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BIODIZEL I OTPADNO JESTIVO ULJE KAO ALTERNATIVNA GORIVA: ANALIZA S ASPEKTA PROCESA UBRIZGAVANJA

Sažetak

U ovom radu će se raspraviti utjecaj uporabe alternativnih goriva na proces ubrizgavanja, karakteristika strujanja u mlaznicama i proces tvorbe mlaza. Rezultati analize dobiveni su na osnovi analiza uz uporabu paketa računske dinamike fluida FIRE, jednodimenzionalnog modela za izračun karakteristika ubrizgavanja i empirijskih izraza za izračun dimenzija kapljica ubrizganog goriva te dometa mlaza.

Kalkulacije su izrađene za konvecionalan sustav ubrizgavanja s linijskom pumpom, visokotlačnim cijevima i mlaznicom sa četiri rupe. Dobiveni rezultati mogu se koristiti za ispravno podešavanje sustava za ubrizgavanje na primjeru uporabe alternativnog goriva umjesto klasičnog dizelskog goriva.

1. Uvod

Ekološki i ekonomski zahtjevi postavljaju nove granice korištenja alternativnih goriva u dizelovim motorima. Zanimljivo je, da je Rudolf Diesel kod konstruiranja svog prvog motora sa samopaljenjem razmišljao o uporabi ulja kikirikija. Dakako, do ranih 70-ih godina i početka prve enrgetske krize upotrijebljeno je uglavnom samo klasično dizelsko gorivo. U tom vremenu zahtjevi za energetsku neovisnost povezani s povećanom ekološkom sviješću doveli su do prvih ideja o uporabi goriva na osnovi biljnih ulja i životinjskih masti, umjesto dizela na osnovi mineralnog ulja. Krajem osamdesetih nekoliko zemalja odlučilo je djelomično zamijeniti dizelsko gorivo s uljima biljnog ili životinjskog porijekla. Švedska i Austrija bile su prve zemlje koje su početkom devedesetih ratificirale zakonodavstvo o biodizelu. Kasnije su isto učinile i neke druge europske zemlje i SAD.

Biodizel ima slične karakteristike kao i dizel dobiven iz mineralnog ulja. Glavna prednost je njegovo poljoprivredno porijeklo, tako biodizel proizveden od biljnih ulja ne donosi neto povećanja emisija CO_2 u atmosferu i ne povećava efekat staklenika /1/2/3/.

Biodizel se može proizvoditi i iz otpadnog jestivog biljnog ulja koje dobivamo u industriji pripreme hrane. Otpadno jestivo ulje mora se profiltrirati, a kasnije se može dodavati kao smjesa klasičnom dizelu i biodizelu ili upotrijebiti kao samostalno gorivo.

Mnoge analize /4-6/ pokazuju, da su emisije čestica (PM particulate material), neizgorjelih ugljikovodika (HC hydrocarbon) i ugljikovog monoksida (CO) u slučaju uporabe biodizela nešto manje ili jednake onima kad se uporabi klasično dizelsko gorivo. Na drugoj strani, emisije dušičnih oksida mogu biti više ili niže. Jedna od vrlo pozitivnih značajki biodizela jesu i dobre karakteristike mazivosti, koje su mnogo bolje od mazivosti dizelskih goriva s manjim sadržajem sumpora /7/. Do danas su poznati nedostaci: veća potrošnja goriva, loš utjecaj na gumene materijale i loše karakteristike kod rada na niskim temperaturama. Analize djelovanja s različitim filtriranim i transesterificiranim otpadnim jestivim uljima /8/ pokazale su povećanje potrošnje goriva i svih emisija osim ugljikovodika.

Glavni cilj većine predstavljenih istraživanja bilo je mjerenje emisije i potrošnje goriva ili na probnom stolu ili kod realnih uvjeta rada motora. Budući da nije bio proveden veliki broj istraživanja utjecaja uporabe biodizela i otpadnog biljnog ulja na proces ubrizgavanja, na karakteristike strujanja u mlaznici i stvaranja mlaza, izvedene su neke prije spomenute analize.

U središtu istraživanja bila je analiza toka u mlaznici kod stacionarnih uvjeta rada te procesa razvijanja mlaza, s uporabom paketa računske dinamike tekućina (CFD) i izračun karakteristika mlaza uz pomoć empirijskih izraza.

2. Karakteristike goriva

Premda čisto biljno ulje i životinjske masti imaju sposobnost izgaranja, ipak se neobrađene rijetko koriste kao gorivo. Biljno ulje ima vrlo visoku viskoznost, uzrokujući slabiju protočnost goriva od spremnika do motora.

Ove probleme može se zaobići grijanjem goriva, uporabom cijevi većih promjera, miješanjem ulja i dizelskog goriva ili kemijskom modifikacijom. Biodizel je opće ime za goriva dobivena od biljnih ulja i životinjskih masti procesom transesterifikacije.

Kod tog procesa se esterske veze u trigliceridima hidroliziraju da bi formirale slobodne masne kiseline, koje u reakciji s metanolom ili etanolom tvore metilni ili etilni ester. Tim procesom dobivamo rjeđe, manje viskozno i više hlapljivo gorivo. Sekundarni produkt tog procesa je glicerin. Zbog tih estera i repične osnove biodizel se obično zove i metilni ester repičnog ulja (MERU).

Karakteristike biodizela mogu varirati ovisno o izvornom ulju. Karakteristike nekih ulja, metilnih estera dobivenih iz različitih izvora i dizelskog goriva uspoređene su u tablici 1.

Tablica 1: Usporedba karakteristika različitih goriva

	Dizel	Biodizel	Canola	Metilni ester životinjske masti (Tallow)	Otpadno jestivo ulje (WCO)
ρ [kg/m^3]	820-845	875-900	922	877	915
ν [mm^2/s]	2-4,5	3,5-5,0	37	4,1	36,7
H [MJ/kg]	42,6	37,3	36,9	39,9	n.p.
Cetanski br.	46	>49	n.p.	58	n.p.

3. Teoretske osnove

3. 1 Karakteristike sustava za ubrizgavanje i mlaznice

Analize su bile izrađene za mlaznicu sa SAC volumenom i četiri rupe s oštrim rubovima na ulaznoj strani. Dimenzije mlaznice predstavljene su u tablici 2 i slici 1.

