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Obravnavanje curka plinskega olja in nadomestnih goriv

A Spray Analysis of Petrol and Alternative Fuels

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V prispevku je obravnavana numerična analiza curkov plinskega olja in nekaterih nadomestnih goriv. Z uporabo paketa računske dinamike tekočin FIRE so bile določene karakteristike curkov (velikost kapljic in domet) plinskega olja, biodizla in odpadnega rastlinskega olja. Nekatere vrednosti karakterističnih veličin curka so bile primerjane tudi z vrednostmi, izračunanimi z uporabo znanih empiričnih modelov za določitev karakteristik curka. Analize so bile izvedene za dva tipa vbrizgalnih šob oz. vbrizgalnih sistemov (neposredni in posredni). V primeru slednjega so rezultati numerične analize primerjani še s fotografijami curka.
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(Ključne besede: vbrizgavanje goriva, olje plinsko olje, biodizel, olja odpadna, olja rastlinska)

This paper presents numerical analyses of sprays of diesel and some alternative fuels. The fuel spray characteristics (the droplet size and the penetration length) of diesel fuel, biodiesel and waste cooking oil were calculated using the computational fluid dynamics program FIRE. Some of the characteristics were calculated using existing empirical models. The analyses were made for two different injection systems: direct and indirect injection. In the case of indirect injection, the results were also compared with fuel-spray photographs.
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(Keywords: fuel injection, diesel fuels, biodiesel, waste cooking oils)

0 UVOD

Z uporabo nadomestnih goriv rastlinskega porekla lahko klasičen dizelski motor z notranjim zgorevanjem obratuje brez prirastka emisij ogljikovega dioksida (CO_2). To pomeni, da se z uporabo teh goriv ne povečuje količina CO_2 v atmosferi. Kot gorivo rastlinskega porekla se običajno uporabljajo estri maščobnih kislin rastlin, to so: oljna repica, sončnično olje, sojino olje ipd. Ti estri se imenujejo biodizel. Lahko pa nadomestna goriva izdelujemo tudi iz odpadnega rastlinskega olja.

Znano je, da lastnosti goriva, kakor tudi njegova sestava, odločilno vplivajo na postopek vbrizgavanja ter s tem neposredno na postopek zgorevanja in nastanek nezaželenih ostankov. Ob upoštevanju dejstva, da se sestava goriv rastlinskega porekla razlikuje od sestave mineralnih goriv, je za prilagoditev delovanja dizelskega motorja z nadomestnimi gorivi potrebno dobro poznavanje omenjenih postopkov.

Z uporabo paketov računske dinamike tekočin (CFD) računalniška oprema dandanes dopušča razmeroma hitre analize postopka

0 INTRODUCTION

A conventional compression ignition engine is capable of running with a zero net emission of a carbon dioxide (CO_2) when alternative fuels based on vegetable oil are used. In this way the concentration of CO_2 in the atmosphere stays the same. For the plant source it is common to use esters from rapeseed, sunflower, soya, etc. These esters are commonly referred to as biodiesel. Alternative fuels can also be made of waste cooking oils.

It is well known that the fuel characteristics and the fuel composition significantly affect the injection process, which in turn has a direct affect on the combustion and emission-formation processes. Since the composition of vegetable-source fuels differs from that of petroleum-based fuels, the conventional compression-ignition engine needs to be adapted to run on alternative fuels. This step requires a good understanding of the injection and combustion processes of alternative fuels.

Today we are able to run relatively fast analyses of the injection and spray-formation processes, as well as the combustion and emission-formation vbrizgavanja, nastanka curka, kakor tudi zgorevanja in nastanka emisij, s čimer lahko že pred prvimi praktičnimi preizkušnjami do neke mere prilagodimo motor novim delovnim razmeram.

Z namenom spoznavanja vplivov nadomestnih goriv na postopek vbrizgavanja in nastanek curka ter možnostjo predelave sedanjih sistemov za obratovanje z nadomestnimi gorivi so bile izvedene tudi analize v tem prispevku.

processes, by using computational fluid dynamics (CFD) programs. By using these tools we are able to partly adjust the engine to the new conditions, even before the first experimental tests.

The objective of this paper is to learn how the alternative fuels affect the injection and spray-formation processes and to get some information about how the existing injection systems should be adapted to run with these fuels.

1 TEORETIČNE OSNOVE

1.1 Lastnosti goriva

Rastlinska olja so zgrajena v obliki trigliceridov, ki jih sestavljajo tri verige ogljikovodikov povezane med seboj z glicerolom. Kot takšna sicer gorijo, a jih v takšni obliki v praksi zelo redko uporabljamo. Njihova največja pomanjkljivost je zelo velika viskoznost, ki povzroča težave z dovodom goriva. Tem težavam se lahko izognemo z gretjem goriva, večjim prerezom cevi ali s kemičnim postopkom esterifikacije, to je s proizvodnjo biodizla. To je postopek, pri katerem esterske vezi v trigliceridih hidroliziramo, s čimer nastanejo proste maščobne kisline, ki po reakciji z metanolom ali etanolom delajo metil- ali etilestre. Njihove lastnosti se lahko razlikujejo v odvisnosti od osnovne rastline.

Kot druga nadomestila se lahko uporabi tudi odpadno rastlinsko olje. To ima podobne lastnosti kakor čisto rastlinsko olje, zato neesterificirano ni najprimernejše za uporabo. Lastnosti biodizla (BIO), plinskega olja (D2) in odpadnega rastlinskega olja (ORO-WCO) so predstavljene v preglednici 1. V predstavljenih analizah je bilo, ne glede na nekatere predhodne negativne izkušnje, uporabljeno rastlinsko olje, pri katerem ni bil izveden postopek esterifikacije.

1.2 Numerična analiza

Numerična analiza je narejena z uporabo programskih paketov RDT FIRE v7.2b in FIRE v.8.1 (AVL) na delovnih postajah HP 9000/782 in 9000/785 oz. osebnem računalniku P3 450 MHz.

