Liquid Biofuels Production and Emissions Performance in Gas Turbines: A Review

Meng Choung Chiong[a], Cheng Tung Chong[a,b,*], Jo-Han Ng[b,c,d], Su Shiung Lam[e], Manh-Vu Tran[f], William Woei Fong Chong[a,b], Mohammad Nazri Mohd Jaafar[a], Agustin Valera-Medina[g]

[a] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
[b] UTM Centre for Low Carbon Transport in cooperation with Imperial College London, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
[c] Faculty of Engineering and the Environment, University of Southampton Malaysia Campus (USMC), 79200 Iskandar Puteri, Johor, Malaysia.
[d] Energy Technology Research Group, Engineering Sciences, University of Southampton, SO17 1BJ, Hampshire, UK.
[e] Eastern Corridor Renewable Energy Group (ECRE), Environmental Technology Programme, School of Ocean Engineering, University Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu, Malaysia.
[f] School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 47500 Bandar Sunway, Selangor, Malaysia.
[g] College of Physical Sciences and Engineering, Cardiff University, Wales, UK.

Abstract

The increasing demand for clean and sustainable energy sources provides the impetus for the development of alternative fuels. Recent development of fuel-flexible gas turbine technologies enables the use of alternative non-fossil fuels that could play key roles in contributing to the global efforts in meeting emissions targets. This review highlights the current state-of-the-art production and properties of alternative fuels such as straight vegetable oil (SVO), biodiesel, bioethanol, bio-oil, hydrogenated vegetable oil (HVO) and Fischer-Tropsch (FT) fuel. This is followed by the evaluation of combustion performances in gas turbines. All of the alternative liquid biofuels have shown their potentials in reduce regulated emissions such as NO_x, CO and soot under favourable operating conditions. Both HVO and FT fuels show comparable performance as that of jet fuel and can be used in aviation gas turbines, although the present day high production cost restricts the large-scale adoption, limiting its utility. They also have considerably higher cetane number than the rest, making it easier for the fuel to ignite. As for stationary power generation gas turbines that need not carry payloads, the other four alternative biofuels of biodiesel, bioethanol, bio-oil and SVO are possible candidates despite the physics-chemical properties variations when compared to fossil fuels. Amongst them, the use of SVO and bio-oil in gas turbines would require the parallel development of fuel supply systems and atomisation technologies to improve the combustion of the fuels. In all, the alternative liquid fuels reviewed provides realistic opportunities for cleaner and more sustainable operation of aviation and power generation gas turbines. Profound understanding on the fundamental combustion characteristics of the fuels are essential to expedite their mass adoption in gas turbine applications.

Keywords: gas turbine; biofuels; alternative fuel; jet fuel; biodiesel; FT fuel

*Corresponding author
Address: Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
81310 Skudai Johor Darul Ta’zim Malaysia
Email: ctchong@mail.fkm.utm.my; Phone: +60(7) 5534631 ; Fax: +60 (7) 5566159

Table of Contents

1.0 Introduction

Biomass-derived alternative fuels produced from renewable biomass are important owing to them being potentially carbon neutral, producing cleaner combustion and having sustainable feedstock supply from existing plantations [1]. From a carbon cycle perspective, carbon dioxide (CO_2) produced from the combustion of fossil fuels are discharged into atmosphere without recycling, whereas biofuels are potentially carbon neutral as the CO_2 produced from the combustion process is reabsorbed for feedstock plant growth. Fig. 1 compares the CO_2 emission cycle between fossil fuels and biofuels.

At present, the usage of biofuels is not yet prevalent despite the positive benefits to the environment. This is due to the high cost associated with biofuels production and the relatively lower crude oil price in recent years. These form the primary reasons for the continued reliance on fossil fuels for power generation. Fig. 2 shows the price comparison of fossil fuel-based compressed natural gas (CNG) and diesel with biofuels, i.e. biodiesel (B99/B100) and bioethanol (E85) since the turn of the millennium [2]. As expected, fossil diesel is consistently cheaper than biodiesel and bioethanol. CNG is relatively cheaper than all of the liquid fuels compared and hovers around US$2 per gasoline-gallon equivalent (GGE) over the past few years. However, the need for high pressurisation and the low energy density of CNG renders it to be less practical as compared to liquid fuel in terms of storage and the inherent power contained.

The US Energy Information Administration reported that only 10% of total energy produced came from renewable sources in 2016, out of which, about 22% was contributed by biofuels [3]. There have been calls to table climate change policies to limit the consumption of fossil fuels in order to reduce the gap between fossil fuels and alternative energy sources [4,5]. In December 2015, 195 countries agreed to a global climate deal during the UN Climate Change Conference in Paris (COP21) to pledge the reduction of greenhouse gases in order to achieve a global temperature rise of below 2 °C above pre-industrial levels [6]. Despite the announcement of the US about their withdrawal from the 2015 Paris agreement in June 2017, global efforts on reducing greenhouse gas emissions continue to gain momentum for most countries [7]. One way to achieve the goal of greenhouse gas emissions reduction is by adopting renewable energy sources [6]. The political will and investment committed in sustainable energy technology catalyst have spurred the production of biofuels, which could subsequently lead to reduction of production cost through economies of scale [8].

Gas turbine is one of the power generation systems that contribute to the global greenhouse gases emissions. The technology of gas turbine started exclusively for the aviation industry in the 1960s but rapidly progressed to become an important power generation system. A key milestone that led to gas turbine's rise as a prominent mode of power generation is the development of combined cycle power plants that incorporates the combination of gas and steam turbines, allowing the energy conversion efficiency to be boosted up to around 60% [9,10]. Additionally, most of the combined cycle power plant are fuelled by natural gas, which makes it cleaner than coal-powered power plants [9].

The capacity factor for natural gas powered combined cycle plants between year 2005 and 2015 in the U.S is shown in Fig. 3. The capacity factor increased from an average of 35% in 2005 to 56% in 2015 [11] owing to increasing demand. The increase in usage capacity signifies the inevitable increase of greenhouse gases production, i.e., CO_2. In order to meet the increasingly stringent environmental legislations and emissions targets, recent research has focused on the development of clean, sustainable biofuels and low emission technologies. In the field of gas turbines, fuel-flexibility technology is desirable from the standpoint of meeting emissions goals and reducing operating costs [12,13]. Potential biomass-derived liquid fuels that have been identified as substitute for conventional fuels or supplemental fuels include straight vegetable oil (SVO), biodiesel, hydrogenated vegetable oil (HVO), bioethanol, bio-oil and Fischer-Tropsch (FT) fuel. This paper critically reviews the production process of liquid biofuels, fuel properties and previous studies related to the performance and combustion characteristics under gas turbine operating conditions.

2.0 Applications of liquid biofuels in gas turbines

Gas turbine is a power generation system that is known to be fuel-robust and able to accommodate different types of fuels. To substitute fossil-based fuels, biomass-derived alternative fuels are attractive options that have gained much interest in recent years in view of their renewability and potentially lower emissions. The development of different techniques and production processes that convert biomass into bioresource energy in recent decade have been rapid. The production pathways of the main liquid biofuels are shown in Fig. 4. In general, straight vegetable oil (SVO) is produced directly from mechanical, chemical and enzymatic extraction methods. Biodiesel is produced via the process of transesterification of vegetable oil. Hydrogenated vegetable oil is produced from SVO and animal fats that undergo hydrogenation and isomerisation processes. By pyrolysing biomass, bio-oil and synthesis gas can be produced. The synthesis gas that contains H_2 and CO derived from pyrolysis and gasification processes can be used to produce Fischer-Trospch (FT) fuel. Bioethanol is produced from biomass via hydrolysis and fermentation processes. The variety of feedstock and production methods used to produce the biofuels result in significant differences in the physical and chemical properties, which subsequently affects the combustion quality and performance in gas turbines. Thus, understanding the physical, chemical and rheology properties of the fuels is essential to ensure system safety, design of fuel-flexible combustor and optimise the performance of existing gas turbine systems. The following sections review in detail the physio-chemical properties, production methods and combustion performance characteristics of each type of biofuels.

2.1 Straight vegetable oil (SVO)

2.1.1 Properties of SVO

Vegetable oil can be used directly as fuel in gas turbines [14,15] and internal combustion engines [16,17]. SVO consists of triglycerides that contain three molecules of fatty acids and one molecule of glycerol [18]. The positive attributes of SVO as alternative fuel are biodegradable, renewable and low sulphur and aromatic content [19]. The viscosity for SVO is about an order of magnitude higher than that of diesel, highlighting the major drawback of SVO in gas turbine application, as shown in Fig. 5. High viscosity of SVO results in inferior atomisation, increases carbon deposition and subsequently reduces combustion efficiency [20,21]. One way to reduce the viscosity of SVO is by preheating the fuel and blend with conventional diesel. Despite the feasible usage of SVO in engines, previous experimental works have shown that the tendency of soot deposition increases with the proportion of SVO in fuel [20,21]. Carbon deposition in the combustion chamber and injection system undesirably shortens the life span of the engine, leading to the increase in maintenance cost [22]. Cetane number is a measure of autoignition quality of a fuel. A fuel that is easier to ignite has higher cetane number. The degree of unsaturation in SVO affects the cetane number. Overall, SVO contains lower cetane number compared to conventional diesel or Jet A-1 as shown in Fig. 5, indicating that SVO is harder to ignite when used as operating fuel. Despite the difference in chemical composition as compared to fossil diesel, the calorific value for SVO (38 MJ/kg) is only marginally lower than that of fossil diesel (42.5 MJ/kg), as indicated in Fig. 5. The calorific value for SVO is lower than fossil diesel by approximately 11% due to the presence of oxygen.

SVO can be derived from a variety of plants such as palm, jatropha, castor, jojoba, karanja, tobacco, rapeseed, sunflower, soybean, candlenut and chestnut. The oil content for these plants typically range from 20-60 %wt [18]. The physical properties of these feedstocks are shown in Table 1. The SVOs from rapeseed, sunflower, palm, peanut and sesame are slightly more viscous (>35 mm^2/s) compared to jatropha, soybean, safflower, and coconut (<35 mm^2/s). Castor SVO has a relatively high viscosity of 250 mm^2/s, which is nearly one order of magnitude higher as compared to other feedstock, making it not ideal for the fuel delivery and injection system. The primary constituents of SVO, fatty acid, can be categorised into saturated and unsaturated types. Saturated-chain fatty acid contains no double bonds between the carbons; while unsaturated chain contains double bonds [23]. The degree of unsaturation is one of the main factors that affect the overall physical properties of SVO [19,24]. In general, higher degree of unsaturation (more double bonds in the chain) leads to lower viscosity of the oil [24,25]. This is due to the existence of double bonds in the fatty acid bending the chains, resulting in the existence in liquid form with lower viscosity [24,25]. On the other hand, feedstocks with lower unsaturation degree, such as those of palm and coconut oil tend to have higher cetane number (40-42) when compared with other feedstock [24]. The variation of SVO's calorific value is correlated to the degree of unsaturation, where feedstock with higher unsaturation degree such as soybean, corn, rapeseed and safflower possess higher calorific value (>39.4 MJ/kg) against those with lower unsaturation degree such as coconut, jatropha and peanut (<38 MJ/kg). SVO with higher degree of unsaturation has higher C/H ratio which results in the elevated calorific values. The density for SVO is generally higher than that of diesel owing to the higher molecular weight of the former. Table 1 shows that SVO density can be correlated to the degree of unsaturation, where SVO with higher unsaturation degree (>1.3) has density below 915 kg/m^3 than those with lower unsaturation degree (<1.3) such as palm and coconut (> 915 kg/m^3).

2.1.2 Production of SVO

The production process of SVO generally consists of five stages: (i) seed storage, (ii) pre-treatment, (iii) oil extraction, (iv) filtration, and (v) storage [19]. As shown in Fig. 4, the methods used to extract oil from seeds or kernels of plants can be categorised as mechanical, chemical and biological extraction [18]. Under mechanical extraction, pressers are used to extract oil. The pressers can be of ram or screw type. Screw presser is able to extract up to 95% of oil from feedstock, while ram presser can extract about 65% of oil from feedstock [18,38]. Chemical extraction utilises solvents such as *n-hexane*, bioethanol or isopropyl alcohol for oil extraction [38]. The overall efficiency of the process is governed by the types of solvent used, pH level, particle size, agitation process and operating temperature [18,38]. A major disadvantage of chemical extraction is the generation of hazardous waste water that is detrimental to the environment and human health if left untreated [18,38]. For biological extraction, enzyme such as alkaline protease is used to extract oil from crushed seed. This method is environmental friendly, but the downside is long processing time (6 hours) and low yield (38%) [18]. Post-extraction treatment is needed for all extraction method as the extracted oil typically contains contaminants and is sticky. Filtration and purification processes are applied to remove solid impurities, degum the sticky oil and neutralise the oil by adding alkali such as sodium hydroxide [19].

