Vol. 38, No. 2 (2016) 197-213

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Biodiesel Performance within Internal Combustion Engine Fuel System - A Review

Z.A. Khan[a], A. Saeed[a], O. Gregory[a], A. Ghafoor[b]

[a] *Bournemouth University NanoCorr, Energy & Modelling Research Group Talbot Campus, Poole, Dorset, UK,*
[b] *National University of Science and Technology, Pakistan.*

Keywords:

Tribology
Biodiesel
Petro-diesel
CI engine
Fuel injection

Corresponding author:

Adil Saeed
Bournemouth University
NanoCorr, Energy & Modelling
Research Group Talbot Campus, Poole, Dorset, UK.
E-mail: asaeed@bournmeouth.ac.uk

A B S T R A C T

This review paper highlights the tribological performance of biodiesel at contacting surfaces in the fuel delivery system of compression ignition (diesel) engines. The focus is on the injection components that include low and high pressure injection pumps, diesel fuel injectors, electro-hydraulic valves, diesel fuel lubricity measurements and effects of biodiesel on the running conditions in a diesel fuel injection system. The common rail system and the distributor pump injection systems with electronic diesel control are among the modern trends that are specifically highlighted. Boundary, mixed and hydrodynamic lubrication regimes together with lubricant oil film thickness, pressure and engine performance are also considered.

1. INTRODUCTION

Petroleum products have played a major role in human history for energy developments [1,2]. The depletion of oil reserves, increase in oil prices and general concerns that arise from the environmental pollution of fossil fuels [3-6] added to continuous efforts by engineers' to prolong automotive engine life [7]. During operation, moving parts of the engines experince wear and friction under dry and/or lubricated conditions, in such conditions tribology plays a vital role in the engines [8,9]. Tribology; defined as the science of friction, wear and lubrication - is vital to modern machinery where the assembly incorporates surfaces in sliding and rolling contacts and is hugely influenced by materials' selection, components selection and surface engineering [10-13]. Tribology starts with the building of a machine that includes material selection, the general component assembly and surface engineering [14]. Research has been condcuted to categorize engineering surfaces during manufacturing, machine condition monitoring, and failure analysis of components [15]. Nonetheless measurements of surface features, accuracy in characterization and classification of tribological surfaces still remain an engineering problem [16].

Existing technologies for reciprocating internal combustion engines are divided into two kind

(a) compression ignition (CI) and (b) spark-ignition (SI) engines [17]. The two forms of fuel oils used for compression ignition engines are (a) renewables (biodiesel) and (b) non-renewables (petrodiesel) [18].

The current review paper focuses on the effects of biodiesel in the contacting areas of CI engine fuel delivery systems made for automobiles. Tribological experiments and surface analysis utilize specialized outfield equipment and related components in the laboratory to study interacting surfaces [19]. Within the fuel delivery system of a CI engine assembly, various components that undergo tribological interactions are low pressure (LP) feed pump, fuel pressure regulator (electro-hydraulic valve), high pressure (HP) fuel injection pump, and diesel fuel injectors [18,20,21]. Common rail system (CRS), distributor pumps (Ve-type) and the rotary pump injection systems with electronic controls are among the modern trends of fuel injection systems commercially available [20,22]. Esters from vegetable oils are considered superior in overall engine performance since they have higher energy yield than animal fat derivatives [23,24].

Analytical methods for measuring diesel fuel lubricity [25] include the ball on cylinder lubricity evaluator (BOCLE machine), the high frequency reciprocating rig (HFRR machine), and the ball on three seats machine - a modified version of the four ball tribo-meter [25-28]. Testing equipment combinations in specific contact situations with varying fuel blends and mechanical loads are the most reliable ways of attaining vital tribological data for reliability control purposes [16,29]. The tribological properties of diverse kinds of reciprocating contacting surfaces using vegetable oils as lubricants have not yet been sufficiently investigated. A prediction tool was developed to calculate the potential for valve recession resulting from the impact and sliding wear in the inlet valve and seat insert of CI engines. However, no model existed at the time to evaluate valve or seat life in use phase. Further, literature search indicate that no comprehensive data is yet available on the electro-hydraulic valve that controls fuel pressure in CRS in the common rail injection systems. As lubricant viscosity affect diesel engine performance [30,31], the tribological assessment of components during engine work can give an indication of the CI engine fuel assembly component wear [32,33].

Studies on petrodiesel and biodiesels have been linked to failures in the CI engine and fuel systems . Investigations on CI engines operating conditions such as engine load, speed, injection timing and pressure have been carried out to show the effects of biodiesel on engine power [3]. Biodiesel is a lubricant fuel which is about 66% better than petro-diesel and reduces long term wear in diesel engine systems [34,35], likewise reduces CO_2 emissions . Remarkable advance in performance, emissions and combustion factors is reported [36] through raising the injector opening pressure, injection timing, injection rate and improving the swirl level when a diesel engine was run by bio-oils [37]. In the lubrication of contact surfaces, the supercritical fluid behavior within the diesel fuel injection system can lead to an increase in fuel compressibility and in turn, change the fuel lubricity/additive behavior.

Statistical data reflects the United Kingdom biodiesel production to be 0.11 billion litres per annum, contributing to a European Union total of 4.5 billion liters [2]. It was found in continuum of sustainable development research that original equipment manufacturers must ensure to minimize wear and friction on contact surfaces by formulating lubricants and additives using chemical that have no harmful effects on the environment [38]). The cost of tribological deficiencies to any economy is the summation of energy and material losses occurring on practically every mechanical device in operation [11,39]. The 'Jost' report suggested that the industry could save considerable revenue through improvements of lubrications and reduction in wear during operations [8].

The latest direction on energy implementation by the European Union on bio-fuels is to enhance biodiesel quality for internal combustion engines. The US Department of Energy revealed that using biodiesels saved Disneyland about 757,082.36 litres of petroleum diesel fuel a year, thereby complementing variable sources like wind and solar power .

2. FUEL DELIVERY TO THE AUTOMOTIVE 4-STROKE COMPRESSION IGNITION ENGINE

2.1 Fuel Injection Technology: Delivery Systems for Diesel Engines

The CI engine system shown in Fig. 1 can be classified into three basic sub-divisions: the fuel feed, the combustion, and the exhaust sub-systems. The fuel feed sub-system supplies fuel from the tank via the delivery pumps, to the fuel injectors [40]. As diesel fuels' (biodiesel and petro-diesel) act as sole lubricants in the injection system's sliding components which are in contact, the fluid experiences change in its physical properties such as viscosity [18,20,40,41].

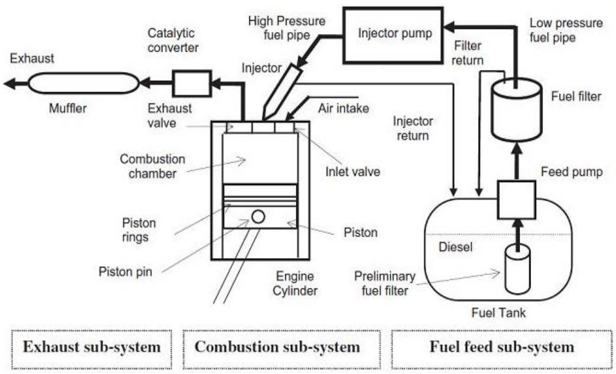

Fig. 1. Schematic of sub-divisions in a typical diesel engine fuel system [40].

Tribology in the fuel feed sub-system, beginning from the fuel tank and ending at the fuel injectors, plays an important role. Fuel injection technology is one of the main drivers towards improving diesel engines' performance and to maximize engine efficiency leads to demand of injector optimization [42]. Diesel systems are classified by the injection pump employed [43] and the growing demand for diesel fuel-injection systems for automotive engines presents need for their pump improvements [20]. Diesel fuel systems available for CI engines includes: In-line fuel-injection pump with mechanical governor or electronic diesel control (EDC); Control-sleeve in-line fuel-injection pump with EDC; Single plunger fuel-injection pump; Distributor fuel injection pump with EDC; Radial-piston distributor injection pump; Common rail accumulator injection system; Unit-injector system and the unit pump system [20,22,44].

2.2. The Common Rail Fuel Injection System for Diesel Engines

A common-rail diesel injection system shown in Fig. 2 consists of three main components: the low-pressure stage, the high-pressure stage, and the electronic control unit (ECU) [45]. The CRS is made up of a fuel tank with a pre-filter, a low pressure pre-supply pump, fuel filter, low-pressure fuel lines, a rail pressure sensor, a pressure-limiting valve, a flow limiter, injectors, and fuel return lines [18,46]. The use of CRS is spreading rapidly due to their microchip control which potentiates flexibility in fuel injection and engine performance as required by customers. CRS are more sensitive to fuel composition and properties [43]. Different CRS vary in design, components and specific functions but operate in the same way [1,2,47]. The high pressure, direct injection ECU operates under the ideal law for electro-hydraulic injectors; the fuel injection is performed at high pressures up to 1350 bar while integrating parameters are engine speed, coolant, air and fuel temperature and pressure. Advantages of the CRS include maintaining high fuel injection pressure on demand to reduce particulate emissions from the engine [48] and making multiple injections per cylinder combustion possible [47].

