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Tribological Issues Related to the Use of Biofuels: A New Environmental Challenge

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Review Article

ABSTRACT

Due to gradual depletion of world petroleum reserves and the impact of environmental pollution of increasing exhaust emissions, there is an urgent need for suitable alternative fuels for use in engines. The heightened awareness of green house gas emissions and global warming compels introduction of more stringent environmental regulations worldwide. Renewable biofuels are considered potential solution for these problems. But use of biofuel is creating tribology related new challenges world over. In this paper a critical analysis of tribology related issue of three main biofuels, namely Straight Vegetable Oil (SVO), biodiesel and alcohols are discussed. Many issues like lubricity of blends, carbon deposit, viscosity, corrosion of engine components, etc are discussed in detail. Quality control of biofuels, identified as a key factor for sustainable market growth of these fuels and can lead to many tribological issues. In this regard a dire need for global harmonized standards is also discussed. Different solutions for alcohol fuel related engine problems are discussed. Critical discussion in relation to the problems due to the use of SVO in engine, like engine performance decrease, injector choking, oil ring sticking, etc took place in this paper. Potential solutions to these problems found by academia as well as industry are discussed here.

Keywords: Engine; alcohol; diesel; gasoline;

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1. INTRODUCTION

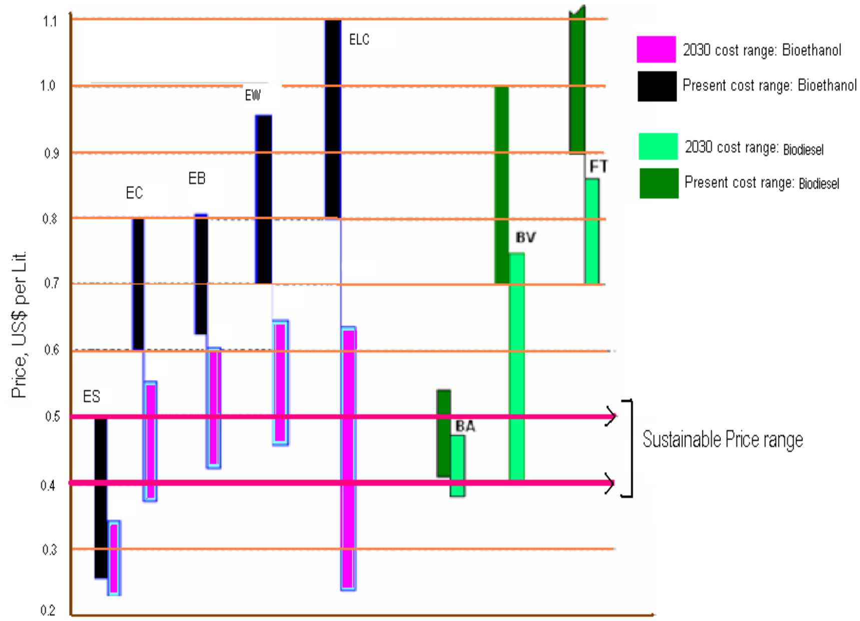
Between 1906 and 2005, records show that global average air temperature near the earth's surface increased by 0.74 ± 0.18°C. If emissions of greenhouse gases, and in particular CO_2, continue unabated the enhanced greenhouse effect may alter the world's climate system irreversibly (Mondal et al., 2011). Rapid socio-economic changes in some developing countries like India, China, etc, are influencing dramatically the fuel consumption pattern world over (Bhangale and Mondal, 2011; Tewari and Mondal, 2011). Diminishing world petroleum reserves and the impact of environmental pollution of increasing exhaust emissions lead to search for a suitable alternative fuels. Recent scorching prices of petroleum based fuel (before global economic recession) and reduced biofuel cost due to advanced technological breakthrough, made biofuel competitive with conventional petro-fuel. Biofuels like SVO, biodiesel, etc. help to curb Green House Gas (GHG) emission, depending on how they are produced. Practically, world bioenergy sector is experiencing flood wave of research and development initiated from both public and private sector. The major drivers for biofuel in developing countries like India are identified as: a. Saving foreign exchange; b. Promoting energy security in the country; c. Promoting environmental security; d. Meeting climate change commitments; e. Promoting renewable energy sources; and f. Generating rural employment opportunities (Anonymous, 2008). Biofuel like SVOs are produced easily in rural areas where there is an acute need for modern forms of energy. In the case of agricultural applications, fuels that can be produced in rural areas in a decentralized manner, near the consumption points will be favored (Mondal et al., 2008). But use of biofuel is creating tribology related new challenges world over. In this paper a critical analysis of tribology related issue of three main biofuels, namely Straight Vegetable Oil (SVO), biodiesel and alcohols are discussed.

