

Preparation of Emulsified Water/Diesel Mixture and Performance Analysis of Diesel Engine operated with this mixture

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ABSTRACT: Water-in-diesel emulsions are fuels for regular diesel engines. The advantages of an emulsion fuel are reductions in the emissions of nitrogen oxides and particulate matters, which are both health hazardous, and reduction in fuel consumption due to better burning efficiency. An important aspect is that diesel emulsions can be used without engine modifications. This review presents the influence of water on the emissions and on the combustion efficiency. Whereas there is a decrease in emissions of nitrogen oxides and particulate matters, there is an increase in the emissions of hydrocarbons and carbon monoxide with increasing water content of the emulsion. The combustion efficiency is improved when water is emulsified with diesel. This is a consequence of the micro explosions, which facilitate atomization of the fuel. The review also covers related fuels, such as diesel-in-water-in-diesel emulsions, i.e., double emulsions, water-in-diesel micro emulsions, and water-in-vegetable oil emulsions, i.e., biodiesel emulsions. A brief overview of other types of alternative fuels is also included.

KEYWORDS: Emulsion, Diesel, Emission, NO_x, Particulate matter, Carbon monoxide, Engine Combustion

I. INTRODUCTION

Emulsions of water in diesel for use in internal combustion engines are easily applicable alternative fuels for the existing vehicle fleet. The emulsion fuel is defined as an emulsion of water in standard diesel fuel with specific additives, surfactants, to stabilize the system. There is a growing interest in the use of diesel emulsions and environmental aspects are the main driving force. As is discussed in some detail below the presence of water has a significant effect on several emission constituents: exhaust gases such as nitrogen oxides (both NO and NO₂, which are collectively referred to as NO_x) and carbon monoxide (CO), as well as black smoke and particulate matter. There may be a certain loss in engine performance due to the presence of water, but the diesel consumption is often reduced. A typical water content of the diesel emulsions is between 10 and 20%.

Both the global and the local effects of the emissions on the environment are of concern for the use of alternative fuels for vehicles. The global effect due to the gradual increase of CO₂ in the atmosphere was the decisive factor behind the Kyoto protocol of 1997. In the transport sector the use of renewable fuels is the most effective way of limiting the net increase of CO₂ in the atmosphere. Also replacement of diesel and gasoline by natural gas will reduce the CO₂ emissions due to its lower carbon-to-hydrogen ratio, although the gain will be much less than for a renewable fuel. For the local effect of the emissions most focus is placed on the health hazardous NO_x and particulate matter emissions. For new engines these emissions are strictly regulated by legislation. In the so-called Euro 4, effective from 2005, and in the coming Euro 5, which will be in force from 2008, the emissions of NO_x, particulate matter, hydrocarbons and carbon monoxide are clearly regulated. For existing vehicles other rules apply.

Large scale use of emulsion fuels is of considerable interest also to the surface chemistry community. Considering the enormous volume of diesel fuel that is being consumed today, a replacement of just a fraction of regular diesel by

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water-in- diesel emulsion would mean that a new and very large application for surfactants had been created. The stability requirements on such emulsions are obvious: they need to stay stable for a specific time and over a wide temperature span. The surfactants used, i.e., the emulsifiers, must burn readily without soot formation and should not contain sulphur and nitrogen. Thus, they should contain only carbon, hydrogen and oxygen and they should preferably not have aromatic rings in their structure. Non ionic surfactants based on aliphatic hydrocarbon tails, such as alcohol ethoxylates, fatty acid ethoxylates and sugar esters of fatty acids, are typical candidates. This review will present the current status of water-in-diesel emulsions and also comment on the development in some related areas.

II. TYPES OF EMULSIONS

Depending upon the nature of the dispersed phase and dispersing medium, the emulsions are classified into two types.

Two-Phase Emulsion: It includes one continuous and one dispersed phase liquid and sometime called primary emulsion. There are two basic form of two-phase emulsion as shown in figure 1.

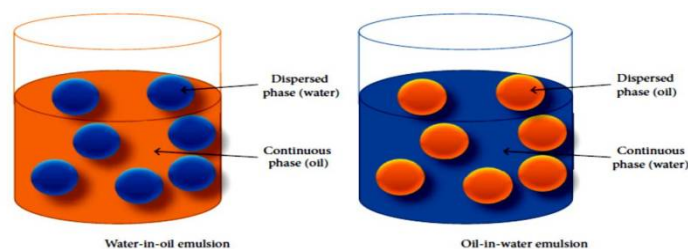


Fig.1 Concept of two-phase water-in-oil and oil-in-water emulsion

Oil-in water emulsions (O/W): The emulsions where oil is the dispersed phase and water is present as the dispersion medium (continuous phase) is called oil in water emulsion. Milk is an example of oil in water emulsion. In milk fat globules are dispersed within water.