1 THEORETICAL BACKGROUND

1.1 Fuel characteristics

Vegetable oils exist in the form of triglycerides, which consist of three hydrocarbon chains connected together by glycerol. Vegetable oils are combustible, but they are rarely used in this form. The problem with vegetable oils is their very high viscosity, which causes problems with fuel flow from the tank to the engine. Those problems can, however, be reduced by preheating the oil and using larger fuel lines or by chemical modification, i.e. producing biodiesel. In this process the ester bonds in the triglycerides are hydrolysed. The result is free fatty acids, which form methyl or ethyl esters after a reaction with methanol or ethanol. The properties of these esters are mainly dependent on the source plant.

An alternative is to use waste cooking oil. But since it has similar properties to pure vegetable oil, in its unesterified form it is not suitable to be used as a fuel. The characteristics of diesel fuel (D2), biodiesel (BIO) and waste cooking oil (WCO) are presented in Tab. 1. The WCO used in the presented analyses was, in spite of past negative experiences, unesterified.

1.2 Numerical analyses

The numerical analyses were made using the CFD programs FIRE v7.2b and FIRE v.8.1 (AVL) on two workstations (HP 9000/782 and HP 9000/785) and a P3 personal computer (450 MHz), respectively.

Preglednica 1. *Lastnosti goriv [1] in [2]*
Table 1. *Fuel characteristics [1] and [2]*

	D2	BIO	ORO / WCO
ρ (kg/m^3)	820 do/to 845	875 do/to 900	915
ν (mm^2/s)	2 do/to 4,5	3,5 do/to 5,0	36,7
H (MJ/kg)	42,6	37,3	-
cetansko št./cetane no.	46	>49	-

1.3 Empirični modeli

Kot hiter kazalnik razvoja sprememb oblike curka in kakovosti razpršitve lahko uporabimo tudi nekatere empirične modele, s katerimi lahko ocenimo srednji Sauterjev premer (d_{32}) in domet curka (L_P). V predstavljenem delu sta bila uporabljena naslednja modela: Filipović [3] (1) za srednji Sauterjev premer kapljic ter Yule-Filipović [4] (2) za domet curka:

1.3 Empirical models

The empirical model for calculating the Sauter mean diameter (d_{32}) and the spray penetration length (L_p) can be used as a tool for fast analyses, showing the tendency of the spray changes and the quality of the atomisation. In this paper, two empirical models were used: Filipović [3] (Eq.1) for the Sauter mean diameter of the droplets, and Yule - Filipović [4] (Eq.2) for the spray penetration length:

$$d_{32}\ \ v\ \mu m = 324,6 \cdot \left(\frac{\rho_a \cdot u_0^2 \cdot d_h}{\sigma_f} \right)^{-0,233} \cdot \left(\frac{\rho_f \cdot d_h \cdot \sigma_f}{\mu_f^2} \right)^{-0,082} \tag{1}$$

$$L_p v\ mm = 2,65 \cdot 10^3 \cdot d_h \cdot \left(\frac{\rho_a \cdot u_0^2 \cdot d_h}{\sigma} \right)^{-0,1} \cdot \left(\frac{\rho_f \cdot u_0 \cdot d_h}{\mu_f} \right)^{-0,3} \cdot \left(\frac{\rho_f}{\rho_a} \right)^{0,08} \quad (2).$$

V enačbah (1) in (2) sta ρ_a gostota zraka, ρ_f gostota goriva, σ_f pomeni površinsko napetost goriva, μ_f dinamično viskoznost goriva, μ_a pa dinamično viskoznost zraka. Iztočna hitrost je označena z u_0, tlačna razlika z Δp, medtem ko d_h pomeni premer odprtine šobe. Vse enote so v skladu s sistemom SI.

In Eq.1 and 2, ρ_a is the air density, ρ_f is the fuel density, σ_f represents the surface tension, μ_f is the viscosity of the fuel, and μ_a is the air viscosity. The outflow velocity is denoted by u_0, Δp is the pressure difference, and d_h is the nozzle hole diameter. The units of all the input values are according to the SI system.

1.4 Vbrizgalni sistemi

V predloženem delu je bil analiziran postopek vbrizgavanja in nastanka curka za dva vbrizgalna sistema: (i) VBRIZGALNI SISTEM 1 (VS1) - klasičen vbrizgalni sistem z linijsko tlačilko in vbrizgalno šobo s štirimi izvrtinami premera 0,375 mm, pri katerem imata odprtini št. 1 in št. 4 nagibni kot kanala odprtine 95°, odprtini št. 2 in št. 3 pa kot 49°, (ii) VBRIZGALNI SISTEM 2 (VS2) - vbrizgalni sistem z rotacijsko tlačilko in šobo s čepom, s premerom odprtine 1,1 mm.

1.4 Injection system

The injection characteristics and the spray formation process were analysed for two injection systems: (i) INJECTION SYSTEM 1 (VS1) – a conventional fuel-injection system with an in-line pump and a four-hole injection nozzle (hole diameter 0.375 mm, holes #1 and #4 have an inclination angle of 95°, whereas holes #2 and #3 have an inclination angle of 49°), (ii) INJECTION SYSTEM 2 (VS2) – an injection system with a rotational pump and a pintle nozzle (hole diameter 1.1mm).

2 ŠTEVILČNI PRIMERI

Analize so bile izvedene pri dveh različnih obratovalnih režimih (največji vrtilni moment (VS1_A) in največja moč (VS1_B) pri VS1 in največji vrtilni moment (VS2_C) ter 80% vrtilne frekvence največje moči (VS2_D) pri VS2 za tri različna goriva: biodizel (BIO), odpadno rastlinsko olje (ORO) in plinsko olje (D2).

Vrtilni frekvenci tlačilke v primeru VS1 sta 600 min^{-1} in 1000 min^{-1}, medtem ko vrtilni frekvenci pri VS2 znašata 1000 min^{-1} in 2000 min^{-1}.