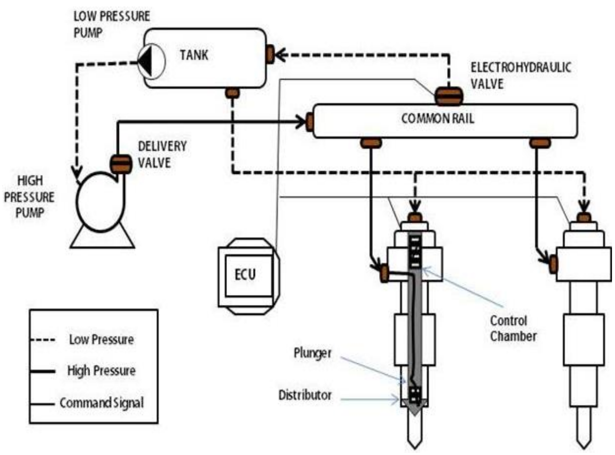

Fig. 2. Schematic of the common rail injection system for CI engines [22,49].

2.3. The Distributor Pump (VE-Type) Fuel-Injection System

The fuel-injection assembly for the distributor pump (VE-type) shown in Fig. 3 includes; (1) fuel tank, (2) fuel filter, (3) fuel-supply pump, (4) injection nozzles, (5) high-pressure injection tubing, (6) governor, and a (7) timing device (if required) [20]. Wear problems have been reported from the use of light oil fuels containing low sulphur in VE-type injection systems. For the injection pump parts to endure higher pressure, they must show better wear resistance [39]. The VE-type mechanical fuel injection system delivers a set quantity of fuel through high-pressure lines to the injectors at each cylinder, while rotating at half of the speed of the engine [20,50].

3. TRIBOLOGICAL CONSIDERATIONS

3.1. Friction in the Fuel Delivery System of the 4-Stroke CI engine

Tribology in diesel injection components involve stresses and deformation arising from the contacts between two or more surfaces in relative motion [51,52]. The two forms of contacts are distinguished as 'conforming' and 'non-conforming' [53]. Motional friction includes sliding, rolling, combined rolling and sliding, drilling friction for uniform activity, non-uniform frictional motion and intermittent motion friction [14]. Persson's contact theory is identified as the more accurate theory for modelling component lubrication and wear problems when compared with the multi-asperity contact theories [33]. Despite decades of tribological research in machines, a complete description of the phenomena taking place between two contacting solids has not yet been achieved [15]. Considering the multi-asperity contact theory for the contact area and load upon contact between the elastic half space and the single rigid asperity of a body, the Hertz theory for penetration is resolved as follows [33]:

$$(\delta) = \xi 1 - \mathrm{u} \tag{1}$$

Where δ is the penetration; u the distance of the approaching half-space from the mean plane of the rough surface and the single rigid asperity and $\xi 1$ is the height of one summit. Therefore considering frictionless contact conditions between a semi-infinite elastic solid (elastic modulus E and Poisson ratio ν) and a rigid, randomly rough surface with the height profile $z = h(\mathrm{x})$, where it is assumed that $h(\mathrm{x}) = 0$. The normalized area of contact of asperities for components in the CI engine fuel delivery system under consideration is given by:

$$\frac{A_c}{A_0} = \mathrm{erf}\left(\frac{1}{m_2^{\frac{1}{2}} E} \frac{F}{A_0}\right) \tag{2}$$

Where A_c/A_0 is the fraction of area in contact for a CI engine, F/A_0 represents the mean pressure in the nominal contact area, m_2 is the moments of the power spectral density (PSD) of a surface profile taken along a direction, and erf is the Gauss error function.

A linear expansion of equation 2 will give the asymptotic Persson's result in the limiting case of small applied *(low)* squeezing pressure as:

$$\frac{A_c}{A_0} = \frac{2}{\pi} \frac{1}{E} \left(\frac{\pi}{m_2}\right)^{\frac{1}{2}} \frac{F}{A_0} \tag{3}$$

Where the interfacial separation u = u(x). An energy approach was recommended [33,54] to solve this model. When the mean contact pressure $\sigma 0$ increases, the separation between the surfaces ($\sigma_0(\mathrm{u})$),will decrease.

Considering $\sigma_0 = \sigma_0\ (u)$ as a function of u. The elastic energy $U_{el}\ (u)$ stored in the contact regions at the interface equals the work done by the external pressure σ_0 in displacing the lower surface of the block toward the substrate. Hence, the equation:

$$\sigma 0(\mathrm{u}) = -\frac{1}{A_0} \frac{dU_{el}}{du} \tag{4}$$

The theory shows that for low squeezing pressures, the real area of contact Ac varies linearly with the squeezing force $\sigma 0 A_0$ (see equation 3) and the interfacial stress distribution and the size-distribution of contact spots are independent of the squeezing pressure. Also on applying a small load, the elastic energy stored in the asperity contact region will increase linearly with the load. This means that it is the 'elastic energy':

$$U_{el}\ (\mathrm{u}) = u_0 \times A_0 \times \sigma_0\ (\mathrm{u}) \tag{5}$$

Where u_0 is a characteristic length which depends on the surface roughness, but independent of the squeezing pressure σ_0. Therefore for small pressures, Eq. 4 will then be expressed as:

$$\sigma_0(\mathrm{u}) \sim e^{-u/u_0} \tag{6}$$

To quantitatively derive the relation for the separation between surfaces $\sigma_0(u)$, an analytical expression for the interfacial elastic energy is needed. From Persson's model of contact mechanics for randomly rough surfaces, it will be deduced that:

$$U_{el} = A_0 E \frac{\pi}{2} \int_{k0}^{k1} dk k^2 P(k, \sigma_0) \Phi((\mathrm{k})) \quad (7)$$

Where $\Phi(k)$ is the power spectral density (PSD) and $P(k,\sigma_0) = Ac(\zeta)/A_0$ is the relative contact area depending on the applied pressure σ_0 when the interface is studied at the magnification $\zeta = k/k_0$. And k_0 and k_1 are the roll-off and short distance cut-off wave vectors of the power spectrum respectively. The surface roughness power spectrum is defined as follows:

$$\Phi(\mathrm{k}) = (2\pi) - 2 \int d^2 x \{h(\boldsymbol{x}) h(0)\} e^{-i\boldsymbol{k}.\boldsymbol{x}} \quad (8)$$

For complete contact in a limiting case, P=1. Substituting (Eq. 8) in (Eq. 4), small squeezing pressure will be calculated as:

$$\sigma_0 = \beta e^{-u/u_0} \quad (9)$$

The length u_0 and parameter β when calculating self-affine fractal surfaces will be dependent only on fractal dimensions D_f, k_0 and k_1.

3.2. Component Wear in the Fuel Delivery System of the 4-Stroke CI engine

Figure 4 illustrates the combined CRS and Ve-Type distributor diesel injection systems. The process of tribology in the CI engine fuel delivery components occur from the point when low pressure fuel is fed from the tank via the LP pump to the HP pump: then pressurized fuel is delivered from the HP pump to the CRS or Ve-Type injectors, until excess fuel is returned to the tank via the electro-hydraulic valve [18,20,22,55].

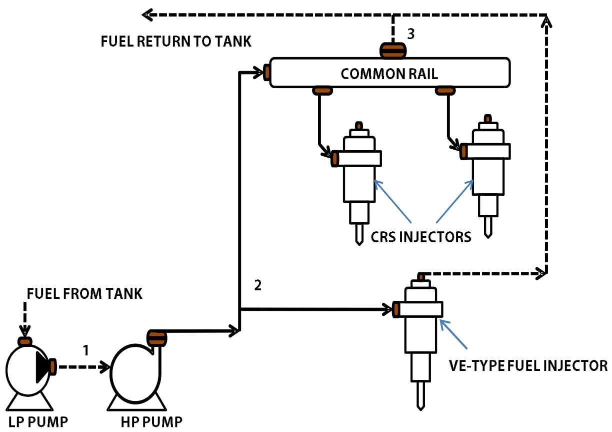

Fig. 4. Combined fuel flow schematic of the CRS and Ve-type injection systems showing components for tribological assessment [20, 22, 49].

A governor or in-built injection timing device is included for the Ve-Type distributor pump [20,50]. Diesel fuel pressure is maintained by the electro-hydraulic valve in the common rail [22,45].

