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USPOREDBA MAKRO-KARAKTERISTIKA MLAZA DIZELSKOG I BIODIZELSKOG GORIVA

Sažetak

Karakteristike ubrizgavanja i formiranja mlaza u prostoru izgaranja jedan su od najvažnijih čimbenika modernih dizelovih motora i imaju značajan utjecaj na efektivne parametre i emisije ispuha. U posljednjih nekoliko desetljeća, biodizelu se kao motornom gorivu sve više posvećuje posebna pažnja. Unatoč tome što ima slične fizičke osobine kao dizelsko gorivo, svejedno veća gustoća, viskoznost i površinski napon mogu ponekad prouzročiti anomalije u procesu ubrizgavanja, kao što su npr. dodir mlaza sa stijenkama komore izgaranja, loše miješanje sa zrakom (prevelike kapljice) i drugo.

U radu su prikazani rezultati istraživanja fizičkih svojstava dizelskog i biodizelskog goriva glede karakteristika ubrizgavanja i mlaza goriva. Utjecaj fizičkih osobina goriva proučavan je uz pomoć fizičko-matematičkog modela, simuliranjem procesa ubrizgavanja u konvencionalnom sustavu. Model je bio razvijen na IEPOI - Inštitut za energetiko, procesno in okoljsko inženirstvo Fakulteta za strojništvo, Univerza v Mariboru, koda Bkin, provjeren eksperimentalno na uređaju i na motoru. U posebnom smo uređaju izmjerili makro karakteristike mlaza (domet, kut, oblik), dok je vremensko prodiranje mlaza u mirujući zrak praćeno visokobrzinskom kamerom (2500 snimaka/s). Uz pomoć 3D programa (AVL "Fire"), dopunjena za ova istraživanja na IEPOI, mogli smo pratiti procese u motoru i odrediti ostale parametre mlaza (promjer kapljice i njihovu distribuciju u aksijalnom prosjeku) u ovisnosti o vremenu i odrediti njihove integralne prosječne vrijednosti i usporediti ih s vrijednostima dobivenih eksperimentom. U radu su prikazani rezultati utjecaja fizičkih osobina goriva i radnih uvjeta na karakteristike ubrizgavanja i mlaza goriva.

Uvod

Globalno onečišćenje atmosfere stakleničkim plinovima danas predstavlja ozbiljan problem. Velik je dio toga onečišćenja uzrokovan fosilnim gorivima korištenima u prijevozu. Primjena alternativnih goriva predstavlja tehničko sredstvo smanjenja emisija konvencionalnih dizelovih motora. Biodizelsko gorivo - alternativa naftnome – moguće je komercijalno proizvoditi putem transesterifikacije biljnih ulja i životinjskih masti s alkoholom i alkalnim katalizatorom. Biodizelsko gorivo ima viši cetanski broj od naftnog dizelskog goriva, ne sadrži aromate, dok sadrži oko 10 % kisika po težini. Navedene karakteristike biodizelskoga goriva smanjuju ispušne emisije ugljičnoga monoksida, ugljikovodika i čestica, u usporedbi s dizelskim gorivom [1][2].

Razlike u fizičkim svojstvima biodizelskoga goriva (poput gustoće, viskoznosti, površinske napetosti i brzine zvuka) mogu izazvati anomalije u oblikovanju mlaza te izazvati nepotrebno povećanje emisija onečišćavala [3],[4],[5],[6]. Veća gustoća, viskoznost i površinska napetost povećavaju trenje između goriva i stijenke sapnice. Tako se smanjuje brzina ubrizgavanja, a povećava tlak ubrizgavanja u konvencionalnom sustavu ubrizgavanja dizelskoga goriva. Duljina penetracije raspršivanja se povećava te se širi kut konusa mlaza, poradi povećanja veličine kapljice i njezinog sporijeg isparavanja [3],[4],[5],[6]. Teorijska razmatranja oblikovanja mlaza spadaju u područje dvofaznih protoka. Brz razvoj mjernih metoda, odgovarajući programski paketi i računalna oprema omogućili su njihovu procjenu.

Cilj je ovoga rada prikazati utjecaj biodizelskoga goriva na svojstva ubrizgavanja za konvencionalne sustave ubrizgavanja u usporedbi s dizelskim gorivom. Razmatrana su fizička svojstva dizela (D2) i biodizela (B100), poput gustoće, viskoznosti, površinske napetosti i brzine širenja zvuka. Tlak ubrizgavanja, podizanje igle sapnice i količina ubrizganog goriva zabilježeni su i izmjereni na sustavima ubrizgavanja goriva pokusnog motora te upotrijebljeni za provjeru matematičkog modela sustava ubrizgavanja. Simultane su faze razvoja mlaza snimane visokobrzinskom kamerom. Rezultati simulacije mlaza i usporedba sa zapisima visokobrzinske kamere su prikazani u ovome radu.