Water – in- oil emulsions (W/O): The emulsion in which water forms the dispersed phase and the oil is present as a dispersing medium (continuous phase) is called water in oil emulsion. They are also termed as oil emulsions. Butter, cold cream, cod liver oil etc. are examples of this emulsion.

Three-Phase Emulsion: Three phase emulsion consist of one continuous phase and two or more dispersed liquid. These emulsions sometimes are called multiphase and secondary emulsion. On the basis of inner and outer phase as shown in figure 1 , 2 named as oil-in- water-in-oil and water-in-oil-in-water.

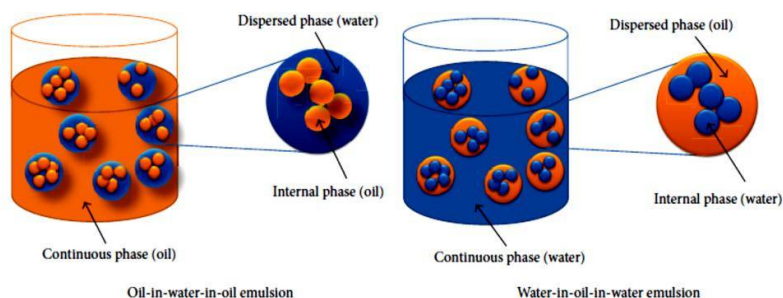


Fig. 2 Concept of three-phase oil-in-water-in-oil and water-in-oil-in-water

Depending on the size of the droplets, the emulsions are classified into two types:

Macro emulsions: The size particles ranges from 0.2 to 50 mm. they are kinetically stable.

Micro emulsions: The size of the particles ranges from 0.01 to 0.02 mm. they are thermodynamically stable.

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Properties of emulsions: [10]

1. Emulsion shows all the characteristic properties of colloidal solution like the Brownian movement, Tyndall effect, electrophoresis etc.
2. These emulsions are coagulated by the addition of electrolytes containing polyvalent metal ions indicating the negative charge on the globules.
3. The size of the dispersed particles in emulsions ranges from 1000 Å to 10,000 Å that is larger than those in the sols.
4. Emulsions can be converted into two separate liquids by methods such as heating, centrifuging, freezing etc.

III. STABILITY

There are three types of instability in emulsions:

Flocculation: is the process by which the dispersed phase comes out of suspension in the form of flakes.

Coalescence: is another form of instability, when very small droplets bump into each other and combine to form progressively larger droplets.

Creaming: Emulsions can also undergo creaming, the migration of one of the substances to the top (or the bottom) of the emulsion under the influence of buoyancy, or under centripetal force when a centrifuge is used.

IV. WATER-IN-DIESEL EMULSIONS

The interest in water-in-diesel emulsions derives from the fact that water in the form of micrometer sized droplets exerts some positive effects on the combustion of the fuel. Water-in- oil emulsions have been formulated and evaluated for most types of fuels, ranging from light hydrocarbons to triglyceride. However, the main interest in the concept lies in water-in- diesel emulsions. The main reason for a stronger interest in incorporating water in diesel than in gasoline is that the high combustion temperature and the high pressure that exist in diesel engines is particularly suitable for the concept. This was found experimentally [1] and verified by theory [2] almost 30 years ago. Use of diesel emulsions has been shown to give several interesting effects, such as (i) reduced nitrogen oxides (NO_x) emission and also lower soot and particulate contents in the exhaust, and (ii) improved combustion efficiency. These aspects on the use of water in diesel emulsions will be discussed below.

Reduced emissions: The presence of water in diesel fuels brings about a considerable reduction in NO_x and in particulate matters (PM) emission [3–8]. It is probably true to say that the effect on the emissions is the main reason for the large interest in diesel emulsions today. It has been reported that 15% water in the diesel can give a reduction in nitrogen oxide (NO_x) emission of up to 35% under regular conditions [9]. Such level of NO_x reduction has also been reported by other authors [6, 10–13]. However, it relates to diesel and other lighter hydrocarbon fractions with very low nitrogen content. For fuels with high nitrogen contents, such as some residual oils, the NO_x in the exhaust comes mainly from oxidation of the nitrogen- containing fuel components and in such cases emulsified water has only small effect on the NO_x level [14]. For diesel fuels there may be a concomitant increase in emission of carbon monoxide (CO) as well as in hydrocarbons [9]. The amount of PM in the exhaust from fuels with high nitrogen contents is normally significantly reduced [14].

