Enhancing the properties of Fischer-Tropsch fuel produced from syngas over Co/SiO2 catalyst: Lubricity and Calorific Value

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Abstract. Bio-fuel produced from renewable sources is considered the most viable alternatives for the replacement of mineral diesel fuel in compression ignition engines. There are several options for biomass derived fuels production involving chemical, biological and thermochemical processes. One of the best options is Fischer Tropsch Synthesis, which has an extensive history of gasoline and diesel production from coal and natural gas. FTS fuel could be one of the best solutions to the fuel emission due to its high quality. FTS experiments were carried out in 16 different operation conditions. Mini structured vertical downdraft fixed bed reactor was used for the FTS. Instead of Biomass gasification, a simulated N₂ -rich syngas cylinder of, 33% H₂ and 50% N₂ was used. FT fuels products were analyzed in GCMS to find the hydrocarbon distributions of FT fuel. Calorific value and lubricity of liquid FT product were measured and compared with commercial diesel fuel. Lubricity has become an important quality, particularly for biodiesel, due to higher pressures in new diesel fuel injection (DFI) technology which demands better lubrication from the fuel and calorific value which is amount of energy released in combustion play very important role in CI engines. Results show that prepared FT fuel has desirable properties and it complies with standard values. FT samples lubricities as measured by ASTM D6079 standard vary from 286µm (HFRR scar diameter) to 417µm which are less than limit of 520µm. Net Calorific value for FT fuels vary from 9.89 MJ/kg to 43.29 MJ/kg, with six of the samples less than EN 14213 limit of 35MJ/kg. Effect of reaction condition on FT fuel properties was investigated which illustrates that in higher pressure Fischer-Tropsch reaction condition liquid product has better properties.

1. Introduction
In previous years, growing concerns about the fast depletion of fossil energy resources and need to reduce greenhouse gas emissions make renewable energy sources much more attractive. The Energy concerns in the world and economic growth in the developing countries are on the drastically rise [1-3] so the energy demands in the field of transportation and manufacturing have increased [1, 2]. Rudolph Diesel, the inventor of the first diesel engine, used vegetable oil (groundnut oil) as fuel in 1900 [4, 5]. His motivation was to improve efficiency and also to down size the price and costs of engines, compared to huge steam engines, so that smaller companies would be able to afford the machinery [6].
During a demonstration he said, “The use of vegetable oils for engine fuels may seem insignificant today, but such oils may become, in the course of time, as important as petroleum and the coal tar products of the present time.” [7]. Ethanol fuel from sugar cane was implemented in Brazil after the 1970’s oil crisis, however the advantages began to disappear due to the enhancement of ethanol fuel costs in 1989 [8]. Over the past few decade, there has been a surge in global warming and climate change which has brought about by fossil fuels, mainly petroleum-based liquid fuels, natural gas and coal [9]. This has renewed interest in biofuels from vegetable oils as alternative fuel more than 100 years after the time of Rudolph Diesel’s predictions [4-6].There are several options for biomass derived fuels production involving chemical, biological and thermochemical processes. Two of the most promising fuels appear to be biodiesel or synthetic fuels such, as Fischer-Tropsch diesel [10]. This is because other potential fuels, such as Ethanol, Methanol and LPG, do not perform as well in modern engines. In addition, in the near future biomass is expected to play an important role and it would be one of the important renewable energy sources [3]. An option for production of renewable fuels from gasified biomass is the Fischer-Tropsch Synthesis (FTS). The FTS is considered as an efficient solution to the problem of finding appropriate substitutes for liquid fossil fuels [11, 12]. Fischer-Tropsch Synthesis is a technology that has an extensive history of gasoline and diesel production from coal and natural gas. The fuel produced by using FT synthesis could be one of the best solutions to the fuels emission due to its high quality. FTS technology devised nearly 90 years ago by Franz Fischer and Hans Tropsch in Germany. Equation 1 represents the main reaction in FTS in which Syngas (Hydrogen and Carbon monoxide) is converted to long chain Hydrocarbons over cobalt catalysts during the reaction [13].

\[
\text{n (CO + 2H}_2\text{)} \rightarrow (\text{CH}_2\text{)}_n +n (\text{H}_2\text{O}) \quad (1)
\]

