Niko Samec, Želimir Dobovišek, Aleš Hribernik

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UTJECAJ EMULZIJE VODE I DIZELSKOG GORIVA NA EMISIJU ISPUŠNIH PLINOVA DIZELOVIH MOTORA

Sažetak

10 i 15%-tnu stabiliziranu emulziju voda/gorivo (v/g) koristili smo s namjerom da se smanje štetne emisije ispušnih plinova. Stabilnu emulziju v/g s dugačkom postojanošću moguće je polučiti dodavanjem male količine odgovarajućeg emulgatora i primjenom vremenski kontroliranog postupka miješanja. Voda pomiješana s gorivom ima jak utjecaj na fizičke procese i kemijsku kinetiku stvaranja smjese, zapaljenje i izgaranje, te značajno smanjuje brzinu reakcija stvaranja zagađivača, posebno NO_X *i čađe. Na osnovi snimljenih krivulja oslobađanja topline i tlaka u cilindru, bilo je moguće naznačiti i razmotriti razlike tijekom izgaranja, uzrokovanih izgaranjem emulzije goriva i vode. Rezultati ispitivanja motora u širokom području opterećenja i brzina vrtnje pokazali su da se emisija* NO_X *i čađe smanjuje od 20 do 50%, a da pri tome ne dolazi do pogoršanja specifične potrošnje goriva.*

1. Uvod

Razvoj motora s unutarnjim izgaranjem godinama slijedi dvostruku strategiju:
- usavršavanje performansi motora i
- smanjenje emisije zagađivača.

Da bi postigli navedenu strategiju, povećanje kakvoće goriva i maziva je vrlo važno. Kemijska poboljšanja goriva i maziva za jako opterećene motore obuhvaćaju brojna tehnološka rješenja s ciljem da se zadovolje traženi zahtjevi kompatibilnosti s okolinom (ekonomičnost, emisija, buka) i zahtjevi tržišta (pouzdanost, trajnost, cijena i dr.). Za usavršavanje karakteristika motora, posebno emisije NO_X i čađe, brojne konvencionalne i nekonvencionalne metode su se pokazale kao vrlo snažno oruđe. Između tih pristupa, dodavanje vode dizelskom gorivu i dodavanje vode benzinu, kao modificiranim gorivima za dizelove i Otto motore, prati dug povijesni put [1]. Izumljeno je nekoliko sustava koji su ispitivani eksperimentalno, a mnogi utjecaji vode na procese izgaranja su teoretski proučavani. Osim toga, dodavanje vode se smatralo vrlo djelotvornim pristupom za smanjenje tvorbe polutanata unutar cilindra, što je istodobno ekonomičan pristup smanjenju emisije NO_x i krutih čestica.

2. Osnove dodavanja vode dizelskom gorivu

Općenito se može zaključiti da prisutnost vodene pare uz reaktante utječe na tijek fizičkih procesa i kemijsku kinetiku izgaranja, te ima blagotvorni učinak na vremensku promjenu brzine oslobađanja topline. Tijekom izgaranja isparavanje vode snižava temperaturu plamena, mijenja kemijski sastav sadržavanjem većih koncentracija radikala -OH, koji kontroliraju brzinu stvaranja NO i oksidaciju čađe, te razrjeđuju zone obogaćene gorivom u komori izgaranja.

Vodu možemo dodavati na više načina:

- neprekinuto u mlaz zraka na jednom mjestu (single point), ili periodično kroz usisni ventil, sustavom s više dovodnih mjesta (multi point) [2], [6],
- voda se ubrizgava izravno u cilindar kroz zasebnu mlaznicu, ili se dodaje gorivu u unutrašnjosti mlaznice, kada se ne ubrizgava gorivo [8],
- slojevitim ubrizgavanjem goriva i vode [8] ili
- s pripremljenom smjesom stabilne emulzije goriva i vode.