2.1.3 Performance of SVO in gas turbines

Direct application of SVO in gas turbine is an attractive option as low cost is incurred from oil processing. However, the viscosity of SVO is an order of magnitude higher than conventional fossil diesel, posing a technical challenge when applied in gas turbine system as highly viscous oil will negatively impact fuel flow delivery and result in inferior spray atomisation process. Some practical steps have been undertaken to overcome the physical properties challenge, including modifying the fuel delivery system by adding fuel preheating capability and using twin-fluid injector that allows variation of the controlling parameters. Blending SVO with conventional fuel is another strategy to maintain low viscosity of the blended fuel. The performances of SVO as a viable gas turbine fuel have been tested by different groups, as shown in Table 2 where the feedstock and control parameters are summarised.

Varying the atomising air-to-liquid ratio (ALR) in a twin-fluid atomiser is an effective control parameter to atomise SVO. Niguse and Agrawal [39] reported a reduction of NO_x level by a factor of 4 when the ALR was increased from 2.0 to 3.0 in a swirl burner operated with SVO, but the CO emission was not obvious when compared with baseline diesel. In a lab-scale lean premixing and prevaporising (LPP) burner, Kun-Balog and Sztanko [40] reported a reduction of CO and UHC emissions by more than 50% when atomising rapeseed oil at higher atomising air pressure. Jozsa and Kun-Balog [41] further identified that SVO has poorer stability limit than diesel under LPP burning conditions, particularly at low atomising air pressure. Further increase of atomising air pressure led to increased flame stability with lower CO, while the NO_x emissions for rapeseed oil were found to be lower as compared to baseline diesel. Hashimoto et al. [42] utilised a gas turbine burner with twin-fluid atomiser to examine the combustion characteristics of jatropha oil. Result showed that NO_x emissions for both diesel and jatropha oil were around 50 ppm and decreased monotonically with the increase of air flow rate.

The increase of ALR led to higher air momentum to effectively disintegrate the viscous fuel into fine droplets for vaporisation. If insufficient atomising air was imparted, inferior atomisation of SVO causes large droplets to move towards the combustor wall, causing lower burning temperature and incomplete combustion that subsequently leads to higher CO emissions. The SVO spray flame appearances varied with ALRs. At ALR < 2, yellow sooty spray flame was established, indicating a poor fuel-air mixing with high level of soot production. Increasing the ALR to beyond 2 resulted in an improved mixing of fine droplets and air, creating flames that were bluish and analogous to a well-premixed flame [39].

As fuel viscosity is inversely proportionate with temperature, preheating the SVO is an effective method to reduce the viscosity to the level of conventional fossil fuel. Sallevelt et al. [43] raised the fuel injection temperature in a series of MGT tests. The SVO’s viscosity was reduced significantly by a factor of 3, leading to improved combustion efficiency with 28% of lower carbon monoxide (CO) emissions. Likewise. Chiaramonti et al. [44] managed to achieve CO reduction by 40% relative to biodiesel when combusting preheated rapeseed SVO (120 °C) in an MGT (Garrett GTP 30-67) [44]. Prussi et al. [14] reported that the effect of preheating of SVO on emissions was significant, where CO was seen to reduce by 28% in an 18 kW micro gas turbine when preheating SVO to 120 °C. Preheating the SVO enables direct application in gas turbine with positive effects on emissions.

There were some attempts to blend SVO in small quantity with fossil fuel, thus removing the need of preheating. Panchasara et al. [45] tested the blends of 10-30% vol. soybean oil with diesel using a gas turbine type burner. The CO emissions for the SVO/diesel blends were reported to increase by 15% as compared to baseline diesel fuel under constant fuel flow rate. The effects of using different SVO feedstock blends on the emissions were studied by Chiariello et al. [15] in a micro gas turbine system. Two types of oils were used, namely sunflower and rapeseed, under partial and full load micro gas turbine conditions. Result showed that sunflower oil exhibited higher propensity of soot formation compared to rapeseed oil blend by a factor of 16.7, owing to the high content of linoleic acid in the former that promotes for the formation of ethene and ethyne during thermal decomposition which are known to be soot precursor [46]. These results show that SVO blends lower soot emissions, although CO was seen to increase. The inherent difference in SVO composition depending on feedstock is another factor that affects emissions.

Despite the high CO emissions, the wide availability, ease of storage, near zero toxicity makes SVO an attractive fuel for micro gas turbines. The issue of high viscosity can be overcome by utilising a twin-fluid atomiser with high ALR and preheating the SVO. Moreover, recent study has shown that using superheated steam as atomising fluid is another possible method of reducing the CO, NO and UHC [40]. These strategies show that SVO can be a potential fuel for micro gas turbine, provided modification to the fuel delivery system and injector system is made to accommodate the high viscosity, and the controlling parameter is optimised to achieve low emissions.

2.2 Biodiesel

2.2.1 Properties of biodiesel

The use of SVO in gas turbine has been associated with many problems, mainly attributed to its high viscosity, low volatility and low cetane number. The SVO can further be processed into biodiesel with properties that meet the European Union and U.S standards. Biodiesel is oxygenated, renewable, biodegradable and inherently contains low level of sulphur [47]. Regardless of feedstock, sulphur content in all biodiesel is below 0.01 %wt, which is lower than standards set by European Union (max 0.02 %wt) and U.S. ASTM (max 0.05 %wt), as shown in Table 3. However, the high viscosity of castor biodiesel does not conform to both EU and US standards. The physical properties of biodiesel are similar to that of diesel in terms of calorific value, viscosity, cetane number and density as shown in Fig. 5. Biodiesel can be used as fuel directly or blended with fossil diesel in engines [48,49]. Table 3 compares the properties of biodiesel from different feedstock against standards.

The properties of biodiesel is influenced by the degree of unsaturation of the molecules [24,51]. Table 3 shows that feedstock with low degree of unsaturation (0.62-1.15) such as palm oil and jatropha produce biodiesel with poorer cold flow properties (pour point ≥ 0 ºC).

Although better cold flow properties were obtained for biodiesels with higher degree of unsaturation (> 1.3) such as rapeseed, soybean, and sunflower, they are still considered inferior when compared with diesel (-21 ºC) or Jet A-1 (-47 ºC). Additives are usually added to biodiesel to further improve the cold flow properties. The EU and US ASTM standards require the flash point for biodiesel to be higher than 120 ºC and 93 ºC, respectively. When compared with conventional fossil fuels, the flash point for typical biodiesel (145 ºC) is much higher than Jet A-l (38 ºC) and fossil diesel (76 ºC), as shown in Fig. 5. The benefit of higher flash point is that storage and transportation of biodiesel becomes relatively safer.

Another important property is oxidative stability, which is the measure of reaction rate between the fuel and oxygen. The unstable fuel reacts with oxygen to form gums, sediments and other deposits which subsequently increase the viscosity of the fuel [24]. Table 3 shows that only coconut, palm, rapeseed, canola and castor-based biodiesels fulfil the requirements set by the EU standard (min 6 hours). Sunflower and peanut-based biodiesels are not able to meet the requirement set by US ASTM standard, which is minimum 3 hours. High oxidative stability indicates low degradability tendency and prolongs storage time for biodiesel. The typical storage time for biodiesel is usually not more than six months [52], while diesel can be stored up to 12 months at ambient temperature [53]. Biodiesel has gained much attention as supplemental fuel in recent years. The US has implemented the biodiesel mixture excise tax credit as part of the policy in diversifying energy portfolio [54]. The Malaysian government has implemented mandatory blending of palm-based biodiesel with diesel at B7 for transport and industrial sectors [55] .

2.2.2 Production of biodiesel

Transesterification is the most common process used to produce biodiesel. The process converts triglycerides into glycerol and biodiesel in the presence of alcohol and catalyst at elevated temperature, as shown in Fig. 6. The conversion process is a stepwise and reversible process where alcohol initially reacts with triacylglycerols to produce diacylglycerols and fatty acid alkyl esters. Further reaction leads to the formation of monoacylglycerols and lastly biodiesel and glycerol. The process is reversible, but the reversible rate is usually negligible due to glycerol being not miscible with fatty acid alkyl esters [56]. The catalysts can be of acid, alkaline or enzyme types, depending on the content of free fatty acid (FFA) in the feedstock [57].

In acid catalysed transesterification, hydrochloric acid or sulfuric acid are commonly used [58,59]. Acid catalysts were reported to give high yields (90%) in a relatively short period of reaction time (1 to 6 hours). Meanwhile, acid catalysts can tolerate higher level of free fatty acids compared to alkaline catalysts [47,60]. Apart from acid catalyst, alkaline such as alkaline metal alkoxides and hydroxides, potassium carbonates and potassium hydroxide can also be used as catalyst in transesterification process. Alkaline metal alkoxides was reported to produce even higher yield (96%) of biodiesel in a short period of reaction time (1 to 6 hours) [57]. The use of alkaline, however, is susceptible to the level of free fatty acids. The fatty acid could react with alkaline catalyst to produce soap that inhibits the separation process [61]. Enzymatic catalyst such as lipase was introduced to overcome the complex processing needed for the by-product treatment in acid and alkali catalyst transesterification process [61]. However, low yield (62% to 71%) and long reaction time (up to 8 hours) for this biodiesel production technique is not favoured for mass production [62]. Another technique for biodiesel production without requiring catalyst is by using methanol under supercritical condition [63]. This supercritical process requires severe operating conditions such as temperature greater than 240 °C and pressure greater than 80 bar [64]. As catalyst is not used in this process, the by-product treatment process is simpler due to the absence of contaminants. The advantage of this process is short reaction time compared to catalytic-based process [63], but the disadvantages are requirement of expensive equipment and high production cost [1]. Methods of producing biodiesels from various types of lipids are summarised in Fig. 4.

2.2.3 Performance of biodiesel in gas turbines

Biodiesel has proven to be a viable substitute fuel or as blend with diesel in compression-ignition engines due to its close resemblance to diesel in physical properties [65]. Further applications of biodiesel in gas turbines system for power generation and as aviation fuel are envisaged. Land-based industrial gas turbine is fuel-robust in nature that allows the use of biodiesel with minimal modification to the existing system but application in aviation-based gas turbine requires stringent compliance to the jet fuel specification. Table 4 and 5 summarise the previous combustion research related to biodiesel combustion in gas turbine type burners and system. It is noted that biodiesels produced from different types of feedstock have been used for testings.

2.2.3.1. Biodiesel spray flame characterisation using gas turbine type burner

The potentials of biodiesel as gas turbine fuels have been investigated using lab scale gas turbine type swirl flame burner. The advantage of using simplified burner allows parametric studies, including comparison of combustion performances, flame structure, emissions with baseline fuels under well-controlled environment. Chong and Hochgreb [66] compared the combustion characteristics of palm [28] and rapeseed [67] biodiesels with baseline diesel and Jet-A1. Biodiesel flames exhibited larger heat release area compared to that of baselines [68]. Soot was not present in biodiesel flame owing to the absence of aromatic rings in the fuel and the fuel-bound oxygen content that assist in the oxidation of soot during combustion. The NO emissions were shown to reduce by ~25% for palm biodiesel as compared to Jet A-1 and diesel at fixed power output of 6 kW [28].

Other researchers who have found the benefits of reduced emissions for biodiesel under swirl flame conditions including Hashimoto et al. [42]. The smoke and soot emissions of jatropha/diesel blends were significantly lower than that of diesel, resulting in lower flame radiation intensity for the biodiesel blends flames. They demonstrated in a gas turbine burner equipped with a pressure atomiser that NO_x emissions for palm biodiesel can be lowered by generating finer spray droplets via increasing the atomising pressure. Finer droplets evaporated at a shorter time scale, reducing localised hot regions that promotes NO_x formation due to droplet burning in diffusion mode [69,70]. Erazo et al. [71] showed that the peak temperature of canola biodiesel (1750 K) was lower compared to diesel (1900 K), hence lower NO_x emissions were detected for the former. Li et al. [72] utilised a gas turbine type burner to compare the spray and combustion properties of rapeseed biodiesel with diesel. Biodiesel spray was found to exhibit longer spray penetration length and smaller spray cone angle compared to diesel owing to its higher density, viscosity, surface tension and boiling point. Similar to the findings shown by Chong and Hochgreb [73], rapeseed biodiesel produced lower NO_x emissions by 21% compared to diesel.

