Strojniški vestnik - Journal of Mechanical Engineering 52(2006)1, 3-14
UDK - UDC 621.43.057:504.05
Izvirni znanstveni članek - Original scientific paper (1.01)

Vpliv biodizla na vbrizgavanje goriva, zgorevanje, nastanek emisij in značilnice dizelskega motorja z neposrednim vbrizgom

The Influence of Biodiesel Fuel on the Injection, Combustion, Emissions and Performance of a Direct-Injected Diesel Engine

Aleš Hribernik
(Fakulteta za strojništvo, Maribor)

Da bi raziskali, kakšen je vpliv biodizla na značilnice zgorevanja in emisije dizelskega motorja, smo opravili primerjalno študijo. Kot pogonsko gorivo dizelskega motorja z neposrednim vbrizgom goriva smo v enakih delovnih razmerah uporabili gorivo D2 in čisti biodizel. Pri tem smo merili osnovne delovne parametre motorja in emisije škodljivih snovi. Prav tako smo posneli potek tlaka v valju motorja in z enodelnim modelom zgorevanja določili potek sprostitve toplote med zgorevanjem. Po poteku sprostitve toplote smo ocenili osnovne makroparametre zgorevanja. Ločeno smo analizirali tudi delovanje sistema za vbrizgavanje goriva. V ta namen smo na preizkuševališču za visokotlačne tlačilke izmerili potek tlaka v visokotlačni cevi in giba igle vbrizgalne šobe ter količino vbrizganega goriva. Tako smo lahko izračunali karakteristiko vbrizgavanja in ocenili osnovne makroparametre vbrizgavanja in jih analizirali v različnih delovnih razmerah.

(Ključne besede: motorji dizelski, biodizel, brizganje goriva, zgorevanje)

A study was carried out on the influence of biodiesel fuel on a diesel engine's performance, exhaust emissions, combustion and fuel-injection processes. These tests were performed on a direct-injected diesel engine using standard D2 diesel and commercial 100% biodiesel fuels. The tests were carried out using both fuels, under the same conditions. The exhaust emissions and the engine performance were measured and compared. The in-cylinder pressure was also measured, and the heat-release-rate 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 quantity of injected fuel was measured, and the injection pressure and injector-needle lift-time history were measured. The injection-rate curves were then computed and some macro-parameters of the injection process were obtained and analysed.

(Keywords: Diesel engines, biodiesel fuels, fuel injections, combustion)

0 UVOD

Že v bližnji prihodnosti lahko pričakujemo povečano uporabo nadomestnih goriv za pogon motornih vozil. Pri tem imajo največjo zmogljivost nadomestna goriva iz obnovljivih virov, katerih glavna prednost pred fosilnimi gorivi je zmanjšanje emisij toplogrednih plinov (predvsem CO_2). K zmanjšanju emisij toplogrednih plinov in emisij škodljivih snovi v celoti, ki jih dandanes zakonodaja vse bolj omejuje, pa pomembno prispeva tudi postopek zgorevanja. Pri tem ima dizelski motor z

0 INTRODUCTION

It is predicted that the use of alternative fuels for the propulsion of road and off-road vehicles will increase in the near future. Alternative fuels from renewable energy sources have the highest potential in terms of greenhouse-gas emissions (particularly CO_2). The very strict emission-policy demands for low emissions of greenhouse gasses and all other harmful emissions from internal combustion (IC) engines, increases the demand for power sources with low emissions and low fuel consumption. This means that the diesel en-neposrednim vbrizgavanjem goriva pomembne prednosti pred drugimi motorji.

Biodizel se že uspešno uporablja kot pogonsko gorivo v dizelskih motorjih vozil na motorni pogon. V bližnji prihodnosti pa lahko pričakujemo še povečano uporabo biodizla. Zaradi velike viskoznosti rastlinskih olj je pri proizvodnji biodizla uporabljena transestrifikacija, katere rezultat je metilni ester (biodizel) z značilnostmi, podobnimi dizelskemu gorivu D2 (preglednica 1). Zato je tako pridobljen biodizel mogoče uporabiti v dizelskih motorjih brez dodatnih posegov v sistem za vbrizgavanje goriva ali zgorevanje. Seveda pa zaradi drugačne sestave goriva prihaja do razlik v postopku zgorevanja in nastanku škodljivih snovi. V nadaljevanju prikazujemo rezultate eksperimentalnih raziskav vpliva izbranega goriva na postopek vbrizgavanja goriva, postopke zgorevanja in nastanek škodljiv snovi. Meritve so bile izvedene na prototipnem motorju TAM BF4L515C. Nastavitev sistema za dovod goriva nismo prilagajali posameznemu gorivu in so ostale med meritvami nespremenjene. Osnovne specifikacije testnega motorja so podane v preglednici 2.

1 VPLIV BIODIZLA NA POSTOPEK VBRIZGAVANJA GORIVA

Poskusi na vbrizgalnem sistemu so potekali na napravi za preizkušanje tlačilk Friedman-Maier tip 12H100_h. Pri tem smo merili potek tlaka v visokotlačni cevi takoj za tlačilko in tik pred vbrizgalno šobo, dvig igle vbrizgalne šobe in količino vbrizganega goriva. Nekatere osnovne značilnosti vbrizgavanja biodizla in goriva D2 prikazuje slika 1.