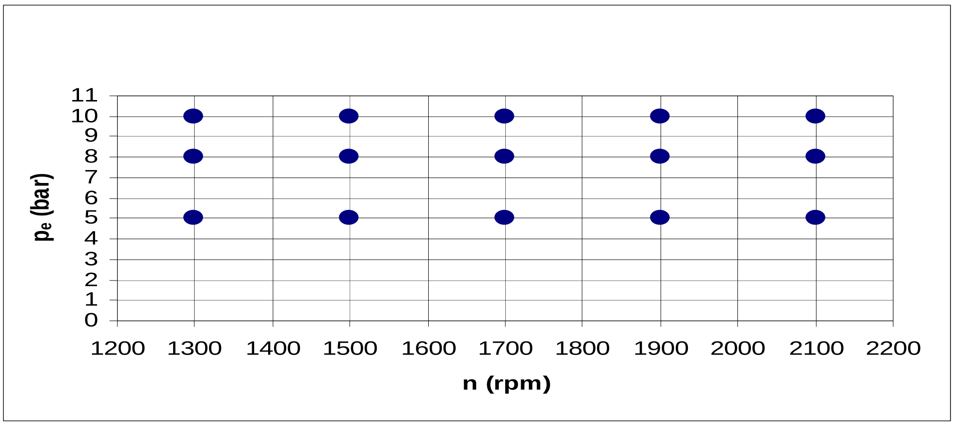
Kratak osvrt na značajke različitih metoda dodavanja i uvođenja vode dat je u literaturi [4].

U prošlosti su u laboratoriju autori ispitivali i proučavali utjecaje dodavanja vode na emisije NO_x i čađe sustavima "single point" i "multi point" [2],[3],[6]. Na osnovi tih rezultata moglo se zaključiti da oba sustava pokazuju gotovo isti blagotvoran utjecaj na smanjenje emisije NO_x, dok je utjecaj na emisiju čađe skoro nezamjetljiv. Osim toga, simulacijom izgaranja u motoru, te uzimajući u obzir kemijsku kinetiku i pojednostavljeno miješanje, numerički smo istraživali fizičko-kemijske utjecaje na stvaranje NO_x i čađe [2]. Razmatranjem naših prijašnjih rezultata, kao i drugih rezultata istraživanja izvršenih [4],[5],[7],[10], zaključili smo da se možemo nadati boljim učincima smanjenja NO_x i čađe, ako na istom motoru nastavimo ispitivanja s emulzijom voda/gorivo.

3. Metodologija ispitivanja i mjerna oprema

Priprema emulzije voda/gorivo dodavanjem vrlo male količine posebnog emulgatora zahtijeva točno određenu metodologiju miješanja, da bi dobili stabilnu emulziju, pri kojoj ne dolazi do razdvajanja sastavnih komponenti u dužem vremenskom razmaku, tako da je emulzija v/g prihvatljiva za uporabu na svim područjima na kopnu i na moru. Za ispitivanja je korišten četverocilindrični zračno hlađeni motor s turbo puhalom.

Slika 1: Prikaz točaka ispitivanja u dijagramu opterećenje – brzina vrtnje
Figure 1: The load-speed test map