FTS is a surface polymerization reaction in which the reaction between CO and \( \text{H}_2 \) takes place on the surface of the cobalt catalysts. This process is described as a Carbide formation on the surface of the catalysts, which is discovered, by Fischer and Tropsch nine decades ago. They assumed that the carbide carbons are decomposed by hydrogen with regeneration of the catalysts metal and can be transformed to hydrocarbons. \( \text{CH}_2 \) entities are formed on the surface of the catalyst and arranged in a row on the surface, which implies the carbide mechanism. Another assumption is freely movement of CH\(_X\) units along the catalyst [13, 14]. Two other reactions occur after a hydrocarbon molecule is released from the catalyst surface and reabsorbed to follow other reaction paths. Methane formation as an unwanted product in FTS is shown in the equation 2 and 3 in which are considered as an irreversible reaction. The other important reaction which occurs in FTS process is water gas shift reaction that produces water as co product; this reaction play vital role in reactors which reaction take place over cobalt catalysts and produce carbon dioxide as an undesirable product [15].

\[
\text{CO + 3H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O} \quad (2)
\]

\[
\text{CO + H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 
\]

Catalysts, reaction conditions, type of reactor, \( \text{H}_2/\text{CO} \) ratio influence on the type of products in FTS [13]. FTS process over cobalt catalyst at normal pressure and temperature of 200-300°C produces linear \( \alpha \) olefins \( \text{C}_n\text{H}_{2n}\text{ }_2 \) as the main products and the small amount of nonlinear products which contain mono methyl branch compounds and also it was considered that by increasing the residence time in reactor, which leads to secondary reactions with the same skeleton of both products, subsequent hydrogenation of olefins forms paraffin \( \text{C}_n\text{H}_{2n}\text{ }_2 \). High pressure Fischer Tropsch Synthesis over cobalt catalyst produces less olefin in favour of Alkane \( \text{C}_n\text{H}_{2n}\text{ }_2 \) content due to increase of the molecular weight[14].

2. Experiments Methodology

2.1. Fixed Bed Reactor system and operating procedures

Figure 1 shows the schematic diagram of the experimental set-up designed and build by H. Mahmoudi [1] that was conducted in a fixed bed reactor. The experimental work of this project
concentrated on developing a miniaturized version of the plant that could achieve the preliminary investigation regarding the F-T process, before scale up to pilot plant and building of a pilot scale bio-fuel generator. For this purpose, a small scale F-T bio-diesel generator via the Fischer-Tropsch synthesis process was designed, built and commissioned in a laboratory of the School of Mechanical Engineering of the University of Birmingham. A mini structured downdraft fixed-bed reactor was employed in order to find the optimum reaction conditions for maximum production of synthetic fuel, as well as to convert the syngas into the synthetic bio-fuel [1]. Experiments were carried out in 16 different operation conditions that indicated in Table 1. The reactor was fixed in a tube furnace in order to provide the heat temperature and to provide the uniform wall temperature; cast iron jacket was installed between the furnace and reactor. Instead of Biomass gasification, a simulated rich syngas bottle of 17% CO, 33% H\textsubscript{2} and 50% N\textsubscript{2} was used [1, 2, 16]. Two liquid/gas separators were used to separate liquid from gaseous products. A Gas Chromatogram Flame Ionization detector (GC-FID) (HP5890) was employed to analyse the HC\textsubscript{1} – HC\textsubscript{8} online. The heavier liquids products were analyzed offline by using Gas Chromatogram Mass Spectrometry (GC-MS) (Perkin Elmer Clarus 600). Utilization of nitrogen-rich syngas (with 50% of N\textsubscript{2} (volumetric percentage)) leads to reduction in production cost of diesel oil by eliminating the need for application of gas recycling loop after production of syngas by air partial oxidation. Waste generated heat of FT reaction could be removed effectively and temperature runaway probability can be minimized by nitrogen gas [1].