Wear occurs as a result of friction and is a major cause of components' failure, depending on applications where sliding contacts are concerned [11]. The distribution of wear is dependent on size and location of deformation in a material that includes formation of cracks, attrition, scaling, pits, scratches, flutes, scuffing, and corrosion. In addition, the lubricant properties, temperature, surface roughness, and material properties are the operating parameter affect the wear process [14,56-57]. Wear within different materials in contact are identified as adhesive, fatigue, abrasive, erosive, chemical, cavitation, corrosive, oxidative, fretting, impact, melting and diffusive wear [11,56]. It was reported that the short term wear of a CI engine component using biodiesel is lower than the wear experienced when running on petro-diesel. The abrasive wear is identified as the most common when lubrication flows along with one body alone without providing support against the other in contact [11]. Generally, low viscosity leads to fuel injection system wear and failure [58] and when too high, viscosity affect the smooth flow and spray quality of diesel fuels [59]. Component wear usually occur within the asperities in contact and could be elastic or plastic depending on different shear strengths of materials. In the injection system of CI engines, only the fuels provide lubrication for component asperities in contact [34,60-61]. Archard's equation (Eq. 10), is a basic technique in predicting and analyzing wear**;** applicable only to sliding contacts as found in CI engine fuel delivery injectors, the low pressure pump and high pressure pump pistons, and on the surfaces of the electro-hydraulic valves, but not to the rolling systems [62]. It is expressed as follows:

$$\mathrm{V} = \frac{KWL}{H} \quad (10)$$

Where V is the wear volume, W is the normal load, L is the sliding distance, and H the penetration hardness of the softer material. K is the wear coefficient as the equation predicts wear to be a linear function of sliding distance and load, which agrees with general experience. Diesel fuel is the sole lubricant supporting CI engine injection system contacting asperities [43,63] and the elasto-hydrodynamic (mixed) lubrication regime that bears chemically reacted films as 'thin-film lubrication' [10]. This condition prevents adhesion between contacting asperities. For adhesive wear in lubricated asperities in contact, the fractional film defect on the condition that the fuel provides thin-film lubrication modelled to be as:

$$\beta = \frac{A_m}{A_r} \tag{11}$$

Where A_m is the area of metal-to-metal contact and β is the proportion to the total real area of contact A_r. In an expanded form, the fractional film defect can be expressed as:

$$\beta = 1 - \exp\left\{-\left[\frac{30.9\times10^5\, T_m^{1/2}}{V_s \times M^{1/2}}\right]\exp\left(-\frac{E_c}{RT_s}\right)\right\} \tag{12}$$

Where M is the molecular weight of the lubricant, T_m is the melting temperature of the lubricant, T_s is the temperature of the interface, V_s is the sliding velocity, and R is the universal gas constant. E_c is the energy required to bring about desorption of molecules; equivalent to the isoteric heat of adsorption. The model has its limitations, which includes isothermal contact conditions [62]. Even though biodiesel provides better lubricity than fossil diesel, corrosive wear and friction may increase due to the tendency of biodiesel to absorb moisture [64]. Component wear from debris produced during sliding contact of surfaces is known as 'three body abrasive wear'. Here, parallel scratches manifest on the surface and are distinguishable from other abrasive mechanisms as three-body wear produces scratches related to the size of the debris [65, 66]. For example, components made with Ni–Cr–Fe–Si–B–C coating exhibited bigger grooves with almost no delamination of the coat during tribo-tests, whereas products coated with Cr_3C_2NiCr exhibited superficial abrasive grooves and minimal delamination of the surface [67,68].

3.3 Wear effect on Component by Petro-diesel and Biodiesel: The Low Pressure Pump

Low pressure (LP) pre-supply diesel fuel pump is usually installed in a CI engine [20,69]. The poor lubricity of ultralow-sulphur diesel fuels leads failures in LP pumps of the fuel injection assembly [70]. Deposits have been observed both in low and high pressure injector pumps [69,71]. The tribological effects of deposits on diesel injection components are misfiring and noticeable reduction in engine performance [71]. The relatively high viscosity values of biodiesel over petro-diesel can lead to increased wear in diesel injection components similar to the fuel delivery pump [72].

3.4 Wear effect on Component by Petro-diesel and Biodiesel: The High Pressure Injector Pump

In a durability test determined the effects of petro and bio-diesel fuel blends on a CRS injection using a surface roughness tester [43]. Analysis after 600 hours of work revealed wear effects on the surface of pump drive shaft, cam and piston. Applying silicon nitride ceramics coatings to the roller-bushings of Ve-type diesel fuel injection pump improves seizure resistance [39]. Seizure or scuffing in a piston pump is the complete halting of motion between contacting asperities; caused by extreme running conditions such as low viscosity, high pressure and speed that leads to the rupture of lubricating films to effect localized damage [69]. The use of piston skirt coating made from 'polytetrafluroethylene' (PTFE) or 'graphite' reduces the risk of scuffing [16]. In Fig. 5 wear pattered on a HP injection pump piston is illustrated.

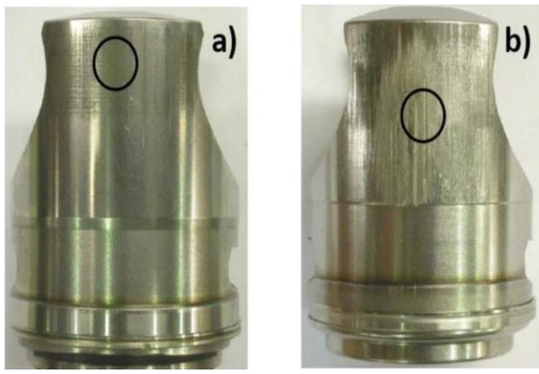

Fig. 5. Wear pattern on a HP injection pump piston (a) normal wear pattern; and (b) misaligned wear pattern as a result of seizure/scuffing.

3.5 Wear effect on Component by Petro-diesel and Biodiesel: Valve Systems

The electro-hydraulic valve of a CRS injection is a pressure sensor driven by the electronic control unit (ECU), that maintains the fuel pressure at a reference value in the common rail [22,73]. A basic CRS electro-hydraulic valve actuator system is made up of three components (1) actuator, (2) pump and (3) controls. Although the rapid valve opening and closing with suitable timings optimize volumetric efficiency, early tribological wear of the check valve end plates, solenoid valve retainer and valve housing were detected due to check valve impact [74]. Hence, Archard's laws for wear [75] was applied to resolve the combustion chamber inlet valve and seat insert wear problems for CI engines [76] as given in Eq. (13) for sliding wear:

$$V = \frac{K P_C X}{h} \tag{13}$$

Where V is the wear volume and is proportional to the contact force, Pc (N). The sliding distance is x (m) and the penetration hardness of the wearing surface is h (N/m^2). K, the non-dimensional wear coefficient, is determined empirically.

The peak load normal to the direction of sliding at the valve/seat interface, Pc, was calculated using the peak combustion pressure, p_p, and the valve head geometry as given by:

$$P_c = \frac{P_p \pi R_v^2}{(1 + U) \sin \theta v} \tag{14}$$

Where $\sin\theta\boldsymbol{v}$ is the valve seating face angle (°) and μ is the coefficient of friction at the valve/seat interface. The load on the valve seat during a combustion cycle is initially zero and then rises to P_c and falls back down to zero. For the purpose of calculating sliding wear volume, an average load P_p was assumed equal to half Pc. In the absence of other data, μ was estimated to be 0.1 for the valve/seat interface, which is a typical value for boundary lubricated steel surfaces.

$$W = KNe^n \tag{15}$$

The impact wear equation (Eq.15) relates to the same form as that applied in erosion studies to model wear mass, W, due to the impact of the valve on the seat during valve closure. Here e is the impact energy per cycle (J) given as $\frac{mv^2}{2}$. Where m is mass of valve and follower added to half the mass of valve spring (Kg); v is the valve velocity at impact (m/s); K and n are empirically determined wear constants and N is the number of loading cycles. It is important to note the difference in operating conditions between the electro-hydraulic valve of the common rail injection system and the combustion chamber inlet valve and seat insert.

3.6 Wear effect on Component by Petro-diesel and Biodiesel: The Fuel Injector(s)

Figure 6 shows a failed fuel injector due to external deformation and clogging of the injector nozzle aperture by carbon deposition. The carbon deposits and diesel injector clogging result from the use of low quality or oxidized fuel in CI engines [71]. Wear on fuel injectors are caused by decrease in fuel flow which results in a reverse flow on the edge material around the aperture, having rough contours and fatigue loads that crack the hardened surface [34].