Analiza z uporabo RDT je za VS1 potekala v diskretiziranem modelu v obliki kocke s stranico 300 mm, za VS2 pa v modelu oblike kvadra izmer 50x50x500 mm. Obe geometrijski obliki predstavljata vbrizgalno komoro. Izmere so bile izbrane v skladu s pričakovanimi dometi in obliko curkov.

Za izračun karakteristik vbrizgavanja, potrebnih za določitev začetnih in robnih pogojev

2 NUMERICAL EXAMPLES

The analyses were made for two different operating conditions: maximum torque (VS1_A) and rated (VS1_B) for injection system 1 (VS1), and maximum torque (VS2_C) and 80% of the rotational speed at maximum power (VS2_D) for injection system 2 (VS2)). Three different fuels were used: biodiesel (BIO), waste cooking oil (WCO) and diesel fuel (D2).

The pump rotational speeds for VS1 were 600 min^{-1} and 1000 min^{-1}, and for VS2 the rotational speeds were 1000 and 2000 min^{-1}.

The CFD analyses were made on the cube model with a side of 300 mm for VS1 and on the block model with sides 50x50x500 mm for VS2. Both geometries represent the injection chamber. The dimensions were set according to the expected spray shapes and the penetration lengths.

The injection characteristics needed for the setting of the initial and boundary conditions were numeričnih analiz, je bil uporabljen enorazsežni matematični model [6] oz. meritve. V primeru VS1 so karakteristike vbrizgavanja za posamezno gorivo dobljene iz rezultatov analize, predstavljene v [7], medtem ko so bile pri VS2 le-te dobljene na podlagi meritev. Tlak v komori je 1 bar, temperatura 313 K. Začetna velikost kapljic in verjetnostna porazdelitev (začetni pogoji) sta določeni v skladu z ugotovitvami predhodne analize [8]. Pri verjetnostnih porazdelitvah v primeru analize nadomestnih goriv je določena velikost kapljic z največjo verjetnostjo za okrog 15% večja od tiste pri plinskem olju.

3 REZULTATI

V nadaljevanju so predstavljeni rezultati numeričnih in empiričnih analiz za vbrizgalni sistem 1 (VS1) in 2 (VS2) ter fotografije curka VS2.

3.1 Vbrizgalni sistem 1

3.1.1 Numerična analiza

Na slikah 1 do 4 so prikazane oblike curka in lega kapljic ob koncu vbrizgavanja, izračunane srednje vrednosti srednjega Sauterovega premera v komori ter največji domet curka pri posameznem gorivu. Na slikah 1 do 3 je velikost kapljic predstavljena z velikostjo krožcev. S slik je razvidno, da je domet curka odpadnega rastlinskega olja večji od dometov biodizla in plinskega olja. Prav tako je jasno vidna razlika med dometi curka v posameznem obratovalnem režimu.

Zanimivo je, da so v primerjavi izračunanih največjih dometov (sl.4) razlike nekoliko manjše, kakor bi lahko sklepali iz grafičnega prikaza curkov. Razlike med grafičnim prikazom in absolutnimi vrednostmi so verjetno posledica tega, da največji domet pomeni pot

obtained by using the one-dimensional mathematical model [6] and the experimental results, respectively. In the case of VS1 the injection characteristics for all three fuels were obtained from the results presented in [7], whereas the characteristics in the case of VS2 were measured. The pressure in the chamber was 1 bar, while the temperature was 313 K. The initial size of the bubble and the probability distributions were defined according to the findings of previous analyses [8]. The bubble-size distribution in the case of the alternative fuels was set 15% higher than in the case of diesel fuel.

3 RESULTS

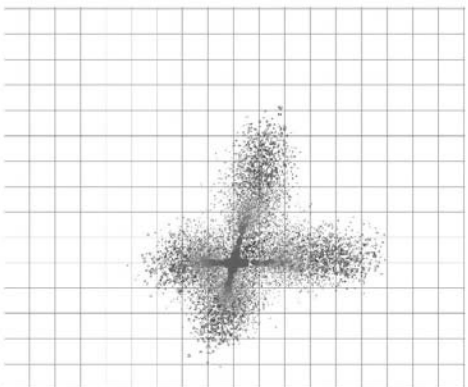
The results of the numerical and empirical analyses for the injection system 1 (VS1) and 2 (VS2) and the fuel-spray photographs for VS2 are presented below.

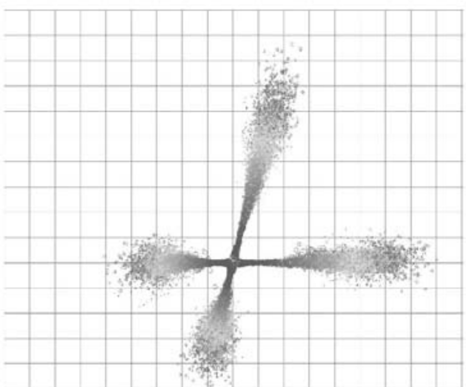
3.1 Injection system 1

3.1.1 Numerical analysis

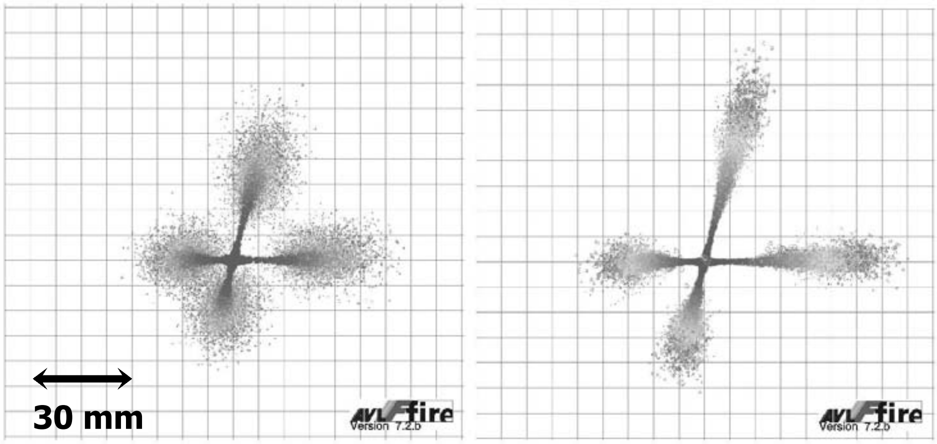
Fig. 1-4 show the spray shapes and the positions of the droplets at the end of the injection process, the calculated mean values of the Sauter mean diameter in the chamber, and the maximum spray penetration length for all three fuels. In Fig. 1-3 the size of the droplets is represented by the size of the circles. From the figures presented below it is clear that the penetration length when using the waste cooking oil is larger than in the case of the biodiesel and the diesel fuel. An obvious difference in the penetration lengths under different operating conditions can also be seen.

