

Review

Effects of Pyrolysis Bio-Oils on Fuel Atomisation—A Review

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Abstract: Bio-oils produced by biomass pyrolysis are substantially different from those produced by petroleum-based fuels and biodiesel. However, they could serve as valuable alternatives to fossil fuels to achieve carbon neutral future. The literature review indicates that the current use of bio-oils in gas turbines and compression-ignition (diesel) engines is limited due to problems associated with atomisation and combustion. The review also identifies the progress made in pyrolysis bio-oil spray combustion via standardisation of fuel properties, optimising atomisation and combustion, and understanding long-term reliability of engines. The key strategies that need to be adapted to efficiently atomise and combust bio-oils include, efficient atomisation techniques such as twin fluid atomisation, pressure atomisation and more advanced and novel effervescent atomisation, fuel and air preheating, flame stabilization using swirlers, and filtering the solid content from the pyrolysis oils. Once these strategies are implemented, bio-oils can enhance combustion efficiency and reduce greenhouse gas (GHG) emission. Overall, this study clearly indicates that pyrolysis bio-oils have the ability to substitute fossil fuels, but fuel injection problems need to be tackled in order to insure proper atomisation and combustion of the fuel.

Keywords: liquid biofuels; pyrolysis bio-oils; fast pyrolysis; fuel atomisation; combustion emissions; pressure atomisers; twin fluid atomisers; gas turbine engines; internal combustion engines; biomass to biofuel conversion; renewable energy



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1. Introduction

Today, global energy supply and demand rely heavily on more conventional and nonrenewable resources such as oil, gas and coal. The increasing global population, however, has caused per capita energy consumption to increase, resulting in a rapid decline in the availability of fossil fuels. Approximately 81% of the world's energy supply was generated in 2017 by fossil fuel-based combustion systems, contributing to around 99% of carbon dioxide (CO₂) emissions output [1]. NASA and NOAA's joint study indicated that 2019 was the 2nd warmest year on record and the time shown was within the world's top-five warm years between 2015 and 2019 [2]. Although worldwide use of combustion process still remains an important energy source, fuel sources can at least be made more sustainable and ecofriendly while minimising the use of nonrenewable conventional resources. The rapid depletion rate of fossil fuels has made it inevitable for renewable energy sources to resolve global environmental issues and the contribution of fossil fuels to global warming and general climate change. Solid fuel biomass combustion are disadvantageous due to their low efficiencies and higher emissions, in particular smoke and particulate matter [3,4] as compared with liquid biofuels. When it comes to using liquid fuels, they are easier to transport (high density) and storage under controlled conditions as compared to solid fuels [5]. Compared to other renewable liquid fuels, pyrolysis bio-oils are derived from biomass and other sources of waste (approximately 10% of the world's energy resources) [6] have been successfully established as feasible renewable fuel sources to promote the

substitution of fossil fuels [7–9]. Biomass utilisation to produce value-added products in all forms (liquid, gas and solid fuels) has been of great interest to researchers around the world. To provide vital energy, biomass can be used in various ways as listed below [6]

- used to produce heat for heating, steam production and thereby generating electricity via direct combustion.
- via gasification process to provide syngas for combustion for generating heat or power generating engines to generate electricity.
- the production of liquid fuel substitute fuel oil in any stationary heating or power generation application by means of a pyrolysis process. A large range of speciality and commodity chemicals may also be produced using the resulting liquid bio-oil.

Pyrolysis separates a significant fraction of the solids found in the initial biomass feedstock into bio-oils and bio char. The latter can then be used as soil amendment [10,11] or in water modified into activated charcoal to be used in water purification. Pyrolysis of biomass produces solid, gas and liquid components. The quantity and quality of these components vary significantly and are influenced by the nature of the biomass (e.g., hardwood, softwood and grasses), composition of the biomass (e.g., proportions of cellulose, hemicellulose, lignin and inorganic elements), structure of the biomass (e.g., linkage between cellulose, hemicellulose and lignin), pyrolysis temperature, residence time, and the use of any catalysts during pyrolysis. Generally, the bio-oil yield increases with the pyrolysis temperature [12], lignin content of the biomass and the presence of catalysts. For example, bio-oil yield of beauty leaf press oil cake increased from 3.2% to 12.5% when the pyrolysis temperature was increased from 300 to 500 °C. The overall yields of bio-oils for different feedstocks are as follows: banana rachis; 28%, palm mesocarp fibre; 34%, cedar wood; 47%, cotton stalk; 55%, poplar; 69% and sawdust; 76% [13].