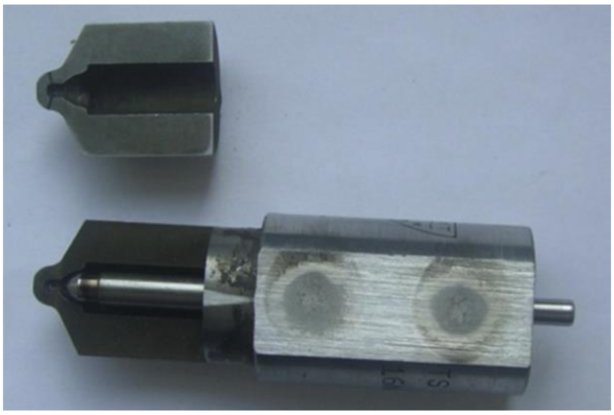

Fig. 6. A fuel injector investigated for signs of wear after spark erosion cutting and spectral analysis [34].

4. Lubrication Regimes in the Fuel Delivery System of the 4-Stroke CI engine

Diverse forms of lubrication are applied to automotive system units during a single cycle to help machine parts in contact to achieve suitable levels of performance [16]. The types of lubrication regimes known include hydrostatic, hydrodynamic, elasto-hydrodynamic and boundary lubrication [10,11,16]. Hydrodynamic and boundary lubrication are the two broad mechanisms that contribute to overall biodiesel/diesel fuel lubricity [5]. Diesel injection pumps rely only on the lubricating properties of diesel fuel as they provide the only lubrication in the engine's fuel system [63]. It is reported [50] that utilizing varying types of fuel with different properties will have different effects on the fuel injection system performance. Fuels require certain lubricant properties to prevent wear on contacting components which includes: temperature, shear rate, pressure and the thickness of generated oil [11], since lower the lubricity of diesel fuel, the higher the wear in some parts of the diesel injection systems [43]. For interacting components in a system that are separated by a liquid lubricant, it is identified [16,77] that the lubricant film thickness is the key operating tribological factor that separates contacting asperities of two bodies in relative motion. Oil film thickness reduces as the unit load increases and increases with a reduction of the loading in the system [78]. The lubricant film thickness ratio (λ) is calculated using the following equation [16].

$$\text{Lubricant film thickness ratio } (\lambda) = \frac{h}{(\sigma^2 surface\ 1 + \sigma^2 surface\ 2)^{1/2}} \quad (16)$$

Where h is the film thickness calculated through the use of classical thin film analysis, assuming a smooth surface. And σ is the root mean square (rms) surface roughness. Studies on contacting asperities with different surface topography indicate that under mixed lubrication conditions, when **λ** is 0.5, the lubrication film can get too thin, prompting asperity penetration that leads to wear from metal-to-metal contact [77].

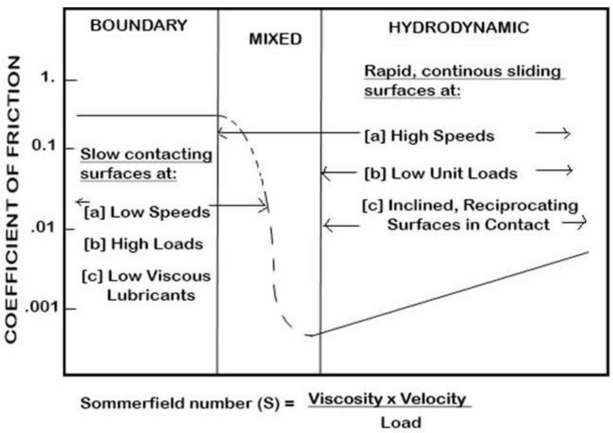

Fig. 7. Lubrication regimes for CI engine injection components and their relationship with friction [10,16,78].

As shown in Fig. 7, the Stribeck plot was employed to give a visual example of two surfaces in relative motion [10]. Separated by a lubricant under different lubrication film regimes, as explained in the literature [16], the plot demonstrates the relationship between the coefficient of friction, oil film thickness ratio and the Sommerfield number - a dimensionless quantity applied broadly to hydrodynamic lubrication [37] in an automobile engine power-train system. It is indicated that a reduction in asperity interaction between two contacting asperities was observed when lubricant emission from the cavities of shot peened and polished balls locally increase film thickness (h) to 25 nm [77].

The Stribeck plot expressed that the boundary lubrication is consequent with metal-to-metal contact, and usually occurs in an engine system where hydrodynamic lubrication has been lacking [16]. The boundary lubrication conditions occur in slow contacting surfaces in relative motion, e.g., the electro-hydraulic valve of the CRS, because lubricating oil has been pressed out from between the interacting surfaces, allowing metal-to-metal contact to produce chemical films or a reaction product to combat wear [5]. Components as valves when separated by low viscous lubricants under the boundary or mixed film lubrication regime, operate by having chemical or physical interactions as useful means of surface protection [11]. Hydrodynamic conditions occurring in diesel injection components as the injectors and both LP/HP pumps, ensure that enough lubrication film is formed on the surface of contacting asperities, preventing metal-to-metal contact that leads to wear [5]. Asperity compressibility from pressure distribution in a mixed lubrication contact depends on such factors as the ratio between the mean film thickness and the asperity heights: including the roughness wave length, the lubricant rheology and compressibility [79].

The major technical issue in working with chemically improved biodiesel fuel in tribological evaluations, is the combined lubricating quality of the fuel and additive mixture [61], considering parameters such as the lubricating quality of the components and the phase behaviour of the mixtures. It is found that the poor lubricity of low-sulphur petro-diesel is caused by the desulphurization process [80]. Density, dynamic viscosity, surface tension, specific heat and vapour pressure are important fuel properties that influence lubrication and fuel injection in CI engines [81]. The effect of various biodiesel blends and petro-diesel on the delivery system during the use phase was conducted [61] and the diesel fuel injection systems were typically designed to suit petro-diesel whose kinematic viscosity is greater than that of pure biodiesel. Biodiesel kinematic viscosity can be improved through fuel blending or chemical additization [82,83].

4.1 Lubricant characteristics of Petro-diesel and Biodiesel in relation with component: The Low Pressure Pump

The Stribeck plot was applied to automotive tribology, relating the coefficient of friction and the lubricant oil film thickness ratio [16]. It is identified that journal and thrust bearings used in LP and HP pump coupling operate in the hydrodynamic lubrication regime while valve trains and piston/ring assembly as used, usually operate between mixed and boundary lubrication conditions. Under the boundary (extreme pressure) lubrication, chemical interaction between contacting bodies and the lubricating fluids take place [11].

4.2 Lubricant characteristics of Petro-diesel and Biodiesel in relation with component: The High Pressure Injection Pump

Alteration in the lubrication properties of diesel fuels can lead to pump failures in a diesel fuel injection system [63,84]. It is reported that the rapeseed biodiesel possesses the best lubricating ability in HP pumps due to the mixture of several fatty acid methyl esters and oxygen-containing compounds [85]. However, oxygen induces corrosive wear but may increase the production of oxides like Fe_3O_4, to potentiate contact interface lubrication films formation. The rotary injection pump is highly prone to 'boundary' lubrication wear, where the lubricating fuel film is thin or depleted and worsens with increasing temperature and loading in the engine system leading to an ultimate pump failure [44].

4.3 Lubrication characteristics of Petro-diesel and Biodiesel in relation with component: Valve Systems

The boundary or extreme pressure lubrication is a situation in which asperity contact between lubricated components are so close [86] that it is possible to distinguish the condition that exists between the fuel lubricant films and the surfaces of the CRS electro-hydraulic valve due to chemical interactions [11]. The lack of boundary lubricants as oxide films in such a situation permeates an increment in the coefficient of friction [10] as expressed in Fig. 7 and can generally lead wear of contacting surfaces. The use of biodiesel (which is rich in oxygen) in CI engines will help to reduce component wear in the valve systems [85] while it was recommended to use ceramic valves made from silicon nitride which would reduce the effect of wear from boundary lubrication [74].

4.4 Lubricity Calculations Relating Viscosities for Pure Fuels and Blends

The dynamic viscosity of biodiesel can be calculated at various temperatures as the viscosity of oil is temperature dependent. Thus, the viscosity is expressed as [80]:

$$\mu = Ae(Ea/RT) \tag{17}$$

For the equation, μ is the fuel viscosity: R represents the universal gas constant, T is temperature in Kelvin and Ea is the activation energy. A generalized equation for predicting the viscosities for blends (percentage mixture of petro-diesel + biodiesel) used by various researchers [80,87] is given as:

$$\eta = Ax\,2 + Bx + C \tag{18}$$

Where η is the kinematic viscosity (mm^2/s), A, B, C are coefficients which are different for different oils and **x** is the biodiesel fraction. However, as shown in Eq. 19, the viscosity for blended fuels using the volume fraction instead of the mass fraction method was utilized [87]. This equation is much closer to measured values and can be expressed by:

$$log\eta_B = m_1 \log\eta_1 + m_2\, log\eta_2 \tag{19}$$

Where η_B is the kinematic viscosity of the blend (mm^2/s), η_1 and m_1 are the kinematic viscosity of the 1st component and its fraction, and η_2 and m_2 are the kinematic viscosity of the 2nd component and its fraction.