Experimental studies have been made on the effect of water in the form of water-in-diesel emulsion on the formation of polycyclic aromatic hydrocarbons, some of which are known to be mutagenic [15]. Emulsion fuels were found to give lower amounts of polycyclic aromatic hydrocarbons in the flame, as well as reduced emission to the atmosphere. A more specific analysis showed a decrease of two substances, pyrene and fluorene, when the fuel was an emulsion. It is believed that the micro explosions see below; promote oxidation of the hydrocarbons, possibly involving attack by hydroxyl radicals. The reduced amount of formed polycyclic aromatic hydrocarbons is probably one of the reasons for the lower amount of soot obtained with emulsion fuels because these hydrocarbons can be seen as precursors for soot particles.

The reduction in soot formation has been demonstrated in several ways. Using a CCD camera with an image intensifier synchronized with a laser pulse it has been shown that the highly sooting region of the spray flame exists along the

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central axis of the flame and that the soot concentration profile is very heterogeneous. Fig. 1 shows how the amount of water in water-in- dodecane emulsion affects the soot formation [16]. As can be seen, there is a very large decrease in soot content by mixing in 5% water. Further addition of water gives only a small extra reduction. It can also be seen that increased water content gives an increase in the time between fuel injection and the peak in soot formation. The time effect is most likely due to either better mixing of air and fuel as a result of the micro explosion phenomenon, or decrease in flame temperature caused by the water, or a combination of the two.

The size of the water drops in the emulsion, i.e., the degree of dispersion of the water, is probably an important factor for the emissions. This issue does not seem to have been studied in a systematic way for diesel fuels. However, for combustion of emulsified heavy fuel oil it was found that the finer the water dispersion, i.e., the smaller the droplets of the water-in-fuel emulsion, the smaller the amount of water was needed to obtain good results in terms of reduced coke emission [17]. Thus, it is the oil–water interfacial area, not the amount of water incorporated in the fuel per se, that governs the efficiency in reducing the emissions. Obviously, good surfactants are needed to formulate emulsions with small water droplets.

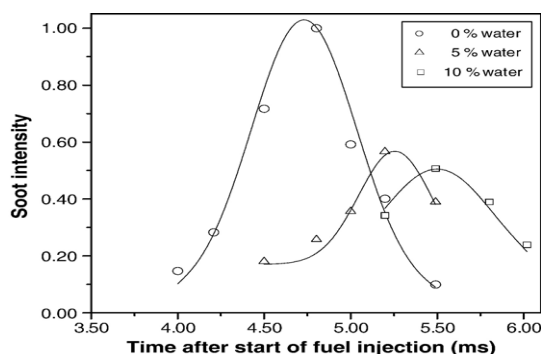


Fig. 3 Effect of water content of water-in-dodecane emulsions as a function of time on the total amount of soot yielded in the diesel spray flame.

A recent report from the Texas diesel fuels project, where emissions of NO_x , CO, PM and hydrocarbons have been monitored together with fuel efficiency, showed a considerable reduction in both NO_x and PM along with a decrease in fuel efficiency (calculated based on total fuel, i.e., on diesel + water in the case of the emulsion). The emulsion fuel, named PuriNOx produce increased levels of specific oxidation products such as formaldehyde, acetaldehyde, acrolein and methyl ethyl ketone [18].

Schlitt and Exner have compared water-in-diesel emulsions with humidified intake air, i.e., water in the form of an aerosol [19]. It was found that both systems reduced the NO_x level compared to traditional diesel fuel. Only the emulsion was effective in reducing also the soot level, however.

The water level in the studies on diesel emulsions varies. Most authors use a water content of 5–10% but higher percentages have also been investigated. It has been claimed that the optimum water content for PM reduction is between 10 and 20% [1]. Samec et al. studied the effect of 10 and 15% water in the diesel on emission levels of NO_x , hydrocarbons and soot, as well as on the specific fuel consumption. The values obtained, relative to the values for neat diesel, are shown in Fig. 2 [20]. As can be seen, there is a considerable reduction in both hydrocarbons and soot already at 10% water. The NO_x reduction seems to be more water dependent and a 15% level is needed in order to obtain a significant effect. However, also the 15% water level did not produce the very high values of NO_x reduction that had been reported in earlier work [9].

