoba nozzle	BOSCH DLLA 5S834	BOSCH DLLA 148S
izvrtine šobe nozzle holes	1 x Φ = 0,68 mm	4 x Φ = 0,375 mm
statični kot predvbrizga injection timing	23 °RG (°CA)	16 °RG (°CA)

Postopka zgorevanja se razlikujeta že v fazi priprave gorljive zmesi zrak - gorivo. V motorju TAM poteka zgorevanje v zračnem vrtincu. Gorivo se pri tlaku preko 800 bar vbrizga skozi brizgalo s štirimi izvrtinami v razmeroma plitvo zgorevalno komoro v čelu bata. Zračni vrtinec, ki nastaja med polnjenjem valja skozi tangentno oblikovane polnilne kanale, zagotavlja hitro izhlapevanje drobno razpršenega goriva in mešanje z zrakom ter preprečuje sedanje goriva na stene zgorevalne komore. V motorju MAN je uporabljen t.i. postopek zgorevanja M. Gorivo se pri tlaku do 500 bar vbrizga skozi brizgalo z eno samo izvrtino. Razmeroma strnjen curek goriva zadene stene krogelno oblikovane globoke zgorevalne komore v čelu bata. Kar 95 odstotkov goriva se v obliki tankega sloja razlije po stenah zgorevalne komore in potrebna je še večja intenzivnost zračnega vrtinca, s katerim se krepi izhlapevanje sloja goriva in njegovo mešanje z zrakom. Ugotovimo torej lahko, da se oba postopka zgorevanja močno razlikujeta. Medtem ko sta v primeru TAM-ovega motorja vpliv predplamenih fizikalnih in kemijskih pojavov enakovredna, pa v primeru MAN-ovega motorja

The combustion processes are completely different, starting with the combustible mixture formation. The TAM engine is characterised by combustion in an air swirl. The fuel is injected at a pressure of up to 80 MPa through a four-hole injector into the shallow omega-shaped combustion chamber positioned in the piston crown. The high-intensity air swirl induced by the tangentially shaped intake valve channel enables the fast evaporation of highly atomised fuel and the fast mixing of fuel vapours with air, thus preventing the impingement of the fuel on the walls of the combustion chamber. The MAN engine uses M-system combustion. The fuel is injected at a pressure of less than 50 MPa through a single-hole injector nozzle, which injects fuel in the form of a compact jet against the wall of a spherical piston bowl. More than 95 % of the fuel hits the walls of the combustion chamber and forms a film. Thus, an air swirl with a much higher intensity is necessary for the fuel to vaporize and form a combustible mixture with the air. It can be concluded that both combustion processes differ significantly. In a TAM engine there is an equal influence of the pre-burn physical and chemical reactions on the combustion process, while the physical processes of fuel film fizikalni pojavi izhlapevanja filma goriva in mešanja z zrakom prevladajo pojave kemijske kinetike.

Med obema motorjema obstajajo tudi pomembne razlike v postopku izmenjave delovne snovi. TAM-ov motor je tlačno polnjen in ima priključen hladilnik polnilnega zraka. Tlaki polnjenja zato presegajo 2 bar, temperature pa kljub hlajenju 50 °C. MAN-ov motor je sesalne izvedbe, tlak in temperatura polnjenja sta enaka razmeram v okolici. Masa zraka, ki napolni valj, je zato v primeru TAM-ovega motorja neprimerno večja, kar omogoča doseganje večjih presežkov zraka, potrebnega za zgorevanje.

TAM-ov motor je hlajen z zrakom, medtem ko ima MAN-ov motor vodno hlajenje, zato spremembe obremenitve in predvsem vrtilne frekvence precej manj vplivajo na temperaturo v valju motorja in predvsem na razmere v zgorevalni komori v dobi zakasnitve vžiga.

V nadaljevanju prikazujemo rezultate eksperimentalnih raziskav vpliva izbranega goriva na postopke zgorevanja in nastanek škodljivih snovi v obeh motorjih. Z namenom, da bi upoštevali tudi vpliv nastavitvte sistema za dovod goriva, ki ga mnogi avtorji enostavno prezrejo, smo nastavitev sistema za dovod goriva v primeru TAM-ovega motorja prilagodili čistemu biodizlu v primeru MAN-ovega motorja pa gorivu D2.

1 EMISIJSKE ZNAČILKE

Meritve na motorju so potekale v preizkuševališču z zavornim dinamometrom, ki omogoča merjenje obremenitvenih in hitrostnih značilk motorja. Poleg osnovnih obratovalnih parametrov motorja, kakor so vrtilna frekvenca motorja in turbokompresorja, navor motorja, pretok zraka in goriva ter višina značilnih temperatur in tlakov v polnilnem in izpušnem sistemu, smo merili tudi koncentracijo plinskih deležev in saj v izpušnih plinih. Koncentracijo NOx smo izmerili s kemoluminiscenčno metodo, koncentracijo nezgorelih ogljikovodikov HC s plamensko ionizacijskim detektorjem, stopnjo sajavosti z AVL-ovim merilnikom, koncentracijo CO z metodo absorbcije nedisperzirane infrardeče svetlobe in koncentracijo O_2 z ZrO_2 zaznavalom.