The relationship between viscosity and pressure for both biodiesel and petro-diesel fuels, using waste cooking oil (WCO) and pure 'rapeseed' biodiesel was determined [88]. The viscosity of the biodiesel was measured at pressures up to 140 MPa using the high-pressure falling sinker viscometer. The pressure vessel, hydraulic fluid, viscometer tube and biodiesel were maintained at a controlled temperature of 20 °C. The viscosities at increasing pressure were obtained from direct measurement of the sinker fall times shown in Figure 8. As reported in the literature, the petro-diesel fuel samples were obtained from refineries in the U.K [88]: the density of biodiesel was determined using the Peng-Robinson equation of state and the fuel viscosities are plotted against increasing applied pressure as shown in Fig. 9.

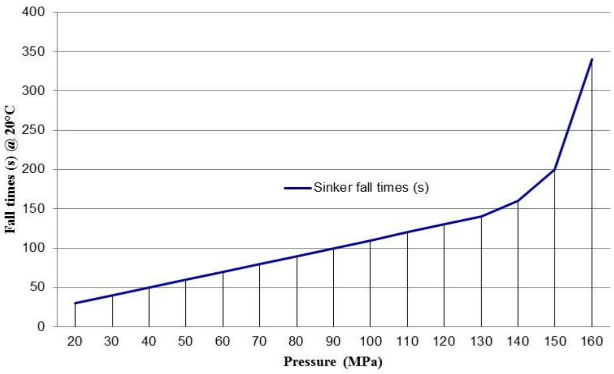

Fig. 8. High-pressure viscometer sinker fall times for WCO biodiesel vs pressure chart [88].

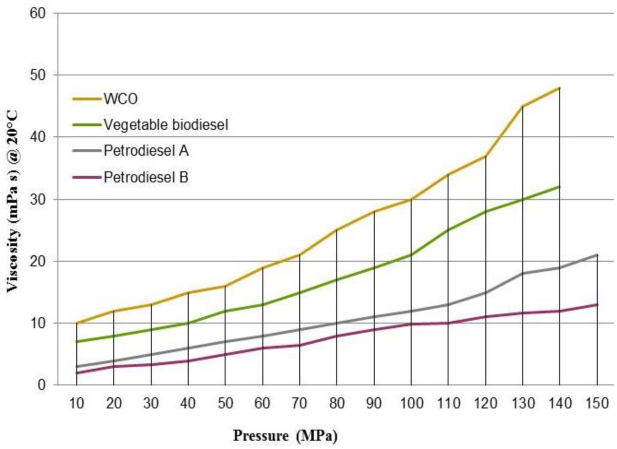

Fig. 9. The relationship between viscosity and pressure for both biodiesel and petro-diesel fuels [88].

5. Properties of Diesel Fuels (Biodiesel and Petro-diesel)

The bulk modulus (K), viscosity (μ) and density (ρ) are the three physical properties as a function of temperature, that have the most influence on fuel injection process [89]. Diesel fuel density plays a key role in the injection system. Injected fuel proportions increase as the fuel density increases thus affecting fuel injection, timing and spray pattern [59]. Diesel fuel viscosity (μ) is the resistance of the fluid to shear or flow in systems and is used in the analysis of fuel performance and motion around solid boundaries [87]. Bio-oils' are more viscous than fossil diesel due to their larger triacylglycerol molecules. The high viscosity influences their spray atomization, vaporization and air/mixing [72]. Pyrolysis (thermo-chemical decomposition of organic materials and transesterification are some of the refining processes that help create fuel oil constituents with lesser molecular mass [6,72]. Biodiesels have a higher Bulk modulus than petro-diesel, meaning better resistance to uniform compression that translates to increase in fluid flow when pressurized [89]. Viscosity plays an important role in the tribological performance of interacting surfaces in a CI engine fuel injection system [35,59,90]. Kinematic viscosity of a fuel is the ratio of absolute or dynamic viscosity to its density. For Newtonian fluids, it is measured as the ratio of a change in pressure to laminar flow in a pipe [91]. Relating mathematically [92] derived the kinematic viscosity for fluids by dividing the absolute viscosity with its density:

$$\nu = \mu / \rho \tag{20}$$

Where ν is the kinematic viscosity; μ is the absolute or dynamic viscosity and ρ is the density. The *caloric value* is a fuel property that designates the quality of the diesel fuel fatty compounds [93], while the ignition quality of diesel fuel is determined by the cetane number (CN) - a property that acts to set-off engine ignition and increases in strength as the carbon chain length and number of double bonds of the fuel increases [24,83,94]. The flash point of diesel is the temperature at which the liquid gives off enough vapour to the surrounding that it can be kindled by a source [83,95]. Petro-diesel has a flash point above 55 °C while 100 % biodiesel (B100) has higher at about 100 °C, interpreting to safety in storage and handling [96]. Cloud point is the temperature at which the fatty compounds in a biodiesel attain saturation and become insoluble in a mixture and the pour point is the lowest temperature that liquid fuels lose their flow properties through crystallization [58]. Therefore biodiesel fuels made from fats or oils with high levels of saturated fatty compounds will exhibit higher cloud and pour points than petro-diesel [93]. The properties of major vegetable oil types and animal fat from beef tallow are presented in Table 1 and the properties of biodiesel fuels (i.e., methyl ester derivate) from different feedstock are presented in Table 2.

Table 1. Properties of Biodiesel fuels from different feedstock and petro-diesel [80,83,95,97].

Fuel	Kin. viscosity (mm2/s, at 40°C)	Density (g/cm^3, at 21°C)	Cetane Number	Flash point (°C)	Cloud point (°C)	Pour point (°C)
Diesel fuel	2.0 - 4.5	0.820 - 0.860	51.0	55	-18	-25
Soybean methyl ester (SME)	4.08	0.884	50.9	131	-0.5	-4
Rapeseed methyl ester (RME)	4.83	0.882	52.9	155	-4	-10.8
Sunflower methyl ester (SME)	4.60	0.880	49.0	1831	1	-7
Tallow methyl ester	5.00	0.877	58.8	150	12	9
Yellow grease methyl ester	5.16	0.873	62.6	-	9	12
Soapstock methyl ester	4.30	0.885	51.3	169	6	-
Palm Methyl ester (PME)	4.40-5.70	0.87-0.88	50-62.4	164-174	13-14.5	15

Table 2. Properties of Biodiesel fuels from different feedstock and petro-diesel [80,83,95,97].

Fuel	Kin. viscosity (mm2/s, at 40°C)	Density (g/cm^3, at 21°C)	Cetane Number	Flash point (°C)	Cloud point (°C)	Pour point (°C)
Diesel fuel	2.0–4.5	0.820–0.860	51.0	55	-18	-25
Soybean methyl ester (SME)	4.08	0.884	50.9	131	-0.5	-4
Rapeseed methyl ester (RME)	4.83	0.882	52.9	155	-4	-10.8
Sunflower methyl ester (SME)	4.60	0.880	49.0	1831	1	-7
Tallow methyl ester	5.00	0.877	58.8	150	12	9
Yellow grease methyl ester	5.16	0.873	62.6	-	9	12
Soapstock methyl ester	4.30	0.885	51.3	169	6	-
Palm Methyl ester (PME)	4.40-5.70	0.87-0.88	50-62.4	164-174	13-14.5	15

5.1 Biodiesel Blending and Additization

Mixing (blending) biodiesel with petro-diesel is one of the most convenient approaches to improve CI engine fuel injection efficiency [70,82]. The physical properties of biodiesel fuels are variable since they are derived from different fatty acids and dependent on the distribution of their triglyceride compounds [95, 98]. The caloric value of biodiesel increases as the percentage of petro-diesel in the blend increases [93,96], though it was reported that biodiesel showed significant improvement at B20 (20 % blend with petro-diesel) based on tribological considerations for all fuel types in a CI engine, without reconfiguring existing engine hardware [26,81]. Chemical additives such as antioxidants, cetane enhancer, corrosion inhibitors, anti-foaming agents to improve fuel tank filling and cold flow improvers are employed to enhance biodiesel quality [24,83]. Diesel viscosity enhancer additives are split into three forms of polymeric hydrocarbons: (1) Polyisobutene, ethylene and propylene co-polymers, butadiene and styrene co-polymers; (2) Polymethacrylates and polyacrylates are categorized by their temperature variation and (3) Polymers with dispersant properties, e.g., tertiary amines, imidazoles, pyrrolidone and pyridines [99]. In a study of coconut oil biodiesel it is indicated that some element additives to reduce friction and wear in CI engine component systems are zinc and phosphorus [32]. As the global pursuit for the sustainable development of renewable fuels continue, several fuel stations in the U.S.A and in the Europe offer B20 blends of biodiesel [100-101], coupled with initiatives to combat rising crude oil prices, biodiesel blending with petro-diesel impact on regional development and to increase employment opportunities and diversifying farmers' activities [7-102].