In one study up to 40% water was used in combustion tests and the general picture of considerably reduced NO_x and smoke reduction and of small effects on CO and hydrocarbon emissions was maintained over the entire composition range [10]. Another study on the use of emulsions with high water content showed a slightly different picture [11]. The NO_x and soot levels were significantly reduced at water contents between 15–45% but there was an increase in the CO and hydrocarbon emissions with increasing water content. The latter increase could, at least partly, be overcome by preheating

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the intake air. Very high water content is hardly economic, however, since it requires high amounts of emulsifier. In addition, one can anticipate stability problems with emulsions of high water-to-hydrocarbon ratios. The Aquazole formulation from TOTAL S.A, which is a water- in-diesel emulsion, has been claimed to bring about a reduction in NO_x emission of up to 30% together with a reduction in black smoke of up to 80% [12,13]. Aquazole also reduces hydrocarbon.

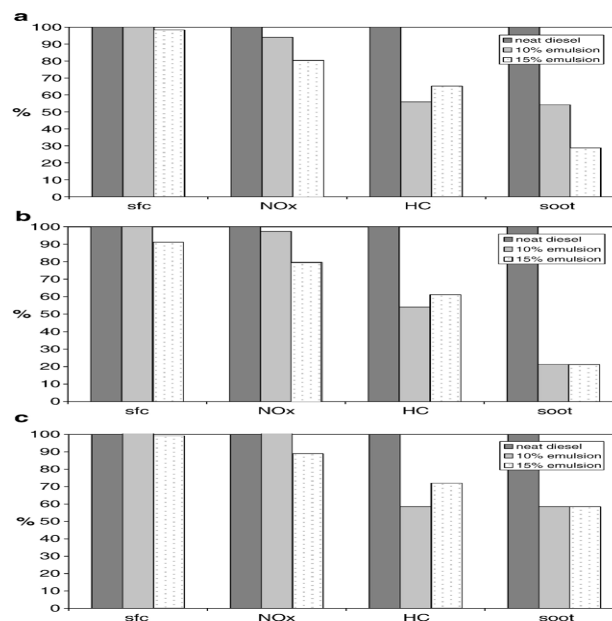


Fig. 4 Relative reductions of specific fuel consumption (sfc) and of exhaust emissions of nitrogen oxides (NO_x), hydrocarbons (HC) and soot.

Engine operating regime: exhaust pressure (p_e) = 10 bar, engine speed (n) = 1700 rpm. Relative reductions of specific fuel consumption (sfc) and of exhaust emissions of nitrogen oxides (NO_x), hydrocarbons (HC) and soot. Engine-operating regime: p_e = 8 bar, n = 1700 rpm. c. Relative reductions of specific fuel consumption (sfc) and of exhaust emissions of nitrogen oxides (NO_x), hydrocarbons (HC) and soot. Engine- operating regime: p_e = 5 bar, n = 1700 rpm.

V. IMPROVED COMBUSTION EFFICIENCY

By investigating emulsion fuels with varying amounts of water Abu-Zaid showed that the presence of water had a positive effect on the combustion efficiency of a single cylinder, direct injection diesel engine [21]. Fig. 3 shows how water in the form of an emulsion affects the engine torque output for various speeds. The emulsions are made using a mixture of two non ionic surfactants, Span 80 and Tween 80, as emulsifiers. The surfactants are used in a combined amount of 2 vol.%. Span 80 is sorbitan monooleate and Tween 80 is ethoxylated (20 oxy- ethylene units) sorbitan monooleate. Span 80 is a very hydro- phobic surfactant and Tween 80 is a very hydrophilic surfactant. When used alone none of them is a good emulsifier but a mixture of the two is known to be efficient and is widely used for various emulsification purposes. It is a generally established fact that a mixture of two surfactants, one more hydrophobic and one more hydrophilic, often gives better emulsification result than a single surfactant with intermediate hydrophilic – lipophilic balance [22,23]. The general appearance of the curves should be interpreted as follows. At low speed, the torque increases as the engine speed increases. At around 1500 rpm the torque starts to decrease because the engine is unable to ingest full charge of air. This effect becomes very pronounced at high speeds (above 3000 rpm in the figure).

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It can be clearly seen from the figure that addition of water in the form of an emulsion has a positive effect on the combustion efficiency. The torque increases with water content over the entire rpm range. When the charge is fired in the cylinder, the water will turn to steam with high pressure.

Another likely reason for the improved combustion efficiency is that the presence of water and, in particular, the presence of the oil–water interface with very low interfacial tension, leads to a finer atomization of the fuel during injection [24]. A finer dispersion of the fuel drops leads to higher contact with the air during the burning process, which is obviously advantageous for the combustion. It has been postulated that water in the fuel improves the combustion process owing to the simultaneous additional rupture of the drops, to the increase in evaporation surface of the drops, and to better mixing of the burning fuel in air [25].