Uporaba biodizla nima vpliva na pretok zraka v sesalnem motorju, zato se zaradi manjše

evaporation and fuel vapour-air mixing dominate over the chemical kinetic processes for any combustion in the MAN engine.

There are some influential differences between both test engines in terms of the gas-exchange process. The TAM engine is turbocharged and equipped with an intercooler. The intake pressures, therefore, exceed 2 bar, and the intake temperature is 50 °C. The MAN engine is naturally aspirated. The intake pressures and temperatures are, therefore, equal to the ambient conditions. Thus, the amount of trapped fresh air in the cylinder is much higher in the TAM engine, which enables higher excesses of air to be used.

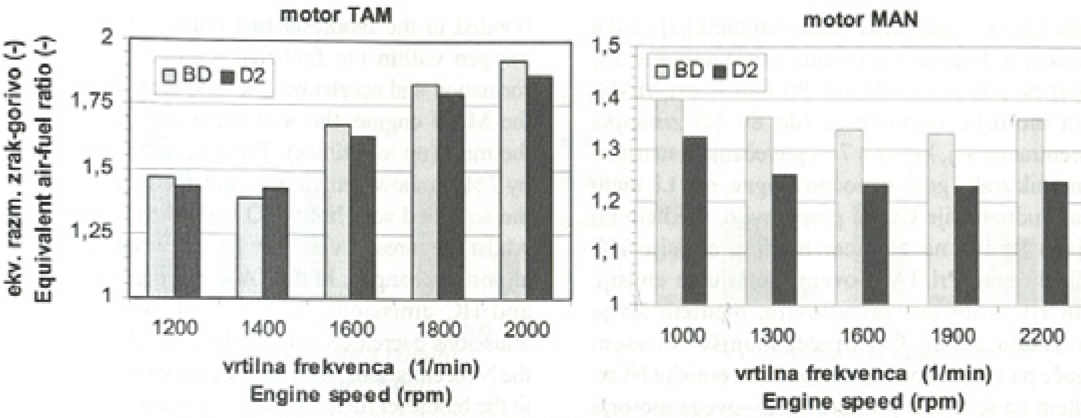
The TAM engine is air cooled, while the MAN engine uses water cooling, which ensures a smaller influence of the engine speed and load on the in-cylinder temperature and other in-cylinder conditions during the combustion delay interval.

The results of this experimental investigation into biodiesel fuel's influence on the combustion processes and emission formations in both test engines are presented in the following. In order to consider any possible differences in fuel-injection strategies, often neglected by some authors, the injection system set-up was purposely optimised for the application of the biodiesel fuel in a TAM engine and for the application of D2 fuel in a MAN engine.

1 EMISSION CHARACTERISTICS

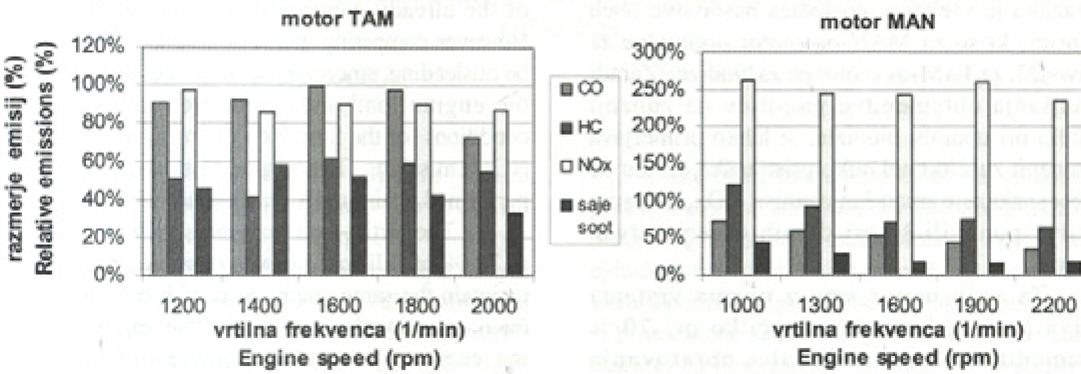
Engine tests were performed on a test bed using a dynamometer that makes it possible to measure the engine's speed and load characteristics. In addition to the basic operationing parameters of the engine, such as engine speed, turbocharger speed, engine load, air mass flow, fuel consumption, pressure and temperature in both the intake and exhaust systems, the concentration of gaseous components and particulates in the exhaust gases was also measured. The NOx concentration was measured using a chemiluminescence analyzer; a flame ionization detector was used for unburned hydro-carbon measurement; the particulates were monitored using an AVL smoke meter; the concentration of CO was measured with a non-dispersive infrared analyzer; and a ZrO_2 sensor was used for the oxygen concentration-measurement.