Pyrolysis bio-oils have the potential to present low GHG emissions as a sustainable carbon-neutral fuel source (Green House Gas) relative to fossil oils [14,15] that makes them important choice for the global energy economy's future fuel. Fuels derived from biomass can be obtained from several different feedstocks. First-generation biofuels such as ethanol and biodiesel derived from edible feedstocks have proven to be of great benefit in various applications as renewable fuel sources, but most of these fuels are no longer expected to benefit significantly from reducing the emission of greenhouse gas. It is known to be economic and sustainable for the future [16,17]. Second-generation biofuels, on the other hand, such as bio-oil pyrolysis derived from raw materials and inedible biomass waste, are more zero-emission and sustainable because they do not compete with agricultural space and human food consumption and thus do not lead to rising food prices [16–18]. A variety of starting materials can be used to make pyrolytic bio-oils [19] but more commonly from lignin-based materials (lignocellulosic) generated from waste wood and other plant-based feedstocks. The final produced bio-oil quality highly depends on the initial quality of the sourced biomass [20,21]. Feedstocks that are cheaper to produce at a given location, using locally available natural resources are the highly preferred biomass sources for bio-oil production. If these feedstocks contain higher proportions of lignin than other components and if they are conducive to produce bio-oils with low O:C ratio, then they are highly preferred over the others as they will generate improved quality of bio-oil. Feedstocks that produce reduced amounts of acetic acid in the bio-oils are also preferred [22]. Lignin based biomass feedstocks have been considered to produce very high quality yields of bio oils. This is attributed to the different physiochemical characteristics of different major components of biomass such as cellulose, hemicellulose and lignin. Feedstocks such as wood, sugarcane bagasse, corn stover, hazelnut shell, walnut shell, olive husks, tea waste and bamboo are some that can provide higher quality bio-oil yields. Biomass contains cellulose, hemicellulose, lignin and inorganic elements. Pyrolysis of biomass results in levoglucosan (from cellulose) which converts into furfuryl alcohol. The hemicellulose will be converted into acetic acid, acetol and furfural. The lignin will be converted into guaiacol, phenol and cresol. The use of catalysts in pyrolysis results in the production of hydroxyacetone and hydroxyacetaldehyde. The interaction between cellulose, lignin and

hemicellulose as well as the inorganic chemicals present in the plant tissues will result in numerous other chemicals such as furans and acetic acid. Some of these products can be converted into biofuels via distillation and hydrotreatment, or they can be used in the synthesis of industrial chemicals and biopolymers [22]. The cost of production of bio-oils is highly dependent upon the scale at which the bio-oils are produced. Some studies have estimated the costs of production of biofuels from biomass. For example, ref. [23] reported that the cost of producing renewable diesel via fast pyrolysis and hydroprocessing of spruce, corn stover and wheat straw were estimated to be $\$1.11 \text{ L}^{-1}$, $\$1.19 \text{ L}^{-1}$ and $\$1.27 \text{ L}^{-1}$, respectively.

The very first biomass pyrolysis was initially developed by the laboratory to process unit scale production in Canada and the United States during the 1980s [24–26]. Since then the technology has proved to be a promising alternative biofuel [27–29]. Growing concerns of the conventional fuel depletion, carbon level rising and global warming pose an increasing need and attention through research for environmentally sustainable fuel sources such as pyrolysis bio-oils and its commercialisation across the major combustion industries. Significant studies on the development of bio-oil produced via pyrolysis have been conducted by the International Energy Agency (IEA) [30,31].