It is interesting that the differences between the calculated values of the penetration length are smaller than the differences between the penetration lengths shown in the figures. These differences are probably the result of the definition of the maximum penetration length, which is equal to the path of the droplet that travelled the

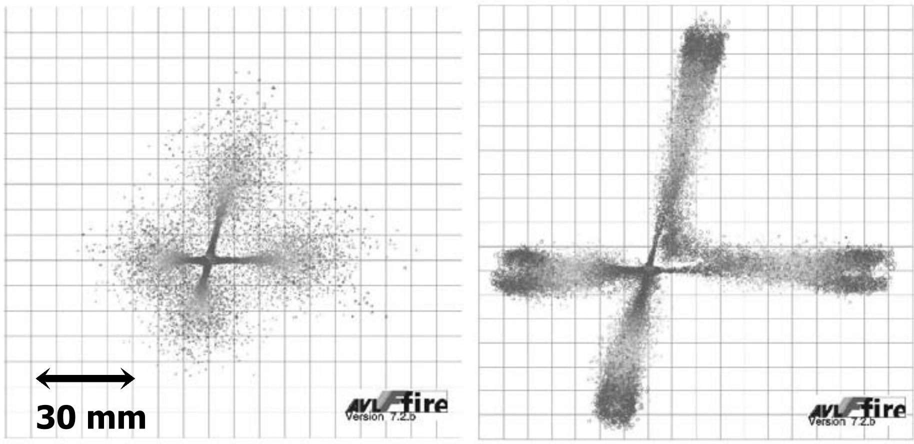




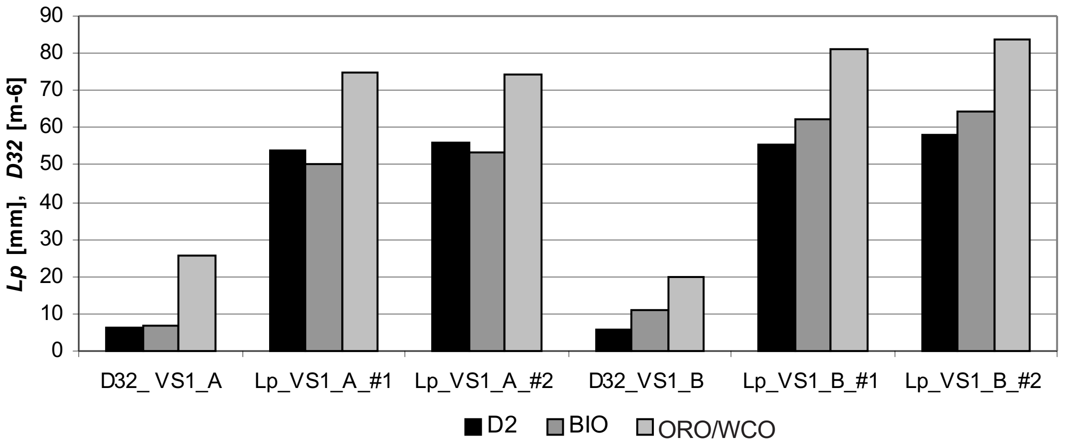
Sl. 1. *Curek plinskega olja (levo: največji vrtilni moment (VS1_A), desno: največja moč (VS1_B))*
Fig. 1. *Diesel fuel spray (left: maximum torque (VS1_A), right: rated (VS1_B))*



Sl. 2. *Curek biodizla (levo: največji vrtilni moment (VS1_A), desno: največja moč (VS1_B))*
Fig. 2. *Biodiesel spray (left: maximum torque (VS1_A), right: rated (VS1_B))*



Sl. 3. *Curek odpadnega rastlinskega olja (levo: največji vrtilni moment (VS1_A), desno: največja moč (VS1_B))*
Fig. 3. *Waste cooking-oil spray (left: maximum torque (VS1_A), right: rated (VS1_B))*



Sl. 4. *NUMERIČNA ANALIZA - primerjava karakteristik curka obravnavanih goriv pri najv. vrt. momentu (D32_VS1_A, LP_vrtilni moment_VS1_A) in največji moči (D32_VS1_B, Lp_VS1_B), D32 je Sauterjev srednji premer , Lp je domet curka, #1 pomeni odprtini 1 in 4, #2 pomeni odprtini 2 in 3*
Fig. 4. *NUMERICAL ANALYSIS – Comparison of spray characteristics at max. torque (VS1_A) and rated (VS1_B): D32 is the Sauter mean diameter, Lp is the penetration length, #1 represent holes 1 and 4, #2 represent holes 2 and 3*

najbolj oddaljene kapljice iz posamezne odprtine. Te pa so zaradi majhne ločljivosti slabše vidne. Pri izračunih srednjih vrednosti srednjih Sauterjevih premerov (sl. 4) v komori je dobro viden trend večanja kapljic z uporabo goriv z večjo viskoznostjo.

Velikost kapljic in domet curka sta glavna kazalnika razpada curka goriva. Boljši razpad curka pomeni, da so kapljice majhne, domet pa čim krajši. Boljši razpad curka vpliva pozitivno na postopek zgorevanja, manjše pa so tudi emisije saj oz. trdnih delcev. Iz predstavljenih rezultatov je razvidno, da je razpad curka najboljši v primeru uporabe plinskega olja, sledi biodizel, medtem ko je razpad curka pri odpadnem rastlinskem olju najslabši.