Postupci ispitivanja

Ispitana su fizička svojstva dizelskog goriva i biodizela. Biodizel korišten u našem ispitivanju proizveden je iz repičina ulja u Pinusovoj rafineriji [7], dok je dizelsko gorivo osigurala tvrtka Petrol [8]. Gustoća goriva izmjerena je mjeračem gustoće DMA 35 PAAR, viskoznost viskozimetrom Herzog Ubbelohde HVU 480, dok je površinska napetost izračunata kao podizanje tekućine u tankoj kapilari [9]:

$$\sigma = \frac{1}{2} \cdot \rho \cdot g \cdot h \cdot r \cdot \left(h + \frac{r}{3} \right), \qquad (1)$$

pri čemu je:

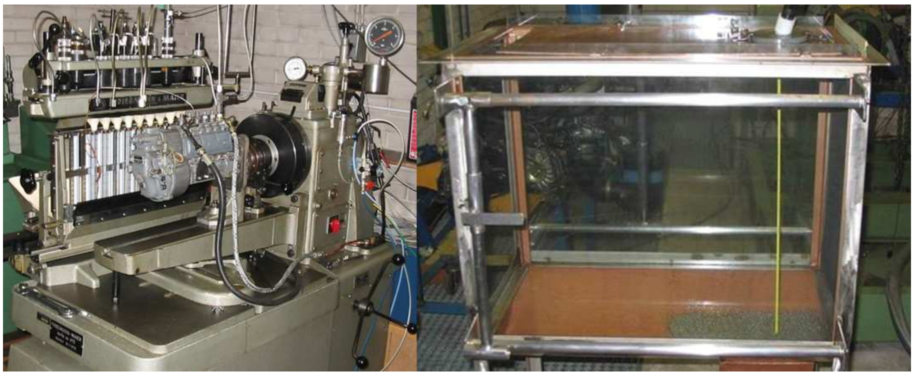
- ρ gustoća goriva [kg/m^3],
- g ubrzanje zbog sile teže [m/s^2],
- h kapilarni uspon [m],
- r promjer kapilare [m].

Sva su fizička svojstva utvrđena na sobnoj temperaturi. Brzina zvuka pri različitim tlakovima izračunata je na temelju vremenskoga odmaka putanje vala tlaka (slika 1).

Slika 1: Uređaj za mjerenje brzine zvuka
Figure 1: Speed of sound measurement

Visokotlačna crpka (Bosch PES6A95D410LS2542) postavljena je na ispitni motor sustava ubrizgavanja goriva (Friedmann-Maier tip 12 H 100-h). Gorivo je ubrizgavano kroz sapnicu (Bosch DLLA5S834) sa samo jednim prolazom u staklenu komoru (slika 2).

Slika 2: Uređaj za ispitivanje sustava za ubrizgavanje goriva sa staklenom komorom
Figure 2: The fuel injection systems test bench and the glass chamber



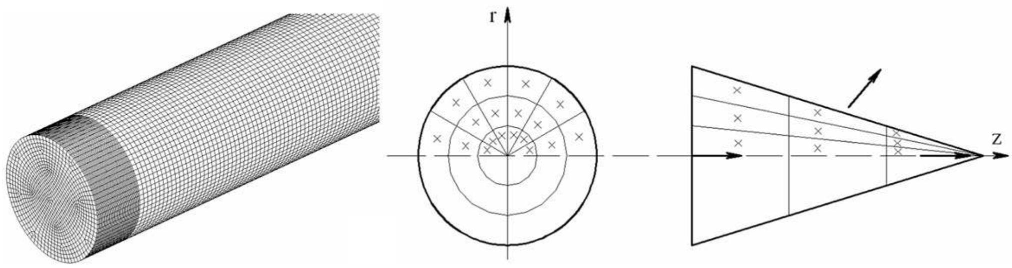
Karakteristike ubrizgavanja goriva uzete su pri punom opterećenju, radnome režimu brzine vrtnje od 800 o/min, pri čemu su zabilježeni tlak i vrijeme podizanja igle. Piezzo-otporni senzor upotrijebljen je za mjerenja tlaka, dok smo induktivni senzor za podizanje igle razvili u vlastitu istraživačkom laboratoriju (na odjelu M.E.UM). Količina ubrizganog goriva također je mjerena. Svi su podaci pohranjeni u računalo uz uporabu programa LabView v6.1. Gorivo je raspršeno u komoru pri sobnoj temperaturi i atmosferskom tlaku. Za snimku mlaza korištena je visokobrzinska digitalna kamera Phantom v4.1 [10]. Ona radi u okruženju programa Windows. Snimke, u boji ili pak monokromne, moguće su od 1000 sličica u sekundi rezolucije 512 x 512 pa do 32000 sličica u sekundi rezolucije 32 x 128 piksela CSR-CMOS. Vrijeme ekspozicije može se prilagoditi neovisno o stupnju uzorka. Nakon nekoliko probnih snimaka, kamera je postavljena 2,5 m ispred mlaza te oko 20 cm od otvora sapnice. Poradi naravi odlika mlaza, odabrano je 2500 sličica u sekundi rezolucije 128 x 512.

Simulacija

Postupke ubrizgavanja goriva simulirao je matematički model Bkin razvijen na Fakultetu strojarstva u Mariboru [11],[12],[13]. Moguće je opisati sve postupke ubrizgavanja unutar konvencionalnog sustava ubrizgavanja i sredstava dobave goriva. Bkin se temelji na valnoj teoriji te rješava 15 diferencijalnih jednadžbi metodom Runge-Kutta reda veličine 4-5. Ulazni podaci sadrže geometriju i radni režim sustava ubrizgavanja. Karakteristike postupka ubrizgavanja zapisane su u izlaznoj datoteci. Za provjeru modela korišteni su izmjereni rezultati.