2. WORLD BIOFUEL SCENARIO

In last five years, global production of biofuel has been doubled and expected to be doubled again in next four years. Production of biofuels (ethanol and biodiesel) exceeded an estimated 53 billion liters in 2007, up 43 percent from 2005 (REN21, Global Status Report 2007). In 2005, global production of Biofuel was 20 Mtoe or 643 thousand barrel per day, which was 1% of global road transport fuel consumption. Many countries world over has recently introduced biofuel friendly policy like Argentina, Australia, Canada, China, Columbia, India, Indonesia, Mexico, Senegal, South Africa, Zambia, etc. Brazil and USA together produce more than 80% of the total global production.

2.1 Future biofuel targets worldwide

Different countries world over set future targets for Biofuels. New U.S. renewable fuels standard requires fuel distributors to increase the annual volume of biofuels blended to 36 billion gallons (136 billion liters) by 2022. The new standard implies that 20 percent of gasoline for road transport would be biofuels by 2022. The United Kingdom has a similar renewable fuels obligation, targeting 5 percent by 2010. Japan's new strategy for long-term ethanol production targets 6 billion liters/year by 2030, representing 5 percent of transport energy. China finalized targets for the equivalent of 13 billion liters of ethanol and 2.3 billion liters of biodiesel per year by 2020. European Commission established a new EU-wide target of 10 percent of transport energy by 2020, extending the previous EU-wide target of 5.75 percent by 2010 (Renewable: Global Status report, 2007). In 2008, India announced an indicative target of 20% by 2017 for the blending of biofuels – bioethanol and bio-diesel. Present and projected future price ranges of different biofuels are presented in figure 1. Top 15 countries in Biofuel production with the present production status are given in below table 1 (WEO 2006).



ES: Ethanol (Sugarcane based); EC: Ethanol (Corn based); EB: Ethanol (Beet based); EW: Ethanol (Wheat based); ELC: Ethanol (Ligno-cellulosic); BA: Biodiesel (Animal fat based); BV: Biodiesel (Vegetable oil based); FT: Fischer Tropsch synthesis biofuel

Fig. 1. Price trend of Biofuel (Mondal et al., 2010)

Table 1. Top 15 countries in Biofuel Production

Country	Fuel ethanol	Biodiesel
	billion liters	
1. United States	18.3	0.85
2. Brazil	17.5	0.07
3. Germany	0.5	2.80
4. China	1.0	0.07
5. France	0.25	0.63
6. Italy	0.13	0.57
7. Spain	0.40	0.14
8. India	0.30	0.03
9. Canada	0.20	0.05
9. Poland	0.12	0.13
9. Czech Republic	0.02	0.15
9. Colombia	0.20	0.06
13. Sweden	0.14	—
13. Malaysia	—	0.14
15. United Kingdom	—	0.11
EU Total	1.6	4.5
World Total	39	6

3. FUEL ALCOHOL

Alcohol is made from renewable resources like biomass from locally grown crops and even waste products such as waste paper, grass, etc. Ethanol is an attractive alternative fuel because it is a renewable bio-based resource and it is oxygenated, thereby providing the potential to reduce particulate emissions in compression–ignition engines. Ethanol was first suggested as an automotive fuel in USA in the 1930s, but was widely used only after 1970. Ethanol production in 2007 represented about 4 percent of the 1,300 billion liters of gasoline consumed globally. Most of the increased production occurred in the United States, with significant increases also in Brazil, France, Germany, and Spain (Mondal et al., 2009). The United States became the leading fuel ethanol producer in 2006, producing over 18 billion liters and jumping ahead of longstanding leader Brazil (Renewable: Global Status report, 2007). Brazilian ethanol production increased to almost 18 billion liters in 2006, nearly half the world's total. All fueling stations in Brazil sell both pure ethanol and gasohol, a 25 percent ethanol/75 percent gasoline blend. Demand for ethanol fuels, compared to gasoline, was very strong in 2007, due to the introduction of so-called "flexible-fuel" cars by automakers in Brazil over the past several years. Such cars are able to use either blend and have been widely embraced by drivers, with an 85 percent share of all auto sales in Brazil. In recent years, significant global trade in fuel ethanol has emerged, with Brazil being the leading exporter (Renewable: Global Status report, 2007). Recently the economics have become much more favorable in the production of ethanol and it is able to compete with standard diesel. Consequently there has been renewed interest in the ethanol–diesel blends with particular emphasis on emissions reductions. Due to increased popularity of ethanol as an alcohol fuel, discussions are limited to ethanol only, in this paper. A summary of principle properties of ethanol, gasoline and diesel is given in table 2 (Agarwal, 2007).