Tablica 2: Dimenzije mlaznice

Promjer otvora mlaznice	d_d	0,375 mm
Dužina kanala otvora mlaznice	l_s	1,0 mm
Promjer SAC komore	D_E	1,0 mm
Promjer sjedišta igle	D_A	1,1 mm
Kut nagiba otvora mlazinice (otvor #1, #4)	$\alpha_{1,4}$	49°
Kut nagiba otvora mlazinice (otvor #2, #3)	$\alpha_{2,3}$	95°
Kut konusa na vrhu igle	α	95°
Kut sjedišta igle	σ	60°
Kut radijalne raspodjele među otvorima #1,#2 i #3,#4	$\delta_{12}=\delta_{34}$	76°
Kut radijalne raspodjele među otvorima #2,#3 i #4,#1	$\delta_{23}=\delta_{41}$	104°
Maksimalan hod igle	h_{max}	0,35 mm

3.2 Definicije koeficijenta istjecanja

Koeficijent istjecanja predstavlja jedan od važnijih parametra uvjeta ubrizgavanja u mlaznici. Definiran je kao kvocijent izmjerenog ili realnog masenog protoka kroz mlaznicu (m_{real}) s teoretskim (m_{th}).

$$\mu = \frac{\dot{m}_{real}}{\dot{m}_{th}} \qquad \text{(en.1)}$$

Teoretski protok određivan je produktom teoretske brzine istjecanja (u_{th}), izlaznog presjeka (A_d) i gustoće goriva (ρ).

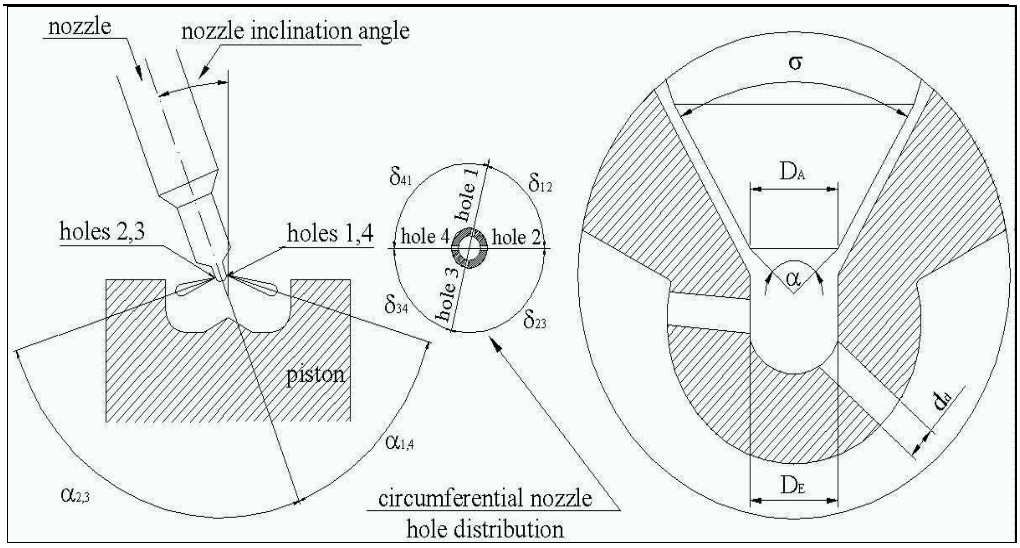
$$\dot{m}_{th} = u_{th} \cdot A_d \cdot \rho \,, \qquad \text{(en.2)}$$

gdje je teoretska brzina dobivena iz Bernoullijeve jednadžbe iz tlačne razlike (Δp) i gustoće:

$$u_{th} = \sqrt{\frac{2 \cdot \Delta p}{\rho}} \,. \qquad \text{(en.3)}$$

Slika 1:Dimenzije mlaznice

Figure 1:Dimensions of the nozzle



4. Uvod u analizu

4.1 Numerička analiza

Numeričke analize bile su izvedene uporabom paketa numeričke dinamike tekućina (CFD) FIRE (ver 6.2b- num.primjer A odnosno 7.2b – num. primjer B). FIRE je CFD program koji upotrebljava metodu konačnih volumena za simulaciju toka tekućine.

U numeričkom primjeru A izrađena je analiza karakteristika strujanja u mlaznici. Analize su bile izvedene pod stacionarnim uvjetima s uporabom modela s jednom četvrtinom stvarnog volumena, što je sukladno s rezultatima nekih prethodnih analiza /11/, gdje je bila uporaba ovakvih modela prepoznata kao podesna za brze analize.

U skladu sa stacionarnim uvjetima dati su tlačni rubni uvjeti na ulazu i izlazu iz mlaznice (100 bara na ulazu i 1bar na izlazu.). Specifikacije goriva korištene za analizu predstavljene su u tablici 1.

Budući da su brzine toka goriva mnogo manje od brzine širenja zvuka, smatra se, da je tok nestješnjiv.

U numeričkom primjeru B radi se o analizi tvorbe mlaza. Analize su izrađene za dva različita režima djelovanja motora: REŽIM 1 – brzina vrtnje pumpe n=650 min^{-1}, maksimalan hod regulacijske letve, REŽIM 2 – n=1050 min^{-1}, maksimalan hod regulacijske letve. U ovom primjeru analizirana su samo tri goriva: dizelsko gorivo, biodizel i otpadno jestivo ulje (WCO).

Gorivo se ubrizgava u manji prostor oblika kocke, koji predstavlja komoru za ubrizgavanje odnosno izgaranje. Tlak u komori je 1 bar, a temperatura 313 K. Karakteristike ubrizgavanja potrebne za definiranje početnih uvjeta u takozvanoj «spray» datoteki definirane su uporabom našeg jednodimezionalnog matematičnog modela za izračun karakteristika ubrizgavanja /12/. Rezultati ubrizgavanja različitih goriva detaljnije su prikazani u literaturi 13.

1.1Empirijski modeli za izračun karakteristika mlaza

Uporabom empirijskih modela analizirani su srednji Sauterov promjer i domet mlaza.

Sauterov promjer kapi definiran je kao:

$$d_{32} = \frac{\sum_i N_i \cdot d_i^3}{\sum_i N_i \cdot d_i^2} \qquad \text{(en.4)}$$

i obično se koristi za definranje atomizacije mlaza goriva. Sauterov srednji promjer (*d_{32}*) predstavlja odnos između zbroja volumena svih kapi i zbroja površina svih kapi.

Drugi značajan parametar tvorbe mlaza je domet mlaza, definiran kao maksimalna dubina prodiranja vrha mlaza.