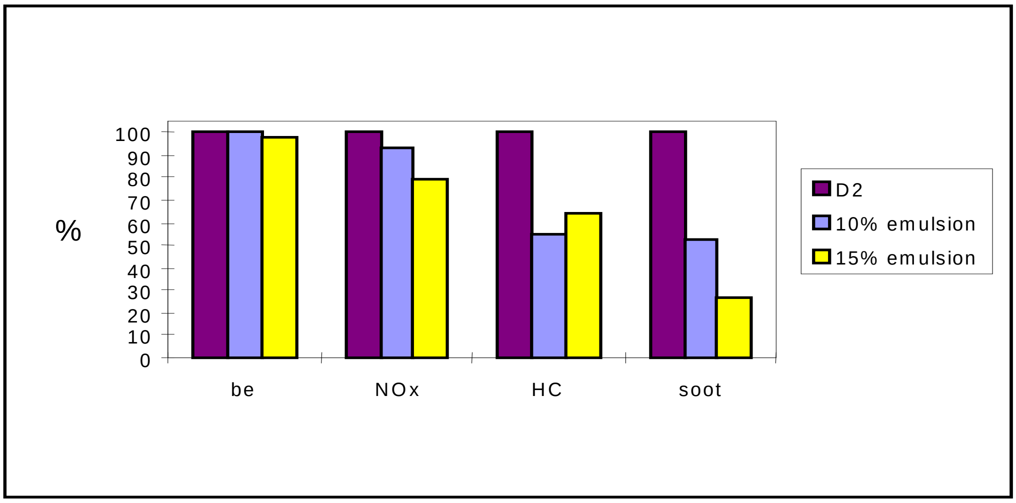


Mapa točaka ispitivanja prikazana je na slici 1 i za svaku točku su zabilježeni podaci pri režimu stabilnog rada motora. Izvršili smo po tri ekperimenta na svakom režimu s dizelskim gorivom i emulzijama s 10% i 15% vode u gorivu. Ispitivanja smo izvodili na kompjutorski vođenoj ispitnoj stanici s kočnicom Zoellner B – 350 AC, mjerenjem svih parametara (temperature, pritisci, potrošnja goriva i zraka i dr.) koji određuju radni režim. Mjerne vrijednosti su bile pohranjene u memoriji kompjutora za naknadnu obradbu i izračunavanje podataka o performansama motora (stupanj punjenja, omjer zrak/gorivo i dr.). Koncentracije pojedinih komponenti izgaranja u ispušnim plinovima su mjerene naznačenom standardnom instrumentacijom: NO, NO_2 (kemilumini-scentni analizator) CO (NDIR), ukupni ugljikovodici THC (FID), O_2 (ZrO tvrdi elektrolit) i zacrnjenje (čađa u Bosch – jedinicama sa AVL analizatorom). Vremenska krivulja indiciranog tlaka istodobno je snimana (KISTLER), pohranjena i obrađivana pri svakom režimu rada motora (slika 1). Izračunavali smo karakteristiku oslobađanja topline, analizirali je, te istraživali utjecaj dodavanja vode na tijek izgaranja, da bi istakli razlike između izgaranja čistog dizelskog goriva i izgaranja emulzije v/g.

4. Rezultati ispitivanja

Usporedba podataka o emisiji (NO_x , ukupni ugljikovodici THC, čađa) i specifičnoj potrošnji goriva (*be*) za tri vrste goriva (dizelsko gorivo te 10 i 15%-tna emulzija v/g), pri tri različita radna režima motora, pokazana je na slikama 2 do 4, smatrajući emisiju dizelskog goriva kao 100%.

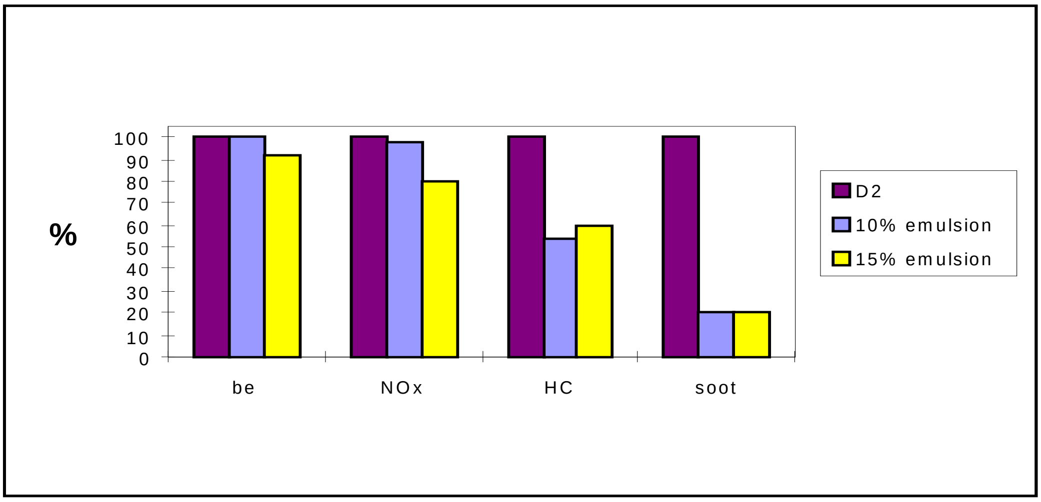
Slika 2: Relativno smanjenje emisije u ispušnom plinu i specifične potrošnje goriva, radni režim motora: p_e=10 bar, n=2100 min^{-1}.
Figure 2: The relative reduction of exhaust emissions and specific fuel consumption. Engine operating regime p_e=10 bar, n=2100 rpm.