The application of biodiesel fuel does not affect the mass flow of air through the naturally



Sl.1. *Vpliv goriva (biodizel DB, D2) na ustrezni razmernik zrak - gorivo*

Fig. 1. *Influence of the applied fuel (biodiesel BD and D2) on the equivalent air-fuel ratio*



Sl. 2. *Relativna sprememba emisij, podana kot razmerje med specifičnimi emisijami, izmerjenimi z biodizlom in gorivom D2 – zunanja značilka*

Fig. 2. *Relative emissions expressed as a ratio of specific emissions with biodiesel and D2 fuel – full load*

potrebe po kisiku ustrezni razmernik zrak - gorivo v MAN-ovem motorju poveča v povprečju za 7 odstotkov (sl. 1). Tudi v TAM-ovem tlačno polnjenem motorju lahko na ta račun opazimo majhno zvečanje ustreznega razmernika zrak - gorivo (do 2%). Šestodstotno zmanjšanje moči motorja z uporabo biodizla [10] namreč v tem primeru zmanjša tudi moč plinske turbine, zato se vrtilna frekvenca turbokompresorja in pretok zraka zmanjšata, kar v okolici največjega navora (sl. 1; n = 1400 min^{-1}) privede celo do 2-odstotnega zmanjšanja ustreznega razmernika zrak - gorivo.

Slika 2 prikazuje relativno spremembo emisij posameznega motorja zaradi uporabe biodizla. Pri tem velja spomniti, da so nastavitve TAM-ovega motorja optimirane za delovanje z biodizlom, medtem ko so nastavitve MAN-ovega motorja najprimernejše za gorivo D2. Osnovna ugotovitev je zmanjšanje emisij CO, HC in saj z uporabo biodizla, kar je pričakovano zaradi 10 %

aspirated engine. The equivalent air-fuel ratio in the MAN engine was, therefore, increased by 7 % (Fig. 1) due to the lower oxygen demand of the biodiesel fuel. On the other hand the equivalent air-fuel ratio increased only slightly in the turbocharged TAM engine (Fig. 1). The reduction of engine power [10] also influenced the decrease of the turbocharger speed as air mass flows by 4 % and the resulting increase in the air-fuel ratio was just 2 %. Moreover, at peak torque (n = 1400 rpm), a 2 % reduction in the air-fuel ratio was observed.

Figure 2 shows the relative change of the specific emissions of both engines due to the application of biodiesel. It should be noted that the injection system set-up was optimised 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 when using biodiesel fuel containing more than 10 % of oxygen is characteristic for both engines. Oxygen deleža kisika v gorivu, ki zniža primanjkljaj kisika v območjih, bogatih z gorivom, zavre nastanek saj in pospeši pojave oksidacije. Pri tem se pri MAN-ovem motorju najmočneje (do 80 %) zmanjša koncentracija saj, ker se s 7 % povečanjem ustrezni razmernik zrak - gorivo močno dvigne, nad t.i. mejo dima. Tudi emisije CO se prepolovijo, medtem ko večjega vpliva na že sicer majhne emisije HC biodizel nima. Pri TAM-ovem motorju se emisije saj in HC približno prepolovijo, medtem ko je zmanjšanje emisij CO precej manjše. Povsem drugače pa vpliva uporaba biodizla na emisije NOx. Medtem ko se le-te v primeru MAN-ovega motorja povečajo za 250 %, pa ostanejo pri TAM-ovem motorju enake, oziroma se celo nekoliko zmanjšajo. Ta razlika je vsekakor posledica nastavitve obeh motorjev, ki so za MAN-ov motor optimalne za gorivo D2, za TAM-ov motor pa za biodizel. Zaradi zmanjšanja obremenitve motorjev na zunanji značilki pri uporabi biodizla, je lahko primerjava na zunanji značilki nekoliko pristranska, na kar še posebej nakazuje zmanjšanje emisij NOx, zato smo meritve ponovili še pri delnih obremenitvah motorja.

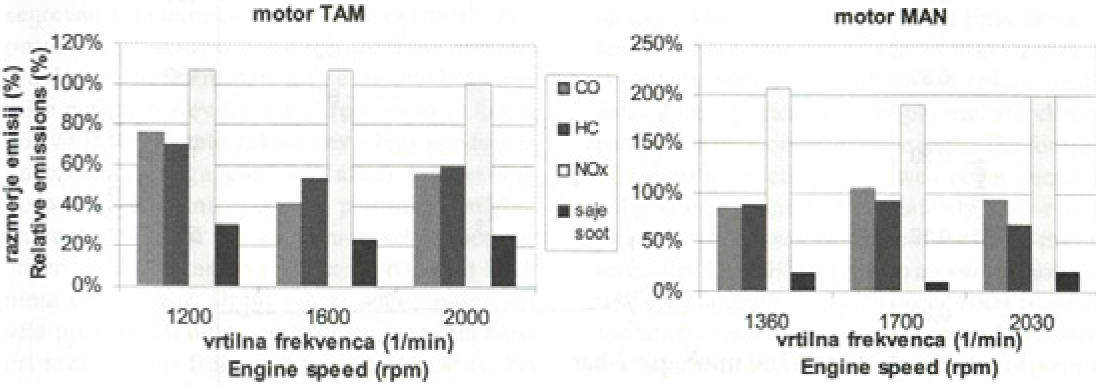
Za vsak motor smo z obema vrstama goriva posneli hitrostno značilko pri 70-% obremenitvi. Osnovni kazalci obratovanja motorja, to sta navor in moč, se pri tem skoraj ne razlikujejo. Razlike v pretoku zraka so v mejah merilne negotovosti. Ponovno pa je z biodizlom zaradi manjše potrebe po kisiku presežek zraka za 2,5 % večji, tokrat pri obeh motorjih, saj pri enaki moči motorja biodizel ne vpliva na delovanje turbokompresorja.