In addition to biomass feedstocks, plastic waste can also serve as a potential fuel source due to its high heating value and its abundant availability. Bio-oils extracted from plastic pyrolysis have been successfully used in internal combustion engines to generate heat and electricity [32]. The quality of the pyrolysis product is highly dependent on the form of plastic waste used in the pyrolysis reactor and the parameters used such as temperature, time of residence and catalyst [33,34]. Due to the similarity between the fuel properties of plastic-derived pyrolysis oils and those of petroleum-based fuels, they can serve as potential fuels for use in internal combustion engines. Most of this research has been performed on diesel engines due to their high handling and high performance over a wider load range. Much of the studies published centred on the use of plastic bio-oils as diesel fuel blends in single-cylinder diesel engines [35–37]. Pratoomyod et al.; investigated use of plastic derived pyrolyzed bio-oil blends but have not reported any combustion performance [38]. Investigations of larger engines found that the engine worked well at a moderate mixing rate but showed poorer engine efficiency and higher emissions such as nitrogen oxides, carbon dioxide and an exceptionally high concentration compared to diesel fuel. High concentrations of nitric oxides were due to local distribution of fuel and temperature in the combustion chamber, which in turn affects emissions and high carbon dioxides which were attributed to delayed fuel burning resulting in higher concentrations of CO_2 . Investigations by Kalargaris and Gu [32], on combustion efficiency and emission analysis in diesel engines using plastic pyrolysis oils, it was shown that the engine ran consistently at with pure plastic bio-oil at loads 75% and higher; with about 90% plastic pyrolysis bio-oil at loads 50% and higher and blended mixtures of plastic pyrolysis oils at all loads. Thermal efficiency of the engine decreased by 3–4% when plastic bio-oil blends were used as compared to diesel. Most reported research shows that more performance parameters need to be studied to obtain the optimum engine performance and to demonstrate successful use of plastic derived bio-oils.

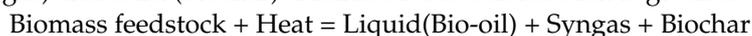
Fundamentally pyrolysis is a thermal process in which in the absence of oxygen, biomass is heated at a temperature between $330 \text{ }^\circ\text{C}$ and $500 \text{ }^\circ\text{C}$. This method helps to break down biomass components such as cellulose, hemicellulose and lignin into different phase-state materials, solids, liquids and gases at the end of the process. The ratio of product yields depends on the velocity of the process. Slower thermal conversion process (slow pyrolysis) results in higher content of solid products as compared to faster speed or fast pyrolysis which results mostly in liquid and/or gas phase. The resulting pyrolysis oil is a dark brown liquid made from a variety of biomass materials. The rapid pyrolysis process usually produces 65–72% of liquid 15–20% of biochar (a black carbon-like material) and 12–18% of noncondensable gases and water (18–22%) along with oxygenated compounds. Physical properties and chemical composition of pyrolysis oils are different from fossil

fuels and present particular atomisation and combustion problems that require attention before being used in practical combustion. Pyrolysis oils can be used in burners, boilers, furnaces, gas turbines and diesel engines [8,39,40]. Power generation engine systems have a wider range of operating requirements to achieve higher performance, requiring consideration of new combustion strategies to operate on alternative fuels. Studies have also shown the efficient use of pyrolysis oils as a substitute for fossil oils in large-scale industrial burners, furnaces and boilers [8,40]. For example, the world's first combined heat and power plant was successfully tested in 2013 by Fortum, Finland, to operate on fast pyrolysis oil [41]. It is observed that in such large-scale combustion applications due to their longer residence times and smaller heat losses, combustion efficiency of pyrolysis oil is much easier to achieve. While there are some successful demonstrations of using pyrolysis oils in gas turbine and diesel engines which otherwise are natural gas and light fuel oil dominated, there are still research challenges that need attention [42,43]. Due to the shorter time of residence and the smaller volume of these engine applications, relatively higher combustion efficiency with lower emissions is important. This is where the fuel injection and atomisation quality are more important especially when using pyrolysis oils in smaller combustor applications which require faster rates of fuel/air mixing and combustion.