U ovom radu odlučili smo se za uporabu Filipovićevog modela za srednji Sauterov promjer kapi /14/ (en.5) i modela Yule-Filipovića za domet mlaza /15/ (en.6).

$$d_{32}[\mu m] = 324.6 \cdot \left(\frac{\rho_a \cdot u_0^2 \cdot d_h}{\sigma_f} \right)^{-0.233} \cdot \left(\frac{\rho_f \cdot d_h \cdot \sigma_f}{\mu_f^2} \right)^{-0.082} \qquad \text{(en.5)}$$

$$L_p[mm] = 2{,}65 \cdot 10^3 \cdot d_h \cdot \left(\frac{\rho_a \cdot u_0^2 \cdot d_h}{\sigma_f} \right)^{-0{,}1} \cdot \left(\frac{\rho_f \cdot u_0 \cdot d_h}{\mu_f} \right)^{-0{,}3} \cdot \left(\frac{\rho_f}{\rho_a} \right)^{0{,}08} \quad \text{(en.6)}$$

Vrijednosti u navedenim jednadžbama su: u_0 srednja brzina na izlazu iz mlaznice, ρ_f gustoća goriva, ρ_a gustoća zraka, σ_f površinska napetost goriva, μ_f dinamički viskozitet goriva, ν_f kinematički viskozitet goriva, d_h promjer otvora mlaznice

Analize su izrađene za dva empirijska primjera: EMPIRIJSKI PRIMJER A (početni i rubni uvjeti isti su kao u NUM. PRIMJERU A) i EMPIRIJSKI PRIMJER B (za usporedbu s rezultatima NUM. PRIMJERA B).

5. Rezultati

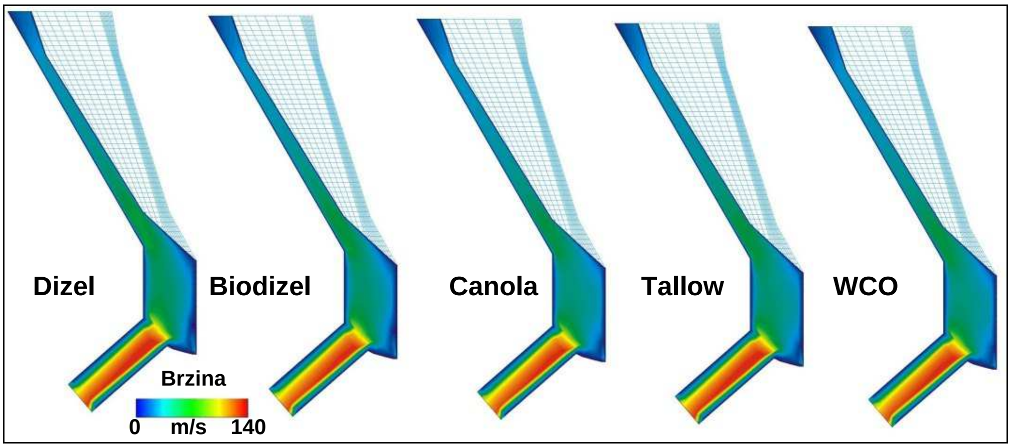
5.1 Rezultati numeričke analize

Rezultati NUMERIČKOG PRIMJERA A predstavljeni su na slikama koje slijede. Budući da nema nekih većih razlika između polja brzina i distribucije tlaka za primjer uporabe različitih goriva, može se zaključiti, da karakteristike goriva kod stacionarnih radnih karakteristika i malih tlačnih razlika nemaju značajan utjecaj na karakteristike toka. Značajnije razlike nastupaju samo kod izračuna turbulentne kinetičke energije.

Iz distribucija tlaka vidna su područja niskih tlakova na gornijim rubovima ulaza u otvore. To je područje osobito veliko kod otvora s većim kutom otklona, kao što smo upoznali već na nekim prethodnim istraživanjima /11/. Na drugoj strani područje niskog tlaka na stijenama otvora mogao bi biti i rezultat uporabljenog modela za izračun turbulencije.

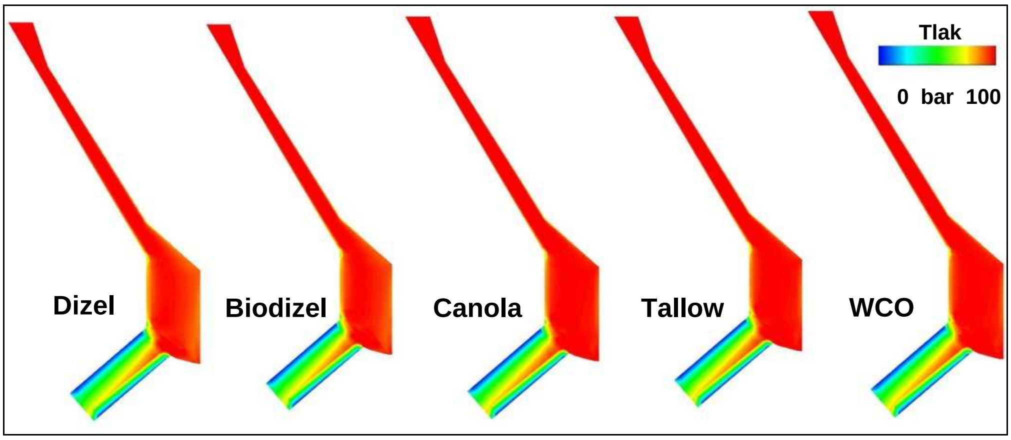
Slika 2: Brzinski profil u otvorima sa 49°(#1,#4)

Figure 2: Velocity profiles at nozzle holes 49°(#1,# 4)



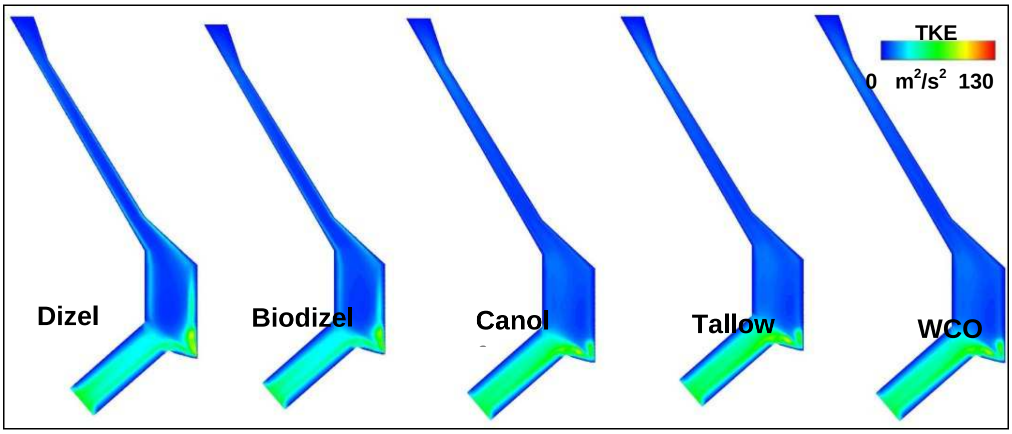
Slika 3: Distribucija tlaka u otvorima sa 49°(#1,#4)