Spremembo specifičnih emisij pri 70-% obremenitvi prikazuje slika 3. Ponovno je za MAN-ov motor značilno občutno zmanjšanje emisij saj, medtem ko je zmanjšanje emisij CO in HC z biodizlom v povprečju le do 10 %. Emisije NOx pa so se za biodizelsko gorivo ponovno podvojile. Povsem drugačna pa je slika pri TAM-ovem motorju. Emisije NOx so do 7 % večje za biodizel, medtem ko je bilo na zunanji značilki prav nasprotno. To potrjuje pravilnost hipoteze, da je treba izvesti primerjavo goriv z vidika emisij v enakih razmerah, česar zunanja značilka ne zagotavlja. Vpliv biodizla na zmanjšanje emisij HC je podoben kakor na zunanji značilki, medtem ko je zmanjšanje emisij CO in saj z biodizlom občutnejše kakor na zunanji značilki.

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, the soot emissions were reduced the 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, whilst the already very low HC emissions remained almost unchanged. In the TAM engine, both the soot and HC emissions were halved, whilst the CO emissions decreased only moderately. With regard to the NOx emissions, both engines responded differently to the biodiesel fuel. The NOx 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 set-up. However, comparing engine emissions at full load may be misleading, since the use of biodiesel fuel reduces the engine load and, therefore, moderates any conditions for the formation of emissions, especially NOx emissions. The engine tests were, therefore, performed again under partial-load conditions.

The partial-load characteristics were measured at 70 % of full load. It was possible, therefore, to maintain the same engine load with both fuels. The main operational parameters of the engine, such as the engine's torque and power did not differ significantly when the D2 fuel was replaced by the biodiesel. The differences in air mass flow were within the measurement uncertainty interval for the naturally aspirated MAN as well as for the turbocharged TAM engine. The air-fuel ratio was again higher by approximately 2.5 % when biodiesel was used, this time for both engines, since the turbocharger operation was unaffected by the engine-load reduction.

The relative change of the specific engine emissions under partial load is presented in Fig. 3. A significant reduction in soot emissions with the biodiesel fuel was again observed for the MAN engine, while the CO and HC emissions reduced, on average, by only 10 %. The NOx emissions increased by 100 %. Quite different results were obtained for the TAM engine. In contrast with full load, the NOx 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 are not fulfilled at full load. The reduction of HC emissions due to the application of biodiesel fuel was similar to the full load, while the CO and soot emissions were reduced much more at partial load.



Sl. 3. *Relativna sprememba emisij, podana kot razmerje med specifičnimi emisijami, izmerjenimi z biodizlom in gorivom D2 – 70 % obremenitev*

Fig. 3. *Relative emissions expressed as a ratio of specific emissions with biodiesel and D2 fuel – partial (70%) load*

2 VPLIV BIODIZLA NA ZGOREVANJE

Potek sproščanja toplote med zgorevanjem lahko določimo z računsko obdelavo indikatorskega diagrama motorja. Zato smo izmerili potek tlaka v valju in gib igle vbrizgalne šobe na prvem valju motorja. Pri tem smo za merjenje tlaka uporabili piezoelektrično zaznavalo, za gib igle induktivno zaznavalo in za merjenje lege ročične gredi motorja optični kodirnik. Vse tri spremenljivke smo izmerili z računalniško podprtim merilnim sistemom s frekvenco zajemanja f_{zaj}= 100 kHz.

Za izračun poteka sproščanja toplote (KST) smo uporabili enotni brezrazsežni model zgorevanja [11]. Preračune smo za oba motorja izvedli pri različnih delnih obremenitvah, pri katerih posamezen motor dosega enake delovne parametre z obema vrstama goriv. Že uvodoma smo dejali, da se postopek zgorevanja v obeh motorjih razlikuje. Zato prikazujemo rezultate v nadaljevanju za vsak motor posebej.

2.1 Vpliv biodizla na zgorevanje v motorju MAN

Za prikaz smo izbrali dva skrajna primera delovnih režimov, majhno obremenitev pri nizki vrtilni frekvenci motorja (sl. 4 a) in veliko obremenitev motorja pri visoki vrtilni frekvenci (sl. 4 b). Iz primerjave rezultatov, dobljenih za obe