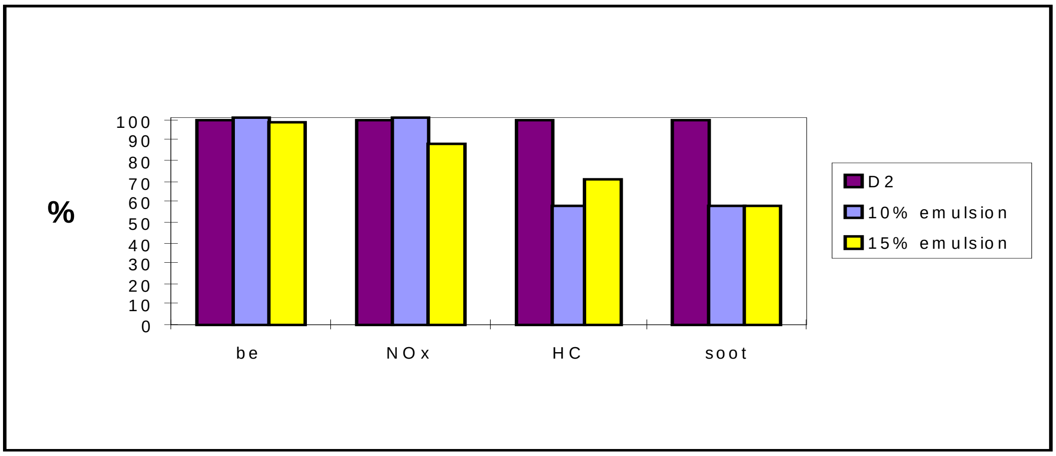
Relativno smanjenje emisije komponente "i" (*ΔE_i)* u ispušnom plinu pod istim radnim uvjetima rada motora izraženo je sa:

$$\Delta E_{i_{rel}}[\%] = \frac{[E]_{i,D2} - [E]_{i,W/F}}{[E]_{i,D2}} \cdot 100 \,. \qquad (1)$$

Slika 3: Relativno smanjenje emisije u ispušnom plinu i specifične potrošnje goriva, radni režim motora: p_e=8 bar, n=1700 min^{-1}.
Figure 3: The relative reduction of exhaust emissions and specific fuel consumption. Engine operating regime p_e=8 bar, n=1700 rpm.



Slika 4: Relativno smanjenje emisije u ispušnom plinu i specifične potrošnje goriva, radni režim motora: p_e=5 bar, n=1500 min^{-1}.
Figure 4: The relative reduction of exhaust emissions and specific fuel consumption. Engine operating regime p_e=5 bar, n=1500 rpm.



Na slikama 5 do 7 prikazana je promjena tlaka u cilindru p_e(bar) i brzine oslobađanja topline Q(J/^{0}CA) u funkciji vremena Θ(^{0}CA-kuta koljenastog vratila, ^{0}KV) za dizelsko gorivo (puna crta) i 10%-tnu emulziju vode u gorivu (isprekidana crta).

Slika 5: Tijek promjene tlaka u cilindru i brzine oslobađanja topline. Radni režim: p_e=10 bar n=1700 min^{-1}. Kut predubrizgavanja 13,5 ^{0}KV prije GMT
Figure 5: In-cylinder pressure and rate-of-heat-release time histories. Engine operating regime p_e=10 bar n=1700 rpm. Injecting timing 13,5 ^{0}CA before TDC

Slika 6: Tijek promjene tlaka u cilindru i brzine oslobađanja topline. Radni režim: p_e=8 bar n=1700 min^{-1}. Kut predubrizgavanja 13,5 ^{0}KV prije gornje mrtve točke GMT.
Figure 6: In-cylinder pressure and rate-of-heat-release time histories. Engine operating regime p_e=8 bar n=1700 rpm. Injecting timing 13,5 ^{0}CA before TDC.

Slika 7: Tijek promjene tlaka u cilindru i brzine oslobađanja topline. Radni režim: p_e=5 bar n=1700 min^{-1}. Kut predubrizgavanja 13,5 ^{0}KV prije GMT.
Figure 7: In-cylinder pressure and rate-of-heat-release time histories. Engine operating regime p_e=5 bar n=1700rpm. Injecting timing 13,5 ^{0}CA before TDC.

Točnijom analizom dijelova razdoblja zapaljenja i dijela izgaranja homogene smjese na krivuljama, prikazanim na slikama 5 do 7, moguće je usporediti razlike vanjskih značajki izgaranja. Ti podaci su za različite uvjete rada motora sažeto prikazani u tablici 1.

