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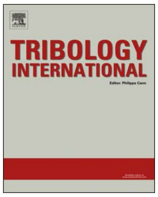

Influence of fatty acid methyl ester composition on tribological properties of vegetable oils and duck fat derived biodiesel

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ABSTRACT

To explore its potential as a biolubricant/additive, the study determines the frictional properties at various lubrication regimes for biodiesels derived from vegetable oils, hydrogenated vegetable oil and animal fat. It is found that the frictional characteristics for the biodiesels can be divided into *Group I* (feedstocks from winter crops) and *Group II* (feedstocks from summer crops, animal fat and hydrogenated vegetable oil). For each of the groups, with decreasing ratio of mono-unsaturated to total saturated fatty acid methyl ester content, the biodiesels' friction force reduces while their load carrying capacity deteriorates. From the experimental results, it is deduced that soybean biodiesel shows great potential as a biolubricant/additive because it possesses low friction force with the highest possible load carrying capacity.

1. Introduction

Global energy demand is estimated to increase from 557 quadrillion BTU (588 EJ) in the year 2014 to 703 quadrillion BTU (742 EJ) in the year 2040 [1]. During this period of time, the energy demand for the transportation sector is also predicted to grow by 27.8% [1]. Such growth pace will have a significant impact on the greenhouse gas emissions. The International Energy Agency (IEA) has identified decarbonisation, in allowing a high efficiency and low-carbon energy sector, to be the core of international efforts to combat climate change due to greenhouse gas emissions [2]. For transportation sector, decarbonisation can be achieved by means of: 1) improving fuel economy through reducing frictional losses in vehicles (higher efficiency) and 2) moving towards alternative fuels/lubricants in order to relieve the heavy reliance on fossil fuels (low-carbon).

Applying effective friction reduction strategies, Holmberg et al. estimate that a drop in CO_2 emission, by as much as 290 million tons in the short term (5–10 years) and 960 million tons in the long term (15–25 years), could be achieved [3]. In a typical passenger car, one third of the fuel energy is used to overcome friction [3]. Aside from the pumping and hydraulic losses, the frictional losses in a passenger car also originate from the piston assembly, bearings, seals and valve-train. The strategies that can be adopted to reduce friction include the application of low friction coatings [4], surface texturing (friction reduction through lubricant micro-reservoirs) [5,6] and a more effective lubricant [7].

Evidently, all of the strategies mentioned above still involve the use of lubricant. The estimated lubricant global consumption for the automotive sector is around 22 million tons in 2015 [8], with a large majority still mineral-based lubricant. It is also found that lubricant-derived emissions could have serious impact on the exhaust-after-treatment system, which might eventually lead to emissions of toxic pollutants [9]. Therefore, in view of the impact of tribology to the environment, a new concept of *Green Tribology* has been introduced. *Green Tribology* refers to the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts [10]. Twelve principles have been formulated for this concept, with one of them focusing on the use of biodegradable lubrication [11].

According to Nosonovsky and Bhushan [11], vegetable oil based or animal fat based natural lubricant should be considered for lubrication in automotive, hydraulic and metal-cutting applications because these lubricants are biodegradable. One possible alternative to petroleum-based lubricant/additive is biodiesel. Biodiesel is defined as monoalkyl esters derived from either vegetable oil or animal fat through transes-

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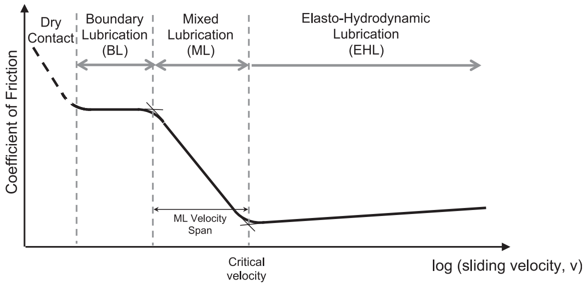

Fig. 1. Stribeck curve (Lubrication regimes).

terification [12]. Aside from producing lower emissions [13], biodiesel is also commonly used as an additive to improve the lubricity of petro-diesel [14,15]. Tribological improvements have been observed when small amount of biodiesel is added to petro-diesel [15–18]. Geller and Goodrum [19] and Hu et al. [20] explained that the biodiesels' fatty acid methyl ester (FAME) composition plays an important role in imparting lubricity.

High Frequency Reciprocating Rig (HFRR) is typically used to understand the lubrication properties of biodiesels, especially to examine its role in fuel lubricity. The HFRR test is conducted along the boundary lubrication regime, focusing mainly on the wear scar diameter. As a result, this neglects the friction related information for a lubricated contact. The frictional properties of a lubricated contact are known to depend on the lubricant properties, applied normal load and also relative sliding velocity [21,22]. The combined effect of all these parameters can be summarised using a Stribeck curve (see Fig. 1), dividing the lubrication regimes into boundary lubrication (BL), mixed lubrication (ML) and elasto-hydrodynamic lubrication (EHL).