Fig. 4 shows the brake specific fuel consumption as a function of engine speed for various contents of water in diesel [21]. Again the water is in the form of a water-in-diesel emulsion using a mixture of Span 80 and Tween 80 as emulsifier. The fuel is here calculated as the hydrocarbon only, i.e., the water in the diesel is not included in the fuel.

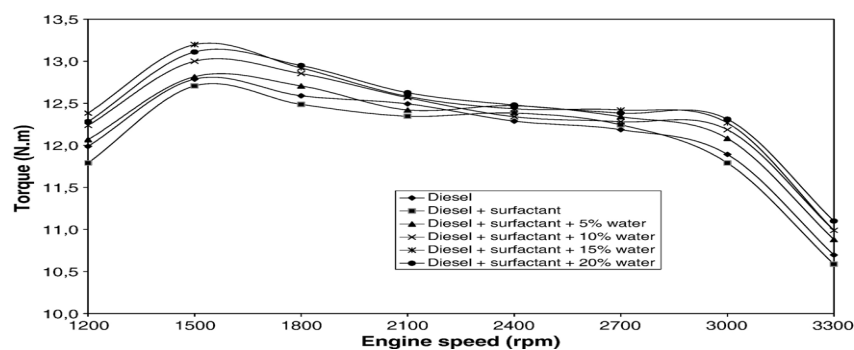


Fig 5 Engine Torque output V/S Engine Speed using water in diesel emulsions as fuel (Redrawn after Ref 21)

Phenomenon, known under the name micro explosion, helps in the atomization of the fuel. The violent disintegration is beneficial for the mixing of fuel and air because the air–fuel inter- facial layer will be larger than in the corresponding process without micro explosions. The net result will be that the combustion reaction and the burning efficiency will be improved; thus, the fuel consumption will be reduced. The micro explosion also helps in suppressing the formation of soot and unburned hydrocarbons, as was discussed in the section “Reduced emissions” above. There is a vast literature dealing with micro explosion of fuel emulsions [16, 30–45] and some of the results reported will be commented on below.

Different methods have been employed to study the micro explosions. Sheng et al. used holography and high-speed photography to study drop combustion in emulsion fuels [33]. A Schlieren optical system together with a high-speed camera has also been used [34]. Hang et al. employed a so-called Fraunhofer holographic system and high-speed Schlieren photographic technique to study the atomization and vaporization of a spray of a diesel emulsion in a high temperature combustion bomb [35]. They showed that the emulsion was better atomized than the neat hydrocarbon. A high-speed video camera with laser illumination has also been used to document the micro- explosions of fuel drops consisting of water in light oil [36].

The micro explosion characteristics of the emulsion drops over a hot plate have been studied and so has the effect of pressure on this drop-plate system [38]. The drop gasification over a hot plate is called the Leiden frost phenomenon [39, 40] and the evaporation characteristics of drops consisting of water-in-hydrocarbon emulsions have been thoroughly investigated by Avedisian [41, 42]. The secondary atomization process has been studied by laser light scattering and a beneficial effect of water on soot formation was detected [43]. Based on systematic work on micro explosions of water-in-hydrocarbon emulsions, using a range of hydrocarbons from hexane to hexadecane, also including gasoline and

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diesel fractions, a mathematical model of the micro explosion phenomenon has been constructed that takes into account variables such as temperature, drop size and parent fuel properties [44].

In a relatively recent work various aspects of micro explosions of water-in-diesel fuels have been studied and a model to predict the occurrence and the strength of micro explosions has been put forward [45]. The authors postulate that the drops formed in the atomization process, which consist of emulsified micro droplets of water in the surrounding diesel fuel, first change their internal structure so that an oil membrane is formed at the boundary. The reason for this is that the water in the micro droplets close to the boundary vaporizes more easily than water confined in micro- droplets in the interior of the droplet, leaving a layer, or membrane, of neat oil surrounding the remaining water-in-diesel emulsion. The thickness of the oil membrane has been calculated to be of the order of 10–20 μm . It is these core-shell drops; see Fig. 5, that burst when the temperature is high enough. The thickness of the oil membrane dictates the strength of the micro explosion. If the membrane is too thin, due to incomplete evaporation of water from the outer water micro droplets, the drops become too unstable. If the membrane has become too thick, there is not enough water left to cause a strong burst.