Figure 3: Pressure distributions at nozzle holes 49°(#1,#4



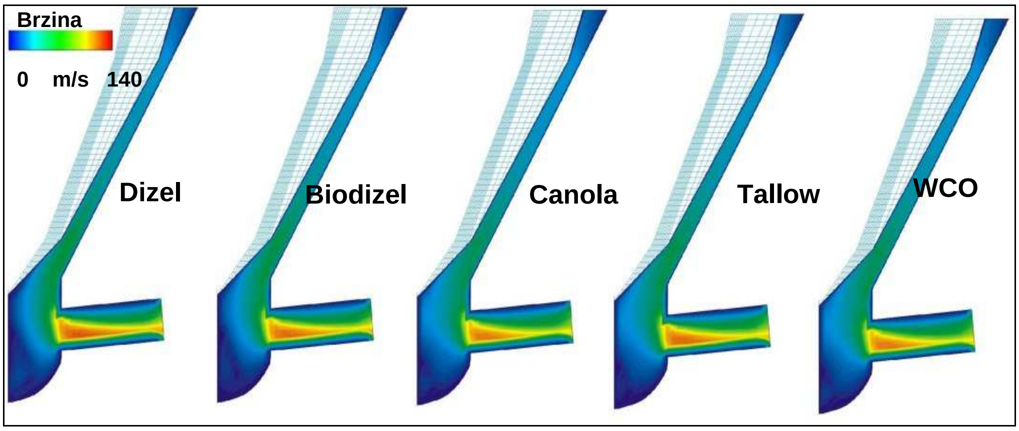
Slika 4: Distribucija turbulentne kinetičke energije u otvorima sa 49° (#1, #4)

Figure 4: Turbulent kinetic energy at nozzle holes 49°(#1,#4)



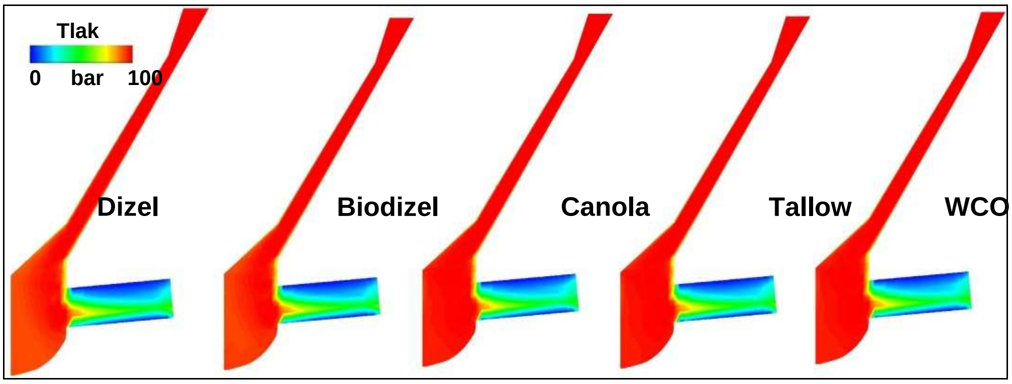
Slika 5: Brzinski profil u otvorima s 95°(#2,#3)

Figure 5: Pressure distributions at nozzle holes 95°(#2,#3)

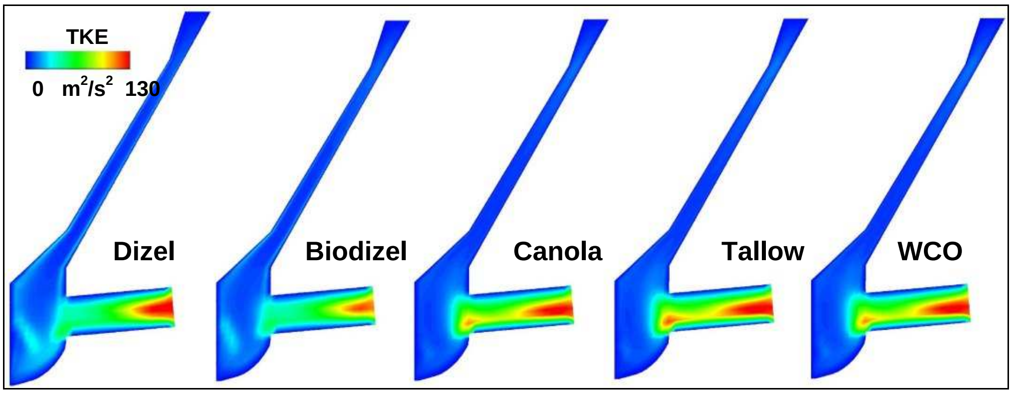


Slika 6: Distribucije tlaka u otvorima s 95°(#2,#3)

Figure 6: Turbulent kinetic energy at nozzle holes 95°(#2,#3 **)**



Slika 7: Distribucije turbulentne kinetičke energije u otvorima s 95°(#2,#3)
Figure 7: Velocity profiles at nozzle holes 95°(#2,# 3)



Na drugoj strani, čak i da su brzinska polja i distribucije tlaka bez nekih većih odstupanja, razlike u vrijednostima izračunatih koeficijenata istjecanja su značajne.

Vrijednosti koeficijenta protjecanja u primjeru uporabe dizela i biodizela imaju najmanje vrijednosti, dok su kod uporabljenih drugih alternativnih goriva gotovo jednake i za oko 2% više od dizela. Budući da se vrijednosti gustoće razlikuju međusobno, u tablici 3 predstavljene su i apsolutne vrijednosti masenih protoka. Najveća količina goriva ubrizgana u satu je dobivena uporabom Canola ulja, koje ima i najvišu gustoću. Uzimajući u obzir niže kalorične vrijednosti goriva na osnovi biljnih ulja i životinjskih masti, veći maseni protok ima pozitivan učinak, budući da je moguće dovesti veću količinu goriva u prostor za izgaranje u istom vremenskom razdoblju.