Izmerjena prostornina vbrizganega goriva je nekoliko večja pri biodizlu. Še posebej velja to pri večji vrtilni frekvenci motorja, ko so hitrosti tlačenja goriva največje in je količina vbrizganega biodizla 4 % večja od količine vbrizganega goriva D2. Tudi trajanje vbrizgavanja (Fi_vbr) je daljše za biodizel, in to predvsem na račun zgodnejšega dviga igle vbrizgalne šobe in zato nekaj večjega kota predvbrizga (Fi_zvbr). Razlike osnovnih parametrov so vendarle zelo majhne, skoraj še v mejah merilne negotovosti, kar potrjujejo tudi rezultati meritev dinamičnih komponent, ki jih prikazuje slika 2. Dvig igle vbrizgalne šobe pri vrtilni frekvenci motorja 1300 min^{-1} je skoraj povsem enak, medtem ko je pri 2100 min^{-1} začetek dviganja igle 0,3 ° OG zgodnejši

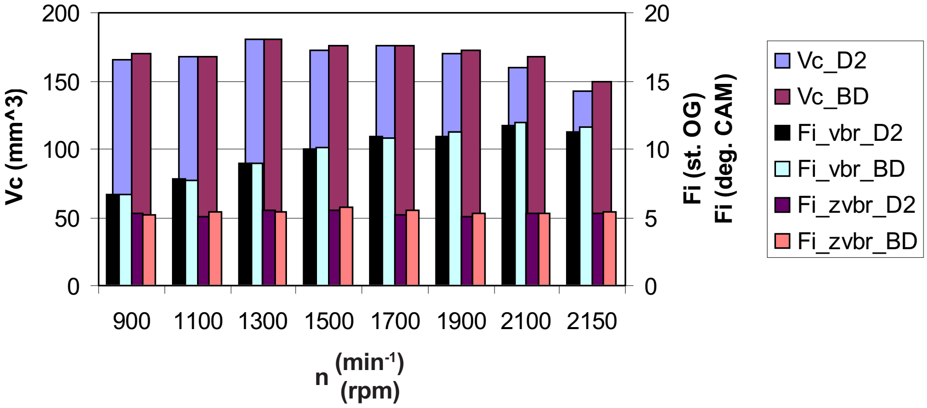
gines, especially direct-injected diesel engines, have a big advantage over other combustion systems.

Biodiesel has already been successfully applied for diesel engines. Today it is used in a mixture with D2 fuel or in pure form, and it is expected that the consumption of biodiesel fuel will grow in the coming years. Due to the high viscosity of raw vegetable oils, a process called "transesterification" is used for the production of biodiesel, the characteristics of which are very similar to those of D2 fuel (Table 1). No modifications to the fuel-injection system or to the combustion process are, therefore, necessary when the D2 fuel is replaced with biodiesel. The combustion process and the emissions formation, however, are altered due to the different compositions of both fuels. The influence of a particular fuel on the fuel injection, the combustion process and the emission formations were experimentally investigated and some of the results are presented in the following paper. The measurements were performed on a TAM BF4L515C prototype turbocharged diesel engine. The injection system setup was not optimized for any particular fuel, and remained unaltered throughout all the tests. The test engine's specifications are given in Table 2.

1 THE INFLUENCE OF BIODIESEL ON THE FUEL-INJECTION PROCESS

The injection system was tested on 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 made of the quantity of injected fuel. Some of the results are presented in Fig. 1.

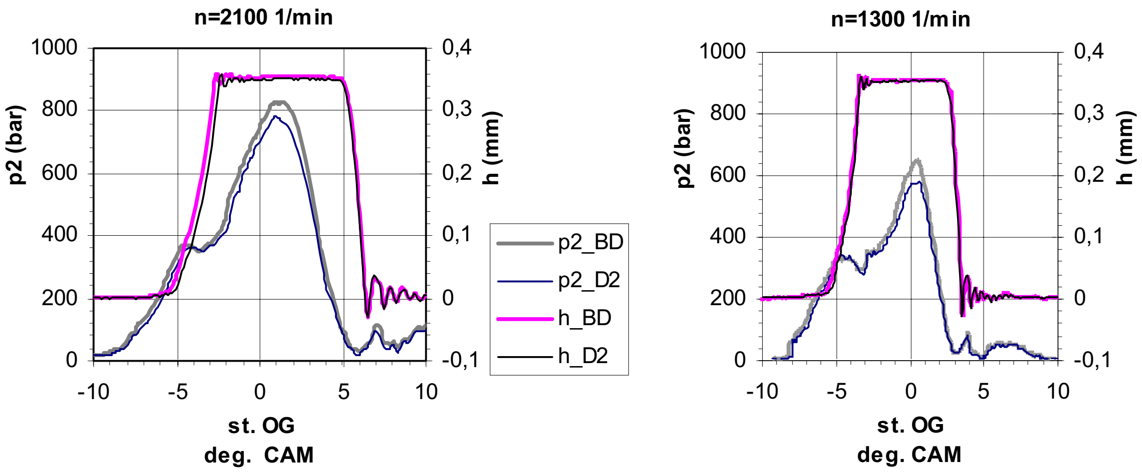
As can be seen, the injected fuel quantity per cycle is higher for biodiesel, especially at higher engine speeds, where the volumetric amount of injected biodiesel exceeds the injected D2 fuel quantity by 4%. The injection duration (Fi_vbr) is longer for biodiesel because of the earlier needle lift and the shorter injection delay. The basic injection parameters, however, differ only a little. The differences are almost within the measurement uncertainty. The dynamic parameters shown in Fig. 2 also prove this. The injector-needle lift trace at 1300 rpm is almost identical for both fuels, while at 2100 rpm a shorter injection delay is observed by the biodiesel and the injector needle opens 0.3 ° CAM earlier than with the D2 fuel. The injector needle's closure at 2100 rpm is identical



Sl. 1. *Primerjava količine vbrizganega goriva (Vc), trajanja vbrizgavanja (Fi_vbr) in kota predvbrizga (Fi_zvbr) za gorivo D2 in biodizel (BD) pri polnem gibu zobate letve visokotlačne tlačilke*
Fig. 1. *Comparison of injected fuel quantity per cycle (Vc), injection duration (Fi_vbr) and injection advance (Fi_zvbr) for D2 and biodiesel (BD) at full rack position of injection pump*

za biodizel, spust pa se ujema z D2. Tudi poteka tlaka pred šobo sta zelo podobna, le da so največji tlaki z biodizlom višji za 4 do 7 odstotkov. Podobno kakor v primeru dviganja igle pa ponovno opazimo za 0,3 ° OG zgodnejše zviševanje tlaka pred šobo pri vrtilni frekvenci motorja 2100 min^{-1}. Sklenemo lahko torej, da zamenjava goriva D2 z biodizlom ne vpliva pomembneje na delovanje vbrizgalnega sistema, kadar so delovne razmere predvsem temperature, v običajnih okvirih in da zato tudi ne zahteva sprememb njegovih osnovnih nastavitev.

for both fuels. The pressure-time history in the high-pressure line close to the injector is also similar, although a 4% to 7% higher maximum pressure is observed with biodiesel. Similar to the needle lift 0.3 ° CAM a quicker pressure rise is indicated at 2100 rpm. It can be concluded, therefore, that the operation of an injection system does not change significantly when D2 fuel is replaced by biodiesel, and no alteration in the injection system setup is necessary when the operation conditions, especially the fuel temperature, remain within tolerance.