Table 2. Properties of ethanol, gasoline and diesel

Parameters	Ethanol	Gasoline	Diesel
Formula	CH_3CH_2OH	C_7H_{16}	$C_{14}H_{30}$
Molecular weight (g/mol)	46.07	100.2	198.4
Density (g/cm3)	0.785	0.737	0.856
Normal boiling point (deg. C)	78	38–204	125–400
LHV (kJ/cm^3)	21.09	32.05	35.66
LHV (kJ/g)	26.87	43.47	41.66
Exergy (MJ/l)	23.1	32.84	33.32
Exergy (MJ/kg)	29.4	47.46	46.94
Carbon Content (wt%)	52.2	85.5	87
Sulfur content (ppm)	0	approx. 200	approx. 250

3.1 Tribological issues with alcohol

The use of ethanol in gasoline engines in the early 1980s resulted in numerous materials compatibility studies, many of which are also applicable to the effect of ethanol–diesel blends in diesel engines and particularly in the fuel injection system. The quality of the ethanol has a strong influence on its corrosive effects (Hardenberg and Ehnert, 1981). In addressing the problems of ethanol Brink et al. (1986) categorized the ethanol carburetor corrosion into three types: general corrosion, dry corrosion and wet corrosion. General corrosion was caused by ionic impurities, mainly chloride ions and acetic acid. Dry corrosion was attributed to the ethanol molecule and its polarity. de la Harpe (1988) reviewed reports of dry corrosion of metals by ethanol and found that magnesium, lead and aluminum were susceptible to chemical attack by dry ethanol. Wet corrosion is caused by azeotropic water, which oxidizes most metals. Freshly formulated blends containing pH neutral dry ethanol would be expected to have relatively little corrosive effect. However, if a blend has been standing in a tank for sufficient time to allow the ethanol to absorb moisture from the atmosphere, it may tend to be more corrosive as it passes through the fuel injection system (de la Harpe, 1988). In addition, the fuel may stand in the fuel injection pump for a number of months, for example, in a combine harvester engine, thus allowing the fuel enough time to corrode parts of the pump internally. Corrosion inhibitors have been incorporated in some additive packages used with ethanol–diesel blends (de la Harpe, 1988). Nonmetallic components have also been affected by ethanol with particular reference to elastomeric components such as seals and O-rings in the fuel injection system. These seals tend to swell and stiffen. Resin-bonded or resin-sealed components also are susceptible to swelling and seals may be compromised (Agarwal, 2007, Bosch, 2001).

A limited range of durability tests have been conducted on ethanol–diesel blends both in the laboratory and in the field. In early studies, tests with blends containing approximately 10% and 15% dry ethanol indicated no abnormal wear in engines correctly adjusted for injection timing (Hansen et al., 1982; Hashimoto et al., 1982; Meiring et al., 1983a). Some engines included in these tests were more sensitive to a lowering of the cetane number and accordingly an increased ignition delay causing piston erosion from severe localized temperatures and pressures. However, a small retardation of injection timing was recommended so as to reduce rates of pressure rise. In the durability tests conducted by Meiring et al. (1983b) no abnormal deterioration of the engine or fuel injection system was detected after 1000 h of operation on a blend containing 30% dry ethanol, small amounts of octyl nitrate ignition improver and ethyl acetate phase separation inhibitor, and the remainder diesel fuel. Recent over-the-road tests by Archer Daniels Midland (ADM), Bloomington, IL, US on two trucks operating on 15% ethanol blend of E diesel have resulted in an accumulation of over 400,000 km on each vehicle with no abnormal deterioration in condition (Marek and Evanoff, 2001). The Chicago Transit Authority (CTA) in the US monitored the condition and overall performance of a fleet of 30 buses, of which 15 were operated on the 15% ethanol blend and 15 were the control and were run on No. 1 diesel. After 4,34,500 km accumulated by the 15 buses running on the blend, no abnormal maintenance or fuel-related problems were encountered (Marek and Evanoff, 2001). Hansen et al. (2001) conducted a farm demonstration project with two John Deere 9400 tractors, two Caterpillar Challenger 95E tractors and two John Deere 9650, one of each vehicle type running on a 10% ethanol blend of ‘‘E diesel’’ using the GE Betz additive, and the other on No. 2 diesel. One of the objectives was to monitor the durability of the vehicles. The John Deere tractors operated for two spring seasons and one Fall season accumulating approximately 700 h with no abnormal deterioration in engine condition, based on oil analyses. The Caterpillar tractors and combines completed two seasons with approximately 380 and 600 h accumulated, respectively, again with no abnormal wear patterns according to oil analysis. A laboratory-based 500 h durability test was performed by Hansen et al. (2000) on a Cummins ISB 235 engine running on a 15% dry ethanol, 2.35% PEC additive and 82.65% diesel fuel. The engine operated at rated speed and maximum load in order to maximize the fuel throughput in the fuel injection system. With the exception of the fuel injection system, no abnormal deterioration in engine condition was detected based on detailed engine component measurements and examination. Calibration checks of both the injection pump and injectors showed that they were within normal tolerances. However, one resin-sealed sensor in the injection pump failed because of possible chemical interaction with the fuel and the injectors exhibited heavy wear from the needle valve action. Further tests are required to verify these results. Long-term durability tests of at least 1000 h are necessary to provide confirmation that ethanol–diesel blends do not adversely affect engine wear compared to the norms established for diesel fuel usage.

Finally it is concluded that long-term durability tests in a range of engines with different fuel injection system configurations will help to confirm that diesel oxygenated with diesel does not adversely affect engine wear compared to diesel fuel. Such tests should be performed in collaboration with engine manufacturers. More interestingly, blending of alcohol with newly available ultra low sulfur diesel, reported to have lubrication issues, has been proven to be an effective lubricity improver by many researchers (Anastopoulas et al., 2002).