Panchasara et al. [45] noted that inferior atomisation for biodiesel is the main factor that promotes NO_x formation. Adjusting the control parameter presents an effective way to improve emissions. Sequera et al. [74] atomised biodiesel using an airblast atomiser and reported a reduction of CO emissions by 50% for biodiesel as compared to diesel under constant fuel mass flow rates. Chong and Hochgreb [68,73] utilised a twin-fluid atomiser and showed that the twin emissions reduction of NO and CO can be effectively achieved with increasing ALR. Simmons and Agrawal [75] employed a flow blurring atomiser to atomise biodiesel and reported a reduction of CO emissions by a factor of 2-3 when the ALR was increased from 2.0 to 2.4 compared to the typical airblast atomiser. The improved emissions were due to increased mixing from flow blurring. A group of researchers from Cardiff investigated the spray combustion characteristics of biodiesel and biodiesel saturated with pyrolysis oil. The biodiesel/pyrolysis oil blend was found to produce higher NO_x emissions than kerosene, while biodiesel shows comparable NO_x with the latter [76]. Despite no explanations yet can adequately elucidate the biodiesel-NO_x effect based on the previous studies, some recent opinions skewed towards fuel chemistry as the fundamental cause of increased biodiesel NO_x emissions [51,77,78].

2.2.3.2. Application of biodiesel in gas turbine system for power generation

The performances of biodiesel combustion at system levels have been tested using actual gas turbines, including those of micro gas turbine, industrial and aviation gas turbine engines. Micro gas turbine can be used for off grid power generation for households, small businesses and rural regions, thus the ability to operate on biodiesel is of interest. Bolszo and McDonell [79] operated a 30 kW MGT (Capstone C30) with soy-based biodiesel and reported higher NO_x emissions than diesel fuel by approximately 13 ppm. Larger droplet size was generated by biodiesel during spray atomisation, leading to higher NO_x emissions as a result of longer evaporation time scale. In another separate MGT (Capstone C30) test, Krishna [80] reported lower NO_x emissions by 60% and 14% for soybean biodiesel at high and low thermal input, respectively, compared to fossil diesel. Both tests showed that soy-based biodiesels could produce conflicting results even in the same gas turbine systems.

Nascimento et al. [81,82] compared the thermal performance and emissions of castor biodiesel and blends with diesel in a 30 kW MGT. CO emissions were found to increase by 50% as compared to diesel at 14 kW engine output power. It was opined that the lower NO_x emissions achieved in the MGT tests were partly contributed by the inferior atomisation of biodiesel which resulted in lower combustion temperature. The size of biodiesel liquid droplets and primary-zone equivalence ratio were larger for biodiesel compared to diesel. The reduction of temperature in primary combustion zone (due to higher equivalence ratio) reduced the emission levels of NO_x pollutants for biodiesel. For MGT that utilises air-blast atomiser, the production of NO_x is affected by the variation of atomising air to liquid ratio. The increase in the percentage of atomising air results in leaner combustion and lower flame temperature, hence the lower NO_x emissions [68,74].

Habib et al. [83] utilised a 30 kW gas turbine engine to examine the performance of soy, canola, recycled rapeseed biodiesel and hog-fat biofuel against Jet A. NO emissions for biodiesel were consistently lower than diesel at lean-burning conditions, with a maximum reduction of up to 75%, while the difference in turbine inlet and exhaust gas temperature between biodiesel and diesel was less than 80 °C and 20 °C respectively. CO emissions were found to be lower for biodiesels as the oxygen in the biodiesel assisted in converting CO into CO_2 [83,84]. The static thrust produced by biodiesel and blends were comparable to that of jet fuel. They reported that fuel efficiency was higher when operating with biodiesels, owing to the oxygen in biodiesel that resulted in more complete combustion [83]. Some have reported improved gas turbine performance due to the oxygen content in biodiesel [81].

The notion of fuel-flexible industrial gas turbine operation is attractive from the point of view of lower operating cost and adaptability to local biofuel sources. Several gas turbine tests have been conducted using biodiesels. Liu et al. [85] investigated the ignition, combustion dynamics and emissions of biodiesel using a Siemens SGT-100 gas turbine. The NO_x emissions for biodiesel were found to be lower than that of diesel for all operating conditions tested. In a semi-closed cycle gas turbine field test conducted by Ellis et al. [86], soot emissions were shown to reduce by 70% and 32% for palm and soy biodiesels, respectively. No significant trend was observed for UHC emissions for all fuels tested despite slightly higher fuel consumption rate for pure biodiesel by 4-7%. Moliere et al. [87] tested rapeseed biodiesel in a GE 6531B industrial gas turbine. No visible smoke was observed during biodiesel combustion and sulphur oxide emissions were less than 1 ppm. These results indicate the positive effects of biodiesel towards the environment. However, there was a reported case where higher UHC emissions were observed when blends of biodiesel (fish oil and canola oil based) with Jet A1 fuel were used in an industrial gas turbine sector rig (Allison/Rolls Royce T56-A-15 combustion systems), accompanied by a slight increase in engine deposits for 20% biodiesel blends due to excessive gum and inferior atomisation [88]. These studies show that due to complexities of gas turbine operation, extensive testings are required when using alternative fuels, as the effect of fuel is not restricted to only combustion, but also downstream of combustor such as the turbine blades.

Power generation for aviation gas turbine is another area that is extensively explored in search for cleaner alternative fuels to replace fossil-based fuels. Although biodiesel is oxygenated, slightly denser and contains lower heating value than conventional jet kerosene, blending biodiesel with jet fuel could result in positive emission benefits without incurring significant performance penalty. Timko et al. [89] achieved lower NO_x by 29% and 23% for 40% and 20% biodiesel blends, respectively in an aviation gas turbine engine (CFM56-7B turbo-fan engine) test. In another biodiesel test in a helicopter turboshaft engine (T63-A-700), Corporan et al. [90] reported that 20% soybean biodiesel/JP-8 blend produced 15% reduction in particle number density at cruising and take-off conditions. Rehman et al. [84] concluded that the oxygen content in a jatropha/diesel blends assisted in the combustion of a 44 kW gas turbines (IS/60 Rovers). Biodiesel was shown to have better fuel efficiency than diesel despite a slight reduction in brake specific fuel consumption (BSFC) by 0.5 kg/kW-hr. The blends however, showed higher emissions of NO_x by 34-42% compared to diesel at the same power output. It was postulated that the higher oxygen content in biodiesel led to higher flame temperature and subsequently higher level of NO_x emissions. Talib et al. [91] utilised a turbojet engine (Armfield CM4) to test the performance of 20% biodiesel/diesel blend compared to Jet

A-1 baseline. It was reported that the former fuel produced a lower thrust by 4%, as expected as the energy content of biodiesel is lower than jet fuel by approximately 17% by mass [28]. These results showed that application of biodiesel in aviation gas turbine is feasible with the benefits of lower emissions but at the expense of performance penalty.

2.3 Hydrogenated vegetable oil (HVO)

2.3.1 Properties of HVO

Hydrogenated vegetable oil (HVO) is also known as green diesel, renewable synthetic diesel, hydrogenated straight vegetable oil (HSVO), hydrodiesel or hydrogenation-derived renewable diesel (HDRD) [92]. Similar to SVO and biodiesel, plants such as rapeseed, palm, castor, sunflower, jatropha, soybean, and animal fat have been used as feedstock to produce HVO [93,94]. The advantage of HVO is its compatibility with existing diesel engine [26,95] and with nearly 0% oxygen content [93,96]. The biodegradability of HVO is poorer compared to SVO and biodiesel [92–94,96].

The calorific value for HVO is higher than that of biodiesel by 16% per mass basis and is comparable with fossil diesel and Jet A-1, as shown in Fig. 5. The cetane number for HVO is higher than both biodiesel and diesel, indicating reduced ignition delay time for engine. The density for HVO is similar to Jet A-1, but less dense than biodiesel and diesel, which makes HVO a good substitute for conventional fuels without incurring weight penalty. The low freezing point of HVO (-25 ºC to -40 ºC) fulfils the requirement of jet fuel to avoid formation of wax in the fuel supply system. Furthermore, HVO has comparable viscosity as Jet A-1 and diesel. The comparable physical properties of HVO with Jet fuel has enabled the former to be certified as alternative jet fuel [4].

2.3.2 Production of HVO

HVO is produced via hydrogenation of vegetable oil in the presence of catalyst and hydrogen [26,95]. The process breaks the double bond (C=C) in the vegetable oil into single bond (C-C). Hydrogen was inserted into the hydrocarbon chain. Apart from carbon and hydrogen atoms, other elements such as sulphur, nitrogen, and oxygen are present in HVO [96]. The presence of these heteroatoms is highly undesirable; as oxygen tends to reduce the heating value while sulphur promotes the formation of sulphur dioxide during combustion process. Hydrogenation process removes these heteroatoms to improve the overall quality of the fuel [26,95]. The hydrogenation process mainly consists of two steps: hydrotreatment that saturates the unsaturated fat (i.e. breaking the C=C), and isomerisation process that forms the branched chains [26,95].

The research on hydrotreatment of vegetable oils has mostly focused on the type of reactors and catalysts. Two types of catalysts were reported to be effective in hydrotreatment of vegetable oils process, namely metal catalysts and sulfided bimetal catalysts [94]. The overall process of hydrogenation of vegetable oil is shown in Fig. 7. Feedstock is supplied to the catalytic reactor to combine with hydrogen at elevated temperature and pressure. The feedstock is pretreated prior sending into reactor. In the reactor, the feedstock undergoes the hydrodeoxygenation, decarboxylation, and hydroisomerisation processes to convert into diesel, water, and oxide of carbon [92]. The hydrotreatment process takes place in a fixed bed reactor at elevated temperature of 300-400 °C and pressure of 30-130 bar in the presence of catalyst. The HVO yield varies from 88% to 99%, depending on the type of feedstock [92]. The produced diesel fuel contains no sulphur, oxygen, aromatic and nitrogen.

2.3.3 Performance of HVO in gas turbines

HVO has been identified as a promising alternative jet fuel due to the absence of oxygen molecules and comparable physical properties to jet fuel [4]. A study conducted by Chan et al. [97] using a turbofan engine (CF700-2D-2) fuelled with HVO has shown lower NO_x emissions compared to Jet A-1. At idling conditions of 80% and 95% engine loads, the 50% HVO/Jet A-1 blend produced up to 0.3 g/kg lesser NO_x than neat Jet A-1. The result concurs with Baranski et al. [98] in a turbojet engine (JetCat P-200) test fuelled with HVO and JP-8, where NO_x emissions for HVO were shown to be consistently lower than that of JP-8 at all operating speeds. The thrust specific fuel consumption for HVO was 16% lower than that of JP-8 at engine speed below 60,000 rpm.

Klingshirn et al. [99] reported lower CO emissions in a gas turbine (T63 A-700) test fuelled with HVO compared to baseline JP-8. CO emissions were consistently lower than that of JP-8 at both the idling and cruising modes with fuel/air ratios of 0.009 and 0.017, respectively. The effect of altitude on the emissions of CO by hydrogenated fuel was investigated by Chishty et al. [100]. The gas turbine performance test was conducted at the altitudes of 1525 m and 6095 m with Jet A-1 and blend of 50% JP-8/hydrogenated renewable jet fuel. Jet A-1 showed higher CO emissions as compared to the blend. The exhaust CO was around 175 g/kg fuel at 6095 m, which is significantly higher than at 1525 m which was about 125 g/kg fuel. Jet A-1 showed slightly higher NO_x emissions than JP-8/hydrogenated fuel blend by a slight difference of 0.3 g/kg fuel.

The improved emission performance of HVO was also reported by Purcher et al. [88,101] in a gas turbine (Allison/Rolls Royce T56-A-15) test operated with HVO. The particulate matter and unburned hydrocarbon emissions were reduced by 96% and 27.7% respectively as compared to baseline Jet A-1. HVO has shown overall positive emissions as opposed to that of fossil jet fuel. Soot concentration and mass deposition were found to reduce significantly for HVO. On top of that, the ignition delay time is also shorter and resistance to extinction is stronger compared to Jet A [102]. Buffi et al. [103] investigated the heat release and emissions profiles of Jet A-1, HRJ (Hydrotreated Renewable Jet Fuel) and their blends using an optical swirl burner. It was reported that HRJ exhibited a more homogenous heat release zone that led to reduced emissions. Meanwhile, the effect of backpressure was also examined, whereas the reduced bulk flow was due to the increase of backpressure that formed a more compact flame brush.