![Figure 1. Schematic diagram of small scale bio-diesel generator via Fischer-Tropsch Synthesis (FTS) process and utilized equipment along with Process Path Flow (PPF) implementation conversion of synthesis gas into the liquid heavy by hydrocarbons (Shown with thicker lines) [1].](image)

2.2. F-T Fuel Characterization

Many researchers state that the most important characteristics for fuel application are density, viscosity, heating value and cetane number due to their strong control over emissions characteristics and engine efficiency, ultimately indicating the quality of the fuel [8]. Literature was examined to find key physicochemical properties for biodiesel and synthetic diesel produced by either transesterification or Fischer-Tropsch. In this paper Lubricity and Heat of Combustion of FT fuel was investigated.

2.2.1. F-T Fuel Composition-Gas Chromatography Analysis. Gas Chromatogram Mass Spectrometry (GC-MS) (Perkin Elmer Clarus 600) used in this study for liquid hydrocarbon products analysis which were collected in a cold trap cooled externally at 283 K using a counter current heat exchanger. The product distributions were analyzed off-line employing a DBI column combined with Gas
Chromatogram Mass Spectrometry (GC-MS). A 1 µL portion of each sample containing the mixture of gasoline, diesel and waxes was injected into the GC with a split ratio of 34:1. Non-reactive inert helium gas was used to carry the gases’ samples through the instrument. The injection port was heated to 573 K; the oven temperature was increased at 8 K/min from 303 K to 493 K and held at this temperature for 5 minutes. For liquid samples, the qualitative analysis was performed to identify the constituents (elements of functional groups) [1]. 16 samples of FT fuels were analyzed and total values and percentage of paraffin, iso-paraffin, olefins and alcohols within each of the gasoline (C_{7}-C_{11}), diesel (C_{12}-C_{22}) and waxes (C_{23+}) were calculated.

2.2.2. Lubricity. Lubricity has become an important quality, particularly for biodiesel, due to higher pressures in new diesel fuel injection (DFI) technology which demands better lubrication from the fuel [17]. Lubricity is simply the ability of the fuel to reduce friction between moving parts within the engine to help it run smoothly. Supposedly, as much as 30% of mechanical energy is consumed by friction [18, 19]. This makes fuel lubrication vital to reduce scarring of components inside the engine. If the fuel does not contain enough lubricating ingredients, it is considered as a “dry fuel” for its incapacity of lubricating the components like fuel delivery and injection system, cylinder liners, etc. [18]. To assess lubricity a tribological test can be performed which measures the size of the wear mark in an HFRR (high frequency reciprocating rig) test [19]. The smaller the wear scar the better the lubricating properties of the fuel, and they must comply with ASTM D6079 maximum value of 520µm.

Assessment of the lubrication properties of FT fuel was carried out on HFRR (PCS Instrument Ltd) according to the EN ISO 12516-1:2006 standard [20]. This is shown schematically in Figure 2a. The test specimens comprised of 6mm diameter steel ball and steel disc. Fuel temperature maintained at 60°C and the volume of the sample used set at 2ml. A humidity and temperature controlled cabinet was employed to provide the laboratory air conditions defined by the standard as shown in Figure 2b. These conditions are defined according to the ISO standard defining air conditions for testing diesel fuel lubricity [20]. During the test the disc was fully submerged in the tested samples at a reciprocation frequency of 50 Hz lasting 75 min. Optical microscopy (with a 100x magnification lens) was used to assess the size of the wear scar on the upper specimen again to the procedure defined by the ISO standard (including a correction factor to account for standard 1.4 kPa water vapour pressure). All of the lubricity experiments were repeated twice and if a difference in corrected wear scar diameters obtained from the same fuel was higher than 20 µm [21].

Figure 2a. Schematic diagram of high frequency reciprocating rig (HFRR) [22].
2.2.3. **Heat of Combustion (Heating Value, Gross Calorific Value).** One of the very important factors in the fuel economy and power deliverability is the calorific value of a fuel. The presence of oxygen in fuel improves combustion properties and emissions but reduces the calorific value. A fuel heating value is a gauge of the amount of thermal energy it releases during its burning and is an influential factor in the fuel economy and power deliverability [24]. There are several values to consider when concentration on the available energy within a fuel, the lower heating value (LHV-net) and the higher heating value (HHV-gross) included. These differ, as the lower HV does not include energy in the combustion of water vapour, whereas the higher does. The net heating value is the appropriate quantity for comparing fuels as the engine exhaust water in gas phase [25]. A diesel engine desires fuels of higher calorific value because it facilitates the heat release during combustion and improves engine performance during combustion [4, 9]. As was stated earlier a high heating value is desired, though a minimum value is not specified in the biodiesel standards ASTM D6751 but is prescribed in EN 14213 at 35 MJ/kg [26].