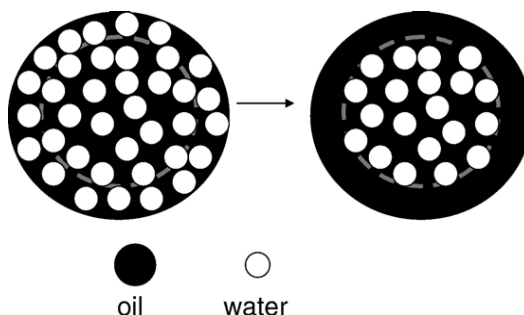


Fig. 6 Formation of the oil membrane in the atomization process after fuel injection in the cylinder. Evaporation of water micro droplets in the periphery gives a membrane of oil.

VI. WATER-IN-DIESEL MICRO EMULSIONS

Micro emulsions are alternatives to emulsions as a means to incorporate water in a fuel. The terms “micro emulsion” and “emulsion” seem to imply that such systems are very similar, differing just in the size of the dispersed component, but that is not the case. There are several fundamental differences between a micro emulsion and an emulsion and the most important characteristics of the two types of systems are summarized in Fig. 6 [50].

Micro emulsion based fuel formulations date back to 1976 when Gillberg and Friberg published a paper on the use of water- in-diesel micro emulsions as fuel [51]. Since micro emulsions consist of much smaller domain sizes than emulsions, one may anticipate that they are superior to emulsions with regard to the atomization process but there are indications that the opposite holds true. As mentioned above, Qingguo and Gollahalli have reported that macro emulsions, i.e., normal emulsions, produced smaller drops in the flame than micro emulsions [37]. In the experiments they used 10% water in so-called Jet-A fuel in both types of formulations. The general characteristics of emulsions

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Emulsion	Microemulsion
Unstable, will eventually separate	Thermodynamically stable
Relatively large droplets (1-10 μm)	Small aggregates (~ 10 nm)
Relatively static system	Highly dynamic system
Moderately large internal surface, moderate amount of surfactant	High internal surface, high amount of surfactant needed
Small oil/water curvature	The oil/water interfacial film can be highly curved

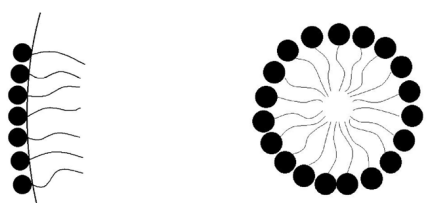


Fig. 7 Characteristic differences between emulsions and micro emulsions. (Redrawn after Ref. [50].)

With regard to emission levels seem to hold true also for micro- emulsions, i.e., NO_x and CO emissions are reduced compared to neat diesel as fuel [52]. Attempts have also been made to add vegetable oils into water-in-diesel micro emulsions, thus combining two approaches: replacement of hydrocarbons by triglyceride oils and introducing water into the fuel.

Systematic studies have been made on combustion of micro emulsions based on hydrocarbons of varying chain lengths. Special attention was paid to the vaporization behavior under dynamic heating conditions. The results indicated that the microstructure of the micro emulsion played a role in the physical effects related to the micro explosion, and, thus, to the combustion process.

Not much has been published on water-in-diesel micro emulsions in recent years. It is probably true to say that the advantages of the micro emulsion approach, in particular the thermodynamic stability, do not compensate for the drawback of the much higher loading of surfactants needed in a micro emulsion formulation compared to an emulsion formulation. The micro emulsion route is probably too costly for a very large scale application, such as fuels for vehicles. Among all different kinds of fuels based on biomass the most accessible ones today are biodiesel and ethanol.

All major oil companies, as well as all major automotive companies, have research programs today related to alternative fuels. There is a general belief that the upcoming shortage of oil, with concomitant rise in oil prices, will accelerate the switch from plain diesel and gasoline to alternative fuels but there are different opinions about which type of products will dominate the market for vehicle fuels in the future. The issue is very complicated because not only cost and performance, but also political considerations, will influence the outcome. For this reason many of the big players in the field have decided to carry on research and field tests on more than one fuel type in order to leave several options open.

88/77/EC (heavy vehicles) and amendments to these directives. In the amendments the limits for emissions have been tightened. The current Euro 4 and the coming Euro 5 in the European Directive 1999/96/EC (amendment to 88/77/EC) set the emission limits for heavy-duty diesel engines,

For the use of alternative fuels the European commission's Green Paper "Towards a European strategy for the security of energy supply" of 2001 sets a target for the transport sector at 20% by 2020. To further strengthen the transition to alternative fuels the directive 2003/30/EC of the European Parliament on "The promotion of the use of bio fuels or other renewable fuels for transport" sets indicative targets on renewable fuels at 2% and 5.75% for 2005 and 2010, respectively.