2.4 Bioethanol

2.4.1 Properties of bioethanol

Bioethanol is a colourless, biodegradable, low toxicity, and highly flammable liquid. Bioethanol has relatively low viscosity (1.5 mm^2/s) and pour point (-78 ºC) which are comparable to jet fuel, as shown in Fig. 5. However, the downside of bioethanol is its low calorific value (only around 63% of fossil diesel) and low flash point (14 ºC). In addition, the low flash point characteristic makes bioethanol an explosive hazard [104].

2.4.2 Production of bioethanol

Bioethanol is produced by fermentation of sugar units derived from the sugar- (sugarcane, sugar beet), starch- (corn, wheat, barley) or cellulosic- (rice straw, wheat straw, wood) based biomass [105]. The pure sugar biomass feedstock (sugarcane and sugar beet) is relatively straightforward to be converted into bioethanol, due to fermentable sugar units that can be obtained relatively easy during extraction process of raw material. Starch-based feedstock such as corn and wheat are more complicated due to the long chain polymers of glucose that cannot be directly fermented. The polymers have to be broken down into monomers before fermentation process [106–108]. Cellulosic feedstock such as wood, straw and bagasse are the most difficult feedstock to breakdown as compared to sugar and starchy biomass due to their constituent parts [106–108].

The production process of bioethanol consists of (i) pre-treatment, (ii) hydrolysis, (iii) fermentation and (iv) purification processes [106–110], as shown in Fig. 4. The purpose of pre-treatment is to break the lignin and cellulose structure of the feedstock to make the feedstock more susceptible to enzymatic attack in hydrolysis process. Sugar biomasses such as sugarcane and sugar sorghum are usually mechanically crushed to extract the sugary juice from their stalks. For starchy-based feedstock, the dry or wet milling processes are commonly used [106–109]. Lignin provides the rigid structure for cellulosic feedstock. Thus, the conversion of lignocellulosic feedstock into ethanol is more difficult compared to sugar and starch based feedstock [106–108]. Steam explosion is one of the pre-treatment methods for cellulosic feedstock, whereas the feedstock is exposed to high pressure saturated steam to break the lignin structure so that the feedstock is more susceptible to hydrolysis [106,110].

Following the pre-treatment is the hydrolysis process which degrades the cellulose and hemicellulose from the raw material into simple sugar units for the fermentation process. Enzymatic hydrolysis has the advantage over the chemical hydrolysis for its lower cost [105]. Cellulase enzymes are typically used to convert the complex cellulose and hemicellulose into simple monomers [111–113]. Fermentation is the process in which sugar units are converted into bioethanol due to the enzymes secreted by microorganisms. Baker's yeast (Saccharomyces) is usually used to convert the glucose into ethanol [105]. Factors that affect the efficiency of fermentation are pH range, genetic stability, temperature range, inhibitor tolerance, and alcohol tolerance [105]. More complex sugar unit such as pentose and hexoses are usually more difficult to be fermented compared to glucose. Nonetheless, several methods have been introduced for pentose and hexoses fermentation, these include using genetically modified microbes [108,114], combination of both fermentation and enzyme hydrolysis [115], mixed cultures of yeasts [116] and fermentation of the pentose and hexose sugars simultaneously in a single reactor by a single microorganism's community [108,109,117].

2.4.3 Performance of bioethanol in gas turbines

Bioethanol is commonly utilised as replacement for gasoline to power the internal combustion engine. One of the commonly used bioethanol blends is E85, which contains 85% bioethanol/ethanol and 15% gasoline. Ethanol-gasoline blends with minimum 10% ethanol proportion are known as gasohol. Gasohol is common in countries such as Brazil, Denmark and the US [118]. Sallevelt et al. [119] examined the emissions of bioethanol combustion in a gas turbine engine (OPRA 2MWe OP16). NO_x emissions for bioethanol were 50% lower than that of diesel for equivalence ratios between 0.15 - 0.35 due to lower thermal NO_x. Moliere et al. [120] reported that neat bioethanol emits 50% NO_x lower as compared to neat naphtha in an industrial gas turbine (GE Frame 6B). Despite lower emissions of NO_x for bioethanol, CO emissions were rather inconsistent [119–121]. Santos and Nascimento [122] fuelled a 30 kW gas turbine with bioethanol at different loadings. A slight increase in CO was observed. Meanwhile, Khalil and Gupta [121] examined the combustion and emissions performance of bioethanol using a swirl burner. Fuel and preheated air were premixed upstream of the combustor prior to injection into the combustion chamber at high velocity (96 m/s) tangentially and in swirling mode. Bioethanol was shown to produce lower CO emissions as compared to kerosene under lean burning mode. Maximum reduction of was up to around 40 ppm at equivalence ratio of 0.8. The decrease in CO emissions was attributed to the excess oxygen that converts CO to CO_2.

Breaux and Acharya [123] studied the effect of water content in ethanol combustion using a swirl burner. It was found the water content reduced the flame temperature. When water content is below 20%, the effect of water on combustion performance was only minor and regarded as insignificant. However, as the water content increased beyond 20%, it impaired the continuous combustion process. Due to reduced flame temperature, NO_x emissions were found decreased from 13 ppm to 3 ppm for 0% and 30% of water content, respectively. Kun-Balog et al. [124] experimentally investigated the emission characteristics of bioethanol in both liquid and aqueous form against diesel and natural gas (NG). The experiment was conducted using a lab-scale swirl burner. The use of bioethanol resulted in 44% lower NO_x than diesel under the same thermal power output, which was attributable to the lower adiabatic flame temperature. The CO and UHC emissions were relatively low for bioethanol. However, aqueous bioethanol resulted in higher NO_x than its liquid counterpart.

2.5 Bio-oil

2.5.1 Properties of bio-oil

Bio-oil is liquid fuel obtained from the biomass pyrolysis. Bio-oil is also known as pyrolysis oil or bio-crude [125]. It is usually dark brown in colour and consists of organic compounds mixture. The pyrolysis process for the production of bio-oil involves heating of organic compound such as cellulose, hemicellulose and lignin in the absence of oxygen [125]. The process produces a range of products including char, bio-oil, and gaseous products. The composition of bio-oil depends on the temperature of the pyrolysis process [105]. At pyrolysis temperature below 600 K, formation of char is dominant. At temperature beyond 800 K, gaseous formation is dominant due to increased reaction rates that break the bond between carbons. For temperature in between 600 K and 800 K, bio-oil formation is dominant [105]. Table 6 shows the composition of bio-oil derived from several feedstocks [126]. Feedstock with high water content such as barley straw produces bio-oil with lower calorific value. Typical pyrolysis oil produced from feedstock with moderate water content (20-27% wt) contains approximately 15-16 MJ/kg of calorific value. While it was demonstrated that palm oil sludge is a promising feedstock, bio-oil produced from palm oil sludge resulted in notably higher calorific value (22.2 MJ/kg) and lower ash contents (0.23 wt%) [127].

Bio-oil is corrosive as it contains substantial amount of formic and acetic acids. Other trace elements such as sodium, calcium, potassium, and vanadium in pyrolysis oil are undesirable as they lead to formation of solid deposition [125,128]. The viscosity of bio-oil is relatively high (15.5 mm^2/s). These undesirable properties of bio-oil have restricted the usage in practical combustion system [129] despite having the advantages of being renewable, sustainable and potentially CO_2 neutral. Post-production methods have been introduced to improve the properties of bio-oil such as (i) hydrodeoxygenation, (ii) hydro-cracking, (iii) emulsification, (iv) steam reforming and (iv) esterification to enable applications in combustion systems [130].

2.5.2 Production of bio-oil

Bio-oil can be produced by 3 different processes, i.e. (a) conventional pyrolysis; (b) fast and flash pyrolysis and (c) hydrothermal liquefaction (HTL) [105,130], as shown in Fig. 4. Conventional pyrolysis operates in the temperature range of 300-650 °C. The residence time is relatively long, typically exceeding half an hour for each batch. Recent studies showed that the yield of bio-oil can be increased with elevated temperature and residence time [131]. The process breaks up the chemical bonds in the feedback, leading to the formation of pyrolysis products [105,130,132]. Fast pyrolysis requires higher operating temperature (650-1000 °C) to decompose the feedstock. The feedstock for pyrolysis can be of any organic biomass. Wood, agricultural wastes, crops, and sewage sludge have been utilised as feedstock for this process [130]. Due to high operating temperature, short residence time of less than 0.2 hour is required. The rapid heating of biomass leads to the formation of volatile vapours, aerosols and char. After rapid cooling, the volatile vapours and aerosol condense into bio-oil [128,133,134].

Flash pyrolysis operates at the temperature as high as 1200 °C. This process requires the shortest residence time (< 0.1 hour) as compared to other forms of pyrolysis. A major advantage of flash pyrolysis is the improved overall energy efficiency of the process

[105,130,132]. The reactor used for fast and flash pyrolysis has to be able to achieve high heating and heat transfer rate to minimise the formation of char.

Hydrothermal liquefaction (HTL) produces bio-oil in an aqueous medium that involves a series of complex processes such as solvolysis, dehydration, decarboxylation, and hydrogenation. The typical operating conditions are temperature ranging 300-400 °C, pressure up to 20 bar, and residence time of 0.2-1 hour. The primary product derived from this process is bio-oil. Contrary to fast and flash pyrolysis, feedstock drying is not necessary, making it suitable for wet biomass [130].

2.5.3 Performance of bio-oil in gas turbines

Gas turbine fuelled with bio-oil generally emits lower NO_x emissions as compared to baseline fuels [135,136]. Beran and Axelsson [136] studied the combustion properties of bio-oil using a micro gas turbine (OPRA OP-16). Emission results showed that NO_x emissions of bio-oil was 25% of that emitted by diesel at full engine loading, which is expected considering the lower calorific of bio-oil (37.6%) compared to the latter. Zheng and Kong [137] studied the emissions of rice husk bio-oil using a combustor fitted with an internal-mixed atomiser. Results showed that NO_x concentration increased from 211 to 370 ppm while SO_x concentration increased from 11.6 to 25.9 ppm as equivalence ratio increased from 1.2 to 2.0. The increase of NO_x emissions was due to oxidation of nitrogen in post-flame region and oxidation of nitrogen compounds in the fuels.

Lopez Juste and Salva Monfort [138] compared the combustion performance of JP-4 and 80% bio-oil/ethanol blends by using a gas turbine burner equipped with pressure swirl atomiser. The emissions of NO_x for bio-oil/ethanol blend were found to be similar to JP-4 at 1 MJ/kg energy input. At a higher energy input of 1.36 MJ/kg, NO_x emissions for JP-4 were 4 times higher than bio-oil, possibly due to higher flame temperature exhibited by JP-4. Lupadin et al. [135] compared several types of alternative fuels against diesel by using a 2.5 MW gas turbine (GT2500) as shown in Table 7. For bio-oil, higher fuel flow rate was needed to achieve comparable output power and exhaust gas temperature as baseline diesel. The fuel flow rate required by diesel to generate 2510 kW of output power was 1071 l/hr while bio-oil required 1800 l/hr of fuel supply to generate 2650 kW of output power. The exhaust gas temperature for both fuels was only differ by 17 °C. Bio-oil emitted higher CO and lower sulphur oxide emissions compared to baseline fuels.

Zadmajid et al. [139] reported that bio-oil and 80/20 bio-oil/ethanol blend showed high emissions of CO at 2284 and 650 ppm, respectively, under swirl burning condition. By using a modified burner with increased swirl and main air supply, the CO and UHC emissions showed significant reduction to below 10 ppm. Apart from burner geometry, the choice of feedstock and quality of bio-oil are important factors that determine the level of emissions. Table 6 shows that bio-oil produced from wood contains higher calorific value and lower viscosity than the other feedstock. Although combustion of bio-oil has shown lower sulphur and nitrogen oxide emissions, direct usage of bio-oil in gas turbine are limited due to inherent inferior properties such as high viscosity and acidity level. Direct bio-oil usage caused high level of particulate matter emissions, while other issues related to bio-oil are solid deposition on turbine due to the presence of trace elements and fuel nozzle blockage during operation [140]. The high viscosity of bio-oil affects fuel atomisation which subsequently leads to reduced combustion efficiency. Preheating of fuel and improvement in atomisation technique can be applied to reduce fuel viscosity. Crayford et al. [141] reported that bio-oil exhibited spray characteristics similar with diesel when preheated the fuel to 80 °C.