6. CONCLUSION

This review indicates that CI engines can run on biodiesel made from various vegetable oils without major modifications to the engine. A retainer washer in the HP pump fuel inlet from the LP pump of a CRS experienced wear when subjected to mechanical loading. To improve engine tribology further studies to establish the most appropriate percentage of biodiesel blending with petro-diesel are recommended. Due to the poor lubricity of ultra-low sulphur diesel fuels, regulatory bodies in Europe and the USA encourage continuous improvement in the development of fuel additives to potentiate biodiesel lubricity. This in effect will aim to further reduce the effect of wear on diesel fuel components and improve the cold weather flow performance of biodiesel in the injection system. Some major technical problems involved in working with chemically improved biodiesel fuel during tribological analysis are the combined lubricating quality of the fuel and additive mixture. The short-term wear on CI engine units using biodiesel is discovered to be favorable than when compared to petro-diesel. However, further studies on the life cycle assessment and the long-term implications of biodiesel use in automobile fuel delivery systems, are urged by researchers. To reduce the effect of wear on fuel injection systems that run on fuels with low lubricity, the use of surface coatings such as silicon nitride ceramics for HP and LP pump roller bushings is encouraged. Some studies recommend materials such as ploytetrafluroethylene for fuel pump piston protection.

Results from a study reveals that allowing the surface roughness on a HP injection pump connecting-cam below 0.025μm, can lead to serious damage to the pump. Modelling of diesel engine valve systems indicated impact wear within slow contacting reciprocating surfaces that entail boundary lubrication, as the major cause of valve recession. Indication from studies show that to measure a particular valve life in use phase, specific wear problems in different engine units have to be isolated for investigation. The tribological impact of diesel fuels on the electro-hydraulic valve that regulates fuel pressure in a common rail system is encouraged by this review.

REFERENCES

[1] J.-H. Ng, H.K. Ng and S. Gan, 'Characterisation of engine-out responses from a light-duty diesel engine fuelled with palm methyl ester (PME)', *Applied Energy*, vol. 90, no. 1, pp. 58-67, 2012.

[2] A. Tadon, A. Kumar, P. Mondal, U.D. Bhangale and T. Dinesh, 'Tribological issues related to the use of biofuels: a new environmental challenge', *British journal for environment & climate change*, vol. 1, no. 2, pp. 28-43, 2011.

[3] J. Xue, T.E. Grift and A.C. Hansen, 'Effect of biodiesel on engine performances and emissions', *Renewable and Sustainable Energy Reviews*, vol. 15, no. 2, pp. 1098-1116, 2011.

[4] M.A. Ceviz, F. Koncuk, O. Kucuk, A.C. Goren and F. Yuksel, 'Analysis of Combustion Stability and Its Relation to Performance Characteristics in a Compression Ignition Engine Fueled with Diesel-biodiesel Blends', *Energy Sources Part A: Recovery, Utilization & Environmental Effects*, vol. 33, no. 10, pp. 990-1003, 2011.

[5] S.K. Hoekman, A. Broch, C. Robbins, E. Ceniceros and M. Natarajan, 'Review of biodiesel composition, properties, and specifications', *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 143-169, 2012.

[6] D.J.P. Selvam and K. Vadivel, 'Performance and Emission Analysis of DI Diesel Engine Fuelled with Methyl Esters of Beef Tallow and Diesel Blends', *Procedia Engineering*, vol. 38, pp. 342-358, 2012.

[7] C.D. Rakopoulos, K.A. Antonopoulos, D.C. Rakopoulos, D.T. Hountalas and E.G. Giakoumis, 'Comparative performance and emissions study of a direct injection Diesel engine using blends of Diesel fuel with vegetable oils or bio-diesels of various origins',

Energy Conversion and Management, vol. 47, no. 18-19, pp. 3272-3287, 2006.

[8] B.J. Hamrock, S.R. Schmid and B.O. Jacobson, 'Fundamentals of fluid film lubrication, 1 ed.', vol. 1. USA: McGraw-Hill, 1994.

[9] K.C. Ludema, 'Friction, wear, lubrication: a textbook in tribology, 1 ed.'. Boca Raton: CRC Press, 1996.

[10] B. Bhushan, 'Tribology: Friction, Wear, and Lubrication', in The Engineering Handbook, R. C. Dorf, Ed., 2nd Edition ed Boca Raton: CRC Press LLC, 2000.

[11] G.W. Stachowiak and A.W. Batchelor, 'Engineering Tribology'. USA: Butterworth-Heinemann, 2001.

[12] T. Hui, F. Sadeghi, R.G. Rateick and M.C. Frank, 'Performance characteristics of jet fuel in heavily loaded contacts', *Tribology Transactions*, vol. 50, no. 2, pp. 154-164, 2007.

[13] M.A. Chowdhury and D.M. Nuruzzaman, 'Experimental investigation on friction and wear properties of different steel materials', *Tribology in Industry*, vol. 35, no. 1, pp. 42-50, 2013.

[14] W.J. Bartz, 'Handbook of tribology and lubrication engineering. Basics of tribology', *Tribologie und Schmierungstechnik*, vol. 58, pp. 65-66, 2011.

[15] P. Podsiadlo, G.W. Stachowiak, P. Podsiadlo and G.W. Stachowiak, 'Classification of Tribological Surfaces Without Surface Parameters', *Tribology Letters*, vol. 16, no. 1, pp. 163-171, 2004.

[16] S.C. Tung and M.L. McMillan, 'Automotive tribology overview of current advances and challenges for the future', *Tribology International*, vol. 37, no. 7, pp. 517-536, 2004.

[17] B.B. Sahoo, N. Sahoo and U.K. Saha, 'Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines-A critical review', *Renewable and Sustainable Energy Reviews*, vol. 13, no. 6-7, pp. 1151-1184, 2009.

[18] P. Stanislav, S. Marta, K. Marko and K. Breda, 'Biodiesel influence on the tribology characteristics of a diesel engine', *Fuel Journal*, vol. 1, no. 6, pp. 970-979, 2008.

[19] A. Ghurri, K. Jae-duk, S. Kyu-Keun, J. Jae-Youn and K. H. Gon, 'Qualitative and quantitative analysis of spray characteristics of diesel and biodiesel blend on common-rail injection system', *Journal of Mechanical Science and Technology*, vol. 25, pp. 885-893, 2011.

[20] H. Tschöke, 'Diesel distributor fuel-injection pumps', Robert Bosch GmbH, Germany, 1999.

[21] S. Pehan, M.S. Jerman, M. Kegl and B. Kegl, 'Biodiesel influence on tribology characteristics of a diesel engine', *Fuel*, vol. 88, no. 6, pp. 970-979, 2009.

[22] P. Lino, B. Maione and A. Rizzo, 'Nonlinear modelling and control of a common rail injection system for diesel engines', *Applied Mathematical Modelling*, vol. 31, no. 9, pp. 1770-1784, 2007.

[23] M.B. Dantas, A.A.F. Almeida, M.M. Conceicao, V.J. Fernandez Jr., M.M. Santos, F.C. Silva, et al., 'Characterization and kinetic compensation effect of corn biodiesel', *Journal of thermal analysis and calorimetry*, vol. 87, no. 3, pp. 847-851, 2007.

[24] J.H. Ng, H.K. Ng and S. Gan, 'Advances in biodiesel fuel for application in compression ignition engines', *Clean Technologies and Environmental Policy*, vol. 12, no. 5, pp. 459-493, 2010.

[25] Z.A. Khan, M. Hadfield, S. Tobe and Y. Wang, 'Residual stress variations during rolling contact fatigue of refrigerant lubricated silicon nitride bearing elements', *Ceramics International*, vol. 32, no. 7, pp. 751-754, 2006.

[26] A.L. Shumacher and A.S. Howell, 'Lubricating Qualities of Biodiesel and Biodiesel Blends', in: *Bioenergy 94': Sixth National Conference, Reno/Sparks*, Nevada, USA, 1994.

[27] M.G. Gee, J.W. Nunn, A. Muniz-Piniella and L.P. Orkney, 'Micro-tribology experiments on engineering coatings', *Wear*, vol. 271, no. 9-10, pp. 2673-2680, 2011.

[28] E. Hu, X. Hu, X. Wang, Y. Xu, K.D. Dearn and H. Xu, 'On the fundamental lubricity of 2,5-dimethylfuran as a synthetic engine fuel', *Tribology International*, vol. 55, pp. 119-125, 2012.

[29] S. Bajpai, P.K. Sahoo and L.M. Das, 'Feasibility of blending karanja vegetable oil in petro-diesel and utilization in a direct injection diesel engine', *Fuel*, vol. 88, no. 4, pp. 705-711, 2009.