IKA C200 oxygen bomb calorimeter according to the ASTM D240 standard was carried out to measure heating value of the FT fuels. The use of gross or net calorific value varies with type of industry. Engine manufacturers use net calorific value and UK boiler manufacturers use gross [27]. Heat of combustion is determined in this test method by burning a weighed sample in an oxygen bomb calorimeter under controlled conditions. The heat of combustion is computed from temperature observations before, during and after combustion with proper allowance for thermochemical and heat transfer corrections. Gross calorific value is gathered from instrument. If the percentage of hydrogen in fuel sample is not known, the net heat of combustion may be calculated as follows [28]:

$$Q_n = 10.025 + (0.7195)Q_g$$

where:

- $Q_n$ = Net heat of combustion at constant pressure, MJ/kg,
- $Q_g$ = Gross heat of combustion at constant volume, MJ/kg.

3. Results and Discussion

3.1. **F-T Fuel Composition-Gas Chromatography Analysis**

Hydrocarbon distribution of FT synthesis on liquid phase of products measured and analysed by PerkinElmer Clarus 60 Gas Chromatography Mass Spectrometry. GC analysis is performed for identifying the hydrocarbon compounds. Table 1 indicates the total values and percentage of paraffin, iso paraffin, olefins and alcohols within each of the gasoline (C_{1}-C_{12}), diesel (C_{12}-C_{22}) and waxes (C_{23+}) which were calculated by analysing the result of GCMS results.
Table 1. F-T Fuel Characterization.

| FT Sample | Temperature (K) | Pressure (bar) | WHSV (NL/gramcatalyst) | W (C7-C11) | W (C12-C22) | W (C22+) | Paraffin | Olefin | Alcohol | Gross Calorific Value (MJ/kg) | Net Calorific Value (MJ/kg) % H unknown | Lubricity (µm) |
|-----------|-----------------|----------------|------------------------|-------------|-------------|----------|----------|--------|---------|-------------------------------|------------------------------------------|-------------|
| FTS 1     | 503             | 10             | 1.8                    | 17.66       | 81.35       | 0.99     | 97.4     | 2.18   | 0.42    | 18.8                          | 13.54                                    | 389         |
| FTS 2     | 503             | 15             | 2.4                    | 21.06       | 77.55       | 1.39     | 92.83    | 4.63   | 2.53    | 56.95                         | 40.99                                   | 342         |
| FTS 3     | 503             | 20             | 3.6                    | 17.52       | 81.53       | 0.95     | 92.27    | 3.39   | 4.34    | 51.45                         | 37.03                                   | 403         |
| FTS 4     | 503             | 25             | 3.6                    | 20.69       | 78.19       | 1.12     | 90.42    | 4.5    | 5.08    | 48.33                         | 34.78                                   | 360         |
| FTS 5     | 518             | 10             | 2.4                    | 26.64       | 71.96       | 1.4      | 98.11    | 1.1    | 0.79    | 49.37                         | 35.53                                   | 296         |
| FTS 6     | 518             | 15             | 1.8                    | 21.12       | 78.08       | 0.08     | 98.68    | 0.81   | 0.51    | 29.15                         | 20.98                                   | 346         |
| FTS 7     | 518             | 20             | 3.6                    | 21.98       | 76.53       | 1.49     | 95.42    | 2.47   | 2.11    | 50.9                         | 36.64                                   | 339         |
| FTS 8     | 518             | 25             | 3.6                    | 14.91       | 81.7        | 3.39     | 96.78    | 2.04   | 1.18    | 51.8                          | 37.28                                   | 417         |
| FTS 9     | 528             | 10             | 3.6                    | 32.76       | 66.76       | 0.48     | 97.11    | 1.82   | 1.07    | 36.2                          | 26.06                                   | 286         |
| FTS 10    | 528             | 15             | 3.6                    | 24.35       | 70.89       | 4.76     | 97.7     | 1.84   | 0.46    | 54.13                         | 38.96                                   | 294         |
| FTS 11    | 528             | 20             | 1.8                    | 23.58       | 75.14       | 1.28     | 98.35    | 1.22   | 0.43    | 43.76                         | 31.5                                    | 336         |
| FTS 12    | 528             | 25             | 2.4                    | 21.56       | 76.78       | 1.66     | 92.83    | 3.59   | 3.58    | 50.62                         | 36.43                                   | 340         |
| FTS 13    | 543             | 10             | 3.6                    | 24.85       | 73.09       | 2.06     | 97.45    | 2      | 0.55    | 13.75                         | 9.89                                   | 320         |
| FTS 14    | 543             | 15             | 3.6                    | 25.035      | 73.93       | 1.04     | 98.96    | 0.57   | 0.48    | 38.16                         | 27.47                                   | 330         |
| FTS 15    | 543             | 20             | 2.4                    | 17.62       | 80.12       | 2.26     | 96.35    | 2.73   | 0.92    | 60.14                         | 43.29                                   | 372         |
| FTS 16    | 543             | 25             | 1.8                    | 24.59       | 73.84       | 1.57     | 98.09    | 1.4    | 0.51    | 57                          | 41.02                                   | 325         |