2.6 Fischer-Tropsch (FT) fuel

2.6.1 Properties of FT fuel

Fischer-Tropsch (FT) synthesis refers to the process of converting syngas into liquid fuels at high temperature conditions in the presence of catalyst [105,132], as shown in Fig. 4. FT fuels are clean compared to fossil fuels due to the absence of nitrogen, sulphur, and aromatics. Hydrocarbon fuels of different chain length can be produced from FT synthesis via any feedstock that contains carbon, e.g. coal, biomass and natural gas. It has been reported that FT fuel is compatible with existing jet engine systems [105] with calorific value of 43 MJ/kg, viscosity of 1.3 mm^2/s at 40 °C and density of 810 kg/m^3 at 15 °C (Fig. 5). These properties are comparable with Jet A-1, making it a potential alternative jet fuels besides HVO [26,142].

2.6.2 Production of FT Fuel

The process of producing FT fuel consists of three main stages as shown in Fig. 8: (i) gasification of biomass into syngas; (ii) gas cleaning and conditioning, and (iii) FT synthesis to produce liquid fuel [105].

The FT process is essentially a stepwise hydrocarbon chain growth process that disintegrates the carbon monoxide and hydrogen in the syngas to form mainly paraffins and olefins as shown in reactions 1 and 2 [143]:

Paraffins: $$n\,CO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + n\,H_2O \quad (1)$$

Olefins: $$n\,CO + 2n\,H_2 \rightarrow C_nH_{2n} + n\,H_2O \quad (2)$$

Both reactors and catalyst are the governing factors that control the products of FT synthesis. Three reactors have been designed and widely used for FT fuel synthesis, namely fixed bed, fluidised bed and slurry reactors [105], as shown in Fig. 9. Fixed bed reactors consist of catalyst tube bundles immersed in steam, whereby the heat from the surrounding steam is absorbed to achieve the FT synthesis process as syngas flows through catalyst tube bundles.

Despite easier to operate, the major drawback is its high capital cost and maintenance work that involves high cost and long down time, which impairs the overall efficiency of the plant [144].

In a fluidised bed reactor, the syngas is heated up before it is exposed to the catalyst. Fluidised bed reactors possess higher heat exchange efficiency compared to fixed bed reactor due to the circulating flow design. The construction of the reactor is also simpler which greatly reduced the overall production cost. On the other hand, catalyst removal from the reactor is also simpler which reduces maintenance time. However, expensive scrubbing system is needed to separate the small catalyst particles from the outlet gas [105,144].

In slurry reactors, the catalyst is suspended in the liquid where the syngas is bubbled. Heat is supplied by the steam flow. Slurry reactors possess excellent heat transfer, thus increases the overall process efficiency. In addition, the ease of catalyst replacement also reduces production cost. The down side of it is the difficulty in separating the catalyst and wax [144,145]. Different types of reactors have their own advantages and disadvantages, the optimum choice depends on the final target products and operating conditions [105].

2.6.3 Performance of FT fuel in gas turbines

The use of FT fuel in gas turbines has been widely researched. Hermann et al. [146,147] examined the performance of FT fuel using a Volvo Aero gas turbine (VT40). FT fuel achieved higher combustion efficiency compared to Jet A-1 for equivalence ratio of 0.1 to 0.2, with a maximum improvement around 2%. Meanwhile, higher NO_x (>3 g/kg) was emitted by FT fuel due to higher flame temperature compared to Jet A-1 (<3 g/kg). However, NO_x emissions against Jet A-1 were also found to be reduced [97,148]. Chan et al. [97] compared the performance of synthetic kerosene with aromatics (SKA), FT synthetic paraffinic kerosene (SPK), and 50-50 blend of Jet A-1 and hydroprocessed SPK using a turbofan engine (CF700-

2D-2). It was reported that FT fuel led to a reduction in NO_x emissions. At 80% engine loading, neat FT fuel achieved a reduction of 32% in NO_x compared to Jet A-1 due to lower primary zone temperature. The CO emissions tend to show a reduction trend when compared with conventional jet fuels [149–151]. Lobo et al. [149,150] compared the emissions of FT fuel against Jet A-1 using a CFM56-7B gas turbine engine. A reduction of 5−10% in carbon monoxide was achieved by FT fuel due to lower fuel viscosity.

Bulzan et al. [152] operated a CFM56-2C1 gas turbine engine fuelled with FT fuel and JP-8. The emission data showed that sulphur dioxide emissions for JP-8 was higher than that of FT fuel by a factor of 2. The low SO_x emissions was due to the absence of sulphur in the FT fuel. Furthermore, soot emissions have been consistently lower for FT fuels compared to baseline fossil fuels [97,100,149–155]. The reduction in soot is largely attributed to the absence of aromatic rings in the fuel [156,157].

Corporan et al. [158] studied the particulate matter emissions of FT fuel using a T63 turboshaft engine and a swirl stabilised combustor. Particulate matter (PM) emissions for neat FT fuel, blend of FT fuel/JP-8 (75/25, 50/50 and 75/25) and neat JP-8 were compared. They found that FT fuel produced the finest particle size compared to blended fuel and neat JP-8. During cruising conditions, particle mass for FT fuel was 95% smaller compared to JP-8, which was attributable to the reduction in soot nuclei. Sulphur oxide emissions for FT fuel were also lower as compared to neat JP-8. Bester and Yates [153] also reported significant reduction in soot for FT fuel by 86.8% compared to baseline fuel. The improved soot oxidation by FT fuel combustion led to reduced fluid flow frictional losses in combustor, thus contributing to an improved thermal efficiency. Thermal efficiency for FT fuel engine was increased by an average of 1.17% at cruising condition. The improvement was attributed to the higher H/C ratio of FT fuel compared to Jet A-1. Table 8 summarises the combustion tests of FT fuel conducted in gas turbine engines.

Transient, ignition and extinction performance of gas turbine engine powered by FT fuel have been widely researched. Vukadinovic et al. [159] investigated the combustion characteristic of FT fuel, Jet A-1 and aromatics-enriched FT fuel using a combustion vessel. Although all of the tested fuels exhibited similar laminar flame velocity for equivalence ratios 0.6 - 1.5, the extinction resistance characteristic for FT fuel was observed to be stronger than that of Jet A. Conversely, Moses et al. [154,155] found no distinct difference in the ignition and extinction performance for synthetic jet fuel and Jet A-1. The study was conducted using a Pratt & Whiney JT-9D engine with a series of take-off cycles was imposed on the engine. There was no significant degradation on engine performance when using synthetic jet fuel. In addition, synthetic jet fuel showed nearly 22% droplet size reduction against Jet A-1 at -40 °C.

Davidson et al. [160] showed that neat FT fuel was more fuel efficient than Jet A-1 in a test using a General Electric CF-700-2D-2 engine. At 80% engine loading, the neat FT fuel achieved 113.5 kg/kN-hour specific fuel consumption, while Jet A-1 achieved 114.5 kg/kN-hour. For transient testing, FT fuel showed slightly slower shaft speed acceleration as compared to Jet A-1. In another testing using TRS-18 gas turbine engine, Davidson et al. [161] reported that there was no significant difference in transient shaft acceleration between FT fuel and Jet A-1. Meanwhile, all fuels tested showed comparable specific fuel consumption at steady state conditions. In real flight tests, synthetic jet fuels showed no obvious sign of engine performance deterioration. Transient engine speed acceleration was comparable to baseline fossil jet fuels [162,163]. The findings were consistent with laboratory testing, implying that FT fuel is a viable alternative jet fuel.

3.0 Considerations of alternative fuels as gas turbine fuels

The inferior viscosity of SVO restricts its usage in existing gas turbine system. Fuel preheating is an effective method to reduce the fuel viscosity. The use of twin-fluid atomiser and elevating the ALR can be deployed to atomise the viscous SVO [14,43,44]. Other atomisation techniques such as flow-blurring atomisation [39] and superheated steam atomisation [40] may be incorporated into fuel preheating system to improve atomisation quality. Nonetheless, comprehensive studies are needed as these techniques are still widely under-researched, leading to a lack of thorough understanding on the overall effect on gas turbine operation.

Although combustion performance of SVO can be potentially improved via advancement in fuel delivery and atomisation technologies, extensive use of SVO may lead to adverse environmental and socioeconomic effects. Ji and Long [164] concluded from their study that overwhelming land occupation for feedstock plantation of first generation SVO causes habitat fragmentation and bio-invasion. Furthermore, Koizumi [165] reported a direct competition between agricultural based biofuel feedstock and food production. Elevating the production of agricultural based biofuel feedstock also gives rise to the cost of agricultural commodity [165]. The advantages of SVO include the simple production process, storage ease and near zero toxicity. However, the use of SVO should not be prioritised for large-scale power generation as the fuel used will divert food away from the market and incurs adverse ecological dilemma.

Direct usage of bio-oil in gas turbine is also limited by its high viscosity. Moreover, the high bio-oil acidity level, high particulate matter (PM) emissions, solid deposition on turbine due to the presence of trace elements and fuel nozzle blockage during operation are additional drawbacks that inhibit direct bio-oil usage in gas turbine [140]. Thus, upgrading the physical properties of bio-oil is a more promising approach to expedite its mainstream application in gas turbine. Among many types of upgrading methods, esterification/solvent addition is undoubtedly the most practical way of enhancing the physical properties of bio-oil owing to its simplicity and involves substantially lower cost [128]. Alcoholic fuels, diesel and biodiesel are possible solvents that have been proposed [166,167]. Nonetheless, endeavour studies are required to acquire overall understanding on the effect of blending ratio on gas turbine performance, long term operation and material compatibility.

Bio-oil can be produced from a variety of organic feedstock such as lignocellulosic, plant and agricultural waste. Diversified bio-oil feedstock minimises its negative socioeconomic and ecological impacts. Nonetheless, physical properties of bio-oil produced from different feedstock are varied. Spray combustion characteristics and emission performance of bio-oil are greatly affected by its compositions such as ash, tar, char, water and nitrogen contents. Comprehensive studies are needed to characterise their individual influence on gas turbine performance. Bio-oil specifications for various gas turbine applications can be subsequently formed based on parametric studies.

For bioethanol, current findings show that is cleaner than fossil-based fuels with considerable lower emissions of NO, CO and UHC at identical thermal output power [124]. The calorific value of bioethanol is inherently lower than diesel and natural gas, thus increasing fuel supply to achieve the identical thermal output power with fossil fuels could undesirably elevate the overall operating cost. Instead of totally replacing fossil fuel, bioethanol can be used as supplementary fuel to be blended with conventional or more viscous fuels. Choi et al. [168] blended ethanol with biocrude-oil and showed a reduction in CO emissions against neat ethanol and biocrude-oil. Martin and Boateng [169] reported that blending switchgrass pyrolysis oil with ethanol in 20/80 ratio by weight achieved comparable CO emissions with neat ethanol but the NO emissions increased considerably. Table 9 compares the feasibility and considerations of different alternative fuels as gas turbine fuels.

Biodiesel has shown to be a viable biofuel in industrial gas turbine in view of its comparable properties with conventional fuels. The stringent requirement of jet fuel compliance limits the application of biodiesel in aviation-based gas turbine, as shown in Table 10. Land-based industrial gas turbine is fuel-robust by design, allowing the use of biodiesel. The similarity in physical properties between biodiesel and diesel enables the application of the former in gas turbine with minimal modification to the existing system. Gas turbine manufacturers have introduced fuel-flexible gas turbine that allows the usage of biodiesel [12,13]. Present studies focus heavily on first and second-generation biodiesels. The shifting trend into third generation biofuel uptake prompts future research to investigate the combustion characteristics of biodiesel made from third generation feedstock such as algae.

Despite the successful test flights with HVO/jet-fuels blends ascertaining its capability for future aviation and power generation industries [171], current studies provide only limited understanding on HVO combustion characteristics in gas turbine. Owing to the difference in chemical composition against conventional jet fuels, thorough understandings on fundamentals HVO combustion characteristics is essential, which include properties such as flame speed, extinction, reactive species quantification effects on combustion performance [172]. Furthermore, assessment of HVO life cycle analysis is also important. Depending on the feedstock types, CO_2 life-cycle for HVO can vary significantly [171]. This is primarily due to HVO being produced from SVO at present stage [94]. Apart from SVO, it was also reported that bio-oil can be converted into HVO via hydrodeoxygenation process [93,94]. This inherently minimises its negative socioeconomic and ecological impacts since wide variety of organic matters can be used as feedstock for producing bio-oil [94,132]. Nonetheless, technical difficulties currently faced by hydrodeoxygenation process include optimum catalyst selection for bio-oil from different feedstock [94]. The optimum temperature selection is another key element in hydrodeoxygenation process to eliminate oxygen contents and elevating the calorific value of HVO produced [94]. In essence, HVO shows comparable physical properties and combustion performance to conventional jet fuels, but sustainable feedstocks such as bio-oil, second and third generation feedstock should be prioritised for future HVO production.