Sl. 2. *Primerjava potekov tlaka pred šobo (p2) in dviga igle (h) za gorivo D2 in biodizel (BD) pri vrtilnih frekvencah motorja 2100 in 1300 min^{-1}*
Fig. 2. *Comparison of pressure traces close to the injector (p2) and needle lift (h) for D2 fuel and biodiesel (BD) at 2100 and 1300 rpm*

2 VPLIV BIODIZLA NA DELOVANJE MOTORJA IN NASTANEK EMISIJ

Meritve na motorju so potekale v preizkuševališču z zavornim dinamometrom, ki omogoča merjenje obremenitvenih in hitrostnih značilnic motorja. Poleg osnovnih obratovalnih parametrov motorja, to so vrtilna frekvenca motorja in turbokompresorja, vrtilni moment motorja, pretok zraka in goriva ter velikost značilnih temperatur in tlakov v polnilnem in izpušnem sistemu, smo merili tudi koncentracijo plinskih komponent 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 absorpcije nedisperzirane infrardeče svetlobe in koncentracijo O_2 z zaznavalom ZrO_2.

2.1 Zunanja značilnica

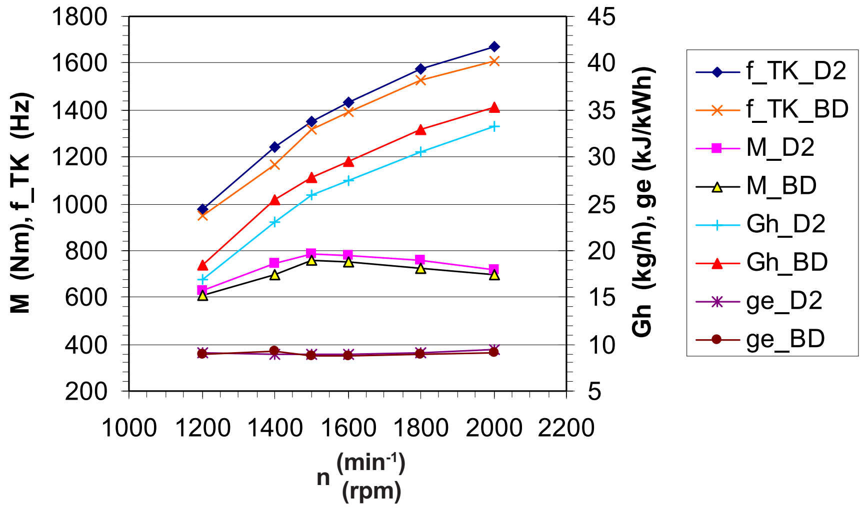
Zunanjo značilnico izmerimo pri največjem gibu zobate letve visokotlačne tlačilke (pri polnem plinu) in s spreminjanjem vrtilne frekvence dvojice motor – zavorni dinamometer. Prikazana je na sliki 3. Ugotovimo lahko, da je doseženi vrtilni moment z biodizlom in posledično tudi moč motorja v celotnem področju vrtilnih frekvenc motorja nižji

2 THE INFLUENCE OF BIODIESEL ON THE OPERATION OF THE ENGINE AND THE FORMATION OF EMISSIONS

The engine tests were performed on a test bed using a dynamometer, which enabled measurements of the engine speed and the load characteristics. In addition, measurements were made of the basic engine operational parameters, such as engine speed, turbocharger speed, engine load, air mass flow, fuel consumption, pressure and temperature in the intake and exhaust systems, and the concentrations of gaseous components and particulates in the exhaust gases. The NOx concentration was measured using a chemiluminescence analyser, a flame-ionisation detector was used to measure the amount of unburned hydro-carbons, the particulates were monitored by an AVL smoke meter, the concentration of CO was measured with a non-dispersive infrared analyser, and a ZrO_2 sensor was used to measure the oxygen concentration.

2.1 The full-load characteristic

The full-load characteristic is measured at the full-rack position of the fuel-injection pump (“full throttle”), by gradual variation of the engine-dynamometer system’s rotational speed. It is presented in Fig. 3. 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. This is to be expected,



Sl. 3. *Primerjava navora (M), vrtilne frekvence turbokompresorja (f_TK), urne porabe goriva (Gh) in specifične porabe energije (ge) pri polni obremenitvi za biodizel (BD) in D2*

Fig. 3. *Comparison of engine torque (M), turbocharger speed (f_TK), fuel consumption (Gh) and brake specific energy consumption (ge) at full load for biodiesel (BD) and D2*

Preglednica 1. *Primerjava fizikalnih in kemijskih lastnosti biodizla in goriva D2 [1] in [2]*
Table 1. *Comparison of physical and chemical properties of biodiesel and D2 fuel [1] and [2]*