Mlaz goriva simuliran je uz pomoć AVL Fire 3D programa. Fizička svojstva goriva i karakteristike postupka ubrizgavanja (poput stupnja ubrizgavanja, opsega, trajanja) razmotrena su i upotrijebljena u Fireovoj "solver steering datoteci", ili pod "korisničke funkcije". Upotrijebljena je cilindrična mreža s gušćom sredinom i površinom ubrizgivača (slika 3).

Slika 3: Mreža i model primarnog raspada mlaza
Figure 3: Mesh and primary break-up model used in the simulations



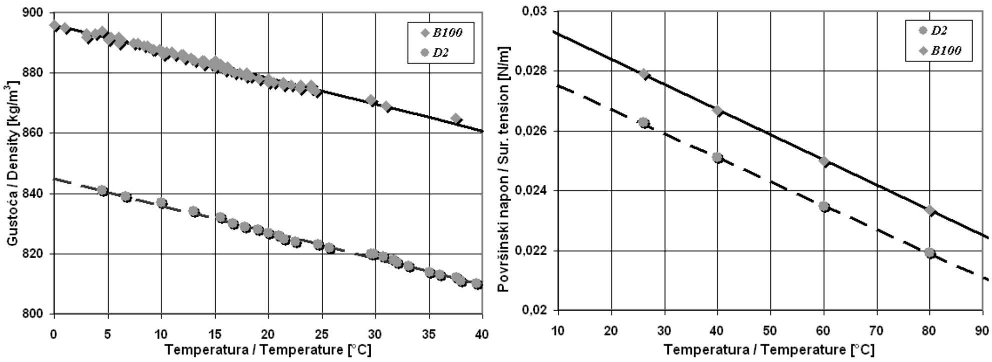
Model "Diesel Core Injection" korišten je za izračun prvotnoga širenja mlaza, dok je sekundarno raspršivanje simulirano uz pomoć modela "Wave". Prvotni model loma razmatra dva neovisna mehanizma: rast vala aerodinamične površine i unutarnja naprezanja izazvana vrtloženjem. Područje koherentne tekuće jezgre na izlazu iz sapnice gdje dolazi do prvotnog širenja mlaza izračunato je na temelju ravnoteže mase tekuće jezgre pri volumenu elemenata koji tvore oblik jezgre (slika 3). Kod sekundarnog modela raspršivanja "Wave" obrađuju se dva režima: jedan pri uvjetima velike brzine raspršivanja i drugi male, uz pristup Rayleigh. U prvome bi slučaju početna veličina promjera kapi trebala odgovarati valnoj duljini najbrže rastućeg, odnosno najvjerojatnije nestabilnog površinskog vala. Model loma tipa Rayleigh stvara kapljice koje su veće od izvornih matičnih kapi. Pretpostavlja se kako ovaj režim ne utječe dovoljno na oblikovanje spreja pod uvjetima tipičnima za visokotlačno ubrizgavanje. [14].

Rezultati

Fizička svojstva

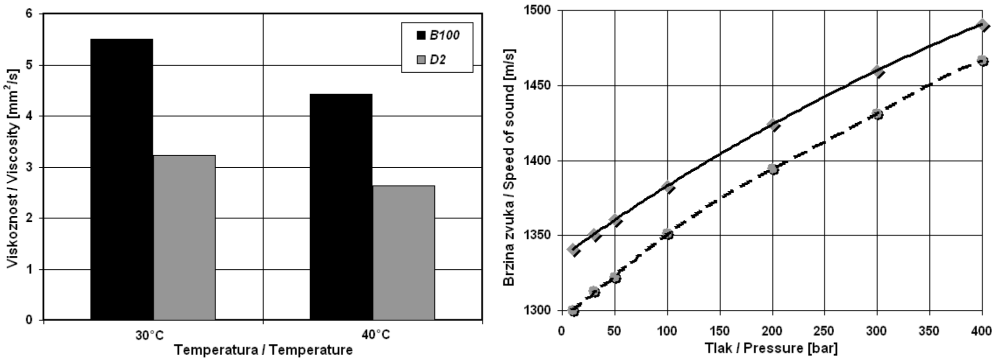
Gustoća i površinska napetost dizelskog goriva i biodizelskog goriva izmjerene su pri različitim temperaturama i prikazane na slici 4.

Slika 4: Temperaturna ovisnost gustoće i površinske napetosti oba goriva
Figure 4: Diesel and biodiesel density and surface tension in temperature dependence



Dijagrami pokazuju kako se i gustoća i površinska napetost obaju goriva mijenjaju gotovo linearno s temperaturom. Biodizelsko gorivo ima približno 6 % višu gustoću i površinsku napetost od dizelskoga goriva. Viskoznost je izmjerena pri dvije različite temperature, 30 i 40℃. Ovisnosti viskoznosti i brz ine širenja zvuka obaju goriva prikazana je na slici 5.