FT fuel has demonstrated superior emissions, transient, ignition and extinction performances against fossil-based jet fuels. Despite the proven feasibility of FT fuel as alternative jet fuel [173], the high production cost prohibits its wide usage. Biomass is regarded as cleaner feedstock option as compared to coal. It is projected by the International Air Transport Association (IATA) [173] that the cost of synthetic jet fuels will approach those of conventional jet fuels by year 2030 due to the climate change policies that favours diversification of energy sources and lower production cost.

4.0 Conclusions

The production methods and properties of six potential alternative liquid biofuels for gas turbine and their combustion performances have been reviewed. HVO and FT have physical properties that resemble jet fuels. The long-chain hydrocarbon of FT fuel and HVO has no oxygen molecule and contains energy density similar to that of jet fuel. The main advantage of these fuels is low pour point that enables application in aviation gas turbine especially at high altitude. Aviation gas turbine tests have shown comparable performance as jet fuel with improved particulate matter emissions. Extensive use of FT fuel and HVO at present stage is mainly inhibited by the high production cost. Biodiesel has slightly poorer physical properties as compared to conventional fossil fuel, notably lower energy content, slightly higher viscosity and density and high pour point. However, biodiesel tend to exhibit cleaner combustion characteristics, as shown by the lower NO_x, CO and soot emissions. The fuel-bound oxygen content can assist local combustion and prohibits the formation of soot.

Biodiesel is a good fuel candidate for stationery gas where the requirement is less stringent as compared to jet fuels.

SVO and bio-oil are potential fuels for micro gas turbines, but the inherent nature of high viscosity and density may result in fuel flow delivery and clogging of atomizer orifice. Modified fuel delivery system with heating capability and improved atomisation technique can be applied to overcome the limitations of the fuels. Bioethanol is another possible choice of biofuels for gas turbine. The properties of bioethanol differ significantly from diesel as the former has low flash point, low viscosity and high vapour pressure. Application of this fuel in gas turbine requires modification in the fuel delivery and fuel storage systems. Studies of bioethanol in gas turbine are relatively scarce although the fuel is widely applied in reciprocating gasoline engine. This review shows that the robust nature of gas turbine and the development of multi-fuel capable gas turbine enable operation with biofuels. This approach is beneficial to the operators from the standpoint of meeting emission targets and reducing operating costs.

Acknowledgements

The authors gratefully acknowledge the financial support from the Ministry of Education and Universiti Teknologi Malaysia (GUP Tier-1, vot no.: 09H79), and the Newton Advanced Fellowship (NA160115) for C.T Chong.

References

[1] Nigam PS, Singh A. Production of liquid biofuels from renewable resources. Prog Energy Combust Sci 2011;37:52–68.

[2] Alternative Fuels Data Center. Alternative Fuel Price Report 2018. http://www.afdc.energy.gov/fuels/prices.html (accessed June 20, 2018).

[3] EIA. U.S. Energy Facts Explained 2017.

[4] ATAG. Beginner's Guide to Aviation Biofuels 2011.

[5] Goldenberg S, Vidal J, Taylor L, Vaughan A, Harvey F. Paris climate deal: nearly 200 nations sign in end of fossil fuel era. Guard 2015.

[6] Cornwall W. Inside the Paris climate deal. Science (80-) 2015;350:1451.

[7] Hai-Bin Z, Han-Cheng D, Hua-Xia L, Wen-Tao W. U.S. withdrawal from the Paris Agreement : Reasons , impacts , and China's response. Adv Clim Chang Res 2017;8:220–5.

[8] ATAG. Powering the future of flight 2011.

[9] Breeze P. Gas turbines and combined cycle power plants. Power Gener. Technol. 2nd ed., Elsevier; 2005, p. 43–61.

[10] Wärtsilä Corporation. Combined Cycle Plant for Power Generation: Introduction 2018. https://www.wartsila.com/energy/learning-center/technical-comparisons/combined-cycle-plant-for-power-generation-introduction (accessed May 7, 2018).

[11] U.S. EIA. Average utilization for natural gas combined-cycle plants exceeded coal plants in 2015 2016.

[12] Kliemke H, Johnke T, Asia P. Gas Turbine Modernization - Fuel Conversion and Special Fuel Applications for the Asian Market 2012:1–20.

[13] Jones R, Goldmeer J, Monetti B. Addressing gas turbine fuel flexibility 2011.

[14] Prussi M, Chiaramonti D, Riccio G, Martelli F, Pari L. Straight vegetable oil use in Micro-Gas Turbines: System adaptation and testing. Appl Energy 2012;89:287–95.

[15] Chiariello F, Allouis C, Reale F, Massoli P. Gaseous and particulate emissions of a micro gas turbine fuelled by straight vegetable oil – kerosene blends. Exp Therm Fluid Sci 2014;56:16–22.

[16] Biona JBM, Licauco J. Performance, smoke characteristics and economics of pre-

heated used vegetable oil utilization in Philippine public utility jeepneys. Clean Technol Environ Policy 2009;11:239–45.

[17] Sonar D, Soni SL, Sharma D, Srivastava A, Goyal R. Performance and emission characteristics of a diesel engine with varying injection pressure and fuelled with raw mahua oil (preheated and blends) and mahua oil methyl ester. Clean Technol Environ Policy 2015;17:1499–511.

[18] Atabani AE, Silitonga AS, Ong HC, Mahlia TMI, Masjuki HH, Badruddin IA, et al. Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew Sustain Energy Rev 2013;18:211–45.

[19] Blin J, Brunschwig C, Chapuis A, Changotade O, Sidibe SS, Noumi ES, et al. Characteristics of vegetable oils for use as fuel in stationary diesel engines - Towards specifications for a standard in West Africa. Renew Sustain Energy Rev 2013;22:580–97.

[20] Agarwal AK, Rajamanoharan K. Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine. Appl Energy 2009;86:106–12.

[21] Haldar SK, Ghosh BB, Nag A. Studies on the comparison of performance and emission characteristics of a diesel engine using three degummed non-edible vegetable oils. Biomass Bioenergy 2009;33:1013–8.

[22] National Renewable Energy Laboratory (NREL). Straight Vegetable Oil as a Diesel Fuel? Washington, D.C.: 2014.

[23] McMurry J. Organic Chemistry. Cengage Learning; 2008.

[24] Hoekman SK, Broch A, Robbins C, Ceniceros E, Natarajan M. Review of biodiesel composition, properties, and specifications. Renew Sustain Energy Rev 2012;16:143–

69.

[25] Canakci M, Sanli H. Biodiesel production from various feedstocks and their effects on the fuel properties. J Ind Microbiol Biotechnol 2008;35:431–41.

[26] Bezergianni S, Dimitriadis A. Comparison between different types of renewable diesel. Renew Sustain Energy Rev 2013;21:110–6.

[27] Baczewski K, Szczawiński P. Investigation properties of rapeseed oil methyl esters/aviation turbine fuel Jet A-1 blends. J KONES Powertrain Transp 2011;18:15–22.

[28] Chong CT, Hochgreb S. Spray combustion characteristics of palm biodiesel. Combust Sci Technol 2012;184:1093–107.

[29] Illinois Clean Fuels. Synthetic Fuel 2018.

[30] Mahapatra SS. Experimentation and Evaluation of Tyre Pyrolysis Oil. National Institute of Technology, Rourkela, 2014.

[31] Oasmaa A, Peacocke C. Properties and fuel use of biomass derived fast pyrolysis liquids. A guide. 2010.

[32] Sandia National Laboratories. Fuels 2017.

[33] Wright L, Boundy B, Badger PC, Perlack B, Davis S. Biomass Energy Data Book. Oak Ridge, Tennessee: 2009.

[34] Xing-Cai L, Jian-Guang Y, Wu-Gao Z, Zhen H. Effect of cetane number improver on heat release rate and emissions of high speed diesel engine fueled with ethanol-diesel blend fuel. Fuel 2004;83:2013–20.

[35] Jayadas NH, Nair KP. Coconut oil as base oil for industrial lubricants-evaluation and modification of thermal, oxidative and low temperature properties. Tribol Int 2006;39:873–8.

[36] Karmakar A, Karmakar S, Mukherjee S. Properties of various plants and animals

feedstocks for biodiesel production. Bioresour Technol 2010;101:7201–10.

[37] Singh SP, Singh D. Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: A review. Renew Sustain Energy Rev 2010;14:200–16.

[38] Achten WMJ, Verchot L, Franken YJ, Mathijs E, Singh VP, Aerts R, et al. Jatropha bio-diesel production and use. Biomass and Bioenergy 2008;32:1063–84.

[39] Niguse Y, Agrawal A. Low-Emission, Liquid Fuel Combustion System for Conventional and Alternative Fuels Developed by the Scaling Analysis. J Eng Gas Turbines Power 2015;138:41502.

[40] Kun-Balog A, Sztankó K. Reduction of pollutant emissions from a rapeseed oil fired micro gas turbine burner. Fuel Process Technol 2015;134:352–9.

[41] Józsa V, Kun-Balog A. Stability and emission analysis of crude rapeseed oil combustion. Fuel Process Technol 2017;156:204–10.

[42] Hashimoto N, Nishida H, Ozawa Y. Fundamental combustion characteristics of Jatropha oil as alternative fuel for gas turbines. Fuel 2014;126:194–201.

[43] Sallevelt JLHP, Gudde JEP, Pozarlik AK, Brem G. The impact of spray quality on the combustion of a viscous biofuel in a micro gas turbine. Appl Energy 2014;132:575–85.

[44] Chiaramonti D, Rizzo AM, Spadi A, Prussi M, Riccio G, Martelli F. Exhaust emissions from liquid fuel micro gas turbine fed with diesel oil, biodiesel and vegetable oil. Appl Energy 2013;101:349–56.

[45] Panchasara H V., Simmons BM, Agrawal AK, Spear SK, Daly DT. Combustion Performance of Biodiesel and Diesel-Vegetable Oil Blends in a Simulated Gas Turbine Burner. J Eng Gas Turbines Power 2009;131:31503.

[46] Schonborn A, Ladommatos N, Williams J, Allan R, Rogerson J. The influence of molecular structure of fatty acid monoalkyl esters on diesel combustion. Combust

Flame 2009;156:1396–412.

[47] Abomohra AE-F, Jin W, Tu R, Han S-F, Eid M, Eladel H. Microalgal biomass production as a sustainable feedstock for biodiesel: Current status and perspectives. Renew Sustain Energy Rev 2016;64:596–606.

[48] Dey AR, Misra RD. Effect of infiltration of bio-lubricant on the performance of a compression ignition engine fuelled with biodiesel blends. Clean Technol Environ Policy 2017;19:553–63.

[49] Nautiyal P, Subramanian KA, Dastidar MG. Experimental investigation on performance and emission characteristics of a compression ignition engine fueled with biodiesel from waste tallow. Clean Technol Environ Policy 2017;19:1667–77.

[50] Giakoumis EG. A statistical investigation of biodiesel physical and chemical properties, and their correlation with the degree of unsaturation. Renew Energy 2013;50:858–78.

[51] Thangaraja J, Anand K, Mehta PS. Biodiesel NOx penalty and control measures - A review. Renew Sustain Energy Rev 2016;61:1–24.

[52] Rothsay Biodiesel. Biodiesel Overview 2010.

[53] BP Australia. Long Term Storage of Diesel 2005.

[54] Alternative Fuels Data Center. Federal Laws and Incentives for Biodiesel 2017.

[55] Malaysia Biodiesel Association. MBA Press Release on Government's Announcement to Implement B10 Programme for Transport Sector and B7 Programme for Industrial Sector 2016.

[56] Moser B. Biodiesel production, properties, and feedstocks. Vitr Cell Dev Biol - Plant 2009;45:229–66.

[57] Helwani Z, Othman MR, Aziz N, Fernando WJN, Kim J. Technologies for production of biodiesel focusing on green catalytic techniques: A review. Fuel Process Technol

2009;90:1502–14.