3.2. Lubricity
The tribological lubricity results for 16 Fischer Tropsch samples are gathered in Table 1. Wear Scar Diameter varies between 286 µm to 417µm. From figure 3a, it can be seen that the change of FT reaction conditions effect on the lubricity of the fuels. Increasing the pressure affects the poor lubricity property and in high temperature lubricity is better. WHSV does not have significant effect on lubricity property. By validating the result with Mahmoudi [1] which stated that optimum condition for fuel production via FTS is high pressure reaction condition, it can conclude that lubricity in higher pressure indicates poor quality. Hydrocarbon distribution of F-T synthesis on liquid products which were measure by GCMS as a function of the lubricity in figure 3b represents that decrease in production of the olefins and gasoline products (C7-C11) could increase the lubricity by controlling the initiation, growth of carbon chain and enhancing the chain termination. From figure 3b it can clearly see that in heavier hydrocarbons by increasing the percentage of the heavier hydrocarbons in product lubricity increases. So by increasing value of the Diesel in liquid product lubricity become poor. In contrast presence of the light hydrocarbons improves lubricity of the F-T fuel. Figure 4 clearly states that all fuel samples are below the ASTM D6079 Maximum limit (520µm) with comparison of the Ultra-Low Sulphur Diesel fuel which was tested in the same condition by HFRR. This contradicts Alleman et al. [29] and Norton et al. [30] who stated that the lack of aromatic content and Sulphur in FT diesel produces unacceptable lubricity fuels. Sulphur compounds in diesel fuels create some natural lubricity which is counterproductive to current aims to reduce the Sulphur content and pollutants in fuels. Additives could be a solution to this and it is thought that biodiesels from transesterification (FAME) can have superior lubricity than other alternative fuels. Best Lubricant fuel is FT 9 which is in low pressure of
10bar and temperature of 528K, however poor lubricant fuel is FT 8 with reaction condition of high pressure 25bar and low temperature 518K.

![Figure 3a. Relation between Lubricity and FTS Reaction Conditions (Pressure, Temperature and WHSV)](image)

3.3. Heat of Combustion

Heating value is the amount of heating energy released by the combustion of a unit value of the fuels. Figure 5a indicates effect of FT reaction condition on Calorific value of fuels. It is desirable to have higher calorific value around 45 MJ/kg for diesel fuel. So in high pressure reaction condition FT fuels have appropriate heating value. Temperature and WHSV do not have any significant effect on Calorific value. Figure 5b shows effect of presence of hydrocarbon distributions on calorific value. Presence of light hydrocarbons causes decrease in calorific value but heavier hydrocarbons does not have any significant effect on amount of heat of combustion. Figure 6 shows comparison between the heating values of the Fischer-Tropsch Fuels produced in School of Mechanical Engineering at

![Figure 4. FT Fuel Lubricity (µm)](image)
University of Birmingham and also ULSD fuel were tested in IKA C200 oxygen bomb calorimeter. Six of these samples are in below limit of 35 MJ/Kg which needed some additives to increase their heat of combustion. FT15 in high pressure 20bar and high temperature 543 K is the fuel with highest net calorific value of 53.29MJ/kg.