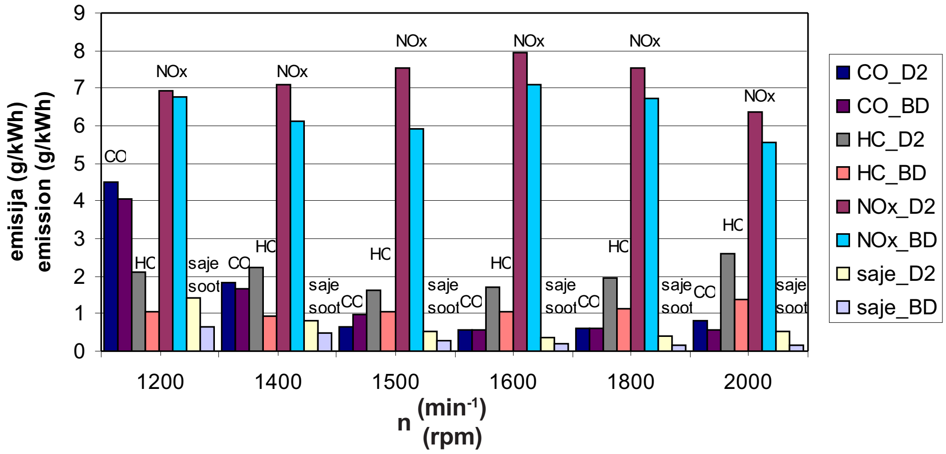
	D2	biodizel Biodiesel
gostota pri 15 °C (kg/m^3) density at 15 °C (kg/m^3)	845	865
viskoznost pri 40 °C (mm^2/s) viscosity at 40 °C (mm^2/s)	2,5	4,3
kurilnost (MJ/kg) caloric value (MJ/kg)	42,6	37,3
cetansko število cetane index	46	> 49
sestava / composition: masni delež / mass fraction C H S O	 0,860 0,134 0,003 -	 0,7750 0,1210 0,0001 0,1040
stehiometrijsko št. (kg zr./kg gor.) stehiometric air to fuel ratio	14,5	12,4

od vrtilnega momenta, ki ga dosega motor z gorivom D2. Razlika je posledica 12,5-odstotne nižje kurilnosti biodizla (preglednica 1). Ker pa je vbrizgana prostornina biodizla večja (slika 1) in je hkrati večja tudi njegova gostota (preglednica 1), je urna poraba biodizla (Gh – slika 3) večja, zato je zmanjšanje vrtilnega momenta in moči motorja z biodizelskim gorivom le do 5 %. Pri tem pa se specifična poraba energije goriva (ge – slika 3) zmanjša v povprečju za en odstotek. Zato lahko končamo z ugotovitvijo, da povzroči uporaba biodizla pri nespremenjenih nastavitvah motorja do 5 % zmanjšanje vrtilnega momenta in moči, medtem

since the calorific value of the biodiesel is 12.5 % lower than that of D2 fuel (see Table 1). From Fig. 3 it also follows that at the full-rack position the biodiesel fuel consumption (Gh – Fig. 3) is higher. There are two reasons for this. Firstly, the biodiesel's density is higher (see Table 1), and secondly, the injected fuel quantity per cycle is also higher (see Fig. 1). The reduction in engine torque and power when the engine is fuelled by biodiesel is, therefore, not as high as 12.5%, but is just 5%, and at the same time the brake-specific fuel consumption (ge – Fig. 3) is reduced by 1%. Therefore, it can be concluded that the engine torque and the power are reduced by 5% and the effective engine efficiency is

Preglednica 2. *Podatki o testnem motorju TAM BF4L515C*
Table 2. *TAM BF4L515C test engine specifications*

Motor Engine	Tlačno polnjeni, 4-taktni dizelski z neposrednim vbrizgom goriva in vmesnim hladilnikom polnilnega zraka; Turbocharged, 4-stroke direct injected diesel engine with intercooler;
število valjev number of cylinders	4
premer × gib bata bore × stroke	125 mm × 145 mm
gibna prostornina total displacement	7117 ccm
tlačno razmerje compression ratio	15,8
dobava goriva / fuelling tlačilka / in-line pump šoba / injector izvrtine šobe / injector holes st. kot predvbr. / pump advance	 BOSCH PES6P120A72 BOSCH DLLA 148S 4 × Φ = 0,375 mm 16 °RG (°CA)



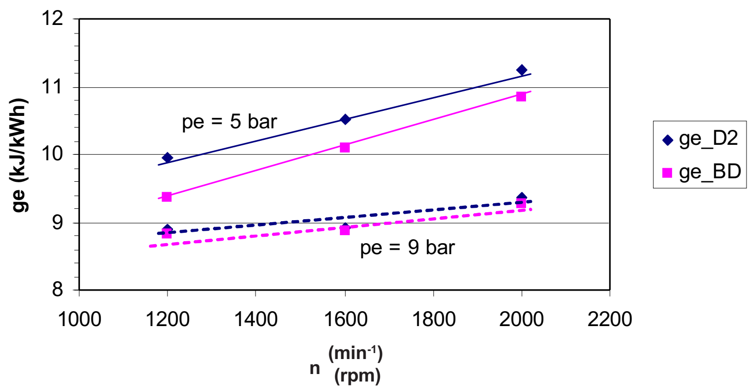
Sl. 4. *Primerjava specifičnih emisij CO, HC, NOx in saj pri polni obremenitvi za biodizel (BD) in D2*
Fig. 4: *Comparison of specific emissions of CO, HC, NOx and particulate (soot) at full load for biodiesel (BD) and D2 fuel*

ko se dejanski izkoristek motorja v povprečju zveča za 0,3 odstotne točke. Pomembnejšega vpliva na delovanje turbokompresorja ne opazimo. Vrtilna frekvenca turbokompresorja in pretok zraka se zmanjšata do 4 odstotke, kar pa ne vpliva kakovostno na postopek zgorevanja, saj je primerjalni razmernik zrak – gorivo zaradi manjše potrebe biodizla po kisiku celo večji kakor v primeru uporabe goriva D2. Pomembnejši vpliv na potek zgorevanja in nastanek škodljivih komponent ima kemijska sestava goriva, predvsem vsebnost kisika (nad 10 %).