Slika 5: Viskoznost i brzina zvuka za dizelsko i biodizelsko gorivo
Figure 5: Viscosity and speed of sound of diesel and biodiesel

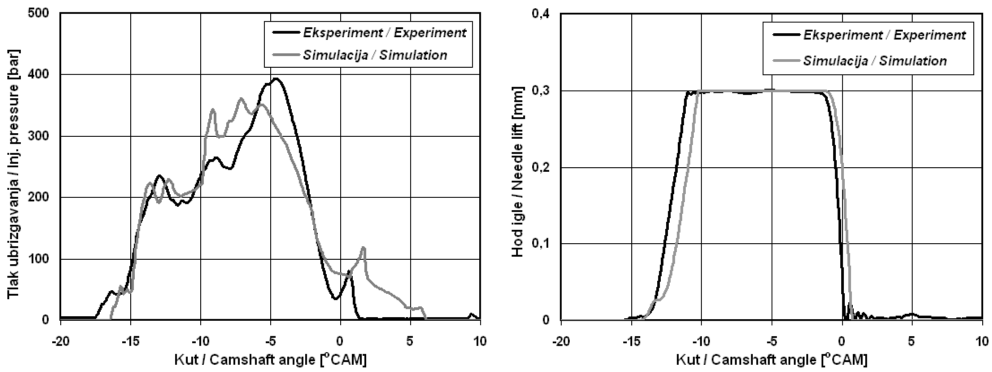


Viskoznost biodizelskog goriva viša je za oko 70 % pri temperaturama 30 i 40 ℃, dok se brzina zvuka u biodizelskom povećava gotovo za oko 2 % u usporedbi s dizelskim gorivom. Fizička svojstva obaju goriva uzeta su kao ulazni podaci za brojčani dio istraživanja.

Karakteristike postupka ubrizgavanja

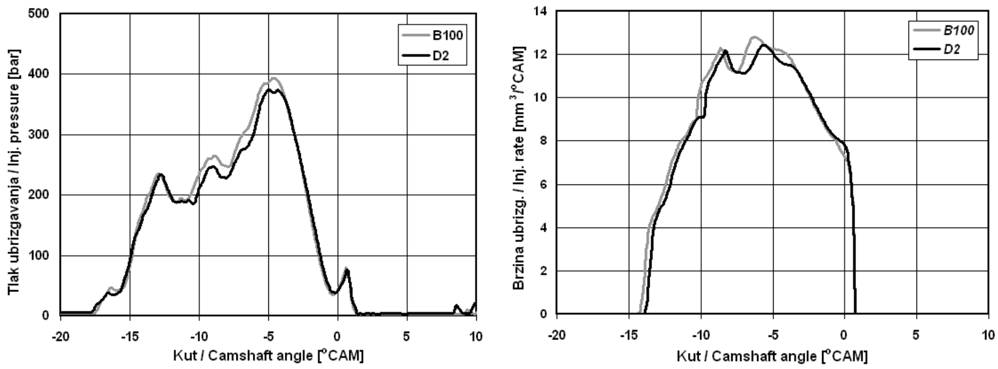
Karakteristike postupka ubrizgavanja izmjerene su kako bi se provjerio matematički model konvencionalnog sustava ubrizgavanja. Slika 6 prikazuje usporedbu podataka o tlaku ubrizgavanja i podizanju igle putem ispitivanja i putem simulacije.

Slika 6: Usporedba podataka tlaka ubrizgavanja i hoda igle (eksperiment i simulacija) puno opterećenje, 800 okretaja/min
Figure 6: Comparison of injection pressure and needle lift data (experiment and simulation) full load, 800 rpm



Nadalje, matematički model omogućuje predviđanje stupnja ubrizgavanja te ga se koristi kao granični uvjet u simulaciji odlika mlaza goriva. Rezultati pokazuju zadovoljavajuću podudarnost i potvrđuju prikladnost matematičkog modela. Usporedba zabilježenih tragova tlaka i stupnja simulacije obaju ispitanih goriva prikazana je na slici 7.

Slika 7: Izmjerena i simulirana vremenska ovisnost tlaka i brzine ubrizgavanja (dizelsko i biodizelsko gorivo), puno opterećenje, 800 okretaja/min
Figure 7: Measured injection pressure and simulated injection rate (diesel and biodiesel comparison), full load, 800 rpm



Valja istaći kako razlike fizičkih svojstava biodizelskog goriva utječu na ubrzanje porasta tlaka, a time i brže otvaranje igle sapnice pri istoj količini ubrizgana goriva za obje vrste goriva (138 mm^3).

Mlaz

Simulacije mlaza izvršene su za oba goriva uz brzinu visokotlačne crpke od 800 o/min pri punom opterećenju. Izmjerene količine ubrizgana goriva, trajanja ubrizgavanja i izračuna stupnja ubrizgavanja upotrijebljene su kao ulazni podaci za granične uvjete mlaza u programu Fire. Izmjere otvora sapnice također su opisane u datoteci solver steering, kako bi se razmotrila mogućnost kavitacija. Usporedba zapisa slijeda razvijanja mlaza dizela i biodizela te rezultati odgovarajućih mlaznih struktura kod istih uvjeta ubrizgavanja dobiveni matematičkom simulacijom prikazani su na slici 8. Budući da su mlazevi ubrizgavani u zrak pri sobnoj temperaturi i atmosferskom tlaku, njihova je penetracija gotovo linearna. Zabilježeni i simulirani mlazevi pokazuju dobro podudaranje za oba goriva. Postoje male razlike između zabilježenih i simuliranih duljina penetracije mlaza, jer nismo mogli započeti snimanje točno u trenutku otvaranja igle. Vremenska razlika između dvije susljedne slike mlaza iznosi 0,0004 sek. Eksperimentalne vrijednosti fizičkih svojstava dizelskog i biodizelskog goriva upotrijebljene su kod simulacije strukture mlaza. Da bi se postigao ispravan oblik mlaza i duljina penetracije te distribucija kapljice goriva, empirijske konstante primarnog i sekundarnog loma valja prilagoditi prema svakom sustavu ubrizgavanja, gorivu i radnom režimu (nisu iste). To je bio dodatni problem riješen prilagodbom programa Fire. Pretpostavljeno je kako se konstante loma mogu prikazati kao:

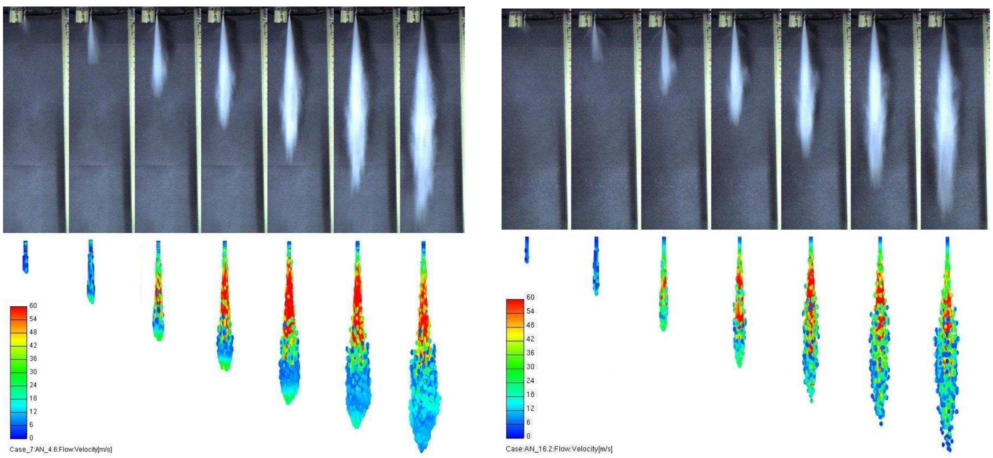
$$C_i = x_1^{a_1} \cdot x_2^{a_1} \cdot x_3^{a_1} \cdot x_4^{a_1} \cdot x_5^{a_1} \cdot x_6^{a_1} \qquad (4.1)$$

gdje je x_i varijabla fizičkih svojstava goriva $(\rho, \mu, \sigma, ...)$ i karakteristika postupka ubrizgavanja $Q_c, p_{ave}, n, ...)$ dok su a_i stvarni brojevi. Eksponenti $a_1, a_2, ...$ izračunati su uz pomoć Newton-Raphson metode rješavanja nelinearnih sustava jednadžbi [15]:

$$a_{i_{n+1}} = a_{i\,n} - \frac{f(a_{i_n})}{f'(a_{i_n})} \qquad (4.2)$$

Jednadžbe za poluempirijske konstante s najbolje odgovarajućim vrijednostima eksponenata potom su ubačene u program Fire.

Slika 8: Usporedba sekvenci prodiranja mlaza tijekom ubrizgavanja dizelskog (lijevo) i biodizelskog goriva (desno), puno opterećenje, 800 okretaja/min, snimci (gore) i simulacija strukture mlaza (dolje)
Figure 8: Comparison of the sequences of the diesel (left) and biodiesel (right) spray development during the injection period, full load, 800 rpm, recordings (above) and simulated spray structure (below)



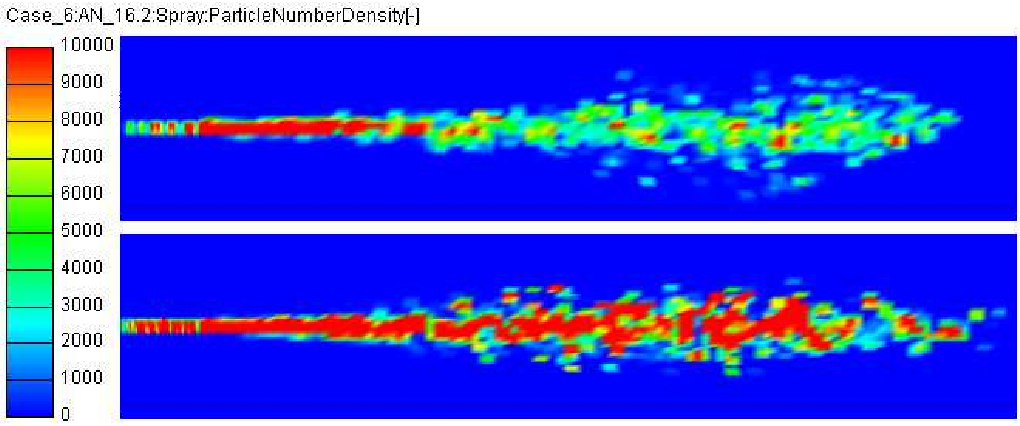
Penetracija mlaza za oba goriva prikazana je u tablici 1. Razlike između stvarnih i simuliranih rezultata manje su od 5 %.