Relativna promjena vanjske karakteristike izgaranja ΔCH_i pri 10%-tnoj emulziji v/g (W/F) (zakašnjenja zapaljenja, gradijent brzine oslobađanja topline, vršak (maks.) tlaka i termodinamičke temperature u cilindru, pomak vrška) u odnosu na isti pri izgaranju dizelskog goriva određivali smo s:

$$\Delta CH_{i_{rel}}[\%] = \frac{[CR]_{i,D2} - [CR]_{i,W/F}}{[CR]_{i,D2}} \cdot 100 \,. \qquad (2)$$

5. Diskusija

Uspoređujući rezultate ovih ispitivanja emulzije voda/gorivo, kao goriva za dizelove motore, s rezultatima naših prethodnih ispitivanja, kada smo vodu dodavali u jednoj točki (način: single point) ili u više točaka (način: multi point), [2],[3],[6] ili s rezultatima istraživanja drugih autora, koji su koristili i druge metode dodavanja vode [4],[8],[10], može se zaključiti da je dodavanje vode u obliku emulzije najpovoljniji pristup ka smanjenju NO_x i čađe te emisije ukupnih ugljikovodika u ispušnim plinovima dizelovih motora, a da pri tome ne dođe do pogoršanja specifične potrošnje goriva. To je istodobno najjeftiniji način, jer nisu potrebne nikakve preinake na opremi motora (pomoćnim uređajima).

Utjecaj omjera vode u gorivu u našim ispitivanjima nije jasno izražen, vjerojatno zbog male razlike udjela vode u emulziji (razlika samo 5%). Ipak, drugi autori su utvrdili pozitivni trend smanjenja emisije polutanata, ako se omjer v/g poveća značajnije, (to je potvrđeno u više izvještaja, npr. [4],[5], što nagovještavaju i rezultati naših ispitivanja). Ako sumiramo naše podatke o emisijama, te odredimo prosječne vrijednosti za čitavo područje ispitivanih radnih režima motora, dobiju se rezultati o općem smanjenju emisija zagađivača u ispušnom plinu dizelovih motora prikazanih u tablici 2, pružajući opću informaciju o mogućnostima snižavanja emisije zagađivača, korištenjem emulzije v/g kao gorivo.

Tablica 1: Usporedba relativnih promjena izvanjskih značajki izgaranja emulzije v/g u pogledu na dizelsko gorivo

Brzina vrtnje koljenastog vratila	srednji indicirani tlak u cilindru	promjena u %				pomak vrška (maks.) u ^{0}KV	
		zakašnjenje zapaljenja	$\left. \frac{dQ}{d\Theta} \right/_{max}$	maks. tlak u cilindru	maks. tempera-tura u cilindru	tlaka	temperature
1700 min^{-1}	p_e=10 bar	+7,4	+19,6	0	-1,3	+1	-1
	p_e=8 bar	+7,4	+9,1	+1	-0,3	0	-1
	p_e=5 bar	+14	+7,5	0	+1,7	-1	-1
2100 min^{-1}	pe=10 bar	+6,6	+26,4	0	+1,66	+2	-1

Primjedba:
+ znači duže (više), + pomak od gornje mrtve točke GMT, - pomak prema gornjoj mrtvoj točki GMT

Tablica 2: Prosječno smanjenje emisije zagađivača u ispušnom plinu dizelovog motora izraženom u %, u usporedbi s emisijom iz čistog dizelskog goriva

v/g %	NO_x	THC	čađa
10	20	52	68
15	18	33	75

Djelovanje vode iz emulzije na fizičke i kemijske procese izgaranja i na brzinu stvaranja zagađivača vrlo je jako. Rezultati sređeni u tablici 1, koji se odnose na zakašnjenja zapaljenja, razdoblje izgaranja homogene smjese reaktanata, mogu se objasniti sljedećim pojavama:

- trajanje zakašnjenja zapaljenja produžava se zbog toplinskog utjecaja vode i usporavajućeg učinka =O i -OH radikala na pretplamene reakcije [4],[7],
- gradijent oslobađanja topline u vremenu izgaranja homogene smjese reaktanata se povećava zbog:
  - produženog zakašnjenja zapaljenja,
  - veće količine smjese reaktanata pripremljene za zapaljenje,
  - boljeg i bržeg formiranja smjese, kao posljedice atomizacije sitnih kapljica (mikro eksplozije) veće brzine isparavanja i boljeg pristupa zraka,
  - promjene fizičkih osobina reaktanata, čime se mijenja brzina prijenosa topline (zračenje plamena).

Ponovno se želi podvući, da kemijska kinetika igra istaknutu ulogu u tijeku izgaranja i stvaranja zagađivača, što je u suglasnosti s našim podacima, koji slijede iz numeričke simulacije izgaranja [2] i iz objava drugih autora [4].