[30] Q. Shu, B. Yang, J. Yang and S. Qing, 'Predicting the viscosity of biodiesel fuels based on the mixture topological index method', *Fuel*, vol. 86, no. 12-13, pp. 1849-1854, 2007.

[31] R.R. Rao, K. Gouthami and J.V. Kumar, 'Effects of velocity-slip and viscosity variation in squeeze film lubrication of two circular plates', *Tribology in Industry*, vol. 35, no. 1, pp. 51-60, 2013.

[32] M.A. Kalam, M.H. Hassan and E.N. Mohamad, 'Wear and lubrication characteristics of a multi-

cylinder diesel engine using vegetable oil blended fuel', *Proceedings of the World Tribology Congress III - 2005*, pp. 553-558, 2005.

[33] G. Carbone and F. Bottiglione, 'Contact mechanics of rough surfaces: a comparision between theories', *Asperity contacts and lubrication aspects*, vol. 46, no. 3, pp. 557-565, 2011.

[34] J. Galle, S. Verhelst, R. Sierens, L. Goyos, R. Castaneda, M. Verhaege, et al., 'Failure of fuel injectors in a medium speed diesel engine operating on bio-oil', *Biomass and Bioenergy*, vol. 40, pp. 27-35, 2012.

[35] A. Demirbas, 'Progress and recent trends in biodiesel fuels', *Energy Conversion and Management*, vol. 50, no. 1, pp. 14-34, 2009.

[36] S.-Y. No, 'Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: A review', *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 131-149, 2011.

[37] X.-L. Wang and K.-Q. Zhu, 'A study of the lubricating effectiveness of micropolar fluids in a dynamically loaded journal bearing (T1516)', *Tribology International*, vol. 37, no. 6, pp. 481-490, 2004.

[38] A. Morina, T. Liskiewicz, Y. Yan and A. Neville, 'Opportunities and challenges for obtaining effective lubricated engineering systems inspired by the lubrication of synovial joints', *Comparative Biochemistry and Physiology - Part A: Molecular & Integrative Physiology*, vol. 146, p. S135, 2007.

[39] K. Noda, S. Kamiya, T. Fujimura and K. Taniguchi, 'Development of ceramic roller-bushings for diesel distributor-type fuel injection pump', *JSAE Review*, vol. 20, pp. 197-201, 1999.

[40] A.S.M.A. Haseeb, M.A. Fazal, M.I. Jahirul and H. H. Masjuki, 'Compatibility of automotive materials in biodiesel: A review', *Fuel*, vol. 90, no. 3, pp. 922-931, 2011.

[41] Z.A. Khan, M. Hadfield and Y. Wang, 'Pressurised chamber design for conducting rolling contact experiments with liquid refrigerant lubrication', *Materials and Design*, vol. 26, no. 8, pp. 680-689, 2005.

[42] A. Ferrari and A. Mittica, 'FEM modeling of the piezoelectric driving system in the design of direct-acting diesel injectors', *Applied Energy*, vol. 99, pp. 471-483, 2012.

[43] O. Armas, S. Martínez-Martínez and C. Mata, 'Effect of an ethanol–biodiesel–diesel blend on a common rail injection system', *Fuel Processing Technology*, vol. 92, no. 11, pp. 2145-2153, 2011.

[44] M.L. Pera, 'The Lubricity of Fuels: Tribology and Lubrication Technology', Le Pera & Associates, Harrisonburg, 2007.

[45] N.H. Chung, B.G. Oh and M.H. Sunwoo, 'Modelling and injection rate estimation of common-rail injectors for direct-injection diesel engines', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 222, p. 1089, 2008.

[46] D. Tziourtzioumis and A. Stamatelos, 'Effects of a 70% biodiesel blend on the fuel injection system operation during steady-state and transient performance of a common rail diesel engine', *Energy Conversion and Management*, vol. 60, pp. 56-67, 2012.

[47] T. Kitchen, 'A Technical Overview of Common Rail Diesel Fuel Systems'. Motor Industry Professional Training and Development, United Kingdom, 2008.

[48] T. Xu-Guang, S. Hai-Lang, Q.I.U. Tao, F. Zhi-Qiang and Y. Wen-Hui, 'The Impact of Common Rail System's Control Parameters on the Performance of High-power Diesel', *Energy Procedia*, vol. 16, Part C, pp. 2067-2072, 2012.

[49] J. Jin, C. Zhong, Z. Zhang and Y. Li, 'Solubilities of benzoic acid in supercritical CO2 with mixed cosolvent', *Fluid Phase Equilibria*, vol. 226, pp. 9-13, 2004.

[50] M. Vojtíšek-Lom, M. Pechout and A. Barbolla, 'Experimental investigation of the behavior of non-esterified rapeseed oil in a diesel engine mechanical fuel injection system', *Fuel*, vol. 97, pp. 157-165, 2012.

[51] A.M. Liaquat, H.H. Masjuki, M.A. Kalam, A. Rasyidi, 'Experimental analysis of wear and friction characteristics of jatropha oil added lubricants', *Applied Mechanics and Materials*, vol. 110-116, pp. 914-919, 2012.

[52] A. Avinash Kumar, 'Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines', *Progress in Energy and Combustion Science*, vol. 33, no. 3, pp. 233-271, 2007.

[53] K.L. Johnson, 'Contact Mechanics, 1st ed'. U.K: Cambridge University Press, 1985.

[54] B.N.J. Persson, 'Contact mechanics for randomly rough surfaces', *Surface Science Reports*, vol. 61, no. 4, pp. 201-227, 2006.

[55] Z. Khan, 'Rolling wear of silicon nitride bearing materials with refrigerant lubrication', in: Society of Tribologists and Lubrication Engineers - 2008 Annual Meeting and Exhibition, Extended Abstracts, 2008.

[56] A. Saeed, Z.A. Khan, M. Hadfield and S. Davies, 'Material Characterisation and Real Time Wear Evaluation of Pistons and Cylinder-liners of the Tiger 131 Military Tank', *Tribology Transactions*, vol. 56, no. 4, pp. 637-644, 2013.

[57] M.F. Vasilache and I. Muscă, 'The control of the lubricant film by the resistive method for scuffing', *Tribology in Industry*, vol. 37, no. 3, pp. 336-339, 2015.

[58] R.E. Reynolds, A. Kasperson, G. Herwick, A.M. Hochhauser, R.L. McCormick and C. Jewitt, 'Changes in Diesel Fuel: The Service Technician's Guide to Compression Ignition Fuel Quality', Downstream Alternatives, Inc., USA, 2007.

[59] M.A. Amani, M.S. Davoudi, K. Tahvildari, S.M. Nabavi and M.S. Davoudi, 'Biodiesel production from Phoenix dactylifera as a new feedstock', *Industrial Crops and Products*, vol. 43, pp. 40-43, 2012.

[60] M.Y. Kim, S.H. Yoon, B.W. Ryu and C.S. Lee, 'Combustion and emission characteristics of DME as an alternative fuel for compression ignition engines with a high pressure injection system', *Fuel*, vol. 87, no. 12, pp. 2779-2786, 2008.

[61] E. Chapman, A. Boehman, K. Wain, W. Lloyd, J.M. Perez, D. Stiver, et al., 'Annual Technical Progress Report for Project Entitled "Impact of DME-Diesel Fuel Blend Properties on Diesel Fuel Injection Systems".' The Pennsylvania State University, The Pennsylvania State University The Energy Institute University Park, PA 168022003.

[62] W.A. Glaeser, C.R. Brundle and C.A. Evans, 'Characterization of tribological materials'. New York: Momentum Press, 2010.

[63] K. Meyer, U. Stolz and P. Rehbein, 'A Tribological Approach to Determine the Friction and Wear Properties of New Environmentally Benign Diesel Fuels in Conjunction with Wear Mechanisms in Critical Parts of Diesel Injection Equipment', in: Tribology Series. vol. 30, C. M. T. T. H. C. C. D. Dowson and G. Dalmaz, Eds., ed: Elsevier, pp. 303-326, 1995.

[64] M.A. Fazal, A.S.M.A. Haseeb and H.H. Masjuki, 'Biodiesel feasibility study: An evaluation of material compatibility; performance; emission and engine durability', *Renewable and Sustainable Energy Reviews*, vol. 15, no. 2, pp. 1314-1324, 2011.

[65] J.M. Guilemany, J.M. Miguel, S. Armada, S. Vizcaino and F. Climent, 'Use of scanning white light interferometry in the characterization of wear mechanisms in thermal-sprayed coatings', *Materials Characterization*, vol. 47, no. 3-4, pp. 307-314, 2001.

[66] G. Xu, F. Sadeghi and M. Hoeprich, 'Residual Stresses Due to Debris Effects in EHL Contacts', *Tribology Transactions*, vol. 40, no. 4, pp. 613-620, 1997.