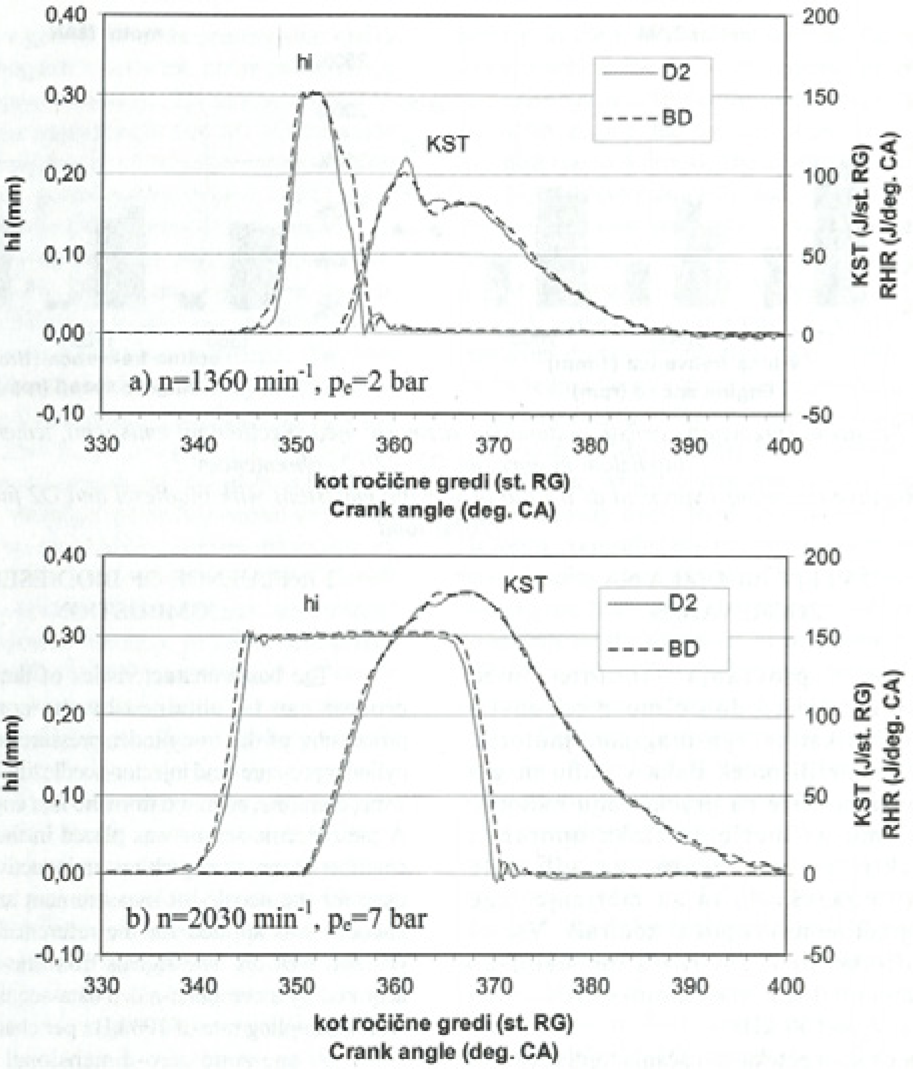
2 INFLUENCE OF BIODIESEL ON COMBUSTION

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 the needle-lift measurement and an optical encoder was applied for the reference crank-angle position pick up. The signals from the sensors were acquired by a computer-aided data-acquisition system with a sampling rate of 100 kHz per channel.

A one-zone zero-dimensional combustion model [11] was used for the prediction of the combustion heat-release rates, the so-called rate of heat release (RHR) curves. The pressure traces acquired under different partial-load engine operating conditions, where the same engine load was obtained with both fuels, were processed. As stated in the introduction, the combustion processes of both tested engines differ significantly, thus the results of the RHR analysis are presented separately for each engine.

2.1 Influence of biodiesel on combustion in the MAN engine

Two extreme engine-operating regimes were selected for the presentation, a low engine speed at low load (Fig. 4a) and a high engine speed at high load (Fig. 4 b). Figure 4 shows that both fuels produce almost identical RHR curves. There is,



Sl. 4. *Primerjava poteka dviga igle vbrizgalne šobe (hi) in KST za biodizel (BD) in gorivo D2 – motor MAN*

Fig. 4. *Comparison of injector needle lift trace (hi) and RHR (KST) curves for biodiesel (BD) and D2 fuel – MAN engine*

gorivi, sledi, da se KST za obe gorivi skoraj povsem ujemajo. Opazimo lahko le majhen fazni odmik, ki se ujema s faznim odmikom med gibom igle vbrizgalne šobe. Začetek vbrizgavanja je zgodnejši, kadar je gorivo biodizel, ker pa je za enak srednji dejanski tlak motorja potrebna večja količina biodizla (10 % nižja kurilnost) je trajanje vbrizgavanja daljše približno 2 °RG na obeh režimih. Pri veliki obremenitvi in vrtilni frekvenci motorja (sl. 4 b) je ujemanje KST skoraj popolno. To nakazuje na dejstvo, da med zakasnitvijo vžiga, ki ga sestavljata fizikalni del, vezan na pojave uparjanja goriva, mešanja z zrakom in