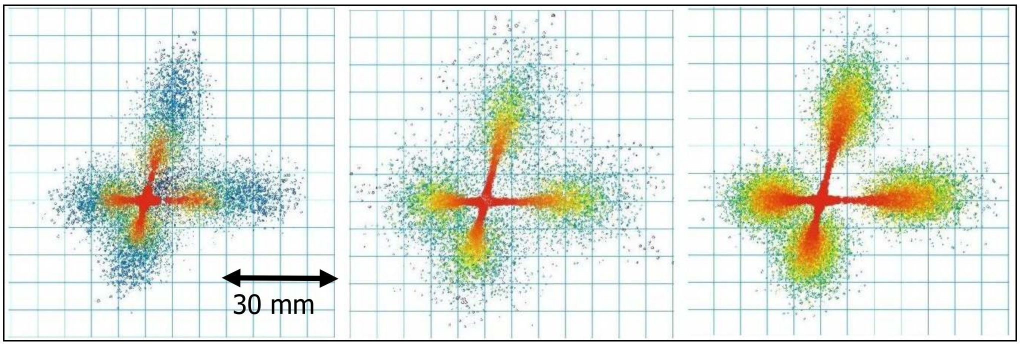
Tablica 3: Rezultati koeficijenta protjecanja i masenog protoka

	Otvor 49°(#1,#4)		Otvor 95°(#2,#3)	
	□	m_{outlet} [kg/s]	□	m_{outlet} [kg/s]
Dizel	0,697	0,009891	0,652	0,00926
Biodizel	0,702	0,010238	0,659	0,00961
Canola	0,713	0,010646	0,671	0,00998
Tallow	0,714	0,010392	0,672	0,00976
Otpadno ulje	0,713	0,010595	0,669	0,00995

Rezultati numerične analize tvorbe mlaza (NUMERIČKI PRIMJER B) prikazani su na slikama 8-11. Na svim režimima vidljivo je da je raspad mlaza u primjeru uporabe otpadnog jestivog ulja značajno slabiji nego u primjeru uporabe dizelskog goriva ili biodizela. Kapi su veće i domet je dulji. Dužina dometa mlaza je posebno velika u REŽIMU 2, gdje bi mlaz mogao kolidirati i sa stijenkama komore za izgaranje odnosno s klipom.

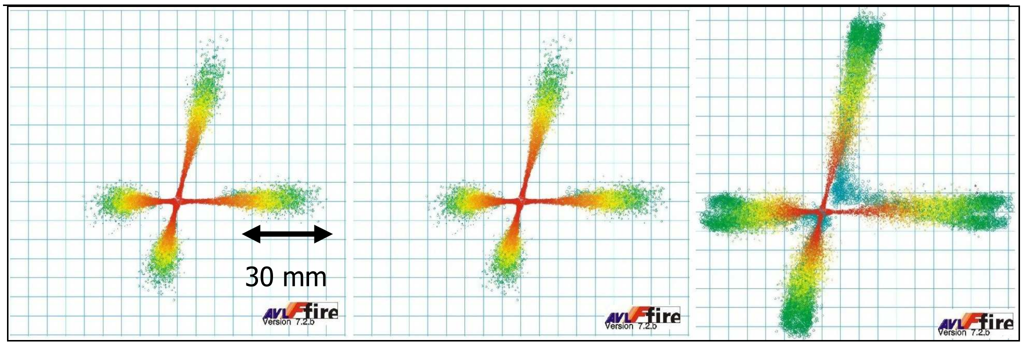
Slika 8: Mlaz goriva: NUM. PRIMJER B–REŽIM 1 (s lijeva: dizel, biodizel, WCO)

Figure 8: Fuel spray: NUM.EXAMPLE B – CASE 1 (From left: Diesel, Biodiesel, WCO)



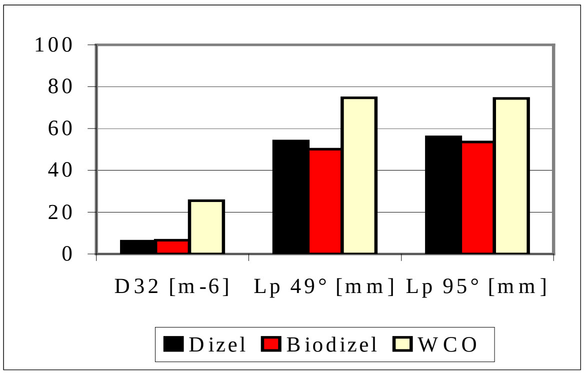
Slika 9: Mlaz goriva: NUM. PRIMJER B–REŽIM 1 (s lijeva: dizel, biodizel, WCO)

Figure 9: Fuel spray: NUM.EXAMPLE B – CASE 2 (From left: Diesel, Biodiesel, WCO)



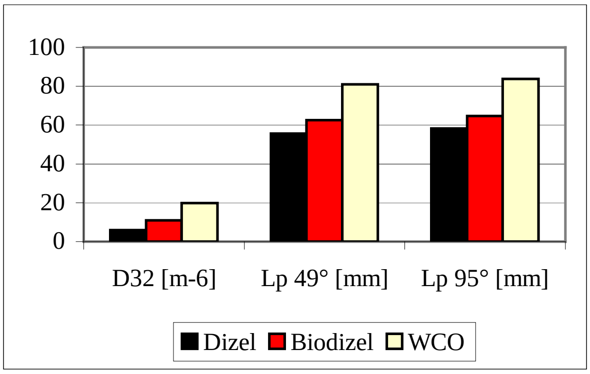
Slika 10: Karakteristike mlaza kod REŽIMA 1, NUM. PRIMJER B