6. Zaključak

Na osnovi rezultata istraživanja možemo izvesti sljedeće zaključke:

1. Emulzija vode i goriva se može uspješno koristiti za umanjenje emisije zagađivača na dizelovim motorima predviđenim za teže uvjete rada.
2. Stabilna emulzija vode u gorivu s dugom postojanošću priprema se dodatkom vrlo male količine emulgatora u smjesu, uz uvažavanje vremenski točno reguliranog postupka miješanja.
3. Ispitivanjem dizelovih motora za vozila s različitim opterećenjima i brzinama vrtnje, koristeći 10 i 15% emulzije v/g, koncentracija NO_x u ispušnim plinovima se može umanjiti za oko 20%, a koncentracija čađe do 50%, a da pri tome gotovo ne pogoršamo specifičnu potrošnju goriva.
4. Odredili smo fizički učinak vode u gorivu na vanjske značajke izgaranja, analizirajući tijek tlaka u cilindru i tijek brzine oslobađanja topline. Usporedbe s izgaranjem dizelskog goriva u dizelovom motoru u uvjetima radnih režima pokazuju da se pri izgaranju 10%-tne emulzije v/g, produžuje zakašnjenje zapaljenja za oko 10%, a gradijent brzine oslobađanja topline (izgaranje se ubrza) poraste do 26%.
5. Diskusija o snažnom utjecaju kemijske kinetike na reakcije zapaljenja i na brzinu stvaranja zagađivača oslanja se na značajnu ulogu =O i -OH radikala, što potvrđuju i naši rezultati, dobiveni numeričkim simuliranjem izgaranja smjese goriva i vode, modeliranjem procesa

izgaranja u motoru te uključivanjem kemijske kinetike s pojednostavljenim miješanjem reaktanata.

6. Pretpostavlja se da je ovaj nekonvencionalni način smanjenja emisija NO_x i čađe u ispušnim plinovima dizelovih motora prihvatljiv za uporabu na motorima za vozila za posebnu namjenu, koji će se prije svega koristiti u urbanim sredinama, ili za stacionarne motore koji moraju zadovoljiti zahtjeve standarda za vrlo niske emisije.

Zahvala

Ovaj rad je obavljen u laboratoriju za istraživanje motora s unutarnjim izgaranjem na Fakulteti za strojništvo Univerze v Mariboru. Autori se zahvaljuju za suradnju g. Andreju Pagonu, g. Gustiju Polaniču, i studentima g. Boštjanu Tašneru i g. Gorazdu Bombeku, koji su prikupili i obradili rezultate ispitivanja motora.

THE EFFECT OF WATER EMULSIFIED IN DIESEL FUEL ON DIESEL EXHAUST EMISSION

Abstract

The 10% and 15% water/fuel (W/F) stabilized emulsions have been used with the purpose to reduce diesel exhaust emissions. The stabilized long-term W/F emulsion may be obtained by adding a small amount of an appropriate emulsifier by applying time controlled mixing procedure. Water mixed with fuel has a strong effect on physics and chemical kinetics of the mixture formation, ignition, premixed and diffusion combustion, significantly reducing the reaction rate of pollutant formation, especially NO_x and soot. From in-cylinder pressure time history and rate of heat release history it was possible to indicate and discuss the differences of combustion development when W/F emulsion is burnt. The results of engine testing in a broad field of engine loads and speeds have shown a NO_x and soot emissions reduction from 20 to 50% without worsening the specific fuel consumption. The experimental results are presented and discussed here.

1. Introduction

Development of internal combustion (IC) engines over the years followed dual strategy:
- improvement of engine performance and
- reduction of pollutant emissions.

To achieve the afore mentioned strategy incrassation the fuels and lubricants quality is of great importance. Some chemical improvements of fuels and lubricants used in heavy duty diesel engines consist of numerous technologies in order to meet demanded levels of environmental compatibility (economy, emissions, noise) and market requirements (reliability, lifetime, price, etc.).

To improve diesel engine characteristics especially NO_x and soot emissions, several conventional and unconventional techniques have proved to be powerful tools. Among these approaches, the addition of water into diesel fuel and addition to gasoline as a modified fuel for spark-ignited engines, has a long history [1]. Several systems have been invented and experimentally investigated and main effects of water on combustion processes have also been theoretically studied. Moreover, the addition of water has been considered as an effective approach to in-cylinder reduction of pollutant formation and at the same time an economical way to reduce NO_x and particulate materials (PM).

2. Background of water addition into diesel fuel

It has been concluded in general, that the presence of water vapour in reactants influences physics and chemical kinetics of combustion and has a beneficial effect on the rate of heat-release history. During combustion, vaporised water reduces the flame temperature, changes chemical composition resulting in higher OH radical concentration controlling the NO formation rate and the soot oxidation, and dilutes reach zones in combustion chamber.