however, a small phase shift, which corresponds to the phase shift of the injector-needle lift traces. The injection starts earlier with the biodiesel fuel and the injection duration is approximately 2 °CA longer under all regimes, since the amount of injected biodiesel fuel has to be 10 % greater at the same engine load due to its lower calorific value. The RHR curves almost completely agree for the high-speed and high-load regime (Fig. 4 b). This implies that physical processes prevail during the ignition delay. The ignition delay, which consists of the physical part, influenced by fuel evaporation, fuel–air mixing and the mixture-heating processes, and the chemical part, connected with segrevanja do temperature vžiga, in kemijski del, povezan s samim vžigom goriva, močno prevladuje fizikalni del, saj se biodizel, ki ima višje cetansko število, kaj hitreje ne vžge kakor gorivo D2 in je zato zakasnitev vžiga neodvisna od uporabljenega goriva. Zaradi razmeroma počasnih fizikalnih pojavov priprave gorljive zmesi zraka in par goriva, je nastanek homogene zmesi v dobi zakasnitve vžiga zavrta, zato KST nima dveh vrhov. Drugi vrh se začne pojavljati šele pri manjših obremenitvah in je najmočnejši pri nizki vrtilni frekvenci motorja (sl. 4 a). Pri tem je delež zgorevanja poprej pomešanih reaktantov le malenkostno manjši za biodizel, kar pa lahko pripišemo tudi negotovosti merjenja in postopka glajenja indikatorskega diagrama. Zato lahko z dokaj veliko verjetnostjo sklenemo, da uporaba biodizla v MAN-ovem motorju s postopkom zgorevanja M ne vpliva na hitrost sproščanja toplote (KST), da pa zagotavlja 10-odstotni delež kisika v gorivu neprimerno boljše pogoje za popolnejšo oksidacijo molekul goriva (zato manjše emisije CO, HC in saj), kar pa ustvarja višje lokalne temperature in pospeši nastanek NOx.

2.2 Vpliv biodizla na zgorevanje v motorju TAM

Ponovno smo za prikaz (sl. 5) izbrali dva skrajna delovna režima. KST za biodizel in gorivo D2 se precej manj ujemajo kakor v primeru MAN-ovega motorja. Ob faznem odmiku se javljajo tudi pomembne razlike v obliki KST. Fazni odmik pa ni več le posledica odmika med gibom igle vbrizgalne šobe, ampak tudi skrajšane dobe zakasnitve vžiga. To pa pomeni, da je postal kemijski delež zakasnitve vžiga pomembnejši, zaradi česar se z uporabo biodizla z višjim cetanskim številom pojavijo pomembne razlike v prvem delu KST. Hitrejši vžig biodizla, torej krajša zakasnitev vžiga, zniža delež homogenega zgorevanja poprej pomešanih reaktantov in skoraj prepolovi najvišjo hitrost homogenega zgorevanja. Zato pa se poveča delež difuznega zgorevanja, ki poteka z večjo jakostjo.

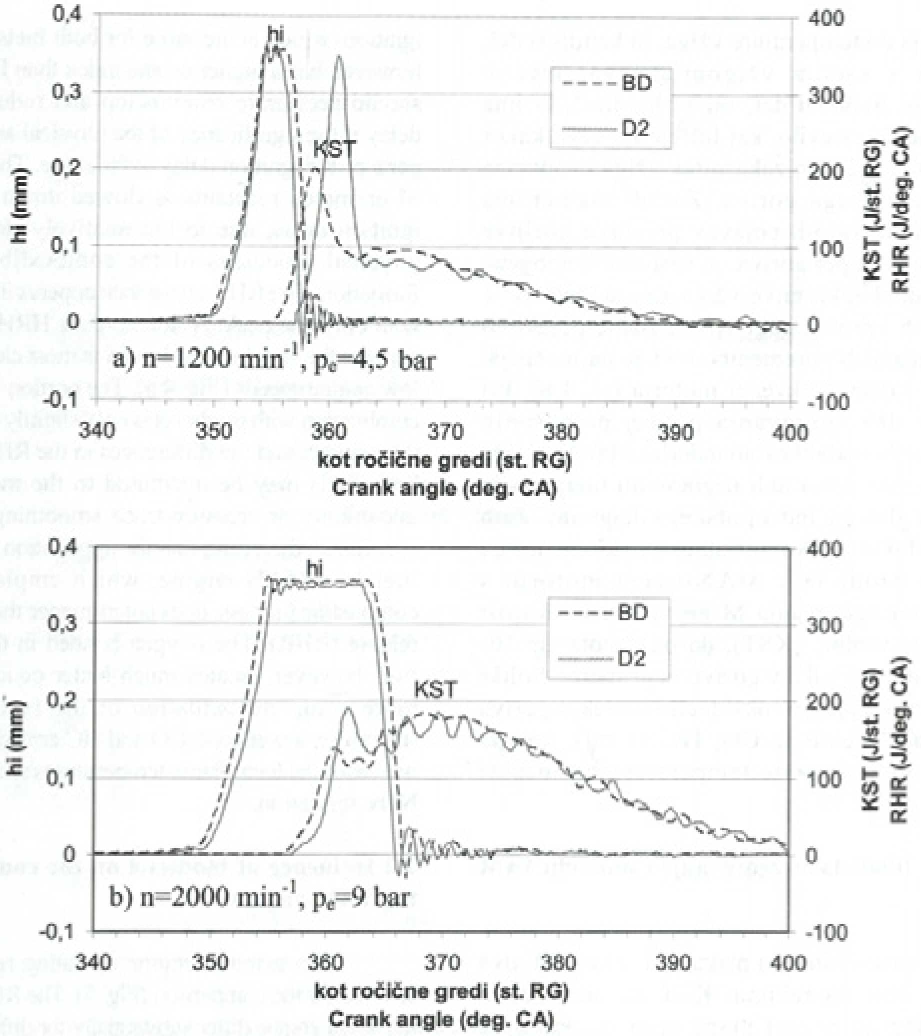
Pri manjši obremenitvi (sl. 5 a) je za gorivo D2 značilno izrazito področje homogenega zgorevanja z velikimi hitrostmi zgorevanja. Javlja se tudi pri biodizlu, a je