Figure 10: Spray characteristics comparison at CASE 1, NUM. EXAMPLE B



Slika 11: Karakteristike mlaza kod REŽIMA 2, NUM. PRIMJER B

Figure 11: Spray characteristics comparison at CASE 2, NUM. EXAMPLE

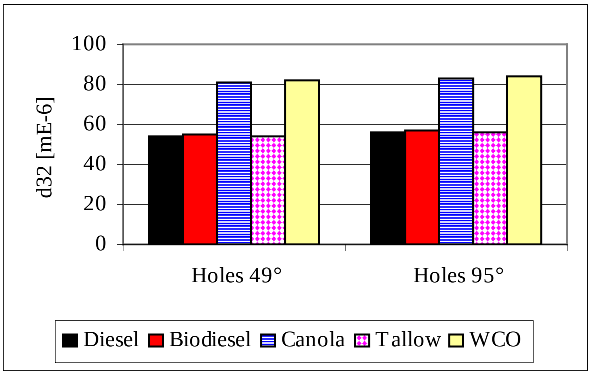


5.2 Rezultati empirijskih izračuna

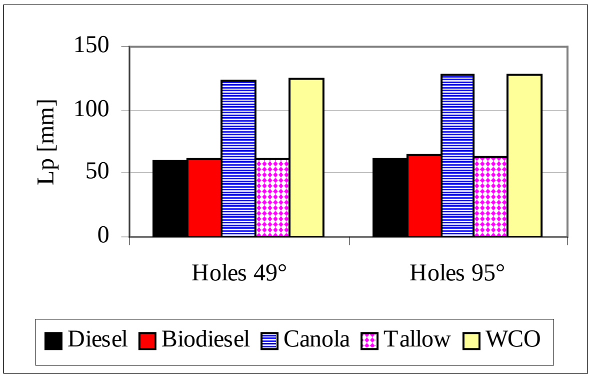
Rezultati izračuna srednjeg Sauterovog promjera u EMPIRIJSKOM MODELU A prikazani su u sljedećim slikama (12-13). Budući da Filipovićev model zahtijeva vrijednost brzine istjecanja, koja je različita za otvore s različitim kutem otklona, rezultati su predstavljeni pojedinačno za svaku rupu. Brzina istjecanja dobivena je uz pomoć Bernoullijeve jednadžbe (en.3).

Iz prikazanih rezultata može se razabrati da su vrijednosti d_{32} u primjeru uporabe alternativnih goriva veće. Rezultati se posebno razlikuju kod uporabe goriva s visokom viskoznošću (Canola i otpadnog jestivog ulja (WCO) - gdje je d_{32} gotovo 4 puta viši uspoređeno s dizelom i 2 puta viši od vrijednosti kod biodizela i tallowa.

Slika 12:Rezultati d_{32}EMP. PRIMJER A
Figure12:d_{32} results EMP.EXAMPLE A



Slika 13:Rezultati L_pEMP. PRIMJER A
Figure 13:L_p results EMP.EXAMPLE A

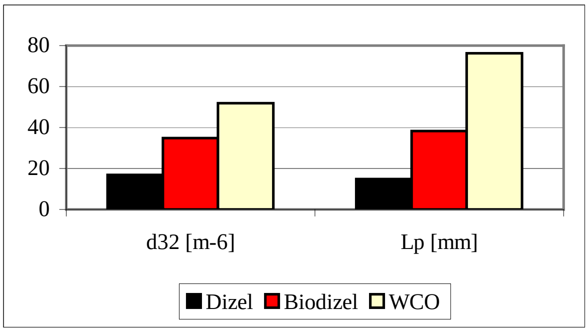


Slični zaključci mogu se donijeti i za maksimalan domet mlaza. Najviše vrijednosti ponovno su dobivene u primjeru uporabe ulja (Canola, WCO). Iz tih rezultata može se zaključiti, da je raspadanje mlaza slabije u primjeru uporabe goriva s višim vrijednostima gustoće i viskoznosti.

Vrijednosti srednjeg Sauterovog promjera i dometa mlaza za EMP. PRIMJER B prikazane su na slikama 14 i 15. Ponovno je najbolja atomizacija mlaza u primjeru uporabe dizelskog goriva. Zanimljivo je da su razlike između karakteristika mlaza za pojedinična goriva u EMP.PRIMJERU B veće nego razlike u NUM.PRIMJERU B.

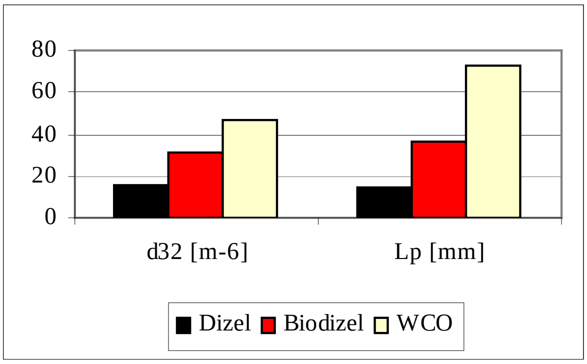
Slika 14: Karakteristike mlaza EMP. PRIMJER B – REŽIM 1

Figure14: Spray characteristics EMP.EXAMPLE B – CASE 1



Slika 15:Karakteristike mlaza EMP. PRIMJER B – REŽIM 2

Figure15: Spray characteristics EMP.EXAMPLE B – CASE 2



6. Zaključci

Iz spomenutih rezultata mogući su sljedeći zaključci:

- Rezultati analize CFD nisu dali signifikantnih razlika između brzinskih polja i tlačnih razlika uporabom različitih alternativnih goriva.
- Uspoređujući rezultate može se utvrditi da su najmanije razlike između rezultata dobivenih uporabom dizela i biodizela.

- U svim primjerima najveće su kapi i najdulji domet mlaza dobiveni u primjeru uporabe otpadnog jestivog ulja (WCO).
- Problem sa slabijim raspadom mlaza WCO kaže da neesterificiran WCO nije povoljan za uporabu kao gorivo u dizelskom motoru. Budući da je atomizacija goriva kod uporabe metilnih estera bolja, WCO se treba esterificirati da bi se mogao uporabiti kao gorivo.

Prema navedenim zaključcima i rezultatima analiza može se zaključiti, da su za bolje razumijevanje utjecaja uporabe alternativnih goriva na proces ubrizgavanja i tvorbe mlaza potrebna još daljna numerička i eksperimentalna istraživanja.

BIODIESEL AND WASTE COOKING OIL AS THE ALTERNATIVE FUELS: THE INJECTION PROCESS ASPECT

Abstract

The presented paper discusses the influence of using alternative fuels on the fuel injection process, in-nozzle flow characteristics and spray formation process. The analysis is performed using the computational fluid dynamics package Fire, a one-dimensional mathematical model for the injection process characteristics calculations and empirical models for calculating the injected droplet mean diameter and spray penetration length. The calculations were performed for the conventional fuel injection system with the in-line pump, high pressure tube and four-hole nozzle with the sac chamber. The results of presented analysis can be used to set properly the fuel injection system for operation with alternative fuels.

1. Introduction

Ecological and economical requirements set new limits in using the alternative fuels in Diesel engines. A look back to the Rudolf Diesel's invention origin shows, his first ideas were using the peanut oil as a fuel for his compression ignition engine. However, until the early 70's, when oil crisis appears, the petroleum oil based diesel fuel was mainly used. At those times, the energy source independence demands connected with rising environmental awareness, lead to the idea of using the vegetable and animal fat based oils instead of petroleum oils. At the end of 80's several countries decided to turn partly to the alternative fuel produced from vegetable sources, generally named Biodiesel. Sweden and Austria followed by some other European countries and USA, were the first states to aim the Biodiesel standard arrangement in early 90's.