![Figure 5a. Relation between Heat of Combustion and FTS Reaction Conditions (Pressure, Temperature and WHSV).](image)

![Figure 5b. Relation between Heat of Combustion and FT Fuel mass fraction.](image)

![Figure 6. FT Fuel Net Calorific Value (MJ/kg).](image)

4. Conclusions

In this paper, Fischer Tropsch Synthesis as one of the best options for biomass derived fuels production is used which has extensive history of gasoline and diesel production from coal and natural gas. FTS fuel could be one of the best solutions to the fuel emission due to its high quality. FT fuel produced in fixed bed reactor over Cobalt catalyst and it has been characterized in GCMS to determine its hydrocarbon distributions. Lubricity and calorific value measured in HFRR and IKAC200 respectively. Results show that prepared fuels in School of Mechanical Engineering at University of Birmingham have good lubricities which are more than Diesel fuel but it comply the ASTM D6079 Standard 520µm. Calorific value of only six samples are below of the limit. And result from graphs
show that high pressure reaction condition improves calorific value of fuels. Because all of the samples have good lubricity so high pressure Fischer Tropsch Synthesis reaction condition produce more desirable fuels. Also Mahmoudi [1] in his PhD thesis used Taguchi method to find an optimum reaction condition which is operating at Temperature 528 K, Pressure 20-25 bar and WHSV 3-3.6NL/gram catalyst. Similarly in high pressure FTS condition, FT fuel has desirable lubricity and calorific value.

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References
[1] Mahmoudi H 2015 Performance of cobalt-based eggshell catalyst in low temperature Fischer tropsch synthesis process to produce long-chain hydrocarbons from synthesis gas utilizing fixed-bed reactor technology PhD Thesis School of Mechanical Engineering The University of Birmingham,
[2] Moazami N, Mahmoudi H, Rahbar K, Panahifar P, Tsolakis A and Wyszynski M L 2015 Catalytic performance of cobalt–silica catalyst for Fischer–Tropsch synthesis: Effects of reaction rates on efficiency of liquid synthesis Chemical Engineering Science 134: pp 374-384
[3] Tristantini D, Lögdberg S, Gevert B, Borg Ø and Holmen 2007 A The effect of synthesis gas composition on the Fischer–Tropsch synthesis over Co/γ-Al2O3 and Co–Re/γ-Al2O3 catalysts Fuel Processing Technology 88(7): pp 643-649
[4] Arbab M I, Masjuki H H, Varman M, Kalam M A, Imtenan S and Sajjad H 2013 Fuel properties, engine performance and emission characteristic of common biodiesels as a renewable and sustainable source of fuel Renewable and Sustainable Energy Reviews 22: pp 133-147
[5] Murugesan A, Umarani C, Subramanian R and Nedunchezhiyan N 2009 Bio-diesel as an alternative fuel for diesel engines—A review Renewable and Sustainable Energy Reviews 13(3): pp. 653-662
[6] Sadeghinezhad E, Kazi S N, Sadeghinejad F, Badarudin A, Mehrali M, Sadri R, and Reza Safaei M, A comprehensive literature review of bio-fuel performance in internal combustion engine and relevant costs involvement.Renewable and Sustainable Energy Reviews, 2014. 30: pp 29-44.
[7] Midland A D, Biodiesel Technical Information. ADM Biodiesel Technical Services.
[8] Sadeghinezhad E, Kazi S N, Badarudin A, Oon C S, Zubir M N M and Mehrali M 2013 A comprehensive review of bio-diesel as alternative fuel for compression ignition engines.Renewable and Sustainable Energy Reviews 28: pp 410-424
[9] Ashraful A M, Masjuki H H, Kalam M A, Rizwanul Fattah I M, Imtenan S, Shahir S A and Mobarak H M 2014 Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: A review Energy Conversion and Management 80: pp 202-228
[10] Torregrosa A J, Broatch A, Plá B and Mónico L F 2013 Impact of Fischer–Tropsch and biodiesel fuels on trade-offs between pollutant emissions and combustion noise in diesel engines Biomass and Bioenergy 52: pp 22-33
[11] Maniatis K and Millich E 1998 Energy from biomass and waste: the contribution of utility scale biomass gasification plants Biomass and Bioenergy 15(3): pp 195-200
[12] Zeng S, Du Y, Su H and Zhang Y 2011 Promotion effect of single or mixed rare earths on cobalt-based catalysts for Fischer–Tropsch synthesis Catalysis Communications 13(1): pp 6-9
[13] Rafiq M H, Jakobsen H A, Schmid R and Hustad J E 2011 Experimental studies and modeling of a fixed bed reactor for Fischer–Tropsch synthesis using biosyngas Fuel Processing Technology, 92(5) pp 893-907
[14] Henrici-Olivé G and Olive S 1984 Mechanism of the Fischer-Tropsch synthesis: Origin of oxygenates. Journal of Molecular Catalysis 24 (1): pp 7-13