Using a tribometer configured for a ball-on-disc, Maru et al. determined the BL and EHL phenomena contributions to the frictional properties for soybean and animal fat biodiesel in comparison with petro-diesel [23]. More recently, Maru et al. compared the method in characterising lubricity for biodiesels using HFRR with a tribometer [24]. Instead of focusing on the wear scar diameter using HFRR, they generated the Stribeck curve to investigate the biodiesel friction performance. Through Stribeck curve test, they managed to observe the transition from mixed to boundary lubrication regime for their tested biodiesels. In order to better understand the boundary interaction along the BL regime of biodiesels, Maru et al. [25] and Chong and Ng [26] measured the nano-scale friction forces at different sliding velocities for biodiesel lubricated contacts using Lateral Force Microscopy (LFM).

As mentioned earlier, biodiesel is commonly used as a fuel lubricity enhancer. Knothe and Steidley explained that the good lubrication properties of biodiesels are attributed to their polarity imparting oxygen atoms [27]. The mechanism involved in imparting lubricity is similar to a friction modifier in a typical lubricant. A friction modifier possesses sufficiently high adsorptivity to metal surfaces due to its polarity, forming a sufficiently thick protective film [28]. Only limited work has been done to explore the capacity of biodiesel as possible alternative friction modifier [29]. The study here intends to determine the frictional properties under pure sliding motion at different lubrication regimes for vegetable oils (coconut, soybean, palm, olive and canola), hydrogenated vegetable oil (shortening) and also animal fat (duck fat) derived biodiesels. It is important to understand the effect of fatty acid methyl ester composition towards the lubrication properties for the tested biodiesels. Therefore, the study also attempts to generate a friction map relating each of the tested biodiesels to their fatty acid methyl ester compositions using a ternary plot. Hitherto, such tribological characterisation approach for biodiesel lubricity has yet been reported in literature.

Table 1
Fatty acid methyl ester compositions for tested biodiesels.

Type of biodiesel	**Fatty Acid Methyl Ester Composition**								
	8:0	**10:0**	**12:0**	**14:0**	**16:0**	**18:0**	**18:1**	**18:2**	**18:3**
Coconut	8.3	6	46.7	18.3	9.2	2.9	6.9	1.7	0
Soybean	0	0	0	0.1	10.3	4.7	22.5	54.1	8.3
Palm	0	0	0.9	1.3	43.9	4.9	39.0	9.5	0.3
Olive	0	0	0	0	11	3.6	75.3	9.5	0.6
Canola	0	0	0	0.1	3.9	3.1	60.2	21.1	11.1
Shortening	0	0	0	0	25.8	5.3	52.1	0	12.0
Duck fat	0	0	0	0.5	23.4	5.0	29.4	34.0	3.2

2. Experimental approach

2.1. Vegetable oil and duck fat derived biodiesel

Biodiesel can be produced from any triglycerides of vegetable oil or animal fat origins through the transesterification process. The process requires a simple global reaction involving the reactants of triglycerides and alcohol reacted at sufficient temperatures with the assistance of acid, alkaline or lipase catalysts. The reaction will produce methyl esters (biodiesel) and the co-product of crude glycerol. The possibility of using any combinations of triglycerides and alcohols mean that biodiesel can have a range of physical properties and chemical compositions.

In this study, biodiesels derived from commercially available feedstocks such as palm, coconut, soybean, olive, canola, hydrogenated vegetable oil and duck fat were selected. The fatty acid methyl ester compositions for the tested biodiesels are given in Table 1. The selection of various types of feedstocks is aimed at representing the entire saturated-unsaturated and monounsaturated-polyunsaturated FAME ranges as illustrated in the ternary plot in Fig. 2.

All of the biodiesels are produced using the same method, where pre-heated triglycerides from vegetable oil, hydrogenated vegetable oil and duck fat are reacted with premixed lye and methanol. The triglycerides are preheated at a fixed temperature of 55 °C for an hour to ensure that all of the feedstocks are in liquid phase. A 1%wt catalyst loading of potassium hydroxide (KOH) and triglyceride-to-methanol molar ratio of 6:1 is used in the reaction to ensure minimal soap production. The reactants then undergo the transesterification process in a reacting vessel at 55 °C for a residence time of four hours. Crude

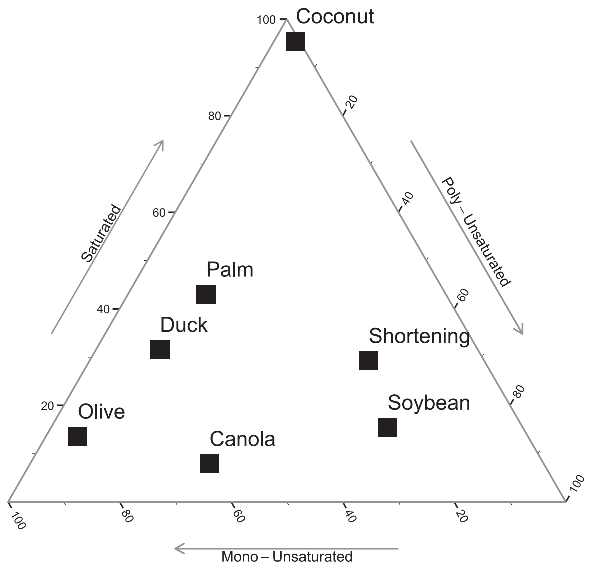

Fig. 2. Ternary plot describing the fatty acid methyl ester composition for the tested biodiesels.