ignition, which is the same for both fuels. Biodiesel, however, has a higher cetane index than D2 fuel, and should accelerate combustion and reduce ignition delay if the significance of the physical and chemical parts of the ignition delay is the same. The formation of premixed reactants is slowed down during the ignition delay, due to the relatively slow-running physical processes of the combustible-mixture formation. The RHR curve then appears in most cases with only one peak. A double-peak HRH curve only appears for very low loads, and is most clearly seen at low engine speeds (Fig. 4 a). The portion of premixed combustion with biodiesel is only slightly lower under this regime, and the differences in the RHR curve for both fuels may be attributed to the measurement uncertainty or pressure-trace smoothing. It can be concluded, therefore, that the application of biodiesel fuel in a MAN engine, which employs the M-combustion process, does not influence the rate of heat release (RHR). The oxygen bonded in the biodiesel fuel, however, creates much better conditions for a more complete oxidation of the fuel molecules (therefore, lower soot, CO and HC emissions), which increases the local flame temperatures and accelerates NOx formation.

2.2 Influence of biodiesel on the combustion in the TAM engine

Two extreme engine operating regimes were selected for the comparison (Fig. 5). The RHR curves of the TAM engine differ substantially for different fuels in comparison to the MAN engine. In addition to the phase shift, there are distinguishable differences in the RHR curve's shape. 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, the quantity of premixed reactants decreased, which then reduced the share of fuel burned with the premixed flame, and lowered the maximum rate of heat release by almost 50 %. The share of combustion with 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



Sl. 5. *Primerjava poteka dviga igle vbrizgalne šobe (hi) in KST za biodizel (BD) in gorivo D2 – motor TAM*

Fig. 5. *Comparison of injector needle lift trace (hi) and RHR (KST) curves for biodiesel (BD) and D2 fuel – TAM engine*

njegova jakost manjša. Razlika je posledica različnih zakasnitev vžiga obeh goriv. Zaradi večje vnetljivosti biodizla so zakasnitve vžiga krajše, manjša je količina poprej pomešanih reaktantov, ki nastajajo v času zakasnitve vžiga, zato je delež goriva, ki zgori s homogenim plamenom tudi manjši, predvsem pa so v tej začetni fazi manjše hitrosti zgorevanja. V področju difuzijskega zgorevanja, ki sledi, so hitrosti zgorevanja za obe gorivi precej manjše (sl. 5 a) in pri obeh obremenitvah je difuzijsko zgorevanje biodizla močnejše, kar lahko pojasnimo z nekoliko boljšo vnetljivostjo biodizla, predvsem pa z dejstvom, da je zaradi

characteristic for D2 fuel under low engine loads (Fig. 5 a). The premixed combustion is far less intense for the combustion of biodiesel. This distinguishing difference is caused by the different ignition delays of the two fuels. The combustibility (cetane index) of biodiesel 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 a premixed flame is also small; therefore, the peak rate of heat release at the beginning of combustion is much smaller. The heat-release rates are much lower for both fuels in the region of the diffusion combustion following the premixed combustion (Fig. 5 a). The diffusion combustion of manjše potrebe po kisiku nastajanje gorljive zmesi v zgorevalnem prostoru hitrejše.

Pri večjih obremenitvah (sl. 5 b) postaja homogeno zgorevanje vse manj izrazito in ga pri veliki vrtilni frekvenci komaj še opazimo. Njegov delež se prepolovi. To je posledica zmanjšanja zakasnitve vžiga, ki se pri povečevanju obremenitve tlačno polnjenega TAM-ovega motorja zmanjša. Zmanjšanje deleža homogenega zgorevanja in njegove jakosti pa pomembno vpliva na znižanje lokalnih temperatur in nastanek NOx. Zato se v tem primeru skupne emisije NOx ne povečajo tako močno kakor v primeru MAN-ovega motorja in ostajajo na ravni emisij NOx ob uporabi goriva D2, medtem ko povečan delež kisika v biodizlu izboljša oksidacijske pogoje in zmanjša koncentracije CO, HC in saj v izpušnih plinih (sl. 3).

3 SKLEP

V prispevku so prikazani rezultati raziskav vpliva biodizla na postopek zgorevanja v dizelskem motorju, vpliva na osnovne parametre delovanja motorja in na emisijo škodljivih snovi. Raziskave smo izvedli na dveh dizelskih motorjih z različnima postopkoma zgorevanja, na sesalnem motorju MAN in tlačno polnjenem motorju TAM. Pri tem smo nastavitve sistema za dovod goriva na motorju MAN prilagodili uporabi D2 goriva, na motorju TAM pa biodizlu. Ugotovitve, ki slede iz primerjave z rezultati, dobljenimi z gorivom D2, so naslednje:

a) emisije

- z uporabo biodizla se emisije CO, HC in saj zmanjšajo na vseh obratovalnih režimih in pri obeh motorjih. Pri tem se najmočneje zmanjšajo emisije saj. Zmanjšanje emisij CO je večje pri MAN-ovem motorju, zmanjšanje HC pa pri TAM-ovem motorju
- emisije NOx pri MAN-ovem motorju se z uporabo biodizla podvojijo in se ne zmanjšajo niti pri delni 70 % obremenitvi, pri TAM-ovem motorju pa so z uporabo biodizla na zunanji značilki zaradi nižjih obremenitev emisije NOx manjše, medtem ko pa se pri izenačenih pogojih delovanja (70% obremenitev) dvignejo nad vrednosti za gorivo D2.