3.2 Potential solutions of tribological issues of fuel ethanol

Blends of ethanol in gasoline are commonly used in vehicles designed to operate on gasoline; however, vehicle modification is required for alcohol fueling because its properties are different from those of gasoline. Ethanol has low stoichiometric air–fuel ratio and high heat of vaporization that requires carburetor re-calibration and increased heating of the air–fuel mixture to provide satisfactory driveability (Kremer et al., 1996). Brazil has most developed technology for the alcohol fueled Otto cycle (4 stroke) internal combustion engines. In order to make alcohol engines more practical, functional, durable, and economical, engineers made several changes in the regular gasoline engines. Use of detergent additive is reported to be a potential solution of injector valve deposit problem of ethanol run engine. Claydon (2008) reported results of engine testing to evaluate the impact of ethanol on inlet valve deposits in gasoline containing up to 24% ethanol. Testing in standard engine tests has shown that introducing Ethanol into standard gasoline will have a tendency to increase inlet valve deposits. Testing has clearly shown that this can, of course, be addressed by using a premium quality fully formulated gasoline detergent additive as shown in figure 2. A summary of ethanol related problems and solutions are presented in the following Table 3.

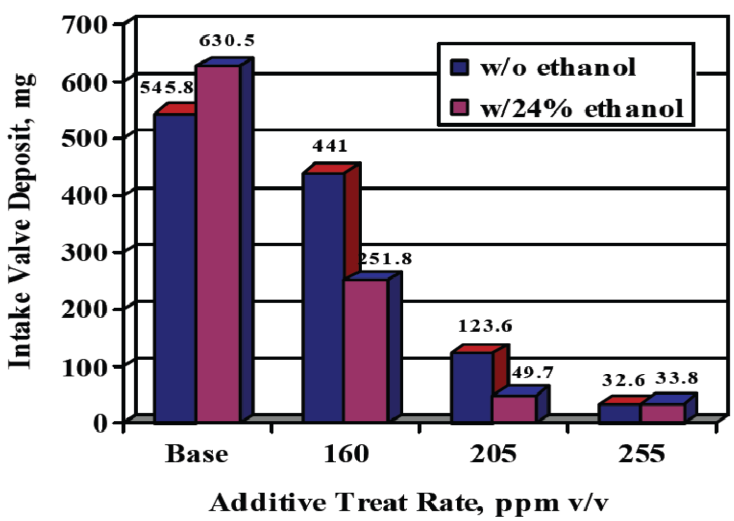


Fig. 2. Comparative intake valve deposit (Claydon, 2008)

Table 3. Problem and potential solutions of issues related to alcohol fuel

Problem	Solution
Alcohol does not evaporate as easily as gasoline.	Intake manifold had to be redesigned to provide more heating for evaporation.
Ethanol has low stoichiometric air–fuel ratio.	The carburetor was regulated and re-calibrated.
Corrosion of fuel tank and fuel line with alcohol	The tin and lead coating of the fuel tank was changed to pure tin. The fuel lines (zinc steel alloy) were changed to cadmium brass.
Requirement of greater fuel flow rates.	The fuel-filtering system was changed and re-dimensioned.
How to reap the advantage of higher octane rating of alcohol.	The compression ratio was increased to about 12:1.
Lack of lubrication resulting from the absence of lead in the fuel.	The valve housings, made of cast-iron, were changed to an iron-cobalt synthetic alloy.
Further reduction of the alcohol engine emissions.	Catalyst of the catalytic converter was changed from palladium and rhodium to palladium and molybdenum.

4. BIODIESEL

Biodiesel is the name of a clean burning mono-alkyl ester-based oxygenated fuel made from natural, renewable sources such as new/used vegetable oils and animal fats. Biodiesel production jumped 50 percent in 2006, to over 6 billion liters globally. Half of world biodiesel production continued to be in Germany. Significant production increases also took place in Italy and the United States (where production more than tripled). In Europe, supported by new policies, biodiesel gained broader acceptance and market share. Aggressive expansion of biodiesel production was also occurring in Southeast Asia (Malaysia, Indonesia, Singapore, and China), Latin America (Argentina and Brazil). Malaysia's ambition is to capture 10 percent of the global biodiesel market by 2010 based on its palm oil plantations (Renewable: Global Status report, 2007).

4.1 Tribological issues with biodiesel

Numerous researchers investigated biodiesel related tribological issues for more than three decades. The quantitative evaluation of metals present in the lubricant gives an indication of engine component wear, and the qualitative analysis identifies the origin of these metals. Most of the research papers available are public domain reported favourable tribological effect of biodiesel. But some investigations revealed some adverse effects also and need to be discussed separately.