[58] Park J, Kim B, Lee JW. In-situ transesterification of wet spent coffee grounds for sustainable biodiesel production. Bioresour Technol 2016;221:55–60.

[59] Kim B, Im H, Lee JW. In situ transesterification of highly wet microalgae using hydrochloric acid. Bioresour Technol 2015;185:421–5.

[60] Atabani AE, Silitonga AS, Badruddin IA, Mahlia TMI, Masjuki HH, Mekhilef S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renew Sustain Energy Rev 2012;16:2070–93.

[61] Sirisomboonchai S, Abuduwayiti M, Guan G, Samart C, Abliz S, Hao X, et al. Biodiesel production from waste cooking oil using calcined scallop shell as catalyst. Energy Convers Manag 2015;95:242–7.

[62] Demirbas A. Comparison of transesterification methods for production of biodiesel from vegetable oils and fats. Energy Convers Manag 2008;49:125–30.

[63] Patil PD, Reddy H, Muppaneni T, Deng S. Biodiesel fuel production from algal lipids using supercritical methyl acetate (glycerin-free) technology. Fuel 2017;195:201–7.

[64] García-Martínez N, Andreo-Martínez P, Quesada-Medina J, de los Ríos AP, Chica A, Beneito-Ruiz R, et al. Optimization of non-catalytic transesterification of tobacco (Nicotiana tabacum) seed oil using supercritical methanol to biodiesel production. Energy Convers Manag 2017;131:99–108.

[65] Cheng Tung C, Jo-Han N, Solehin A, Srithar R. Oxygenated palm biodiesel: Ignition, combustion and emissions quantification in a light-duty diesel engine. Energy Convers Manag 2015;101:317–25.

[66] Chong CT, Hochgreb S. Spray Flame Study Using a Model Gas Turbine Swirl Burner. Appl Mech Mater 2013;316–317:17–22.

[67] Chong CT, Hochgreb S. Spray flame structure of rapeseed biodiesel and Jet-A1 fuel.

Fuel 2014;115:551–8.

[68] Chong CT, Hochgreb S. Spray and combustion characteristics of biodiesel: Non-reacting and reacting. Int Biodeterior Biodegrad 2015;102:353–60.

[69] Hashimoto N, Ozawa Y, Mori N, Yuri I, Hisamatsu T. Fundamental combustion characteristics of palm methyl ester (PME) as alternative fuel for gas turbines. Fuel 2008;87:3373–8.

[70] Lefebvre AH, Ballal DR. Gas Turbine Combustion: Alternative Fuels and Emissions. 3rd ed. CRC Press; 2010.

[71] Erazo JA, Parthasarathy R, Gollahalli S. Atomization and combustion of canola methyl ester biofuel spray. Fuel 2010;89:3735–41.

[72] Li L, Zhang X, Wu Z, Deng J, Huang C. Experimental study of biodiesel spray and combustion characteristics. Powertrain Fluid Syst Conf Exhib 2006.

[73] Chong CT, Hochgreb S. Flame structure, spectroscopy and emissions quantification of rapeseed biodiesel under model gas turbine conditions. Appl Energy 2017;185:1383–92.

[74] Sequera D, Agrawal AK, Spear SK, Daly DT. Combustion Performance of Liquid Biofuels in a Swirl-Stabilized Burner. J Eng Gas Turbines Power 2008;130:32810.

[75] Simmons BM, Agrawal AK. Combustion Science and Technology Flow Blurring Atomization for Low- Emission Combustion of Liquid Biofuels. Combust Sci Technol 2012;184:660–75.

[76] Kurji H, Valera-Medina A, Runyon J, Giles A, Pugh D, Marsh R, et al. Combustion characteristics of biodiesel saturated with pyrolysis oil for power generation in gas turbines. Renew Energy 2016;99:443–51.

[77] Balakrishnan A, Parthasarathy RN, Gollahalli SR. Effects of degree of fuel unsaturation on NOx emission from petroleum and biofuel flames. Fuel

2016;182:798–806.

[78] Lanjekar RD, Deshmukh D. A review of the effect of the composition of biodiesel on NOx emission, oxidative stability and cold flow properties. Renew Sustain Energy Rev 2016;54:1401–11.

[79] Bolszo CD, McDonell VG. Emissions optimization of a biodiesel fired gas turbine. Proc Combust Inst 2009;32:2949–56.

[80] Krishna CR. Performance of the Capstone C30 Microturbine on Biodiesel Blends 2007:1–11.

[81] Nascimento MAR, Lora ES, Corrêa PSP, Andrade R V., Rendon MA, Venturini OJ, et al. Biodiesel fuel in diesel micro-turbine engines: Modelling and experimental evaluation. Energy 2008;33:233–40.

[82] Nascimento MAR, Sierra R. GA, Silva Lora EE, Rendon MA. Performance and Emission Experimental Evaluation and Comparison of a Regenerative Gas Microturbine Using Biodiesel From Various Sources as Fuel. J Energy Resour Technol 2011;133:22204.

[83] Habib Z, Parthasarathy R, Gollahalli S. Performance and emission characteristics of biofuel in a small-scale gas turbine engine. Appl Energy 2010;87:1701–9.

[84] Rehman A, Phalke DR, Pandey R. Alternative fuel for gas turbine: Esterified jatropha oil-diesel blend. Renew Energy 2011;36:2635–40.

[85] Liu K, Wood JP, Buchanan ER, Martin P, Sanderson VE. Biodiesel as an Alternative Fuel in Siemens Dry Low Emissions Combustors: Atmospheric and High Pressure Rig Testing. J Eng Gas Turbines Power 2010;132:11501.

[86] Ellis W, Lear WE, Singh B, Srinivasan A, Student M, Candidate D, et al. Flameless Combustion of Biofuels in a Semi-Closed Cycle Gas Turbine. 46th AIAA Aerosp. Sci. Meet. Exhib., Reno, Nevada: American Institute of Aeronautics and Astronautics;

2008, p. AIAA 2008-1140.

[87] Moliere M, Panarotto E, Aboujaib M, Bisseaud JM, Campbell A, Citeno J, et al. Gas turbines in alternative fuel applications: Biodiesel field test. Proc Asme Turbo Expo 2007, Vol 1 2007:397–406.

[88] Pucher G, Allan W, LaViolette M, Poitras P. Emissions From a Gas Turbine Sector Rig Operated With Synthetic Aviation and Biodiesel Fuel. J Eng Gas Turbines Power 2011;133:111502.

[89] Timko MT, Herndon SC, De La Rosa Blanco E, Wood EC, Yu Z, Miake-Lye RC, et al. Combustion products of petroleum jet fuel, a fischer-tropsch synthetic fuel, and a biomass fatty acid methyl ester fuel for a gas turbine engine. Combust Sci Technol 2011;183:1039–68.

[90] Corporan E, Reich R, Monroig O, DeWitt MJ, Larson V, Aulich T, et al. Impacts of biodiesel on pollutant emissions of a JP-8-fueled turbine engine. J Air Waste Manage Assoc 2005;55:940–9.

[91] Abu Talib AR, Gires E, Ahmad MT. Performance Test of a Small-Scale Turbojet Engine Running on a Palm Oil Biodiesel - Jet a Blend. J Fuels 2014;2014:1–9.

[92] Bart JCJ, Palmeri N, Cavallaro S. Biodiesel Science and Technology. Woodhead Publishing Limited; 2010.

[93] Atsonios K, Panopoulos KD, Nikolopoulos N, Lappas AA, Kakaras E. Integration of hydroprocessing modeling of bio-liquids into flowsheeting design tools for biofuels production. Fuel Process Technol 2018;171:148–61.

[94] Patel M, Kumar A. Production of renewable diesel through the hydroprocessing of lignocellulosic biomass-derived bio-oil: A review. Renew Sustain Energy Rev 2016;58:1293–307.

[95] Singh D, Subramanian KA, Garg MO. Comprehensive review of combustion,

performance and emissions characteristics of a compression ignition engine fueled with hydroprocessed renewable diesel. Renew Sustain Energy Rev 2018;81:2947–54.

[96] Sonthalia A, Kumar N. Hydroprocessed vegetable oil as a fuel for transportation sector: A review. J Energy Inst 2017:1–17.

[97] Chan TW, Chishty W a., Canteenwalla P, Buote D, Davison CR. Characterization of Emissions From the Use of Alternative Aviation Fuels. J Eng Gas Turbines Power 2015;138:11506.

[98] Baranski JA, Hoke JL, Litke PJ, Schauer FR. Preliminary Characterization of Bio-fuels using a Small Scale Gas Turbine Engine. 49th AIAA Aerosp Sci Meet Incl New Horizons Forum Aerosp Expo 2011:1–10.

[99] Klingshirn CD, DeWitt M, Striebich R, Anneken D, Shafer L, Corporan E, et al. Hydroprocessed Renewable Jet Fuel Evaluation, Performance, and Emissions in a T63 Turbine Engine. J Eng Gas Turbines Power 2012;134:51506.

[100] Chishty W a, Davison CR, Bird J, Chan T, Cuddihy K, McCurdy M, et al. Emissions Assessment of Alternative Aviation Fuel At Simulated Altitudes. Proc. ASME Turbo Expo 2011, Vancouver, British Columbia, Canada: ASME (Paper No. GT2011-45133); 2011, p. 51–61.

[101] Pucher G, Allan W, Poitras P. Characteristics of deposits in gas turbine combustion chambers using synthetic and conventional jet fuels. J Eng Gas Turbines Power 2013;135:1469–78.

[102] Hui X, Kumar K, Sung CJ, Edwards T, Gardner D. Experimental studies on the combustion characteristics of alternative jet fuels. Fuel 2012;98:176–82.

[103] Buffi M, Valera-medina A, Marsh R, Pugh D, Giles A, Runyon J, et al. Emissions characterization tests for hydrotreated renewable jet fuel from used cooking oil and its blends. Appl Energy 2017;201:84–93.

[104] Astbury GR. A review of the properties and hazards of some alternative fuels. Process Saf Environ Prot 2008;86:397–414.

[105] Luque R, Campelo J, Clark J, editors. Handbook of biofuels production. Woodhead Publishing Limited; 2011.

[106] Vohra M, Manwar J, Manmode R, Padgilwar S, Patil S. Bioethanol production: Feedstock and current technologies. J Environ Chem Eng 2014;2:573–84.

[107] Zhang K, Pei Z, Wang D. Organic solvent pretreatment of lignocellulosic biomass for biofuels and biochemicals: A review. Bioresour Technol 2016;199:21–33.

[108] Zabed H, Sahu JN, Boyce AN, Faruq G. Fuel ethanol production from lignocellulosic biomass: An overview on feedstocks and technological approaches. Renew Sustain Energy Rev 2016;66:751–74.

[109] Aditiya HB, Mahlia TMI, Chong WT, Nur H, Sebayang AH. Second generation bioethanol production: A critical review. Renew Sustain Energy Rev 2016;66:631–53.

[110] Balat M. Production of bioethanol from lignocellulosic materials via the biochemical pathway: A review. Energy Convers Manag 2011;52:858–75.

[111] Bhatia L, Johri S, Ahmad R. An economic and ecological perspective of ethanol production from renewable agro waste: a review. AMB Express 2012;2:65.

[112] Ndimba BK, Ndimba RJ, Johnson TS, Waditee-Sirisattha R, Baba M, Sirisattha S, et al. Biofuels as a sustainable energy source: An update of the applications of proteomics in bioenergy crops and algae. J Proteomics 2013;93:234–44.

[113] Singh R, Srivastava M, Shukla A. Environmental sustainability of bioethanol production from rice straw in India: A review. Renew Sustain Energy Rev 2016;54:202–16.

[114] Talebnia F, Karakashev D, Angelidaki I. Production of bioethanol from wheat straw: An overview on pretreatment, hydrolysis and fermentation. Bioresour Technol

2010;101:4744–53.

[115] Foust TD, Aden A, Dutta A, Phillips S. An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion processes. Cellulose 2009;16:547–65.

[116] Sánchez ÓJ, Cardona C a. Trends in biotechnological production of fuel ethanol from different feedstocks. Bioresour Technol 2008;99:5270–95.

[117] Carere CR, Sparling R, Cicek N, Levin DB. Third Generation Biofuels via Direct Cellulose Fermentation. Int J Mol Sci 2008;9:1342–60.

[118] Schlager N, Weisblatt J, editors. Alternative Energy. Thomson Gale; 2006.