Ethanol (bio ethanol) is another widely accepted renewable fuel. Like FAME it can be used as a blend with a regular diesel or as neat ethanol. Scania AB has developed special engines dedicated for bio ethanol as fuel. The emission improvements compared to regular diesel are large. PM is reduced by 80% and NO_x by 28%, and also reductions in CO and HC emissions are achieved (80 and 50% respectively). Ethanol can also be used in blends with gasoline. A well-known concept is the flexi-fuel vehicles that can run on 85% ethanol (E85). In Brazil the majority of the cars are run on

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neat ethanol, produced from sugar cane. Also low-level blends of ethanol are used; in the United States blends of 10% ethanol and 90% gasoline, known as E10, are available and in Europe blends of 5% ethanol and 95% gasoline, called E5 are used. All car manufactures have approved the use of E5/E10 in the ordinary gasoline cars. The gasoline oxygenating additive, ETBE, ethyl tert-butyl ether, is made from ethanol and isobutylene and can be used as a replacement for MTBE, methyl tertbutyl ether. Ethanol as such is also an oxygenating additive. These additives act as octane enhancer and thus suppress knocking, which is the uncontrolled self-ignition. Ethanol is mainly produced from sugar cane, wheat or wine. Intensive research is being conducted on lignocelluloses as raw material. Gasification processes of biomass will give biogas-to-liquid fuels (BtL fuels). The biomass can have various origins, such as black liqueur, forestry residues, or municipal or industrial waste products. The resulting fuels are methanol, DME and Fischer–Tropsch diesel.

VII. SUMMARY

Alternative fuels cover a broad range of fuels, some of which, including water-in-diesel emulsions are readily available, while other types require further investigations, are produced in very limited amounts or require specially designed, i.e., dedicated, engines. Even if the water-in-diesel emulsion fuel has only a limited effect on the reduction of fossil CO₂, it is still beneficial from an environmental point of view because it brings about a reduction in the levels of both NO_x and particulate matters (PM).

REFERENCES

- [1] Cook DH, Law CK. Combust Sci Techno pp 217-18, 1978.
- [2] Law CK, Combust Sci Technol pp 17-29, 1977.
- [3] Ballester JM, Fueyo N, Dopazo C. Fuel, pp 692-97, 1996.
- [4] Gunnerman RW, Russel RL. SAE Tech Pap, pp 97-104, 1997.
- [5] Andrews GE, Bartle SW, Pang SW, Nurein AM, Williams PT, Proceedings of the International Centre for Heat and Mass Transfer, New York, NY, USA., pp.613. Sept 1987.
- [6] Bernhardt W, Weidmann K. Erdol Kohle Erdgas Petrochem, pp 40-86, 1987.
- [7] Hall D, Thorne C, Goodier S. SAE Spec Publication, SP-1802:153, 2003
- [8] Tsukahara M, Yoshimoto Y, International Congress and Exposition, Warrendale, PA, USA: SAE, pp.71, 1992.
- [9] Lawson A, Vergeer EC, Mitchell EW, Dainty ED. Heavy-Duty Diesel Emission Control: A Review of Technology, vol. 36. Montreal, Quebec, Canada: CIM; pp. 238, 1986.
- [10] Park JW, Huh KY, Lee JH. Proc Inst Mech Eng Part D J Automobile Eng; 215:83, 2001
- [11] Afify EM. Report ARO194353EG (DTIC No ADA-161-652). Raleigh, NC, USA: North Carolina State University. 106 pp, 1985.
- [12] Barnaud F, Schmelzle P, Schulz P. SAE Spec Publication; SP-1551:95. 2000
- [13] Fromager M, Schmelzle P, Schulz P. 2nd International Symposium on Fuels and Lubricants, Symposium Papers, New Delhi, Mar 10–12, vol. 2; pp. 435. 2000.
- [14] Hall RE. Trans ASME J Eng Power, 98:6425, 1976
- [15] Kozinski JA. Combust Flame; 96:249. 1994
- [16] Kadota T, Yamasaki H. Prog Energy Combust Sci;28:385. 2002
- [17] Sjogren A. Proc of the 16th Symp (Int) on Combustion, MIT, Pittsburgh, The Combustion Institute; pp. 297. 1977.
- [18] Matthews R, Hall M, Anthony J, Ullman T, Lewis D. SAE Spec Publication, SP-1834:79, 2004
- [19] Schlitt H-G, Exner P. Glueckauf-Forschungsh; 52:278, 1991
- [20] Samec N, Kegl B, Dibble RW. Fuel ;81:2035, 2002
- [21] Abu-Zaid M. Energy Convers Manag ;45:697, 2004
- [22] Holmberg K, Jönsson B, Kronberg B, Lindman B. Surfactants and Poly- mers in Aqueous Solution. 2nd ed. Chichester: Wiley; pp. 461, 2003.
- [23] Rosen MJ. Surfactants and Interfacial Phenomena. New York: Wiley Inter- science; pp. 326, 1989.
- [24] Walavalkar AY. Ph D Thesis, Pennsylvania State University, 2001.
- [25] Dryer FL. Proc of the 16th Symp (Int) on Combust, MIT, Aug 15 Pittsburgh, The Combustion Institute; pp. 279, 1976.
- [26] Ganesan S, Ramesh AJ. J Inst Energy;75:2, 2002
- [27] Sawa N, Kajitani S. International Congress and Exposition. Detroit, Feb 24–28, . Warren dale, PA, USA: SAE; pp. 97, 1992.
- [28] Lin C-Y, Wang K-H. Fuel ;83:537. 1992.
- [29] Hsu BD. International Congress and Exposition, Detroit, SAE 860300, Warren dale, PA, USA; pp.14, 1986.
- [30] Wang CH, Law CK. 1983 Fall Meeting of the Western States Section of the Combustion Institute. Combustion Institute (Paper). Pittsburgh, PA, USA: Combustion Inst; pp 25, 1983.
- [31] Wang CH, Law CK. Combust Flame; 59:53, 1985
- [32] Wang C-H, Chen J-T. Int Commun Heat Mass Transfer 23:823, 1996.