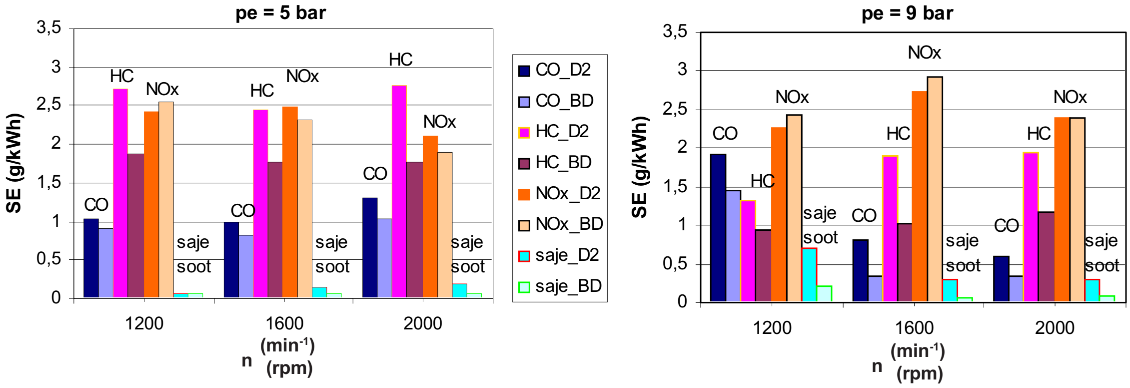
Rezultate izmerjenih emisij (zaradi primerljivosti so podane specifične emisije) pri zunanji značilnici motorja prikazuje slika 4. Osnovna ugotovitev primerjave specifičnih emisij pri polni obremenitvi motorja je zmanjšanje vseh emisij z uporabo biodizla. Pri tem je zmanjšanje emisij CO,

increased by approximately 0.3 percentage points when the D2 fuel is replaced by biodiesel, and the engine setup is unaltered. The operation of the turbocharger is not significantly effected by the application of biodiesel. Turbocharger speed and the air mass flow are reduced by 4%. This, however, does not influence the combustion process, since the oxygen demand of the biodiesel is lower than that of the D2 fuel, and the equivalent air-to-fuel ratio is higher when biodiesel is used. The combustion process and the emission formation is, however, strongly influenced by the chemical composition of the fuel, especially the content of bonded oxygen (over 10% for biodiesel).

The measured engine emissions (specific emissions are given for comparison) at full load are shown in Fig. 4. As can be seen, all the emissions are reduced at full load when biodiesel is applied. Reductions in CO, HC and soot emission can be ex-



Sl. 5. *Primerjava specifične porabe energije (ge) pri delnih obremenitvah za biodizel (BD) in D2*
Fig. 5. *Comparison of break specific energy consumption (ge) at partial load for biodiesel (BD) and D2*



Sl. 6. *Primerjava specifičnih emisij (SE) CO, HC, NOx in saj pri delnih obremenitvah za biodizel (BD) in D2*
Fig. 6. *Comparison of specific emissions (SE) of CO, HC, NOx and particulate (soot) at partial load for biodiesel (BD) and D2 fuel*

HC in saj pričakovano zaradi 10-odstotnega deleža kisika v gorivu, kar zmanjša primanjkljaj kisika v območjih, bogatih z gorivom, zavre nastajanje saj in pospeši postopke oksidacije. Prav slednje bi zato lahko povzročilo tudi povečanje emisije NOx o čemer poročajo tudi drugi avtorji ([1] do [4]), kar pa se ni zgodilo. Da bi ugotovili, ali je pojav zmanjšanja emisij NOx posledica 5-odstotnega znižanja obremenitve na zunanji značilnici motorja pri uporabi biodizla, smo meritve ponovili še pri delnih obremenitvah motorja.

2.2 Hitrostne značilnice pri delni obremenitvi

Posneli smo dve hitrostni značilnici motorja; pri srednjem dejanskem tlaku (obremenitvi) p_e= 9 bar in p_e= 5 bar. Osnovni kazalci obratovanja se pri tem skoraj ne razlikujejo. Razlike v vrtilnih frekvencah turbokompresorja in pretoka zraka so v mejah merilne negotovosti. Ponovno pa je zaradi manjše potrebe po kisiku presežek zraka do 4 odstotke večji pri biodizlu, predvsem pri manjši obremenitvi motorja pa je pomembno manjša tudi specifična poraba energije goriva (slika 5). Razlike presegajo 5 odstotkov in jih ne moremo pojasniti z merilno negotovostjo, ampak z ugotovitvijo, da se po vsej verjetnosti izboljša dejanski izkoristek motorja zaradi zgodnejšega pričetka zgorevanja (slika 8) in tudi mirnejšega teka motorja, kakor ugotavljamo v poglavju 3.

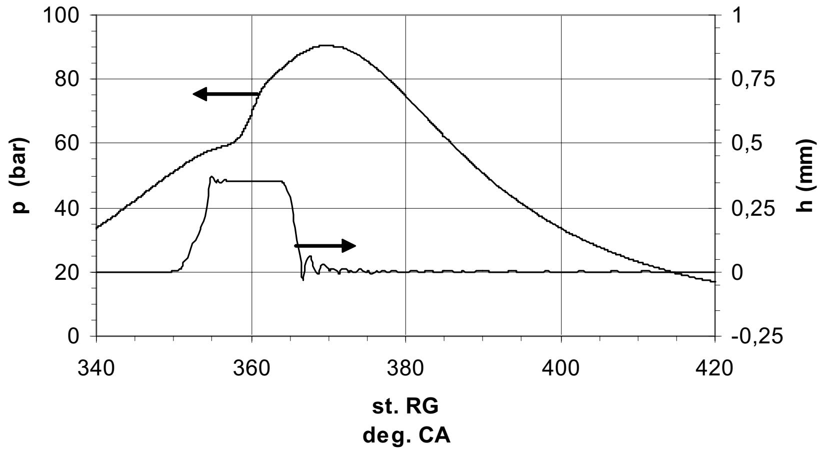
Specifične emisije motorja pri delnih obremenitvah so prikazane na sliki 6. Ponovno je za vse merilne točke značilno občutno zmanjšanje emisij CO, saj in HC z biodizlom. Emisije NOx so pri majhni obremenitvi motorja (p_e= 5 bar) in večjih vrtilnih frekvencah še zmeraj nekoliko nižje z biodizlom,

pected, since the oxygen bonded in the biodiesel (10% oxygen content) reduces the deficit of oxygen within the fuel-rich regions, hinders soot formation, and accelerates the oxidation processes. The latter, however, should increase NOx emissions, as reported by other authors ([1] to [4]), but did not occur in this case. The possible reason is a 5% reduction in the engine load following the application of the biodiesel. In order to prove this, measurements were also performed under a partial engine load.