Tablica 1: Duljine prodiranja mlaza pri punom opterećenju, brzina vrtnje 800 o/min

	gorivo	
prodiranje mlaza	dizelsko	biodizelsko
snimka [cm]	31,9	32,8
simulacija [cm]	32,5	34,7
razlika [%]	1,9	4,9

Kut mlaza biodizela je manji (uži sprej) i dulji. Udio količine goriva može se ocijeniti na temelju gustoće broja čestica. Uzdužni su presjeci obaju goriva prikazani na slici 9. Moguće je primijetiti kako je mlaz dizelskog goriva u većoj mjeri atomiziran u odnosu na onaj biodizelskog. Moguće je primijetiti i veću gustoću unutar srednjega mlaza.

Slika 9: Gustoća broja čestica (dizelsko gorivo – gore, biodizelsko gorivo – dolje)
Figure 9: Particle number density (diesel - up and biodiesel - down)



Prosječne vrijednosti odlika strukture raspršivanja sažete su u tablici 2.

Tablica 2: Prosječne vrijednosti karakteristika raspršivanja
Table 2: Average values of spray characteristics

gorivo fuel	dizelsko diesel	biodizelsko biodiesel
srednji aritmetički promjer / arithmetic mean diameter D_{10} [μm]	48,39	14,0
srednji Sauterov promjer / Sauter mean diameter D_{32} [μm]	48,48	17,67
dužina jezgre / core length [cm]	1,074	1,525

Zaključci

Fizička svojstva biodizelskog goriva i njihov utjecaj na razvoj mlaza i na makro odlike mlaza ispitani su i uspoređeni s onima dizelskoga goriva.

Ispitivanja i matematička simulacija potvrdili su kako je, unatoč gotovo identičnim fizičkim svojstvima dizelskog i biodizelskog goriva, njihov utjecaj na otvaranje igle i stupanj ubrizgavanja utvrđen, iako je količina ubrizganog goriva neznatno različita. Gotovo se isto može zaključiti i o postupku penetracije mlaza te općenitim makro odlikama strukture mlaza. Mlaz biodizela je uži, donekle gušći i dulji. Iako su razlike male, mogu utjecati na postupak stvaranja ispravne smjese goriva i zraka i tako utjecati na prvo razdoblje zapaljenja goriva (odgoda zapaljenja i rast gradijenta tlaka), s obzirom na rezultate prikazane u tablicama 1 i 2 u tekstu.

Da bi se simulacijama postigle ispravne makro odlike mlaza, nekoliko se empirijskih konstanti pojavljuje u primarnom i sekundarnom modelu raspršivanja, uzimajući u obzir svojstva goriva i radni režim, što još valja ispitati i utvrditi. Poluempirijske jednadžbe prikazane su u tekstu.

Simulacija raspršivanja mlaza tekućeg goriva i dalje je složen problem. Postojeće teorije raspršivanja mlaza u fine kapljice na području u blizini vrha sapnice dosad još nisu eksperimentalno potvrđene, poradi nedostatka zadovoljavajućeg eksperimentalnog pribora. Radi toga su potrebne još brojne pretpostavke u matematičkome opisu raspršivanja tekućine i daljnjeg tijeka atomizacije kapljica. Ukratko, rezultati našega istraživanja oblikovanja mlaza jasno pokazuju kako je za daljnji razvoj matematičkog modela na temelju zakonitosti dinamike tekućina prijeko potrebno dodatno poznavanje postupka raspršivanja na temelju eksperimentalnih rezultata.

Zahvala

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DIESEL AND BIODIESEL MACRO-SPRAY CHARACTERISTICS

Abstract

Characteristics of fuel injection and spray formation in the engine combustion chamber are most important factor of up-to-date diesel engines, influencing their effective performance parameters and exhaust emissions. During last few decades alternative automotive fuels, such as biodiesel have received salient attention. Even though it has similar physical properties as diesel fuel, higher density, viscosity and surface tension of biodiesel may have a dominant influence on the spray formation and sometimes cause spray anomalies - such as contact between fuel and combustion chamber, poor mixing with air (bigger fuel droplets) etc.

Results of the investigation about the impact of the diesel and biodiesel fuel physical properties on the injection and spray characteristics are presented in the paper. Physical properties of both have been examined and used in the mathematical model of the conventional injection system. The model was derived in IEPO - Institute for Power, Process and Environmental Engineering Faculty of mechanical engineering, University Maribor, simulation code Bkin, and was verified by experiment carried out on the fuel injection system test bench and on the engine. In a special test chamber the macro-characteristics of the spray injected into motionless air at the atmospheric pressure and room temperature (spray penetration distance, angle, and spray shape) have been measured and spray images were recorded by the high-speed camera (2500 frames/s). Using 3D simulation program (AVL "Fire") and including for the purpose of these investigations a few new estimates, the injection process for both fuels have been simulated and compared with the results obtained by experiments. These results are presented and discussed in the paper.

Introduction

Global atmosphere pollution with greenhouse gases has become a serious problem of today. A part of this pollution is caused by the use of fossil fuels in transportation. Application of alternative fuels provides technical means to decrease emissions of conventional diesel engines. Biodiesel, an alternative for petroleum fuel can be commercially produced through esterification of vegetable oils and animal fats with alcohol and alkaline catalyst. Biodiesel has a higher cetane number than petroleum diesel fuel, no aromatics, and contains around 10% of oxygen by weight. These characteristics of biodiesel reduce exhaust emissions of carbon monoxide, hydrocarbons and particulate matter in comparison to diesel fuel [1][2].