b) postopek zgorevanja

Vpliv je v največji meri odvisen od postopka nastanka zmesi gorivo - zrak, zato občih ugotovitev,

the biodiesel is more intensive at both engine loads. The explanation for this is a higher cetane index, and, in particular, the lower oxygen demand of biodiesel, which intensifies the formation of a combustible mixture and its combustion with the diffusion flame.

The portion of premixed combustion is less explicit at high engine loads (Fig. 5 b), and for biodiesel it is already hardly noticeable. Its share is reduced by 50 % for both fuels due to 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 NOx formation. The increase of NOx 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 (Fig. 3).

3 CONCLUSION

This paper presents experimental results from research on the influence of biodiesel fuel on the combustion process, emission formation and engine operating parameters of a diesel engine. This research was performed using naturally aspirated MAN and turbocharged TAM engines, both employing different combustion processes. The injection system set-up was purposely optimised for the application of D2 fuel in the MAN engine and for the application of biodiesel fuel in the TAM engine. The following conclusions can be made from a comparison of those results obtained for both biodiesel and D2 fuels:

a) emissions

- the emissions of CO, HC and soot are reduced under all engine operating regimes in both engines when the biodiesel fuel is used. 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.
- the NOx emissions are doubled in the MAN engine and, moreover, do not decrease even under a partial 70% load when the biodiesel fuel is applied. In the TAM engine, specific NOx emissions decrease at full load and increase slightly over the values for D2 fuel under equal load conditions (70 % load) when the biodiesel fuel is applied.

b) combustion process

The combustion process, especially combustible mixture formation, plays a very important role, thus, no

razen da se poveča ustrezni razmernik zrak – gorivo, ne moremo dati;
- za postopek M (motor MAN) velja:
  - v dobi zakasnitve vžiga in med zgorevanjem prevladujejo fizikalni pojavi nad kemijskimi,
  - potek zgorevanja se ne spremeni – KST ostaja skoraj nespremenjena za obe gorivi;
- za postopek zgorevanja v zračnem vrtincu (motor TAM) pri uporabi biodizla velja:
  - skrajša se zakasnitev vžiga,
  - jakost zgorevanja predhodno pomešanih reaktantov se zmanjša do 40 %,
  - povečata se jakost in delež difuzijskega zgorevanja,
  - trajanje zgorevanja ostaja enako,
  - zmanjša se gradient višanja tlaka, kar je posebej izrazito pri manjših obremenitvah motorja, zato je tek motorja bolj gladek in tih.

generalization of findings can be made. The conclusions for the individual engines are as follows:
- M – system combustion (MAN engine)
  - the physical processes prevail over the chemical ones during ignition delay,
  - the combustion process is unaltered – the rate of heat release (RHR curves) is almost the same for both fuels;
- combustion in air swirl (TAM engine) when using biodiesel fuel:
  - the ignition delay is reduced ,
  - the intensity of the premixed combustion is reduced by up to 40 %,
  - the intensity and share of the diffusion combustion is increased,
  - the combustion duration remains unchanged,
  - the combustion pressure gradient is reduced and, therefore, the engine's operation is smoother and quieter, especially for low engine loads;

4 LITERATURA
4 REFERENCES

[1] Miyamoto, N., Ogawa, H., Nurun, N., Obata, K., Arima, T., Smokeless, low NOx, high thermal efficiency, and low noise diesel combustion with oxygenated agents as main fuel, *SAE paper 980506*

[2] Giacomo, N.D., Beatrice, C., Bertoli, C., Diesel combustion improvements by the use of oxygenated synthetic fuels, *SAE paper 972972*

[3] 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*

[4] 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*

[5] 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*

[6] 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*

[7] May, H., Hattingen, U., Theobald, J., Weidmann, K., Koenig, A. (1998) Untersuchung des Betriebs- und Abgasemissiosverhaltens eines Dieselmotors mit Oxidationskatalysator, *MTZ Motortechnisches Zeitschrift* 59 (1998) 2, str.: 112 – 123

[8] Hribernik, A. (2006) Vpliv biodizla na vbrizgavanje goriva, zgorevanje, nastanek emisij in značilnice dizelskega motorja z neposrednim vbrizgom, *Strojniški vestnik* letnik 52, št. 1, 2006, str.: 3 do 14

[9] Yamane, K., Ueta, A., Shimamoto, Y. (20019 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 2001)*, July 1-4, 2001, Nagoya, str.: 402 do 409

[10] Hribernik, A., Kegl, B. (2007) Influence of biodiesel on the combustion and emission formation in a direct injection (DI) diesel engine, Energy & Fuels, 2007, 21, str. 1760 do 1767

[11] Heywod, J. B. (1988) Internal combustion engine fundamentals, *McGrawHill*, New York

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