3.1.2 Empirična analiza

Rezultati empirične analize karakteristik curka so prikazani na sliki 5, od koder je ponovno jasno razviden najboljši razpad curka v primeru uporabe plinskega olja (D2).

3.2 Vbrizgalni sistem 2

3.2.1 Numerična analiza

V primeru VS2 je bila numerična analiza izdelana le za dizelsko gorivo. Rezultati za obravnavana obratovalna režima (VS2_C in VS2_D) so prikazani na slikah 6 in 7. Izračunan največji domet v primeru VS2_C je okrog 240 mm, pri VS2_D pa okrog 210 mm. Srednji Sauterjev premer kapljic znaša v prvem primeru okrog 65 μm, v drugem pa okrog 62 μm. Na slikah 6 in 7 velikost krogel pomeni velikost kapljic.

longest distance. Because of the low resolution figures these are not easily seen. It is mainly the core of the spray that can be observed from the figures. The calculated values of the Sauter mean diameter (Fig. 4) show that the values are larger for fuels with a higher viscosity.

The droplet size and the penetration length are the most important parameters, showing the quality of the spray atomisation. By the term ‘better atomisation’, we understand that the droplets are smaller and the penetration length is shorter. The quality of the atomisation positively effects the injection and combustion process and the soot emission. From the above-presented results it is clear that the atomisation is the best in the case of the diesel fuel, followed by the biodiesel and the waste cooking oil.

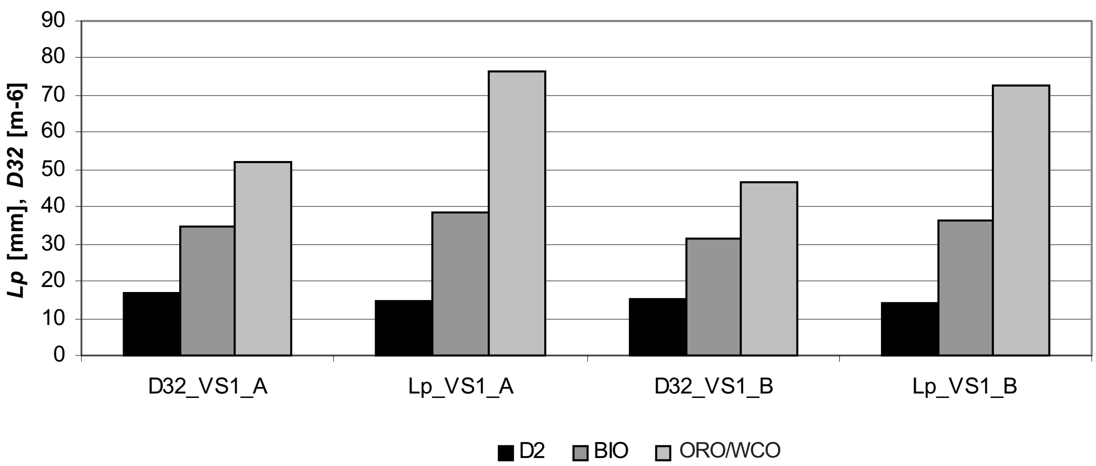
3.1.2 Empirical analysis

The empirical analysis results of the spray characteristics are presented in Fig. 5, where it can be seen that the best atomisation is calculated for the diesel fuel (D2).

3.2 Injection system 2

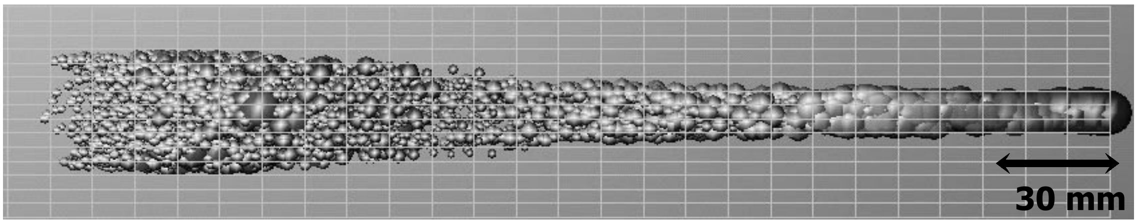
3.2.1 Numerical analyses

For VS2 the numerical analyses were made only for the diesel fuel. The results for both operating conditions – VS2_C and VS2_D – are presented in Fig. 6 and 7. The calculated maximum penetration length for VS2_C is about 240 mm, whereas for VS2_D it is 210 mm. The Sauter mean diameter is 65 μm for the first case and 63 μm for the second case. The size of the spheres in Fig. 6 and 7 represents the size of the droplets.

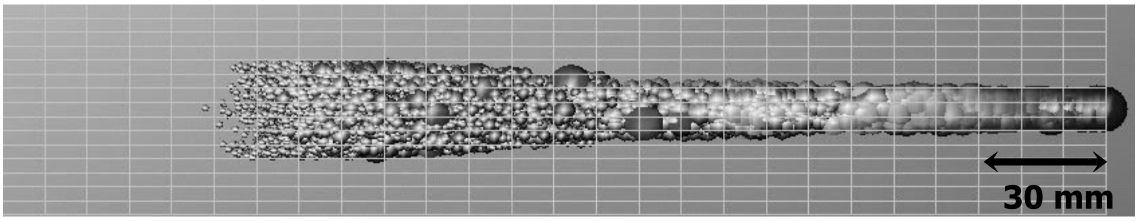


Sl. 5. *EMPIRIČNA ANALIZA - primerjava karakteristik curka obravnavanih goriv pri največjem vrtilnem momentu (D32_VS1_A, LP_VS1_A) in največji moči (D32_VS1_A, Lp_VS1_B) , D32 je Sauterjev srednji premer , Lp je domet curka*