Water may be added into the fuel in several ways:

- continuously into air stream via single-point system, or periodically through intake valves via multi-point system [2],[6].
- water is injected directly into the cylinder through a separate nozzle, or introduced into fuel within the injection nozzle, when fuel injection does not take place [8],
- by stratified fuel-water injection [8], or
- through the preparation of the stabilized water/fuel emulsion.

A short review of some features of different methods of water addition and introduction is given in [4].

During the past, the effects of single and multi-point water addition systems on NO_x and soot emissions of a vehicular heavy duty diesel engine have been investigated [2],[3],[6] and studied. Based on these results, it may be concluded that both of the systems showed practically the same beneficial influence on the NO emission reduction, but a rather poor effect on soot emission. Besides this, bysimulating the fuel/water combustion by applying an engine combustion model with detailed chemical kinetics and simplified mixing, the chemical-physical effects on NO and soot formation have been numerically investigated [2]. Considering our previous results as well as the results of several other investigations performed recently [4],[5],[7],[10], we have concluded that more promising effects on NO_x and soot reduction may be expected if we turn our attention to the water/fuel emulsion using the same engine in our experiments.

3. Experimental approach and set-up

The water/fuel emulsion preparation, by adding a very small amount of special emulsifier, requires a very precise mixing methodology in order to obtain a stable emulsion with no separation of constituents during a long period, which is acceptable for the practical application of W/F emulsion in all fields of land and marine use. A vehicular four cylinder air-cooled, turbo-charged engine has been used in these experiments.

The load-speed test map is presented in Fig. 1 and all the data have been taken at each point during the stabilized engine operating regime. Three series of experiments have been carried out, using, in each series, either pure D2, 10%, or 15% W/F emulsions. The engine test was carried out on a completely computer-controlled Zolner B-350AC test bench, where all the important data (temperatures, pressures, fuel and air consumption) determining engine operating regime were measured and stored for further processing and computing engine performance data (volumetric efficiency, air-fuel equivalence ratio etc). The concentrations of some combustion products in the engine exhaust gases were measured with the indicated standard instrumentation: NO, NO_2 (Chem.-lum. Analyser), CO (NDIR), THC(FID), O_2 (ZrO hard electrolyte) and soot (AVL soot analyser, Bosch unit).

The indicative pressure (KISTLER) time history was in-line monitored, stored and processed at each regime. The rate of heat release was computed and analysed in order to study in detail the influence of water addition on combustion development and to point out the differences between D2 and W/F emulsion combustion.

4. Experimental results

The comparison of the exhaust emission data (NO_x, HC, soot) and specific fuel consumption (*be*) for three different fuels (D2, 10% WF and 15% W/F emulsion) and three different engine operating regimes are presented in Figures 2 to 4, considering the D2 pollutant emission as 100%.

The relative emission reduction of component "i" in the exhaust gases, at the same engine operating conditions, is expressed as follows:

$$\Delta E_{i_{rel}}[\%] = \frac{[E]_{i,D2} - [E]_{i,W/F}}{[E]_{i,D2}} \cdot 100 . \qquad (1)$$

In Figures 5 to 7, in-cylinder pressure and rate-of-heat-release time histories are presented for different fuels (D2 fuel-solid curve, 10% W/F emulsion-dashed curve). Analysing in detail the ignition and premixed combustion period section of time histories, shown in Figures 5 to 7, a comparison of external combustion characteristics can be made, and the data are summarised in Table 1 for different engine operating conditions.

The relative change of external combustion characteristic ΔCH_i of 10% W/F emulsion (ignition delay, gradient of heat-release, in-cylinder peak pressure and thermodynamic peak temperature, shift of peak positions), in relation to D2 fuel combustion, is calculated as:

$$\Delta CH_{i_{rel}}[\%] = \frac{[CR]_{i,D2} - [CR]_{i,W/F}}{[CR]_{i,D2}} \cdot 100 . \qquad (2)$$

Table 1: Relative change of diesel engine external combustion characteristics

n rpm	engine operating regime	changes in % in relation to D2				change in °CA in relation to D2	
		ignition delay	$\left. \frac{dQ}{d\Theta} \right/_{max}$	in-cylinder peak pressure	thermodynamic peak temperature	shift of peak pressure position °CA	shift of peak thermodynamic position °CA
1700	p_e=10 bar	+7,4	+19,6	0	-1,3	+1	-1
	p_e=8 bar	+7,4	+9,1	+1	-0,3	0	-1
	p_e=5 bar	+14	+7,5	0	+1,7	-1	-1
2100	pe=10 bar	+6,6	+26,4	0	+1,66	+2	-1