4.1.1 Favourable tribological effect of biodiesel

The lubricity issue is significant, because the advent of low-sulfur petrodiesel fuels and, more recently, ultralow- sulfur diesel (ULSD) fuels, as required by regulations in the United States, Europe, and elsewhere, has led to the failure of engine parts such as fuel injectors and pumps, because they are lubricated by the fuel itself (Knothe and Steidley, 2005). It was reported that neat biodiesel possesses inherently greater lubricity than petrodiesel, especially low-sulfur petro-diesel, and that adding biodiesel at low blend levels (1%-2%) to low-sulfur petro-diesel restores lubricity to the latter (Schumacher, 2005; Lacey and Westbrook, 1995) or aviation fuel (Anastopoulos et al., 2005). Such effectiveness was reported for even lower (<1%) blend levels or higher (10%-20%) levels. Chausalkar et al. (2008) studied the effects of biodiesel blends on engine performance and lubricating oil. Two long duration endurance tests of 1000 hrs were conducted using petroleum diesel and 5 % biodiesel blend (B5) on a new generation multicylinder Euro II compliant engine. SAE grade 15W 40 engine oil meeting API CH4 was used for both the tests. The change in viscosity of engine oil with both the fuels is within the specified oil rejection limits. The minor difference in engine viscosity change by using B5 as fuel is within the repeatability values of engine test (Fig. 4). Endurance test of B5 indicates Fe levels between 7 ppm – 35 ppm which is very well below the specified lubricant rejection limit of 150 ppm. The wear values of the Fe for petrodiesel are in the range of 25-65 ppm (Chausalkar et al., 2008). Moreover, other metals such as Cu, Al, Si etc are well within the specified limits for both the fuels.

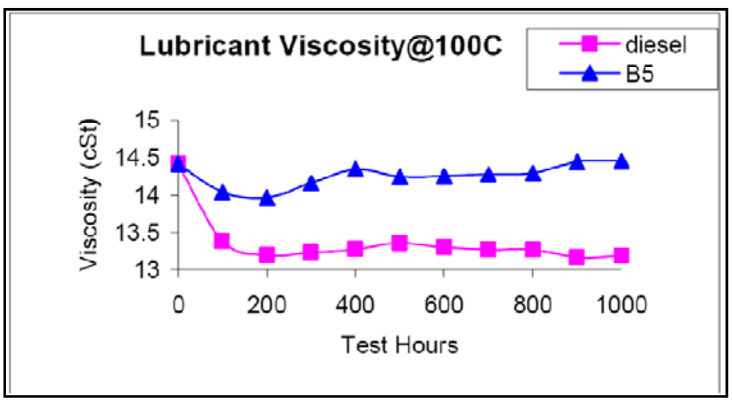


Fig. 3. Variation of lubricants viscosity with time (Chausalkar et al., 2008)

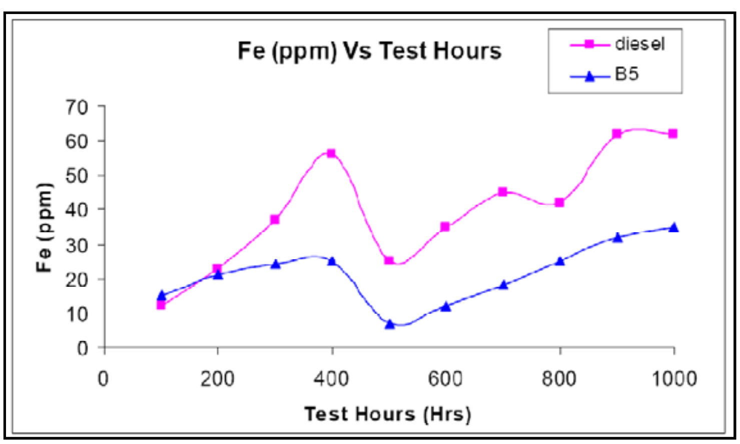


Fig. 4. Variation of Fe content with time (Chausalkar et al., 2008)

These results seem to imply that the alkyl esters that largely comprise biodiesel are responsible for this lubricity enhancement. Free fatty acids enhanced the boundary lubrication behavior of sunflower oil formulations (Fox et al., 2004). Esters of vegetable oils with hydroxylated fatty acids such as castor and lesquerella oils improved lubricity at lower levels than the esters of nonhydroxylated vegetable oils (Goodrum et al., 2005; Drown et al., 2001). Oxidized biodiesel showed improved lubricity, compared to its non-oxidized counterpart (Wain and Perez, 2002).