There have been several research articles that focus on using the fuel itself [44–47] and its practical applications [8,39,43,48–51], but there have not been many studies on the importance of fuel atomisation and spray quality which is crucial for the performance and emissions of a combustion system. Pyrolysis bio-oils have higher water content, viscosity and coking tendency that are particularly challenging for fuel atomisation which can cause incomplete combustion leading to higher emissions. A higher surface-to-volume ratio of smaller droplets supports evaporation, which in turn increases the fuel/air mixture and combustion properties and eventually contributes to improved flame stability [52,53]. The fuel must be able to vaporise and correctly mix with the oxidant, ignite and burn fully within the shortest time and volume of the combustion chamber for successful fuel spraying. This can only be achieved with a spray of fine droplets with a homogeneous distribution within the combustion chamber. Some of the challenging properties of pyrolysis oil have been enhanced by adding methanol or ethanol as polar solvents that help improve volatility and calorific value that reduces the viscosity and acidity of the resulting fuel. Some experimental work has been reported mixing pyrolysis bio-oil with ethanol [54]; however, ethanol is very expensive and adding too much ethanol results in reduced heat flow from the flame [55]. The key purpose of this review paper is to address published studies on the effects of bio-oil pyrolysis on fuel atomization and spray combustion. Within the scope of this paper, most relevant spray combustion studies in the field of gas turbines and diesel engines are highlighted. The paper discusses the use, status and production of biomass pyrolysis fuels and potential R&D on pyrolysis fuels.

2. Pyrolysis Products and Their Fuel Properties

Pyrolysis of biomass feedstocks produces three products, viz., liquid (bio-oil), gas (syngas) and solid (biochar). Biomass feedstock reaction is given as:



Based on operating parameters such as heating rate, pyrolysis temperature, and residence time, the pyrolysis process can be split into three groups: (1) slow pyrolysis, (2) fast pyrolysis, and (3) flash pyrolysis. Different pyrolysis results are provided by these different conditions. As shown in Table 1 below, the yield of the product depends on the pyrolysis type and its relative operating condition. Flash pyrolysis for the production of bio-oil, followed by fast pyrolysis and slow pyrolysis, is the most widely used pyrolysis procedure.

Table 1. Outcomes of pyrolysis obtained from various pyrolysis technologies [56,57].

Pyrolysis	Operating Conditions	Product Yield
Slow Pyrolysis	Temperature: 300–700 °C Vapor residence time: 10–100 min Heating rate: 0.1–1 °C/s Feedstock size: 5–50 mm	Bio-oil: ~30%wt Biochar: ~35%wt Gases: ~35%wt
Fast Pyrolysis	Temperature: 400–800 °C Vapor residence time: 0.5–5 s Heating rate: 10–200 °C/s Feedstock size: 3 mm	Bio-oil: ~50%wt Biochar: ~20%wt Gases: ~30%wt
Flash Pyrolysis	Temperature: 800–1000 °C Vapor residence time: 0.5 s Heating rate: 1000 °C/s Feedstock size: 0.2 mm	Bio-oil: ~75%wt Biochar: ~12%wt Gases: ~13%wt

In terms of physical properties and chemical analysis of petroleum-based and other biodiesel fuels, pyrolysis bio-oils derived from biomass vary significantly. In terms of groups of compounds that have different polarities and a wide variety of molecular weights and boiling points, the chemical composition of pyrolysis oils is very different. They are made of more acidic and viscous liquids that often contain solids and a high proportion of chemically undissolved water. Water and additives differ in the calorific value, density and viscosity of pyrolysis liquids. The pyrolysis oil properties reported in Table 2 [58] are only for fast pyrolysis biooils reported within the literature. Compared with those of the number 2 diesel fuel [59], biodiesel fuel obtained from plant-based source [59], biodiesel fuel obtained from animal fat source [59], and 100% vegetable oil [59,60] along with test procedure used to obtain those properties. It has been observed through the review of fuel properties [58,61], that compared to fossil oils and other biodiesel fuels, fast pyrolysis bio-oils have higher viscosity, making them an unfavourable choice for fuel atomisation. The high water content results in flame instabilities due to the lower calorific value (LHV), slow vaporization leads to delayed ignition and lower flame temperatures and burning rate. Compared to fossil fuels that are not oxygenated, pyrolysis oils are extremely oxygenated, making pyrolysis oils immiscible with fossil fuels. The immiscible solids within pyrolysis oils contain inorganic ash and char which contributes towards harmful emissions [62]. The property values for diesel fuel, biodiesel#1, biodiesel#2 and 100% refined vegetable oil fuel were experimentally determined with the relevant measurement uncertainties [59]. Density measurements using volumetric glassware were carried out by gravity at 25 °C. In order to ensure data repeatability and consistency, three tests were performed. Compared to biodiesel, diesel is a lighter fuel, while the density of VO (925 kg/m³) is the highest. In order to obtain a particular rate of heat release into the combustion chamber, density measurements are critical for determining the volumetric flow rate of the fuel. Using chemical component analysis, lower heating value (LHV) values were calculated [59].