[15] Guettel R and Turek T 2008 Reactors for Fischer-Tropsch Synthesis. Institute of Chemical Process Engineering Clausthal University of Technology. Chem. Eng. Technol, 2008

[16] Moazami N, Mahmoudi H, Panahifar P, Rahbar K, Tsolakis A and Wyszynski M L 2015 Mathematical Modeling and Performance Study of Fischer-tropsch Synthesis of Liquid Fuel over Cobalt-silica. Energy Procedia 75: p. 62-71

[17] Knottje J V G and Jurgen Krahl J The Biodiesel Handbook. 2005: AOCS Press. 303

[18] Hazrat M A, Rasul M G and Khan M M K 2015 Lubricity Improvement of the Ultra-low Sulfur Diesel Fuel with the Biodiesel. Energy Procedia 75: pp 111-117

[19] Maru M M, Trommer R M, Cavalcanti K F, Figueiredo E S, Silva R F and Achete C A 2014 The Striebeck curve as a suitable characterization method of the lubricity of biodiesel and diesel blends. Energy 69: pp 673-681

[20] BSI, BS EN ISO 12156-1:2006 Diesel Fuel, Assessment of lubricity using the high frequency reciprocating rig (HFRR) Part I. Test Method

[21] Magí´n Lapuerta R G and John R. Agudelo 2009 Lubricity of Ethanol-Biodiesel-Diesel Fuel Blends. Energy & Fuels 24: p 6

[22] Sukjit E 2013 Synergistic Effects of Alcohol Based Renewable Fuels: Fuel properties and Emissions. PhD Thesis School of Mechanical Engineering. The University of Birmingham

[23] Eslami F 2013 Properties, Performance and emissions of biofuels in blends with gasoline. PhD Thesis School of Engineering. The University of Birmingham

[24] Gandure J, Ketlogetswe C and Temu A 2014 Fuel properties of biodiesel produced from selected plant kernel oils indigenous to Botswana: A comparative analysis. Renewable Energy 68: p. 410-420.

[25] Bezergianni S and Dimitriadis A 2013 Comparison between different types of renewable diesel. Renewable and Sustainable Energy Reviews 21: pp 110-116

[26] Ali O M, Mamat R, Abdullah N R and Abdullah A A 2016 Analysis of blended fuel properties and engine performance with palm biodiesel–diesel blended fuel. Renewable Energy 86: pp 59-67

[27] Piaszyk J 2012 Animal Fat (Tallow) as Fuel for Stationary Internal Combustion Engines. PhD Thesis School of Mechanical Engineering. The University of Birmingham

[28] Standard A N 2007 Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter / ASTM D240-02. 2007 ASTM International United States

[29] Alleman T L and McCormick R L 2003 Fischer-Tropsch Diesel Fuels - Properties and Exhaust Emissions: A Literature Review. SAE International Technical Paper 2003-01-0763 DOI: 10.4271/2003-01-0763

[30] Norton P, Vertin K, Bailey B, Clark N N, Lyons D W, Goguen S and Eberhardt J 1998 Emissions from Trucks using Fischer-Tropsch Diesel Fuel. SAE International Technical Paper 982526 DOI: 10.4271/982526