4.1.2 Some serious tribological problems with biodiesel

Some researchers reported adverse effect of biodiesel on tribological performance of engine and requires futher attention. Fontaras et al. (2009) investigated with neat soybean-oil derived biodiesel (B100) and its 50 vol.% blend with petroleum diesel (B50) on a Euro 2 diesel passenger car. Metals concentration in the lubricant was determined, in order to assess the biodiesel impact on wear. The analysis of the lubricating oil samples showed that the use of B50 and B100 may lead to increased wear in terms of higher amounts of metallic elements, originated from the different moving parts. Even though biodiesel demonstrates better lubricity properties compared to diesel fuel, the wear of various vital parts of the engine seems to be higher during the test fuel application. Iron and copper content implies cylinder and bearing wear, respectively (Agarwal, 2007), and these, appear to be increased by 67% and 272%, respectively. Batko et al. (2008) investigated the aspect of lubricity in steel–aluminium association for regular petroleum-based diesel fuel, methyl esters of colza oil (RME), and their mixtures. The study, of a laboratory character, was done using a friction machine with a roller-ring friction couple. The value of sample wear was determined by means of the gravimetric method, using an analytical balance. On the basis of the research it was found that a small supplement of RME to diesel fuel causes a sudden increase of sample wear. The highest wear value was obtained with a 20% supplement of RME. As a whole, supplement of methyl esters of colza oil to diesel fuel causes significant increase of wear in the steel-aluminium friction couple. The results are given in figure 5. A possible explanation for indications of higher wear is that high biodiesel concentrations partly dissolve the lubricant, a mechanism which is probably more intense on the cylinder wall lubricating film. The friction coefficient of the engine’s moving parts increases, resulting in higher wear. Moreover, it is possible that some acidic components are formed during the combustion process, and these can be dissolved in the lubricant. This may result in corrosive wear due to the higher total acidity of the lubricant. This appears as an interesting area for further research.

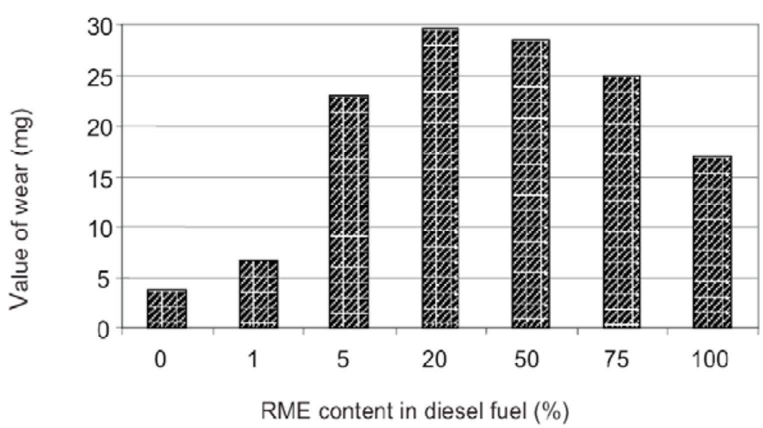


Fig. 5. Value of sample wear by weight with respect to RME content in diesel fuel (Batko et al., 2008)

5. STRAIGHT VEGETABLE OIL (SVO) AS ENGINE FUEL

Vegetable oil is a promising alternative because it has several advantages- it is renewable, environment friendly and produced easily in rural areas, where there is an acute need for modern forms of energy (Harrington, 1986; Kloptenstem, 1988; Srinivasa and Gopalakrishnan, 1991; LePori et al., 1992; Masjuki and Salit, 1993; Pramanik, 2003; Karaosmanoglu, 1999). In the case of agricultural applications, fuels that can be produced in rural areas in a decentralized manner, near the consumption points will be favoured. For agricultural applications where small amounts of fuel are consumed in every engine, use of neat vegetable oil is likely to be more attractive than the transesterified oil (bio diesel) as no chemical processing is needed (Narayana Reddy and Ramesh, 2006). Depending upon climate and soil conditions, different nations are looking into different vegetable oils for diesel fuels. For example, soybean oil in the USA, rapeseed and sunflower oils in Europe, palm oil in Southeast Asia (mainly Malaysia and Indonesia), jatropha oil in India and coconut oil in Philippines are being considered as substitutes for mineral diesel (Agarwal, 2007). In 2005-06, cumulative world production of seven major oil seeds, namely soybean, cottonseed, rapeseed, peanut, sunflower, palm kernel and copra, stood at 390.29 million tons (Mt), whereas that figure for nine major vegetable oils stood at 117.97 Mt. Comparative price trend of crude petroleum and soybean oil, one of the most important vegetable oils in terms of oilseed production and oil production, is given in figure 2 (OPEC, 2007; USDA,2007). It is clear from figure 6 that in last decade crude petroleum price experienced a steep rise when vegetable oil price exhibits a within range fluctuation. It is imperative that the expansion of alternative bifuel is also a matter of sufficiently high petroleum prices (Mondal et al., 2008).

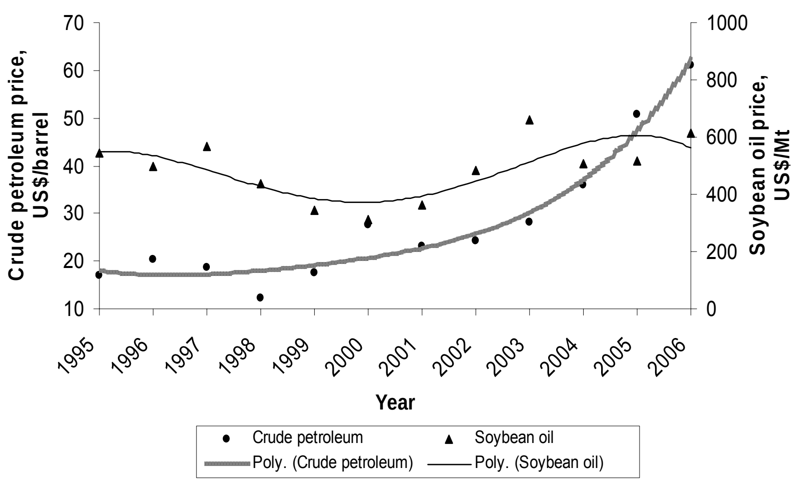


Fig. 6. Comparative trend of price of crude petroleum and soybean oil (Mondal et al., 2008)