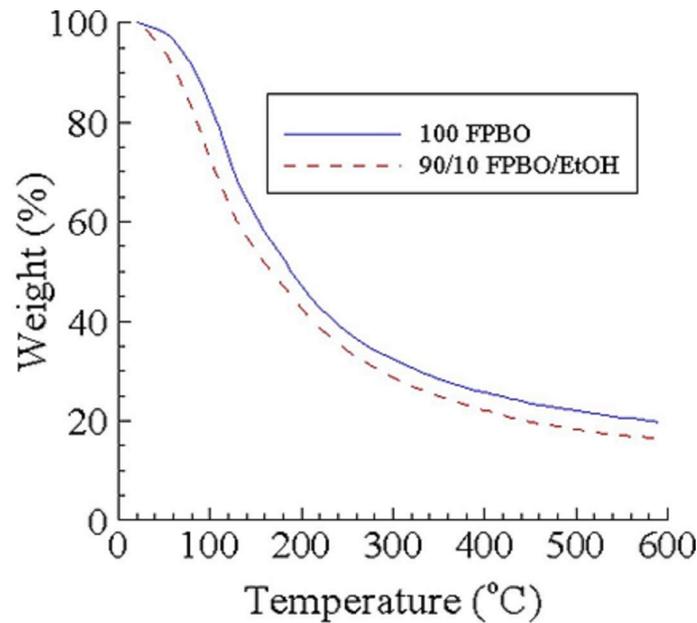
Table 2. Fuel property values for different fuels [58–61].

Property Parameter	100% Fast Pyrolysis Bio-Oil	Diesel Fuel Commercial Grade No-2	Biodiesel#1 Methyl Soyate from Soybean Oil	Biodiesel#2 Methyl Soyate from Chicken Fat	100% Refined Vegetable Oil
Density (kg/m ³) @ 25oc	1256	834–842	880–890	868–896	925–935
Surface Tension (N/m) @ 25oc	34×10^{-3}	28.2×10^{-3}	30.1×10^{-3}	30.7×10^{-3}	31.1×10^{-3}
Kinematic Viscosity (m ² /s) @ 25oc	81×10^{-6}	3.88×10^{-6}	5.61×10^{-6}	6.14×10^{-6}	53.74×10^{-6}
Water Content (%wt)	25.5	0.06	17	16	21
C-H-O-N (%wt)	45.79–7.11 47.10–0	87–13 0–(<0.01)	-	-	-
Solids Content (%wt)	0.1	-	-	-	-
TGA Residue (%wt)	19.7	-	-	-	-
LHV (MJ/kg)	16.9	44.6	38.01	37.66	37
Acidity (pH)	2-3	-	-	-	-

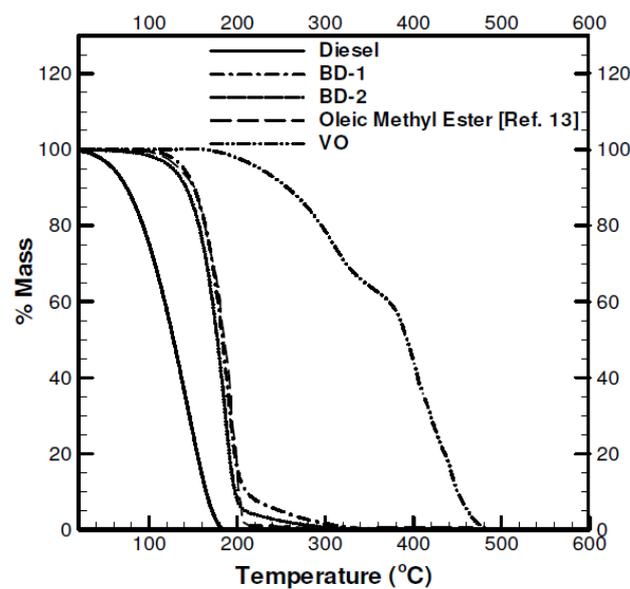
3. Fuel Property Effects on Fuel Spray Atomisation and Combustion