[67] G. Bolelli, B. Bonferroni, J. Laurila, L. Lusvarghi, A. Milanti, K. Niemi, et al., 'Micromechanical properties and sliding wear behaviour of HVOF-sprayed Fe-based alloy coatings', *Wear*, vol. 276–277, pp. 29-47, 2012.

[68] A. Warhadpande, F. Sadeghi, R.D. Evans and M. N. Kotzalas, 'Influence of Plasticity-Induced Residual Stresses on Rolling Contact Fatigue', *Tribology Transactions*, vol. 55, no. 4, pp. 422-437, 2012.

[69] B. Terry, 'Impact of Biodiesel on Fuel System Component Durability'. The Associated Octel Company Limited CRC Project No. AVFL-2a, 2005.

[70] G. Knothe and K.R. Steidley, 'Lubricity of components of biodiesel and petrodiesel. The origin of biodiesel lubricity', *Energy and Fuels*, vol. 19, no. 3, pp. 1192-1200, 2005.

[71] D. Ciolkosz, 'Using Biodiesel Fuel in Your Engine'. The Pennsylvania State University, USA, 2009.

[72] A.M. Williamson and O. Badr, 'Assessing the viability of using rape methyl ester (RME) as an alternative to mineral diesel fuel for powering road vehicles in the UK', *Applied Energy*, vol. 59, no. 2-3, pp. 187-214, 1998.

[73] Z. Zhen and S. Zongxuan, 'Rotational angle based pressure control of a common rail fuel injection system for internal combustion engines', in: *American Control Conference, ACC '09.*, , Hyatt Regency Riverfront, St. Louis, MO, USA, 2009.

[74] T.S. Kaushal and K.E. Weber, 'Advanced Diesel Engine Component Development Program. Final Report - Tasks 4-14'. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. Lewis Research Center: Contract DEN 3-329, Detroit, U.S.A, 1994.

[75] J.F. Archard and M.T. Kirk, 'Lubrication at Contact Points', *Mathematical and physical sciences*, vol. 261, pp. 532-550, 1960.

[76] R. Lewis, R. Dwyer-Joyce, A. Brooks and T. Slatter, 'Valve Recession: From Experiment To Predictive Model', *VDI Berichte*, vol. 1813, pp. 79-93, 2004.

[77] M. Vrbka, I. Křupka, P. Svoboda, P. Šperka, T. Návrat, M. Hartl, et al., 'Effect of shot peening on

rolling contact fatigue and lubricant film thickness within mixed lubricated non-conformal rolling/sliding contacts', *Tribology International*, vol. 44, no. 12, pp. 1726-1735, 2011.

[78] A. Dhar, A.K. Agarwal and V. Saxena, 'Measurement of dynamic lubricating oil film thickness between piston ring and liner in a motored engine', *Sensors and Actuators A: Physical*, vol. 149, no. 1, pp. 7-15, 2009.

[79] B. Jacobson, 'Thin film lubrication of real surfaces', *Tribology International*, vol. 33, no. 3-4, pp. 205-210, 2000.

[80] A.A. Refaat, 'Correlation between the chemical structure of biodiesel and its physical properties', *International Journal of Environmental Science and Technology*, vol. 6, no. 4, pp. 677-694, 2009.

[81] J.A. Morón-Villarreyes, C. Soldi, A.M. de Amorim, M.G. Pizzolatti, A.P. de Mendonça Jr and M.G.M. D'Oca, 'Diesel/biodiesel proportion for by-compression ignition engines', *Fuel*, vol. 86, no. 12-13, pp. 1977-1982, 2007.

[82] Y. Xu, Q. Wang, X. Hu, C. Li and X. Zhu, 'Characterization of the lubricity of bio-oil/diesel fuel blends by high frequency reciprocating test rig', *Energy*, vol. 35, no. 1, pp. 283-287, 2010.

[83] DPChip. (2012, 31/07/2012). Diesel History. Available: http://www.dpchip.com/home/diesel-history/

[84] C. Georgescu, L.C. Solea and L. Deleanu, 'The influence of degumming process on tribological behaviour of soybean oil', *Tribology in Industry*, vol. 37, no. 3, pp. 330-335, 2015.

[85] E. Sukjit and K.D. Dearn, 'Enhancing the lubricity of an environmentally friendly Swedish diesel fuel MK1', *Wear*, vol. 271, no. 9-10, pp. 1772-1777, 2011.

[86] Y. Zhang, 'Boundary lubrication-An important lubrication in the following time', *Journal of Molecular Liquids*, vol. 128, no. 1-3, pp. 56-59, 2006.

[87] E. Alptekin and M. Canakci, 'Determination of the density and the viscosities of biodiesel–diesel fuel blends', Renewable Energy, vol. 33, no. 12, pp. 2623-2630, 2008.

[88] J.M. Paton and C.J. Schaschke, 'Viscosity measurement of biodiesel at high pressure with a falling sinker viscometer', *Chemical Engineering Research and Design*, vol. 87, no. 11, pp. 1520-1526, 2009.

[89] F. Boudy and P. Seers, 'Impact of physical properties of biodiesel on the injection process in a common-rail direct injection system', *Energy Conversion and Management*, vol. 50, no. 12, pp. 2905-2912, 2009.

[90] V. Pecina-Quintero, J.L. Anaya-López, C.A. Núñez-Colín, A. Zamarripa-Colmenero, N. Montes-García, J.L. Solís-Bonilla, et al., 'Assessing the genetic diversity of castor bean from Chiapas, México using SSR and AFLP markers', *Industrial Crops and Products*, vol. 41, pp. 134-143, 2012.

[91] A. Abollé, L. Kouakou and H. Planche, 'The viscosity of diesel oil and mixtures with straight vegetable oils: Palm, cabbage palm, cotton, groundnut, copra and sunflower', *Biomass and Bioenergy*, vol. 33, no. 9, pp. 1116-1121, 2009.

[92] W. Zhang, W. Yuan, X. Zhang and M. Coronado, 'Predicting the dynamic and kinematic viscosities of biodiesel–diesel blends using mid- and near-infrared spectroscopy', *Applied Energy*, vol. 98, pp. 122-127, 2012.

[93] D.K. Bora and D.C. Baruah, 'Assessment of tree seed oil biodiesel: A comparative review based on biodiesel of a locally available tree seed', *Renewable and Sustainable Energy Reviews*, vol. 16, no. 3, pp. 1616-1629, 2012.

[94] W. Ying, L. Genbao, Z. Wei and Z. Longbao, 'Study on the application of DME/diesel blends in a diesel engine', *Fuel Processing Technology*, vol. 89, no. 12, pp. 1272-1280, 2008.

[95] M. Canakci and H. Sanli, 'Biodiesel Productions from various feedstocks and their effects on fuel properties', *Journal of Therm., Anal., Calorim.*, vol. 35, no. 5, pp. 431-441, 2008.

[96] M. Gumus and S. Kasifoglu, 'Performance and emission evaluation of a compression ignition engine using a biodiesel (apricot seed kernel oil methyl ester) and its blends with diesel fuel', *Biomass and Bioenergy*, vol. 34, no. 1, pp. 134-139, 2010.

[97] P. McCarthy, M.G. Rasul and S. Moazzem, 'Analysis and comparison of performance and emissions of an internal combustion engine fuelled with petroleum diesel and different bio-diesels', *Fuel*, vol. 90, no. 6, pp. 2147-2157, 2011.

[98] T.P. Thomas, D.M. Birney and D.L. Auld, 'Optimizing esterification of safflower, cottonseed, castor and used cottonseed oils', *Industrial Crops and Products*, vol. 41, pp. 102-106, March 2012 2012.

[99] M.J. Souza de Carvalho, P. Rudolf Seidl, C.R. Pereira Belchior and J. Ricardo Sodré, 'Lubricant viscosity and viscosity improver additive effects on diesel fuel economy', *Tribology International*, vol. 43, no. 12, pp. 2298-2302, 2010.

[100] D. Uy, R.J. Zdrodowski, A.E. O'Neill, S.J. Simko, A.K. Gangopadhyay, M. Morcos, et al., 'Comparison of the effects of biodiesel and mineral diesel fuel dilution on aged engine oil properties', *Tribology Transactions*, vol. 54, no. 5, pp. 749-763, 2011.

[101] P. Upham, P. Thornley, J. Tomei and P. Boucher, 'Substitutable biodiesel feedstocks for the UK: a review of sustainability issues with reference to the UK RTFO', *Journal of Cleaner Production*, vol. 17, no. 1, pp. S37-S45, 2009.

[102] C. Bomb, K. McCormick, E. Deurwaarder and T. Kåberger, 'Biofuels for transport in Europe: Lessons from Germany and the UK', *Energy Policy*, vol. 35, no. 4, pp. 2256-2267, 2007.