Differences in the physical properties of biodiesel (such as density, viscosity, surface tension and sped of sound) may induce anomalies in the spray formation and cause the unnecessary increase of pollutant emissions [3][4][5][6]. Higher density, viscosity and surface tension increase the friction between the fuel and the nozzle wall, what causes the reduction of injection velocity and increases the injection pressure in the conventional diesel fuel injection system; furthermore the spray penetration lengths becomes longer and the spray cone angle wider, due to larger droplet size and slower droplet vaporisation respectively [3][4][5][6]. Theoretical investigations of spray formation belong to the field of the two-phase flows. Rapid development of measuring methods, suitable programme packages and computer equipment enabled their evaluation.

The aim of this paper is to illustrate the influence of biodiesel on the fuel injection characteristics in comparison to diesel fuel. Diesel (D2) and biodiesel (B100) physical properties, such as density, viscosity, surface tension and speed of sound were analysed. Injection pressure, nozzle needle lift and volume of injected fuel were recorded and measured using the fuel injection system test bench and applied in the injection system's mathematical model verification. Successive phases of spray development were recorded with a high-speed camera. The results of spray simulation and the comparison with high-speed camera recordings are shown in this paper.

Experimental procedures

Diesel and biodiesel fuel physical characteristics were analysed. Biodiesel used in our experiment was produced from rapeseed oil in the Pinus refinery [7], while the diesel fuel was supplied by the Petrol company [8]. Fuel densities were measured with the Density meter DMA 35 PAAR, viscosity with the Herzog Ubbelohde Viscometer HVU 480, while surface tension σ was calculated from the observed rise of a liquid in a thin capillary [9]:

$$\sigma = \frac{1}{2} \cdot \rho \cdot g \cdot h \cdot r \cdot \left(h + \frac{r}{3} \right), \quad (1)$$

where:

- ρ fuel density [kg/m^3],
- g acceleration due to gravity [m/s^2],
- h the capillary rise [m]
- r the radius of the capillary [m].

All physical properties were defined at the room temperature. The speed of sound at different pressures was calculated for from the pressure wave travelling time delays (Figure 1).

The high pressure pump (Bosch PES6A95D410LS2542) was mounted on the fuel injection systems test bench (Friedmann-Maier type 12 H 100-h). Fuel was injected trough the injector (Bosch DLLA5S834) with only one hole into the glass chamber (Figure 2).

Fuel injection characteristics were taken at full load, 800 rpm operating regime, pressure and needle lift time traces were recorded. Piezzo-resistive sensor was used for pressure measurements and inductive sensor developed in our Engine Research Laboratory (at M.E.Dept.UM) was used for needle lift measurements. The volumes of injected fuel were also measured. All the data were stored in the computer using program LabView v6.1. The fuel spray was injected into the chamber at the room temperature and at the atmospheric pressure. For the spray filming the high-speed digital camera Phantom v4.1 was used [10]. It operates in Windows environment. Colour or monochrome recordings can be taken from 1000 fps at 512 x 512 up to 32000 fps at 32 x 128 pixel CSR-CMOS. Exposure time can be adjusted independent of sample rate. After some test recordings, the camera was placed at 2,5 m in front of the spray and about 20 cm from the nozzle's hole. Due to the nature of spray characteristics, 2500 fps at the resolution 128 x 512 was chosen.

Simulation

Fuel injection processes have been simulated by the mathematical model Bkin developed on the Faculty of mechanical engineering Maribor [11][12][13]. All injection processes within the conventional injection system and fuel supply devices can be described. The Bkin is based on the wave theory and solves 15 differential equations with Runge-Kutta method of order 4-5. Input data consist of injection system geometry and operation regime. Injection process characteristics are written in the output file. Measured results have been used for the model verification.

The fuel spray was simulated by the AVL "Fire" 3D program. Fuel physical properties and injection process characteristics (such as the injection rate, volume, duration,…) were considered and used in the "Fire" "solver steering file" or as the "user functions". Cylindrical mesh with higher density in the middle section and at the nozzle area was used (Figure 3). The "Diesel Core Injection" model was chosen to calculate the primary break-up of the spray, while the secondary break-up was simulated with the model "Wave". The primary break-up model considers two independent mechanisms: aerodynamic surface wave growth and internal stresses caused by the turbulence. The coherent liquid core region at the nozzle exit where primary break-up occurs is calculated from a mass balance of the liquid core at volume elements forming the core shape (Figure 3).

In the "Wave" secondary break-up model, two regimes are treated; one at high spray velocity conditions and at low sprays velocity conditions using the Rayleigh approach. In the first case the initial size of the droplet diameter is supposed to be equal to the wavelength of the fastest growing or most probable unstable surface wave. Rayleigh type break-up model produces droplets that are larger than the original parent drops. It is assumed, that this regime has not a significant effect on spray formation under conditions typical for high pressure injection [14].

Results

Physical properties

Diesel and biodiesel density and surface tension were measured at different temperatures and are shown in Figure 4.

The diagrams show that both density and surface tension of both fuels changes almost linearly with the temperature. Biodiesel has approximately 6% higher density and surface tension as diesel fuel. The viscosity was measured at two different temperatures, 30 and 40℃. The dependencies of the v iscosity and the speed of sound of both fuels are shown in Figure 5.

The Biodiesel viscosity is for about 70% higher at the temperatures 30 and 40℃, while the speed of sound in biodiesel increases nearly about 2% in comparison with diesel fuel. Physical properties of both fuels were introduced as the input data in the numerical part of the investigations.