Biodiesel has similar characteristics as petroleum based diesel fuel. The main advantage is its agricultural source, so Biodiesel produced from plants doesn't contribute to net rising of the CO_2 emissions in the atmosphere and consequently to the greenhouse effect /1-3/.

Biodiesel can be produced not only from vegetable source oils and animal fats, but also from the waste cooking oil from the catering industry. Waste cooking oil can be cleaned and either mixed together with other fuels (petroleum diesel, Biodiesel) or used alone.

Many analyses /4-6/ showed that the emissions of the particulate matter (PM), unburned hydrocarbons (HC) and carbon monoxide (CO) when using Biodiesel are less or at least equal to those of the petroleum diesel fuel. On the other side the nitrogen oxides emissions could be lower as well as higher. One of the Biodiesel strength is also its lubrication characteristic, which is much better in comparison to those of the low sulphur diesel fue /7/ To date known disadvantages are slightly higher fuel consumption, negative influence on the rubber materials and bad low-temperature operation conditions. Analysis on operation with different filtered and transesterifeid waste cooking oils /8/ showed the increase of fuel consumption and all emissions expect HC.

Major goals of most of the presented investigations were measurements of the emissions and fuel consumption either on test beds or at real operation conditions. On the other side no specific results considering the alternative fuels influence on the injection process, fuel spray formation and in-nozzle flow were presented, so those problems are discussed in the following paper. The kernel of the presented research was the computational fluid dynamics (CFD) analysis of the in-nozzle flow at the steady state conditions and spray formation process at two different real operating conditions.

2. Fuel characteristics

Even though vegetable oil and animal fats could be burned as pure vegetable oil, they are rarely used in this way. The problem of vegetable oil is that it has a very high viscosity, causing the problems concerning the fuel flow from the tank to the engine. Those problems can be mitigated by preheating the oil and using larger fuel lines, by blending the vegetable oil with diesel fuel or by chemical modification, i.e. producing the Biodiesel. Biodiesel is a generic name for fuels obtained by transesterification of the vegetable or animal oils.

At this process the ester bonds in triglyceride are hydrolysed to form free fatty acids, which react with methanol or ethanol to form methyl or ethyl esters. This produces thinner, less viscous and more volatile fuel. A by product of this process is glycerine. Because of those Methyl esters Biodiesel fuels are commonly named Rape Methyl Ester (RME).

Table 1:Comparison of typical properties of different fuels /3,9,10/

	Diesel	Biodiesel	Canola	Tallow methyl ester	Waste cooking oil
ρ [kg/m^3]	820-845	875-900	922	877	915
ν [mm^2/s]	2-4,5	3,5-5,0	37	4,1	36,7
H [MJ/kg]	42,6	37,3	36,9	39,9	n.d.
Cetane number	46	>49	n.d.	58	n.d.

The characteristics of Biodiesel may vary in dependence of the source oil. Properties of some oils, methyl esters, received from different sources, and diesel fuel are compared in Table 1.

3. Theoretical background

3.1 Fuel injection system and nozzle characteristics

Analyses were made for four-hole nozzle with sac volume and sharp edges at the nozzle hole inlet sides. Dimensions of the tested nozzle are presented in Table 2 and Figure 1.

Table 2: Nozzle dimensions

Nozzle hole diameter	d_d	0,375 mm
Nozzle hole channel length	l_s	1,0 mm
Sac chamber diameter	D_E	1,0 mm
Needle seat diameter	D_A	1,1 mm
Nozzle hole inclination angle (holes #1, #4)	$\alpha_{1,4}$	49°
Nozzle hole inclination angle (holes #2, #3)	$\alpha_{2,3}$	95°
Needle tip cone angle	α	95°
Needle seat cone angle	σ	60°
Angle of the radial hole distrib. between #1,#2 and #3,#4	$\delta_{12}=\delta_{34}$	76°
Angle of the radial hole distrib. between #2,#3 and #4,#1	$\delta_{23}=\delta_{41}$	104°
Maximal needle lift	h_{max}	0,35 mm

3.2 Flow coefficient definitions

Flow coefficient, nevertheless its simplicity, represents one of the most important values, representing the fuel injection conditions at the nozzle. It is defined as the ratio between the measured or real (m_{real}) and theoretical (m_{th}) mass flow injected through the nozzle.

$$\mu = \frac{\dot{m}_{real}}{\dot{m}_{th}} \qquad \text{(eq.1)}$$

The theoretical mass flow rate is calculated from the product of theoretical outflow velocity (u_{th}), outflow area (A_d) and fuel density (ρ):

$$\dot{m}_{th} = u_{th} \cdot A_d \cdot \rho \ , \qquad \text{(eq.2)}$$

where the theoretical outflow velocity can be derived, according to Bernoulli equation, from the pressure difference (Δp) and fuel density:

$$u_{th} = \sqrt{\frac{2 \cdot \Delta p}{\rho}} \ . \qquad \text{(eq.3)}$$

4. Introduction to analysis

4.1 Numerical analysis

Numerical analyses were taken by using the CFD program FIRE (6.2b – NUM. EXAMPLE A respectively 7.2b – NUM. EXAMPLE B).

In NUMERICAL EXAMPLE A the analyses of the in-nozzle flow were obtained. Analyses were made at the steady state conditions using one-quarter nozzle volume models, since some recent researches showed adequacy of those models for fast computational analysis /11/.

According to steady state analysing conditions, pressure boundary conditions at the in- and outlet are specified (100 bar at inlet and 1 bar at the outlet.). The specifications of fluids used for analysis are presented in Table 1. Since the maximal velocities are much smaller than the speed of sound, the fluids were supposed to be uncompressible.

The NUMERICAL EXAMPLE B deals with the spray formation analysis. Analyses were made at two different engine operating conditions: CASE 1 – pump rotational speed n=650 min^{-1}, max. duration of delivery and CASE 2 – n=1050 min^{-1}, max. duration of delivery. In this case only the diesel fuel, Biodiesel and waste cooking oil were analysed. The fuel is injected into the discrete cubic volume representing the injection/combustion chamber. Pressure in the chamber is 1 bar and temperature is equal to 313 K. The fuel injection characteristics (quantity of injected fuel and injection rate diagram) needed to set the initial conditions in the spray file were defined using our one-dimensional mathematical model for fuel injection characteristics calculations /12/. The results of fuel injection characteristics calculations for different alternative fuels are in detail presented in /13/.