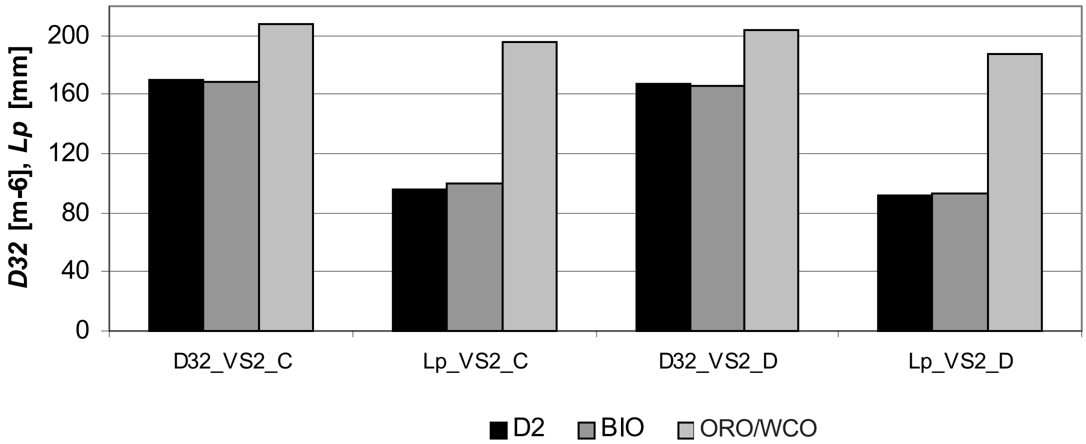
Fig. 5. *EMPIRICAL ANALYSIS - Comparison of the spray characteristics at max. torque (VS1_A) and rated (VS1_B): D32 is the Sauter mean diameter, Lp is the penetration length*



Sl. 6. *Curek plinskega olja pri največjem vrtilnem momentu (VS2_C)*
Fig. 6. *Diesel fuel spray at maximum torque (VS2_C)*



Sl. 7. *Curek plinskega olja pri 80% vrtilne frekvence največje moči (VS2_D)*
Fig. 7. *Diesel fuel spray at the 80 % of maximum power rotational speed (VS2_D)*



Sl. 8. *EMPIRIČNA ANALIZA - primerjava karakteristik curka obravnavanih goriv pri najv. vrt. momentu (D32_VS2_C, LP_VS2_C) in 80% vrt. frekvenci najv. moč (D32_VS2_D, Lp_VS2_D) , D32 je Sauterjev srednji premer , Lp je domet curka*
Fig. 8. *EMPIRICAL ANALYSIS - Comparison of spray characteristics at the max. torque (VS2_C) and at the 80% of rotational speed of the maximum power (VS2_D): D32 is the Sauter mean diameter, Lp is the penetration length*

3.2.2 Empirična analiza

Rezultati empirične analize za VS2 so prikazani na sliki 8. Na prvi pogled je razvidno, da uporabljena modela napovesta razmeroma kratke curke z velikimi vrednostmi srednjih Sauterjevih premerov, kar ni v skladu s predhodnimi numeričnimi ugotovitvami (sl. 7 in 8) ter v nadaljevanju predstavljenimi fotografijami curka (sl. 9 in 10).

3.2.3 Fotografiranje curka

Za primer VS2 je bilo v okviru Laboratorija za motorje z notranjim zgorevanjem Fakultete za strojništvo Maribor izvedeno fotografiranje curka (sl. 9 in 10).

Zaradi razmeroma preprostega postopka in izvedbe je kakovost slik sorazmerno slaba, vidni pa

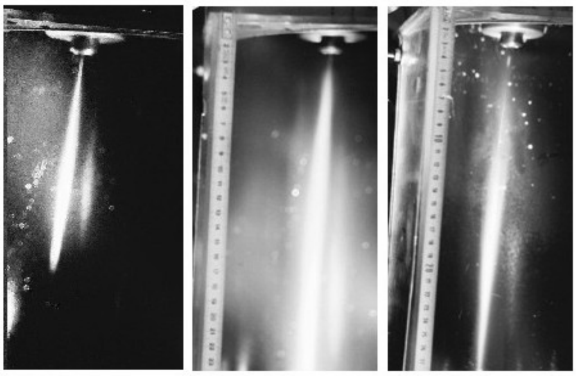
3.2.2 Empirical analysis

The empirical analysis results for VS2 are presented in Fig. 8. It can be clearly seen that the empirical models gave rather short sprays with relatively high values of the Sauter mean diameter, which is not in accordance with the numerical results (Fig. 7 and 8) and the photographs (Fig. 9 and 10) for this case.

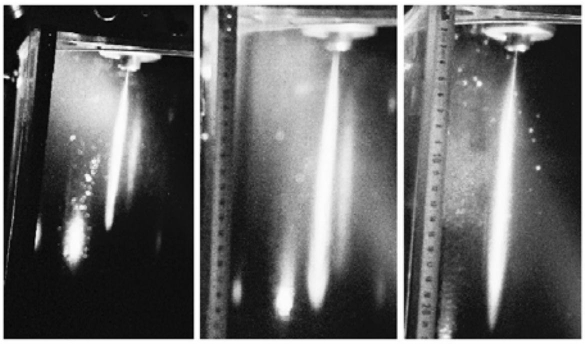
3.2.3 Spray photography

For VS2 the spray photographs were taken at the Engine Research Laboratory of the Faculty of Mechanical Engineering, Maribor (Fig. 9 and 10).

The quality of presented photographs is relatively low, due to the low resolution and the back



Sl. 9. *Fotografije curkov pri VC2_C (od leve: plinsko olje, biodizel, odpadno rastlinsko olje)*
Fig. 9. *Spray photographs for VS2_C (from left: diesel fuel, biodiesel, waste cooking oil)*



Sl. 10. *Fotografije curkov pri VC2_D (od leve: plinsko olje, biodizel, odpadno rastlinsko olje)*
Fig. 10. *Spray photographs for VS2_D (from left: diesel fuel, biodiesel, waste cooking oil)*

Preglednica 2. *Domet curka, dobljen s fotografij*
Table 2. *Spray penetration length acquired from the spray photographs*

	VC2_C	*VC2_D*
D2	*150 mm*	*120 mm*
BIO	*230 mm*	*185 mm*
WCO	*280 mm*	*215 mm*

so tudi številni odsevi. Kljub temu je bilo mogoče do neke mere določiti največji domet pri posameznem obratovalnem režimu.