5.1 Problems with SVO as fuel and some potential solutions

Direct use of vegetable oil can lead to many problems (particularly in direct ignition engine) like coking and trumpet formation on the injectors to such an extent that fuel atomization does not occur properly or even prevented as a result of plugged orifices, carbon deposits; and oil ring sticking (Vellguth, 1983; Dunn and Bagby, 2000). Thickening or gelling of the lubricating oil may also occur due to contamination by vegetable oils (Meher et al., 2006). Two severe problems associated with the use of vegetable oils as fuels are oil deterioration and incomplete combustion (Peterson et al., 1983). High viscosity (about 11-17 times higher than diesel fuel) (Schwab et al.,

1987) and lower volatility of vegetable oils and particularly animal fats lead to formation of deposits in engines due to incomplete combustion and incorrect vaporization characteristics (Yahya and Marley, 1994; Ghassan et al., 2004; Meher et al., 2006). Because of their unsaturation, vegetable oils are inherently more reactive than diesel fuels. Polyunsaturated fatty acids were very susceptible to polymerization and gum formation caused by oxidation during storage or by complex oxidative and thermal polymerization at the higher temperature and pressure of combustion (Peterson et al., 1983). The gum did not combust completely, resulting in carbon deposits and lubricating oil thickening. Consequently, these effects lead to deposition on the injector, forming a film that will continue to trap fuel and which can interfere with combustion (Baldwin et al., 1982; Korus et al., 1982). Use of vegetable oils in unmodified diesel engines leads to reduced thermal efficiency and increased smoke levels (Senthil Kumar et al., 2003; Senthil Kumar et al., 2001). These problems are associated with large triglyceride molecule and its higher molecular mass and can be avoided by modifying the engine less or more according to the conditions of use and the oil involved. Micro-emulsification, pyrolysis and transesterification are the remedies used to solve the problems encountered due to high fuel viscosity (Ramadhas et al., 2004).The probable reasons for the problems and the potential solutions of using vegetable oil as fuel are shown in table 4 (Harwood, 1984; Ma and Hanna, 1999; Mondal et al., 2008).

6. BIOFUEL STANDARDS

Quality control of biofuels, identified as a key factor for sustainable market growth of these fuels and can lead to many tribological issues. The quality variability of biofuel has been an issue in the recent past and is largely a function of the large number of feed-stocks, processes and supply points [Wilkes, 2008]. It has been claimed that Vegetable oil motor fuels of E DIN 51605 quality can be used without problems in utility vehicles, trucks, agricultural machines, buses, and in stationary engines such as compact heat and power plants (Möller, 2006). Germany and EU have done biodiesel standard for rapeseed methyl ester, and their biodiesel standard names are DIN E51606 and EN 14214, respectively. The USA has produced biodiesel standard for soybean methyl ester. Japan and Korea have also produced biodiesel standards. The EU standard EN 14214 is often used as the reference for other nations considering adoption of biodiesel standards and have greatly improved quality and consistency. Other initiative, like Biofuel Accreditation Program covering biofuel producers in USA and Canada meeting ASTM D-6751 quality standards and defined distribution management practices, may be recalled in this regard. Introduction of similar regional standards around the world are becoming more common. An example is Indian Standard 15607:2005 [IS 15607:2005] for biodiesel to be used as a diesel fuel blend stock. A comparison of biodiesel standards of Germany, USA, Korea and Malaysia is presented in table 5 (Kalam and Masjuki, 2008). As there is no global harmonized standard for biofuels, an international initiative is required to bridge this gap (Wilkes, 2008).

7. CONCLUSIONS

- Increased use of biofuel is inevitable due to diminishing world petroleum reserves, stringent emission norms and climate change policy and scorching price of petro fuel.
- Use of biofuel is creating tribology related new challenges world over.
- Different challenges related to tribological issues of most common three biofuels, namely, ethanol, biodiesel and SVO are discussed as reported in world literature over last three decades. Potential solutions to these problems found by academia as well as industry are discussed here.
- Quality control of biofuels, identified as a key factor for sustainable market growth of these fuels and can lead to many tribological issues. It is concluded that there is a dire need for global harmonized standards on biofuel.