[119] Sallevelt JLHP, Beran M, Axelsson L-U, Pozarlik AK, Brem G. Bioethanol Combustion in an Industrial Gas Turbine Combustor: Simulations and Experiments. J Eng Gas Turb Power 2014;136:1–8.

[120] Moliere M, Vierling M, Aboujaib M, Patil P, Eranki A, Campbell A, et al. Gas Turbines in Alternative Fuel Applications: Bio-Ethanol Field Test. ASME Turbo Expo 2009 Power Land, Sea, Air, Orlando, Florida, USA: ASME (Paper No. GT2009-59047); 2009, p. 341–8.

[121] Khalil AEE, Gupta AK. Fuel flexible distributed combustion for gas turbine engines. Appl Energy 2013;109:267–74.

[122] Santos EC dos, Nascimento MAR do. Performance and Emission Experimental Evaluation and Comparison of a Regenerative Gas Turbine Using Ethanol as Fuel. ASME Turbo Expo 2012 Turbine Tech. Conf. Expo., Copenhagen, Denmark: ASME (Paper No. GT2012-68202); 2012, p. 105–12.

[123] Breaux BB, Acharya S. The effect of elevated water content on swirl-stabilized ethanol/air flames. Fuel 2013;105:90–102.

[124] Kun-Balog A, Sztankó K, Józsa V. Pollutant emission of gaseous and liquid aqueous

bioethanol combustion in swirl burners. Energy Convers Manag 2017;149:896–903.

[125] Zhang Q, Chang J, Wang T, Xu Y. Review of biomass pyrolysis oil properties and upgrading research. Energy Convers Manag 2007;48:87–92.

[126] Oasmaa A, Solantausta Y, Arpiainen V, Kuoppala E, Sipilä K. Fast Pyrolysis Bio-Oils from Wood and Agricultural Residues. Energy & Fuels 2010;24:1380–8.

[127] Thangalazhy-Gopakumar S, Al-Nadheri WMA, Jegarajan D, Sahu JN, Mubarak NM, Nizamuddin S. Utilization of palm oil sludge through pyrolysis for bio-oil and bio-char production. Bioresour Technol 2015;178:65–9.

[128] Xiu S, Shahbazi A. Bio-oil production and upgrading research: A review. Renew Sustain Energy Rev 2012;16:4406–14.

[129] Lujaji FC, Boateng AA, Schaffer MA, Mullen CA, Mkilaha ISN, Mtui PL. Pyrolysis Oil Combustion in a Horizontal Box Furnace with an Externally Mixed Nozzle. Energy and Fuels 2016;30:4126–36.

[130] Saber M, Nakhshiniev B, Yoshikawa K. A review of production and upgrading of algal bio-oil. Renew Sustain Energy Rev 2016;58:918–30.

[131] Nizamuddin S, Baloch HA, Mubarak NM, Riaz S, Siddiqui MTH, Takkalkar P, et al. Solvothermal Liquefaction of Corn Stalk: Physico-Chemical Properties of Bio-oil and Biochar. Waste and Biomass Valorization 2018:1–12.

[132] Naik SN, Goud V V., Rout PK, Dalai AK. Production of first and second generation biofuels: A comprehensive review. Renew Sustain Energy Rev 2010;14:578–97.

[133] Gollakota ARK, Kishore N, Gu S. A review on hydrothermal liquefaction of biomass. Renew Sustain Energy Rev 2018;81:1378–92.

[134] Bridgwater a. V. Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy 2012;38:68–94.

[135] Lupandin V, Thamburaj R, Nikolayev A. Test results of the GT2500 gas turbine

engine running on alternative fuels: bio oil, ethanol, bio diesel and heavy oil. ASME Turbo Expo 2005 Power Land, Sea, Air, Reno, Nevada: ASME (Paper No. GT2005-68488); 2005, p. 421–6.

[136] Beran M, Axelsson L-U. Development and Experimental Investigation of a Tubular Combustor for Pyrolysis Oil Burning. J Eng Gas Turbines Power 2014;137:31508.

[137] Zheng JL, Kong YP. Spray combustion properties of fast pyrolysis bio-oil produced from rice husk. Energy Convers Manag 2010;51:182–8.

[138] López Juste G, Salvá Monfort JJ. Preliminary test on combustion of wood derived fast pyrolysis oils in a gas turbine combustor. Biomass and Bioenergy 2000;19:119–28.

[139] Zadmajid S, Albert-Green S, Afarin Y, Thomson MJ. Optimizing a Swirl Burner for Pyrolysis Liquid Biofuel (Bio-oil) Combustion without Blending. Energy and Fuels 2017;31:6065–79.

[140] Kallenberg A. Liquid Bio Fuels for Gas Turbines. Lund University, 2013.

[141] Crayford A, Bowen PJ, Kay PJ. Comparison of Gas-Oil and Bio-oil Spray Performance for Use in A Gas Turbine. Proc. ASME Turbo Expo 2010 Power Land, Sea Air, vol. 22, Glasgow, UK: ASME (Paper No. GT2010-23485); 2010, p. 9–14.

[142] Smagala TG, Christensen E, Christison KM, Mohler RE, Gjersing E, McCormick RL. Hydrocarbon renewable and synthetic diesel fuel blendstocks: Composition and properties. Energy and Fuels 2013;27:237–46.

[143] Ojeda M, Rojas S, editors. Biofuels from Fischer-Tropsch Synthesis. Nova Science, Inc; 2010.

[144] Ail SS, Dasappa S. Biomass to liquid transportation fuel via Fischer Tropsch synthesis - Technology review and current scenario. Renew Sustain Energy Rev 2016;58:267–86.

[145] Wang T, Wang J, Jin Y. Slurry reactors for gas-to-liquid processes: A review. Ind Eng

Chem Res 2007;46:5824–47.

[146] Hermann F, Hedemalm P, Orbay R, Gabrielsson R, Klingmann J. Comparison of Combustion Properties Between a Synthetic Jet Fuel and Conventional Jet A1. ASME Turbo Expo 2005 Power Land, Sea, Air, Reno, Nevada, USA: ASME (Paper No. GT2005-68540); 2005, p. 389–97.

[147] Hermann F, Klingmann J, Gabrielsson R, Pedersen JR, Olsson JO, Owrang F. Chemical Analysis of Combustion Products From a High-Pressure Gas Turbine Combustor Rig Fueled by Jet A1 Fuel and a Fischer-Tropsch-Based Fuel. ASME Turbo Expo 2006 Power Land, Sea, Air, Barcelona, Spain: ASME (Paper No. GT2006-90600); 2006, p. 523–32.

[148] Timko MT, Yu Z, Onasch TB, Wong HW, Miake-Lye RC, Beyersdorf AJ, et al. Particulate emissions of gas turbine engine combustion of a fischer-tropsch synthetic fuel. Energy and Fuels 2010;24:5883–96.

[149] Lobo P, Hagen DE, Whitefield PD. Comparison of PM emissions from a commercial jet engine burning conventional, biomass, and fischer-tropsch fuels. Environ Sci Technol 2011;45:10744–9.

[150] Lobo P, Rye L, Williams PI, Christie S, Uryga-Bugajska I, Wilson CW, et al. Impact of alternative fuels on emissions characteristics of a gas turbine engine - part 1: gaseous and particulate matter emissions. Environ Sci Technol 2012;46:10805–11.

[151] Mordaunt CJ, Lee S, Vickey K, Mensch A, Santoro RJ, Schobert H. Further Studies of Alternative Jet Fuels. ASME 2009 Int. Mech. Eng. Congr. Expo., Lake Buena Vista, Florida: ASME (Paper No. IMECE2009-12940); 2009, p. 1–10.

[152] Bulzan D, Anderson B, Wey C, Howard R, Winstead E, Beyersdorf A, et al. Gaseous and Particulate Emissions Results of the Alternative Aviation Fuel Experiment (AAFEX). Proc. ASME Turbo Expo 2010 Power Land, Sea Air, Glasgow, UK: ASME

(Paper No. GT2010-23524); 2010, p. 1195–207.

[153] Bester N, Yates A. Assessment of The Operational Performance of Fischer-Tropsch Synthetic-Paraffinic Kerosene in A T63 Gas Turbine Compared to Conventional Jet A-1 Fuel. Proc. ASME Turbo Expo 2009 Power Land, Sea Air, Orlando, Florida: ASME (Paper No. GT2009-60333); 2009.

[154] Moses CA, Biddle TB, Seto SP, Lewis C, Williams RC, Roets PNJ. Combustion and Operational Characteristics of Sasol CTL Fully Synthetic Jet Fuel. IASH 2007, 10th Int. Conf. Stability, Handl. Use Liq. Fuels, Tucson, Arizona: International Association for Stability, Handling and Use of Liquid Fuels; 2007.

[155] Moses C a., Roets PNJ. Properties, Characteristics, and Combustion Performance of Sasol Fully Synthetic Jet Fuel. J Eng Gas Turbines Power 2009;131:41502.

[156] Cheng MD, Corporan E, Dewitt MJ, Landgraf B. Emissions of volatile particulate components from turboshaft engines operated with jp-8 and fischer-tropsch fuels. Aerosol Air Qual Res 2009;9:237–56.

[157] Brem BT, Durdina L, Siegerist F, Beyerle P, Bruderer K, Rindlisbacher T, et al. Effects of Fuel Aromatic Content on Nonvolatile Particulate Emissions of an In-Production Aircraft Gas Turbine. Environ Sci Technol 2015;49:13149–57.

[158] Corporan E, DeWitt MJ, Belovich V, Pawlik R, Lynch AC, Gord JR, et al. Emissions characteristics of a turbine engine and research combustor burning a Fischer-Tropsch jet fuel. Energy & Fuels 2007;21:2615–2626.

[159] Vukadinovic V, Habisreuther P, Zarzalis N. Experimental Study on Combustion Characteristics of Conventional and Alternative Liquid Fuels. J Eng Gas Turbines Power 2012;134:121504.

[160] Davison CR, Canteenwalla P, Chalmers JLY, Chishty WA. Sea Level Performance of a CF-700 Engine Core with Alternative Fuels. Proc. ASME Turbo Expo 2015 Turbine

Tech. Conf. Expo., Montreal, Quebec, Canada: ASME (Paper No. GT2015-42230); 2015.

[161] Davison CR, Chishty W a. Altitude Performance of a Turbojet With Alternate Fuels. Proc. ASME Turbo Expo 2011, Vancouver, British Columbia, Canada: ASME (Paper No. GT2011-45132); 2011, p. 39–50.

[162] IATA. IATA 2009 Report on Alternative Fuels. 2009.

[163] Kinder R, J D., Henry M, Crenfeldt, G., LeDuc GF, Zombanakis, G.P., Abe Y, et al. Sustainable bio-derived synthetic paraffinic kerosene (bio-SPK) jet fuel flight tests and engine program results. 9th AIAA Aviat. Technol. Integr. Oper. Conf., American Institute of Aeronautics and Astronautics (Paper No. AIAA 2009-7002); 2009.

[164] Ji X, Long X. A review of the ecological and socioeconomic effects of biofuel and energy policy recommendations. Renew Sustain Energy Rev 2016;61:41–52.

[165] Koizumi T. Biofuels and food security. Renew Sustain Energy Rev 2015;52:829–41.

[166] Krutof A, Hawboldt K. Blends of pyrolysis oil , petroleum , and other bio-based fuels : A review. Renew Sustain Energy Rev 2016;59:406–19.

[167] Nor W, Wan R, Hisham MWM, Ambar M, Hin TY. A review on bio-oil production from biomass by using pyrolysis method. Renew Sustain Energy Rev 2012;16:5910–23.

[168] Choi SK, Choi YS, Kim SJ, Jeong YW. Characteristics of flame stability and gaseous emission of biocrude-oil/ethanol blends in a pilot-scale spray burner. Renew Energy 2016;91:516–23.

[169] Martin JA, Boateng AA. Combustion performance of pyrolysis oil/ethanol blends in a residential-scale oil-fired boiler. Fuel 2014;133:34–44.

[170] Schmidt JH. Life cycle assessment of fi ve vegetable oils. J Clean Prod 2015;87:130–8.

[171] Zhang C, Hui X, Lin Y, Sung C-J. Recent development in studies of alternative jet fuel combustion: Progress, challenges, and opportunities. Renew Sustain Energy Rev 2016;54:120–38.

[172] Blakey S, Rye L, Wilson CW. Aviation gas turbine alternative fuels: A review. Proc Combust Inst 2011;33:2863–85.

[173] IATA. IATA 2012 Report on Alternative Fuels. 2012.