4.2 Empirical models for spray characteristics

By using the empirical models two spray characteristics were analysed: Sauter mean diameter and spray penetration length.

The Sauter mean diameter, defined as:

$$d_{32} = \frac{\sum_i N_i \cdot d_i^3}{\sum_i N_i \cdot d_i^2} \qquad \text{(eq.4)}$$

is commonly used for the definition of the fuel spray atomisation. Sauter mean diameter (d_{32}) represents the ration between the sum of the droplets' volumes to the sum of the droplets' surfaces.

The other important parameter considering the spray formation is spray penetration length (L_p), defined as the maximum distance travelled by the tip of the spray.

For the analysis presented in this paper we chose the model presented by Filipović /14/ (eq.5) for the Sauter mean diameter and the model by Yule and Filipović /15/ (eq.6) for calculating the spray penetration length.

$$d_{32}[\mu m] = 324.6 \cdot \left(\frac{\rho_a \cdot u_0^2 \cdot d_h}{\sigma_f} \right)^{-0.233} \cdot \left(\frac{\rho_f \cdot d_h \cdot \sigma_f}{\mu_f^2} \right)^{-0.082} \qquad \text{(eq.5)}$$

$$L_p[mm] = 2{,}65 \cdot 10^3 \cdot d_h \cdot \left(\frac{\rho_a \cdot u_0^2 \cdot d_h}{\sigma_f} \right)^{-0{,}1} \cdot \left(\frac{\rho_f \cdot u_0 \cdot d_h}{\mu_f} \right)^{-0{,}3} \cdot \left(\frac{\rho_f}{\rho_a} \right)^{0{,}08} \qquad \text{(eq.6)}$$

The values in above equations are: u_0 mean velocity at the nozzle outflow, ρ_f fuel density, ρ_a air density, σ_f surface tension of the fuel, μ_f dynamic viscosity of the fuel, ν_f kinematic viscosity of the fuel, d_h nozzle hole diameter.

Two empirical examples are introduced again: EMPIRICAL EXAMPLE A (Initial and boundary condition meet the conditions of NUM.EXAMPLE A.) and EMPIRICAL EXAMPLE B (For comparison to the NUM.EXAMPLE B results).

5. Results

5.1 Numerical analysis results

Results of the NUMERICAL EXAMPLE A are presented on the following figures. Since there are no major differences between the velocity flow fields and pressure distributions for different fuels it can be stated the fuel properties obviously don't have a significant influence on the flow characteristics at those (low) pressure drops.

Significant differences occur only considering the turbulent kinetic energy. From pressure distributions (figure 3, figure 6) the area of low pressure at the upper nozzle hole could be seen. The area is especially wide at the nozzle holes with higher inclination angle, as it was already found at some previous analysis considering nozzle flows /11/. At the other side the low pressure area at the nozzle hole walls could be also the result of the turbulence and the geometry models employed.

On the other side, in spite of the similarities in the velocity fields and pressure distributions the differences considering the flow coefficients are significant.

Table 3: Flow coefficient and mass flow results for different fuels

	Hole 49°(#1,#4)		Hole 95°(#2,#3)	
	μ	m_{outlet} [kg/s]	μ	m_{outlet} [kg/s]
Diesel	0,697	0,009891	0,652	0,00926
Biodiesel	0,702	0,010238	0,659	0,00961
Canola	0,713	0,010646	0,671	0,00998
Tallow	0,714	0,010392	0,672	0,00976
Waste Cooking Oil	0,713	0,010595	0,669	0,00995

The flow coefficient in case of using the petroleum diesel and Biodiesel are the lowest, while at the other alternative fuels and WCO, the values are almost on the same level, which is about 2 % higher. Since the fuel densities differ from fuel to fuel, also the absolute values of the mass outflow is presented in Table 3. The largest quantity of fuel injected per second is obtained by using the canola oil, which also has the highest density. Considering the lower calorific value of vegetable/animal based oil, this has a positive effect since larger quantity of fuel can be injected per time.

The spray formation process analysis (NUMERICAL EXAMPLE B) results are shown on Figures 8-11. From both cases it could be stated, that Diesel and Biodiesel fuels yield better atomisation than WCO. The droplets of WCO are larger and the penetration length is longer. The penetration length is especially long in CASE 2, where the spray could also cause problems related the collision of fuel with the combustion chamber walls.

5.2 Empirical calculations results

The results of the Sauter mean diameter of the EMPIRICAL EXAMPLE A are presented in following chart (Figures 12,13). Since the model presented by Filipović considered the outflow velocity, which differs between nozzle holes with different inclination angles, the results are presented for each hole separately. The outflow velocities are calculated from the Bernoulli equation (eq.3).

From the presented results it could be stated the empirical model predicts rather high values of d_{32} by using the alternative fuels. Values are especially high by using the fuels with higher kinematic viscosity (Canola and WCO) - almost 4 time those of the diesel fuel, while at the tallow and Biodiesel the values are almost 2 times higher. Similar observations could be also made for the penetration length. The values are much higher in cases where oils (Canola, WCO) are used. From those results it could be stated again, that the fuels with higher viscosity and density gave worse atomisation.

The Sauter mean diameter and the spray penetration length in EMP. EXAMPLE B are presented on Figures 14 and 15. Again the spray atomisation is the best when Diesel fuel is used. Interesting are larger differences between the calculated values of different fuels in EMP.EXAMPLE B when compared to the differences between the results in the NUM. EXAMPLE B.

6. Conclusions

From the above mentioned results the following conclusions could be made:

- CFD analysis results showed no significant difference between the results of velocity flow fields and pressure distribution by using different fuels.
- The smallest difference between the droplets diameter occurs between diesel fuel and Biodiesel.
- In all cases the largest droplets and the longest spray penetration lengths are predicted when the WCO is used.
- The problems with worse atomisation of the WCO indicate that the non-esterified WCO isn't convenient to be used as a fuel. Since the atomisation of the Methyl esters is better, the WCO should be esterified first and than used as a fuel.

According to the results it could be stated that for better understanding of the alternative fuel influence on the injection process and spray formation some further numerical and experimental analyses would be necessary.

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665.334.94 ulje canole, genetski modificirane uljane repice	Canola oil, oil of geneticaly modified rape seed
532.529.6 dinamika raspršavanja i dometa mlaza	jet dispersion and penetration dynamics
.001.572 gledište ispitivanja na teorijskom modelu	theoretical model investigation viewpoint

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