S fotografij je razvidno, da je domet v obeh primerih najkrajši v primeru uporabe plinskega olja, najdaljši pa v primeru odpadnega rastlinskega olja. Izmerjene vrednosti so predstavljene v pregl. 2. Vidno je tudi, da je kot curka v bližini odprtine največji pri plinskem olju, kar kaže na boljši razpad goriva. Pri nadomestnih gorivih, posebej pri odpadnem rastlinskem olju, je vidna nit goriva na izstopu iz odprtine, ki se začne trgati komaj na razdalji okrog 70 mm v primeru VS2_C (sl. 9) oz. 50 mm v primeru VS2_D (sl.10). Šele od tukaj dalje lahko govorimo o razpadu curka.

3.3 Razprava

Kljub temu, da se rezultati numerične in empirične analize, kakor tudi vrednosti določene s

scattering of the stroboscope lamp. Both are the result of a relatively simple procedure. Nevertheless, we were able to measure the spray penetration length under certain operating conditions.

From the photographs it is clear that the penetration length is always the shortest when using diesel fuel, and the longest when using waste cooking oil. The measured values are presented in Tab. 2. The spray-cone angle is the largest for the diesel fuel, which also indicates better atomisation of the spray. For the alternative fuels, especially the waste cooking oil, a filament of the fuel at the nozzle outlet can be observed. This starts to decay at a distance of about 70 mm from the nozzle outlet, for VC2_C (Fig. 9), and at about 50 mm for VC2_D (Fig. 10). From this point on we can talk about the spray atomisation.

3.3 Discussion

Even though the results of the numerical and empirical analyses as well as the results obtained fotografijami, medsebojno v celoti ne ujemajo, lahko ugotovimo, da je v vseh analizah zaznan podoben trend spreminjanja karakterističnih veličin curka. Na podlagi podobnih gibanj lahko analiziramo ter do neke mere določimo, kakšen vpliv ima posamezno gorivo na postopek vbrizgavanja, zgorevanja in tvorbe nezaželenih produktov zgorevanja.

Tako je v vseh primerih, pri vseh analizah, najslabši razpad curka zaznan pri uporabi odpadnega rastlinskega olja, najboljši pa v primeru plinskega olja. Vrednosti za biodizel so v skoraj vseh primerih med obema omenjenima gorivoma. V odvisnosti od uporabljene analize so te enkrat bližje vrednostim plinskega olja, drugič pa bližje tistim pri odpadnem rastlinskem olju.

Glede na to, da je biodizel danes praktično že v uporabi; dovoljenje za uporabo le-tega pa je tudi na svojih najsodobnejših dizelskih motorjih odobrilo precejšnje število proizvajalcev [9], je na vprašanje smiselnosti in ustreznosti uporabe tega goriva že bolj ali manj odgovorjeno. Vsekakor pa velja pri starejših vbrizgalnih sistemih, ki so bili razviti zlasti za klasično gorivo in dosegajo manjše tlake vbrizgavanja, pred uporabo nadomestnih goriv razmisliti o morebitni predelavi vbrizgalnega sistema in zgorevalnega prostora.

Na tem mestu se vprašanje ustreznosti oz. vpliva na postopke vbrizgavanja, zgorevanja in tvorbe nezaželenih produktov zgorevanja postavlja bolj za odpadno rastlinsko olje, ki bi lahko ob predstavljenih rezultatih povzročalo nepopolno zgorevanje ter s tem povezan nastanek nezaželenih ostankov zgorevanja. Težave se lahko pričakujejo predvsem s predolgim dometom in s tem povezanim zadevanjem goriva ob steno zgorevalne komore, zato je pametno poiskati možnost spremembe geometrijske oblike zgorevalne komore v primeru delovanja motorja z odpadnim rastlinskim oljem. Na podlagi tega lahko po predstavljenih analizah do neke mere že zanesljivo trdimo, da nepredelano odpadno rastlinsko olje ni primerno gorivo za dizelske motorje.

Če na temelju dobljenih karakteristik curka odpadnega rastlinskega olja vseeno do neke mere poskusimo določiti, kako je z emisijami, lahko zapišemo naslednje. V splošnem pri dizelskem motorju, ki obratuje s plinskim oljem, velja, da v primeru slabšega razpada curka prihaja do povečanja emisij saj oz. trdnih delcev. Ne glede na to, da rezultati pri odpadnem rastlinskem olju kažejo najslabši rezultat, teh sklepov zaradi drugačne sestave goriva ne moremo neposredno prenesti na odpadno rastlinsko olje. Rastlinska olja imajo namreč v molekulah vezanega več kisika, kar bi lahko ugodno vplivalo na postopek zgorevanja tudi v primeru slabšega razpada oz. v primeru, ko ni velikega presežka zraka. Težava je tudi v tem, da so trdni delci, ki nastajajo pri postopku zgorevanja nadomestnih goriv, svetlejše barve od tistih pri plinskem olju, zato jih z optičnimi merilnim tehnikami ne moremo zaznati.

Glede drugih emisij lahko do neke mere sklepamo, da bi lahko bile emisije NO_x, zaradi slabšega

from the photographs differ significantly, we were able to determine that the trend in the changes of the characteristic values is the same for all the analyses. On this basis we are able to discuss the results and to define how a specific fuel is affecting the injection, combustion and emission-formation processes, at least to some extent.

The worst spray atomisation was always obtained when waste cooking oil was used as a fuel; the best results were obtained for the diesel fuel. The values for the biodiesel were always in between. Depending on the analyses used, the results for the biodiesel were closer to one or other fuel.