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- [33] Sheng H-z, Chen L, Wu C-k. International Congress and Exposition. Detroit, Feb 27–Mar 2 1995. Warrendale, PA, USA: SAE; pp. 231, 1995.
- [34] Mizutani Y, Fuchihata M, Muraoka M. Atomization and Sprays. J Int Inst Liq At Spray Syst; 11:521, 2001
- [35] Hang X, Yunbiao S, Chongji Z, Yuanji M. Proceedings of the 5th International Conference on Liquid Atomization and Spray Systems - ICLASS-91, Jul 15–18 National Institute of Standards and Technology, Gaithersburg, MD, USA; pp. 307, 1991
- [36] Fuchihata M, Ida T, Mizutani Y. Nippon Kikai Gakkai Ronbunshu B-hen/ Trans Jpn Soc Mech Eng Part B; 69:1503, 2003.
- [37] Qingguo L, Gollahalli SR. Proceedings of the Energy-Sources Technology Conference, Jan 23–26 1994, vol. 57. New York, NY, USA: ASME; pp. 15, 1994.
- [38] Cho P, Law CK, Mizomoto M. J Heat Transfer; 113:272, 1991.
- [39] Biancé A-L, Clanet C, Quere D. Phys Fluids; 15:1632, 2003
- [40] Avedisian CT. Proceedings of the 4th International Microgravity Combustion Workshop, May 19–21 1997. Cleveland, OH, USA: NASA; pp. 467, 1997.
- [41] Avedisian CT, Fatehi M. Int J Heat Mass Transfer; 31:1587, 1988
- [42] Mattiello M, Cosmai L, Pistone L, Berreta F, Massoli P. Proceedings of the 24th International Symposium On Combustion, Jul 5–10 1992. Pittsburgh, PA, USA: Combustion Inst.; pp. 1573, 1992.
- [43] Tsao KC, Wang CL. International Congress and Exposition, Detroit, SAE 860304, Warrendale, PA, USA; pp. 15, 1986.
- [44] Fu WB, Hou LY, Wang L, Ma FH. Fuel Process Technology 79:107, 2002
- [45] Lin C-Y, Wang K-H. Fuel; 82:1367, 2003.
- [46] Lin C-Y, Wang K-H. Fuel; 83:507, 2004.
- [47] Lin C-Y, Wang K-H. J Environ Sci Health Part A Toxic/Hazard Subst Environ Eng; 39:1345, 2004.
- [48] Lin C-Y, Wang K-H. Energy Fuels; 18:477, 2004.
- [49] Holmberg K, Jönsson B, Kronberg B, Lindman B. Surfactants and Polymers in Aqueous Solution. 2nd ed. Chichester: Wiley; pp. 139, 2003.
- [50] Gillberg G, Friberg S. Symp on Evaporation and Combust of Fuel Droplets, Aug 29–Sep 3 1976, vol. 21; pp. 731, 1976.
- [51] Ahmad I, Gollahalli SR. J Propuls Power; 10:744, 1994.
- [52] Neuma de Castro Dantas T, da Silva AC, Neto AAD. Fuel; 80:75, 2001