2.2 Partial load characteristic

Two engine-speed characteristics were measured; at mean effective pressures of p_e = 9 bar and p_e = 5 bar. The main engine operational parameters do not differ significantly when the D2 fuel is replaced by the biodiesel. The differences in the turbocharger speed and the air mass flow are within the measurement uncertainty interval. The air-to-fuel ratio is again higher by approximately 4% when biodiesel is used, due to its lower oxygen demand and, as can be seen from Fig. 5, the brake-specific fuel consumption is reduced, which is especially significant for low engine loads. The differences in the brake-specific fuel consumption exceed 5% and cannot be explained by the measurement uncertainty. It is far more probable, as stated in section 3, that the reduced ignition delay and the earlier combustion start (Fig. 8), together with a smoother engine operation, increase the engine's efficiency.

The specific engine emissions under partial load are presented in Fig. 6. The reduction of CO, HC and particulate emissions is again characteristic for all engine operational points when using biodiesel. A reduction in NOx emissions is only observed under a



Sl. 7. *Izmerjeni potek tlaka v valju (p) in hod igle (h) vbrizgalne šobe (gorivo D2, n=1600 min^{-1}, pe = 9 bar)*
Fig. 7. *Measured in-cylinder pressure trace (p) and injector needle lift trace (h) (D2 fuel, 1600 rpm, pe = 9 bar)*

medtem ko povzroči biodizel pri večjih obremenitvah motorja (p_e= 9 bar) do 7 odstotno povečanje emisij NOx.

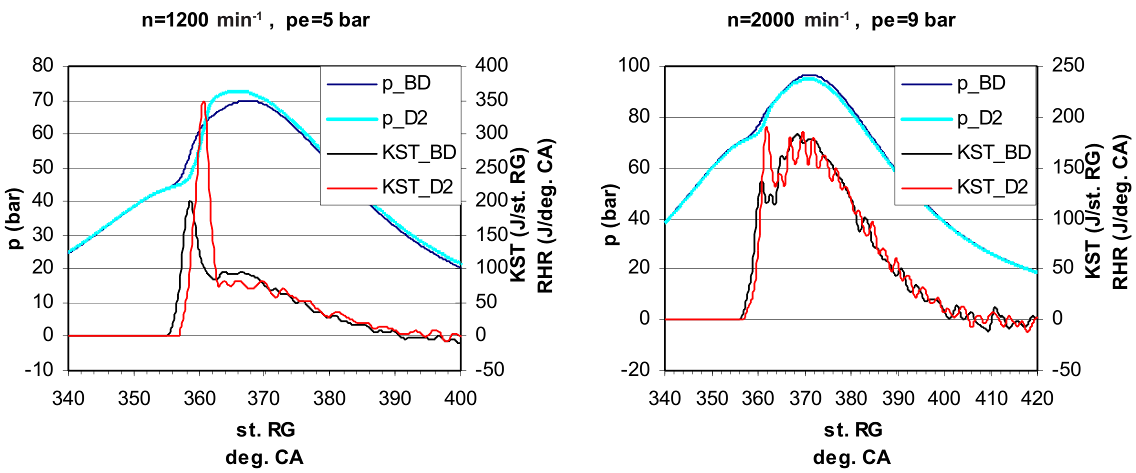
low load (p_e= 5 bar) and a high engine speed, while at a higher engine load (p_e= 9 bar), an increase in NOx emissions by up to 7% is observed.

3 VPLIV BIODIZLA NA ZGOREVANJE

3 THE INFLUENCE OF BIODIESEL ON THE COMBUSTION PROCESS

Osnovne značilnosti postopka zgorevanja lahko pridobimo z računsko obdelavo indikatorskega diagrama motorja. V ta namen smo najprej izmerili potek tlaka med zgorevanjem in dvig igle vbrizgalne šobe za prvi valj motorja. V zgorevalni prostor smo namestili piezoelektrično zaznavalo, za merjenje giba igle pa smo uporabili induktivno zaznavalo. Primerjalno lego ročične gredi smo sledili z optičnim kodirnikom. Anologne signale smo

The basic characteristics of the combustion process can be obtained by the computational processing of an in-cylinder pressure trace. The in-cylinder pressure and the time history of the injector needle lift were, therefore, acquired from the first engine cylinder. A piezoelectric sensor was placed into the combustion chamber for the 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 compu-



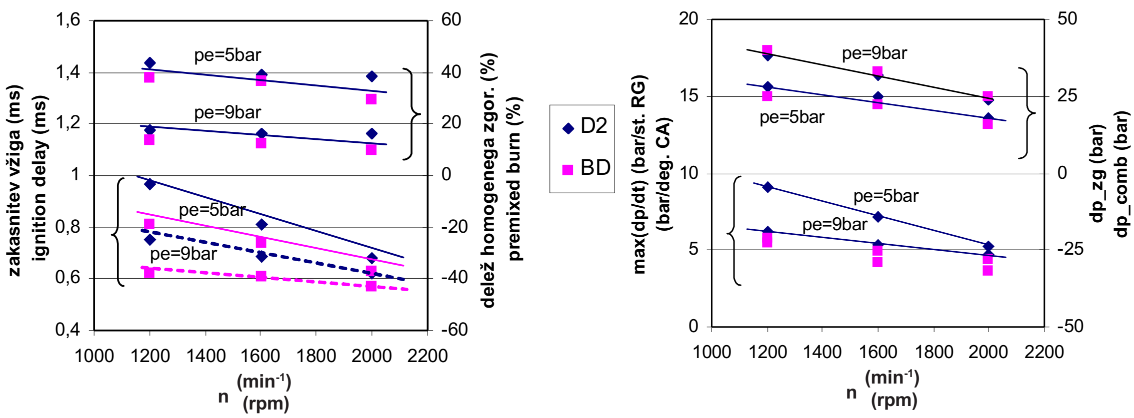
Sl. 8. *Primerjava poteka tlaka v valju (p) in KST za biodizel (BD) in D2 gorivo (D2)*
Fig. 8. *Comparison of in-cylinder pressure trace (p) and RHR curve for biodiesel (BD) and D2 fuel*