Injection process characteristics

To verify the mathematical model of the conventional injection system, injection process characteristics were measured and compared with the computed data. The Figure 6 shows the comparison of the injection pressure and needle lift histories obtained by experiment and by simulation.

Further more, the mathematical model enables to predict the injection rate and it has been used as the boundary conditions in the fuel spray characteristics simulation. The results show satisfactory agreement and confirm the adequacy of the mathematical model. Comparison of recorded pressure traces and simulation rates of injection for both investigated fuels are shown in the Figure 7.

It should be pointed out that differences in biodiesel physical properties effect faster pressure rise and consequently sooner nozzle's needle opening at the same injected fuel volumes of both fuels (138 mm^3).

Spray

Spray simulations have been carried out for both fuels at HP pump speed 800 rpm and at full load. Measured injected fuel volume, injection duration and calculated injection rate, were used as the input data of spray boundary conditions in the "Fire" program. Nozzle's hole geometry was also described in the solver steering file in order to consider possibility of cavitations. The comparison of sequences of diesel and biodiesel spray development recordings and the results of corresponding spray structures at the same injection instants obtained by mathematical simulation are presented in Figure 8. Because sprays were injected into the air at the room temperature and at the atmospheric pressure, spray tip penetrations are almost linear. Recorded and simulated sprays show good agreement for both fuels. There are small differences in the recorded and simulated spray penetrations lengths because we were unable to start filming exactly at the same instant of needle opening. Time difference between two consecutive spray images is 0,0004 sec. Experimental values of diesel and biodiesel physical properties were used in the spray structure simulation.

In order to achieve correct the spray shape, the penetration lengths and the fuel droplet distribution, the empirical constants of the primary and the secondary break-up model should be adjusted for each injection system, fuel and working regime (they are not the same). This was the additional problem solved by the modification of the "Fire" program. It has been assumed that the break-up constants may be presented as:

$$C_i = x_1^{a_1} \cdot x_2^{a_1} \cdot x_3^{a_1} \cdot x_4^{a_1} \cdot x_5^{a_1} \cdot x_6^{a_1}, \qquad (4.1)$$

where x_i is the variable of fuel physical properties $(\rho, \mu, \sigma, ...)$ and injection process parameters $Q_c, p_{ave}, n, ...)$ and a_i are real numbers. Exponents $a_1, a_2, ...$ have been calculated by using the Newton-Raphson method to solve nonlinear equations systems [15]:

$$a_{i_{n+1}} = a_{i\,n} - \frac{f(a_{i_n})}{f'(a_{i_n})}. \qquad (4.2)$$

Equations of semi-empirical constants with most appropriate exponent's values were then inserted into the program "Fire".

Data of the spray tip penetration lenght for both fuels are shown in Table 1. Differences between actual and computed results are less than 5%.

The biodiesel spray cone angle is smaller (narrower spray) and longer. Fuel volume share can be observed by using particle number density. The longitudinal spray cuts of both fuels are shown in the Figure 9. It may be noticed that the diesel spray is more atomised in relation to biodiesel spray. Higher spray density within the middle spray area can be observed.

The average values of spray structure characteristics are summarised in the Tab. 2.

Conclusions

Physical properties of biodiesel and diesel fuel and their influence on the spray developments and on the macro spray characteristics have been investigated and the results compared.

It has been confirmed by experiment and by mathematical simulation, that in spite of nearly identical diesel and biodiesel physical properties, different influence on the injection needle opening and injection rate have been found out, although the quantities of injected fuels have not differ significantly. Nearly the same may be concluded upon spray tip penetration process and overall spray structure macro characteristics. The biodiesel spray is narrower, a bit denser and longer in the comparison with diesel fuel. Differences are small, however they may influence correct fuel-air mixture formation process and therefore effect the first period of fuel ignition (the ignition delay and the pressure rise gradient), respecting the results shown in Table 1 and 2. in the text.

In order to achieve correct macro spray-characteristics by simulations, several empirical constants appearing in the primary and secondary break-up model, taking into the account fuel properties and operating regime, must be investigated and determined. The semi-empirical equations are presented in the texts.

Simulation of liquid fuel jet disintegration is still a complex problem. The existing theories of the jet break-up into fine droplets in the near area of the nozzle tip have so far never been experimentally validated, because of the lack of the satisfying experimental instrumentation. This causes that in the mathematical description of the liquid break-up and further droplet atomisation processes many assumptions based mostly on the investigator intuition must be made. To sum up, the results of our investigations into spray formation clearly demonstrate that further development of mathematical model based on the laws of fluid dynamics badly needs additional knowledge on spray break-up processes obtained by experimental findings.

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621.436.038.3	atomizacija i ubrizgavanje biodizelskog goriva tlakom	biodiesel fuel atomization and fuel injection by pressure
.001.575	gledište ispitivanja na materijalnom modelu	material model investigation viewpoint
.001.573	gledište ispitivanja na matematičkom modelu	mathematical model investigation viewpoint
532.525	istjecanje iz sapnica	flow through nozzles
532.529	strujanje dvofaznih fluida	flow of two phase fluids
665.753.4	dizelsko gorivo	diesel fuel
665.3.094.942	biodizelsko gorivo	biodiesel fuel

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