As biodiesel is already available on several markets and since many engine producers allow it to be used in their diesel engines [9], the questions concerning its suitability are more or less answered. However, conventional injection systems, which were primarily designed for use with diesel fuel and for which injection pressures are lower, need to be redesigned before using alternative fuels. In particular, the combustion chamber should be redesigned.

The suitability and the influence on the processes of injection, combustion and emission formation, should be discussed for the waste cooking oil, since these factors could cause incomplete combustion followed by emission formation. The problems could occur due to a high penetration length and possible collision with the combustion-chamber walls. For this reason possible ways of changing the combustion-chamber geometries when waste cooking oil is used as a fuel should be discussed. According to these discussions we can already confirm the statement that unmodified waste cooking oil is not suitable for use as a fuel in compression-ignition engines.

Based on the presented waste cooking-oil spray characteristics we can try to predict the emissions, to some extent. In general, the soot emissions of a compression-ignition engine operating on diesel fuel are bigger when the fuel atomisation is worse. However, despite the fact that the spray atomisation in the case of waste cooking oil was the worst, we cannot directly transfer these statements to the case of waste cooking oil, since the structure of the fuel is different. Vegetable oils have more oxygen bonded in the molecule, which positively affects the combustion process, even if the spray atomisation is bad and there is no large excess of air. The other problem is that the particulate matter during the alternative-fuel combustion process is brighter than in case of diesel fuel. This means it cannot be measured with conventional optical methods.

Regarding the other emissions, the emission of NO_x could be smaller since the combustion temperatures could be lower due to worse atomisation.

razpada curka, nekoliko manjše, česar pa zaradi razlik v sestavi goriva ponovno ne moremo zanesljivo trditi.

4 SKLEP

Na podlagi predstavljenih rezultatov so mogoči naslednji sklepi v zvezi z uporabo plinskega olja, biodizla in odpadnega rastlinskega olja v dizelskem motorju:

Vse analize kažejo podobne usmeritve vplivov goriva na značilnosti curka.

Biodizel in odpadno rastlinsko olje pri postopku vbrizgavanja obeh vbrizgalnih sistemov dajeta večje kapljice in imata daljši domet, kar je posebej očitno v primeru odpadnega rastlinskega olja.

Prve analize kažejo, da bi lahko uporaba nadomestnih goriv na klasičnih vbrizgalnih sistemih oz. motorjih, zasnovanih za uporabo plinskega olja, povzročala težave z zadevanjem curka goriva ob stene zgorevalnega prostora oz. vdolbine na batu.

Predstavljeni rezultati kažejo, da bodo za boljše poznavanje vpliva nadomestnih goriv na postopek vbrizgavanja potrebne še podrobnejše analize. Tako bo treba opraviti še številne meritve obratovalnih značilnosti motorja ter pred tem po možnosti tudi curka vbrizganega goriva. Prav tako je smiselno izboljšati sistem za vidno opazovanje curka (fotografiranje), kakor tudi vpeljati sodobnejše tehnike merjenja značilnosti curka. Nenazadnje pa bo treba razmišljati tudi o modelih vbrizgavanja (RDT), ki bodo dovolj natančno popisali pogoje pri nadomestnih gorivih.

5 ZAHVALA

Za rezultate meritev karakteristik vbrizgavanja VS2 in sodelovanje pri fotografiranju curka se avtorja najlepše zahvaljujeta sodelavcem Fakultete za strojništvo Maribor, mag. Gorazdu Bombeku, Avgustu Polaniču in Andreju Pagonu ter študentu Borutu Peklarju.

But there is again the question how the fuel structure influences these processes.

4 CONCLUSION

The following conclusions can be made regarding the use of diesel, Biodiesel and waste cooking oil in a compression-ignition engine:

All the analyses gave similar trends concerning how the fuel affects the spray characteristics.

The penetration length is higher and the droplets are bigger when the Biodiesel and the waste cooking oil are used. The results vary, particularly in the case of waste cooking oil.

The first analyses show that the use of alternative fuels in conventional injection systems, i.e. engines designed for diesel fuel, could cause problems related to the collision of the spray with the chamber wall or the piston.

The presented results show that for a better understanding of the alternative fuel's influence on the injection process some further analyses need to be made. In future, many additional measurements of the engine characteristics should be made. The system for optical spray observation should be modified. And last, but not least, the CFD models should be modified in order to run the analyses with alternative fuels more accurately.

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6 LITERATURA
6 REFERENCES

[1] DIN V 51606, Ausgabe:1994-06 Flüssige Kraftstoffe; Dieselkraftstoff aus Pflanzenölmethylester

[2] Koerbitz, W. (1999) Biodiesel production in Europe and North America, *an Encouraging Prospect, Renewable Energy 16*, 1078-1083

[3] Filipović I. (1983) Analiza motornih parametra ubrizgavanja alternativnih goriva, PhD Thesis, *Mašinski fakultet Univerze u Sarajevu*, Sarajevo.

[4] Yule, A.J., I. Filipović (1992) On the break-up times and lengths of diesel sprays, *Int. J. Heat and Fluid Flow,* 13, 197-206.

[5] Hiruyasu, H. et al. (1980) Fuel spray characterization in diesel engines, combustion modelling in reciprocating engines, 369-408, Plenum Press.

[6] Kegl, B., An improved mathematical model of conventional FIE processes, SAE 950079.

[7] Volmajer, M., B.Kegl, P.Pogorevc (2002) Injection characteristics of an in-line fuel injection system using the nadomeste fuels*, Journal of KONES*, vol.9, no.1-2, 259-267.

[8] Volmajer, M., B. Kegl (2001) Obravnavanje curka plinskega olja, Diesel-spray analysis. *Strojniški vestnik*., letnik 47, št. 10, 627-636.

[9] BIODIESEL: Aussagen der Fahrzeughersteller, UFOP, Berlin, 2002 (http://www.ufop.de/Freigaben.pdf)

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