zbrali z računalniško podprtim zbiranjem podatkov z uporabo merilnih algoritmov iz programskega okolja LabVIEW. Uporabljena frekvenca zbiranja je bila 100 kHz po kanalu. Primer izmerjenih rezultatov je prikazan na sliki 7. Na podlagi izmerjenih potekov tlaka v valju motorja smo nato izračunali potek sprostitve toplote med zgorevanjem, t.i. značilnico sprostitve toplote (KST). Uporabili smo enodelni brezrazsežni model zgorevanja [5], zapisali sistem enačb o ohranitvi mase in energije v valju motorja ter ga rešili z numerično integracijo z uporabo osebnega računalnika. Tako smo izračunali KST pri vseh (v poglavju 2.2 predstavljenih) delnih obremenitvah motorja. Izkazalo se je, da se pri enakih obremenitvah motorja KST za izbrano gorivo ne spremenijo pomembneje pri spremembi vrtilne frekvence. Zato smo na sliki 8 prikazali dva značilna poteka KST za obe gorivi.

Pri manjši obremenitvi (p_e = 5 bar – slika 8) je za gorivo D2 značilno izrazito področje homogenega zgorevanja z velikimi hitrostmi zgorevanja. Javlja se tudi pri biodizlu, a je njegova intenzivnost manjša. Razlika nastane zaradi različnih zakasnitev vžiga obeh goriv, ki jo lahko opazujemo na sliki 9. Zaradi večje vnetljivosti biodizla so zakasnitve vžiga krajše. Manjša ko je količina predhodno pomešanih reaktantov, ki nastajajo v času zakasnitve vžiga, manjši je tudi delež goriva, ki zgori s homogenim plamenom (slika 9), predvsem pa so v tej začetni fazi manjše hitrosti zgorevanja. V področju difuzijskega zgorevanja, ki sledi, so hitrosti zgorevanja za obe gorivi precej

ter-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 the injector-needle lift traces obtained by measurements are presented in Fig. 7. The measured pressure traces were used for combustion heat-release-rate predictions, the so-called rate-of-heat-release (RHR) curves. A one-zone zero-dimensional combustion model [5] was used in order 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. All the pressure traces acquired under partial-load engine operational conditions (as presented in section 2.2) were processed this way, and RHR curves were obtained. The RHR curves obtained at the same engine load do not change significantly with engine speed. The two characteristic RHR curves for each fuel are, therefore, presented in Fig. 8.

An significant portion of premixed combustion with a high heat-release rate is characteristic for D2 fuel at a low engine load (p_e = 5 bar – Fig. 8). Premixed combustion is far less intense with the combustion of biodiesel. This difference is caused by the different ignition delays of the two fuels, as presented in Fig. 9. The combustibility (cetane number) of biodiesel is higher and, thus, its ignition delay is shorter. The quantity of premixed reactants that are formed during ignition delay is small and the share of fuel that burns with a premixed flame is also small (Fig. 9), 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 com-



Sl. 9. *Primerjava zakasnitve vžiga, deleža homogenega zgorevanja, največjega gradienta tlaka (max(dp/dt)) in povečanja tlaka med zgorevanjem (dp_zg) za biodizel (BD) in D2 gorivo*
Fig. 9. *Comparison of combustion delay, premixed burn, maximal pressure gradient (max(dp/dt)) and combustion pressure rise (dp_zg) for biodiesel (BD) and D2 fuel*

manjše (slika 8) in pri obeh obremenitvah je difuzijsko zgorevanje biodizla intenzivnejše, kar lahko pojasnimo z nekoliko boljšo vnetljivostjo biodizla, predvsem pa z dejstvom, da je zaradi manjše potrebe po kisiku nastajanje gorljive zmesi v zgorevalnem prostoru hitrejše.

Pri večjih obremenitvah (p_e = 9 bar - slika 8) postaja homogeno zgorevanje vse manj izrazito in ga pri biodizlu komaj še opazimo. Njegov delež se prepolovi (slika 9). To je posledica zmanjšanja zakasnitve vžiga (slika 9), ki se pri povečevanju obremenitve motorja zmanjšuje.

Potek zgorevanja se kaže tudi v poteku tlaka med zgorevanjem. Pri majhnih obremenitvah motorja povzroči začetno intenzivno zgorevanje predhodno pomešanih reaktantov goriva D2 in zraka velike gradiente tlaka. Tlak se zvišuje hitreje kakor pri biodizlu (slika 8) in kljub kasnejšemu pričetku zgorevanja prej doseže vrh, ki je bliže notranji mrtvi legi in zato višji (sliki 8 in 9). Tudi pri večjih obremenitvah motorja je zaradi daljše zakasnitve vžiga gradient naraščanja tlaka pri gorivu D2 večji kakor pri biodizlu. Razlike pa ne presežejo 20 odstotkov. Slika 9 pokaže zelo dobro povezanost med zakasnitvijo vžiga in največjim gradientom tlaka. Ugotovimo lahko tudi, da se s povečanjem obremenitve motorja največji gradient povišanja tlaka zniža. Zato je vrh tlaka precej bolj oddaljen od notranje mrtve lege in se ujema z drugim vrhom KST, ki je v območju difuzijskega zgorevanja (slika 8). Ker je difuzijsko zgorevanje z biodizlom intenzivnejše so tudi najvišji tlaki zgorevanja (povišanje tlaka med zgorevanjem (slika 9)) višji kakor z gorivom D2.