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APPENDIX

Table 3. Summary of problems of using vegetable oils as fuel in diesel engine

Problem	Probable cause	Potential solution
Short-term		
1. Cold weather starting	High viscosity, low cetane, and low flash point of vegetable oils	Preheat fuel prior to injection. Chemically alter fuel to an ester
2. Plugging and gumming of filters, lines and injectors	Natural gums (phosphatides) in vegetable oil. Other ash.	Partially refine the oil to remove gums. Filter to 4-microns.
3. Engine knocking	Very low cetane of some oils. Improper injection Timing.	Adjust injection timing. Use higher compression engines. Preheat fuel prior to injection. Chemically alter fuel to an ester.
Long-term		
4. Coking of injectors on piston and head of engine	High viscosity of vegetable oil, incomplete combustion of fuel. Poor combustion at part load with vegetable oils.	Heat fuel prior to injection. Switch engine to diesel fuel when operations at part load. Chemically alter the vegetable oil to an ester
5. Carbon deposits on piston and head of engine	High viscosity of vegetable oil, incomplete combustion of fuel. Poor combustion at part load with vegetable oils.	Heat fuel prior to injection. Switch engine to diesel fuel when operations at part load. Chemically alter the vegetable oil to an ester.
6. Excessive engine wear	High viscosity of vegetable oil, incomplete combustion of fuel. Poor combustion at part load with vegetable oils. Possibly free fatty acids in vegetable oil. Dilution of engine lubricating oil due to blow-by of vegetable oil.	Heat fuel prior to injection. Switch engine to diesel fuel when operation at part loads. Chemically alter the vegetable oil to an ester. Increase motor oil changes. Motor oil additives to inhibit oxidation.
7. Failure of engine lubricating oil due to polymerization.	Collection of polyunsaturated vegetable oil blow-by in crankcase to the point where polymerization occurs.	Heat fuel prior to injection. Switch engine to diesel fuel when operation at part load. Chemically alter the vegetable oil to an ester. Increase motor oil changes. Motor oil additives to inhibit oxidation.

Table 4. Comparative biodiesel standard of different countries

		Standardization of biodiesel				
Country		**Germany**	**USA**	**Korea**	**Malaysia**	
Standard /specification		**DIN E 51606**	**ASTM D6751**	**B20**	**B100**	**LPPP[a]**
Date		1-Sep-97	10-Jan-02	30-Sep-04	Aug-05	
Application		FAME	FAME	FAME	FAME	FAME
1	Density 15 ºC (g cm^{-3})	0.875-0.9	0.8-0.9	0.86-0.9	0.8783	0.87-0.9
2	Viscousity 40 ºC (mm^2s^{-1})	3.5-5.0	1.9-6.0	1.9-5.5	4.415	5-Apr
3	Distillation 95% (ºC)	–	≤ 360	–	–	–
4	Flash Point (ºC)	> 100	> 130	> 120	182	150-200
5	Cloud Point (ºC)	–	–	–	15.2	(-18)-0
6	CFPP (ºC)	0/-10/-20	–	–	15	(-18) -3
7	Pour Point (ºC)	–	–	–	15	(-21)-0
8	Sulfur (% mass)	< 0.01	–	< 0.001	< 0.001	< 0.001
9	CCR 100% (%mass)	< 0.05	< 0.05	–	–	–
10	10% dist.resid. (%mass)	–	–	< 0.5	0.02	0.025
11	Sulfated ash (%mass)	< 0.03	0.02	< 0.02	< 0.01	< 0.01
12	(Oxid) Ash (%mass)	–	–	< 0.02	–	–
13	Water and sediment (mg kg^{-1})	< 300	< 500	< 500	< 500	< 500
14	Oxidation stability (hrs.110 $ºC^{-1}$)	–	–	> 6	–	–
15	Total contam. (mg kg^{-1})	< 20	–	< 24	–	–
16	Cu-corros. (3 h 50 $ºC^{-1}$)	1	< No.3	1	1a	1a
17	Cetane no. (-)	> 49	> 47	–	–	–
18	Acid Value (mg KOH g^{-1})	< 0.5	< 0.8	–	< 0.08	< 0.03
19	Methanol (%mass)	< 0.3	–	< 0.2	< 0.2	< 0.2
20	Ester content (%mass)	–	–	> 96.5	98.5	98-99.5
21	Monoglycerides (%mass)	< 0.8	–	< 0.8	< 0.4	< 0.4
22	Diglycerides (%mass)	< 0.4	–	< 0.2	< 0.2	< 0.2
23	Triglycerides (%mass)	< 0.4	–	< 0.2	< 0.1	< 0.1
24	Free glycerol (%mass)	< 0.02	0.02	< 0.02	< 0.01	< 0.01
25	Total glycerol (%mass)	< 0.25	0.24	< 0.25	< 0.01	< 0.01
26	Iodine no. (-)	< 115	–	–	58.3	53-59
27	C18:3 and high. Unsat. Acids (%mass)	–	–	< 1	< 0.1	< 0.1
28	Phosphorous (mg kg^{-1})	< 10	< 10	< 10	–	–
29	Alcaline met. (Na, K) (mg kg^{-1})	< 5	–	< 5	–	–
30	Linolinec acid (%mass)	–	–	< 12	< 0.5	< 0.5
31	Lubricity 60 ºC (µm)	–	–	< 460	–	–

[a] *Low pour point palm diesel*