Remark:
\+ means longer (higher), + shift from TDC, - shift towards TDC

5. Discussion

By comparing the results of this investigation carried out with water/fuel emulsions as fuels with the results of our previous experiments, when water was added to the fuel separately via single and multipoint injection [2],[3],[6] or with the results of other authors when other modes of water addition were applied [4],[8],[10], it may be concluded that water addition via W/F emulsion is the most proper approach to decrease NO_x, soot and THC emissions in the diesel engine exhaust, without worsening the fuel consumption. It is also the cheapest way, since no changes on the engine or its ancillaries are needed.

The effect of W/F ratio was not so clearly expressed in our experimental results, probably because of smaller differences of water fraction in emulsion. However, if the W/F ratio is increased, the trend of pollutant emission reduction, (reported elsewhere, ie. [4],[5]) has a positive gradient of reduction, as may be estimated from our experimental results as well.

Summarizing our emission data by averaging them over the whole field of engine operating regimes (Figure 1), the reduction of pollutant emission is given in Table 2 and offers general information on pollutant abatement by using W/F emulsion as fuel.

Table 2: Average reduction of pollutant emission in % related to D2 exhaust emissions.

W/F %	NO_x	THC	soot
10	20	52	68
15	18	33	75

The impact of water in fuel emulsion on the physics and chemistry of combustion and pollutant formation rates is very strong. The findings reported in Table 1 relating to the ignition delay and premixed burning may be explained by the following phenomena:

- the duration of ignition delay is longer, as a consequence of thermal effect of water and O, OH radicals influence to slow down preflame reactions [4],[7],
- the gradient of heat release during premixed combustion was increased because of:
  - prolonged ignition delay,
  - higher amount of prepared ignitable mixture,

- better and faster mixture formation as a consequence of finer drop atomisation (micro explosion), higher rate of evaporation, and better oxygen access,
- change of reactant physical properties influencing also the rate of heat transfer (radiation from flame).

Again it may be emphasised that chemical kinetics plays also a dominant role in combustion development and pollutant formation, which is in agreement also with data obtained by numerical simulation [2],[4].

6. Conclusion

Based on the results of the experimental investigation the following conclusions can be made.

1. Water/fuel emulsion can be successfully used to reduce heavy-duty diesel engine exhaust pollutant emissions.
2. A stabilized long-term W/F emulsion can be obtained by adding a very small amount of emulsifier and following a well time-controlled mixing procedure.
3. By testing the vehicular diesel engine under several loads and speeds, using 10% and 15% W/F emulsions, NO_x concentration in the exhaust gas has been reduced by nearly 20% and theconcentration of soot (Bosch unit) up to 50%, practically without worsening the specific fuel consumption.
4. The physical impact of water in fuel on external diesel combustion characteristic has been evaluated by analysing in-cylinder pressure, and rate-of-heat-release time histories. In relation to D2 fuel combustion, the ignition delay became longer for about 10% and the gradient of rate-of-heat-release during premixed burning increased up to 26%, when W/F emulsions were used as fuels under the same engine operating conditions.
5. The strong influence of chemical kinetics on ignition reactions and on the rate of pollutant formation is discussed, emphasising the role of O and OH radicals, taking into account our results obtained by numerical simulation of water-fuel mixture combustion, employing an engine combustion model with detailed chemical kinetics and simplified mixing.
6. It is assumed, that this unconventional technique to reduce NO_x and soot emissions in diesel exhaust is quite a suitable technique to be employed on vehicular diesel engines for special purposes working primarily in urban areas or on stationary engines, if they have to satisfy ultra low emission standards.

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621.436.019 izgaranje u dizelovom motoru	combustion in diesel motor
621.436.047 regulacija paljenja	ignition timing
621.436.068.6 poboljšanje emisije dizelovog motora	diesel engine emission improvement
.002.61 gledište sastava	composition standpoint
546.174 dušikovi oksidi	nitrogen oxydes
662.613.13 čestice čađe u ispušnim plinovima	carbon particles in exhaust gases

Autori / Authors:

Niko Samec, e-mail: niko.samec@uni-mb.si; Želimir Dobovišek, Aleš Hribernik
Univerza v Mariboru, Fakulteta za strojništvo, Maribor, Slovenija

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