4 SKLEP

V prispevku so prikazani rezultati raziskave vpliva biodizla na postopka vbrizgavanja goriva in zgorevanja v dizelskem motorju, vpliva na osnovne parametre delovanja motorja in na emisijo škodljivih snovi. Pri tem nastavitev sistema za dovod goriva nismo prilagajali posameznemu gorivu in so ostale med meritvami nespremenjene. Ugotovitve, ki slede iz primerjave z rezultati, dobljenimi z gorivom D2, so naslednje:

a) postopek vbrizgavanja
- količina vbrizganega goriva se poveča do 4%,
- pri velikih vrtilnih hitrostih se skrajša zakasnitev vbrizga,

bustion (Fig. 8). The diffusion combustion of biodiesel is more intensive at both engine loads. The explanation for this is the higher cetane number and, in particular, the lower oxygen demand of biodiesel, which intensifies the formation of combustible mixture, and its combustion with a diffusion flame.

The portion of premixed combustion is less explicit at the high engine load (p_e = 9 bar – Fig. 8) and for biodiesel it is already hardly noticeable. Its share is reduced by 50% (Fig. 9) for both fuels, due to the shorter ignition delay, which is characteristic for high engine loads (Fig. 9).

The combustion process is reflected in the pressure trace during combustion. The intense combustion of the premixed reactants at the beginning of D2 fuel combustion at low engine load, causes very high pressure gradients. In-cylinder pressure increases much faster by the combustion of D2 fuel (Fig. 8) and reaches its peak earlier although the biodiesel ignites earlier. Its peak is, therefore, closer to the top dead centre and, thus, higher than with the combustion of biodiesel (Figs. 8 and 9). Higher combustion pressure gradients are also observed with the combustion of D2 fuel at high engine loads. The differences in the pressure gradients, however, do not exceed 20%. Figure 9 shows the very good correlation between the ignition delay and the maximum combustion-pressure gradient. Furthermore, it can be stated that the maximum combustion-pressure gradient decreases with engine load. The combustion pressure peak is, therefore, further from the top dead centre and it coincides with the second peak of the RHR curve, which is in the region of diffusion combustion (Fig. 8). In addition, since the diffusion combustion of biodiesel is more intense, the maximum combustion pressure at high engine load is higher when the D2 fuel is replaced by the biodiesel.

4 CONCLUSION

This paper presents the results of experimental research into the influence of biodiesel on the fuel-injection and combustion process of diesel engines. The influence of biodiesel on the basic engine operational parameter and the emission formation is also studied and presented. The engine setup was not optimised for any particular fuel and it remained unaltered during the tests. The following conclusions can be made from a comparison of the results obtained for the biodiesel and D2 fuels:

a) the fuel-injection process
- the amount of injected fuel is increased by up to 4%,
- the injection delay reduces with engine speed,

- največji tlak vbrizgavanja se zveča do 7 odstotkov;

b) postopek zgorevanja

- skrajša se zakasnitev vžiga,
- intenzivnost zgorevanja predhodno pomešanih reaktantov se zmanjša do 40 odstotkov,
- povečata se intenzivnost in delež difuzijskega zgorevanja,
- trajanje zgorevanja ostaja enako,
- zmanjšuje se gradient povišanja tlaka, kar je posebej izrazito pri manjših obremenitvah motorja, zato je tek motorja bolj gladek in tih;

c) osnovni parametri delovanja motorja

- imenska moč in vrtilni moment motorja se zmanjšata za 5 odstotkov,
- urna poraba goriva na zunanji karakteristiki se v povprečju poveča za 8 odstotkov,
- dejanski izkoristek motorja se poveča, to povečanje je značilno predvsem za majhne obremenitve in znaša do 1,5-odstotne točke;
- primerjalni razmernik zrak gorivo se poveča;

d) emisije

- emisije CO, HC in saj se zmanjšajo na vseh obratovalnih režimih,
- specifični indeks emisije NOx je na zunanji značilnici zaradi manjših obremenitev manjši, medtem ko pa se pri izenačenih pogojih delovanja dvigne nad vrednosti pri gorivu D2.

- the maximum injection pressure increases by up to 7%;

b) the combustion process

- the ignition delay is reduced,
- the intensity of premixed combustion is reduced by up to 40%,
- the intensity and share of diffusion combustion is increased,
- the combustion duration remains unchanged,
- the combustion-pressure gradient is reduced and, therefore, the engine operation is smoother and quieter, especially at low engine loads;

c) the engine operational parameters

- the maximum engine power and torque are reduced by 5%,
- the fuel consumption at full load is increased by 8%,
- the brake-effective engine efficiency is increased; an efficiency improvement of up to 1.5 percentage points is observed at low engine loads,
- the equivalent air-to-fuel ratio is increased;

d) emissions

- the emissions of CO, HC and particulates are reduced for all engine operational regimes,
- the specific NOx emission index at full engine load is lower because of the lower engine load, while it exceeds the specific NOx emission index values for D2 fuel, under equal engine-operational conditions.

5 LITERATURA
5 REFRENCES

[1] Yamane, K., Ueta, A., Shimamoto, Y. (2001) 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. 402-409.

[2] Tritthart, P., Zelenka, P. (1990) Vegetable oils and alcohols – additive fuels for diesel engines, *SAE Paper 905112.*

[3] Bouché, T., Hinz, M., Hieber, D., Tschoeke, H. (1997) Einfluss verschiedener Pflanzenoel-Eigenschaften auf Verbrennung und Schadstoffbildung in einem direkteinspritzenden Dieselmotor, *MTZ Motortechnische Zeitschrift*, 58 (1997) 3, str. 148-153

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

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

Avtorjev naslov: prof. dr. Aleš Hribernik
Univerza v Mariboru
Fakulteta za strojništvo
Smetanova 17
2000 Maribor
ales.hribernik@uni-mb.si

Author's Address: Prof. Dr. Aleš Hribernik
University of Maribor
Faculty of Mehanical Engineering
Smetanova 17
SI-2000 Maribor, Slovenia
ales.hribernik@uni-mb.si

Prejeto:
Received: 12.10.2005

Sprejeto:
Accepted: 16.11.2005

Odprto za diskusijo: 1 leto
Open for discussion: 1 year