3.1. Fuel Volatility and Thermal Stability

Thermogravimetric analysis is an experimental method to assess the thermal stability and/or volatile quality of a substance by monitoring the shift in weight when heating a sample. With increase in temperature, a volatile sample loses mass and at most, loses all of its mass after a certain temperature and the remaining mass remains. Volatility has a significant effect on the evaporation of gasoline, which in turn impacts the processes of fuel-air mixing and combustion. For instance, in diffusion mode, poor evaporation may cause fuel droplets to burn. The resulting high flame temperatures are known to produce higher NO_x, CO and soot emission concentrations [59]. Fuel samples (8 to 17 mg) were characterised using the TA 2950 analyser TA instruments. The target temperature was set at 600 °C and the test was carried out with a heating rate of 5 °C/min from room temperature to 600 °C in an air atmosphere supplied at a rate of 90 cm³/min. Figure 1a shows the TGA analysis for fast pyrolysis bio-oil [2] and Figure 1b shows the TGA profiles for diesel, BD#1, BD#2 and VO [59]. It is shown from Figure 1a that fast pyrolysis bio-oil and blend with ethanol did not reach a zero sample weight percent, indicating that both of these fuels are prone to fuel coking, presence of solid content within the fuel, and harmful emissions [2]. Results from Figure 1b [59] show that diesel fuel evaporates easily when heated to 80 °C and vaporises completely at about 180 °C. Similar volatility characteristics are shown by both biodiesel fuels; no mass loss when heated below 100 °C, rapid mass loss (or vaporisation) at temperatures above 150 °C and near full vaporisation at about 225 °C. Vegetable oil is the fuel the least volatile, with negligible mass loss at 225 °C. It is evident that in order to completely prevaporize the fuel, the VO would need substantially higher thermal input from the flame to the fuel droplets, thereby producing a mixture of homogeneous fuel air before combustion.



(a)



(b)

Figure 1. TGA Analysis of Pyrolysis Oils, Diesel and Biodiesel Fuels. (a) TGA Analysis of Pyrolysis oils [2]. (b) TGA Analysis of Diesel and Biodiesel [59].

3.2. Water Content

It is important to maintain homogenous and even quality fuel for efficient atomisation and spray combustion. A high-water content (more than 30 wt%) in the fuel separates into two phases of differing properties. It is observed from Table 2 that pyrolysis oils have slightly higher water content compared to 100% refined vegetable oils and lower compared to both biodiesel fuels and diesel fuel. Pyrolysis reactions and the moisture present in the original feedstocks are the result of the high water content of pyrolysis bio-oil [47,49]. The high degree of steam cracking also increases the amount of water in the fuel product during the pyrolysis process [63]. Higher fuel water content indicates instability of combustion/flame resulting in lower density, delay of ignition due to slow vaporisation, poor atomisation of fuel, and decreased flame temperatures and combustion rates, resulting in increased emissions [64,65].

3.3. Surface Tension, Density, and Viscosity

At room temperature of 25 °C, pyrolysis bio-oils have a surface tension of approximately 34 mN/m, close to that of standard vegetable oils, higher than diesel fuel and other biodiesel fuel. For example, a fuel's surface tension depends on its water and char content; higher water content contributes to higher surface tension measured compared to diesel fuel at 28 mN/m at 25 °C [59] with no water content. In determining the fuel volumetric flow rate, density measurements are critical in order to obtain a precise heat release rate in the combustion chamber. Pyrolysis oils density depends on the fuel's water content [8] and is about 40% higher than that of fossil oils and about 15% higher compared to vegetable oils. Kinematic viscosity is a significant physical property that affects both the drop in pressure in the fuel line and the atomisation of the combustion chamber fuel. Pyrolysis bio-oils have a viscosity of an order of magnitude higher, compared to transportation fuels, such as diesel or gasoline. High viscosity of fuel causes excessive pressure drop and large droplet spray, which reduces combustion performance. For instance, Table 2, indicates that biodiesel viscosity is 45–55% higher compared to diesel. In order to overcome the pressure drop in the fuel supply line, the higher fuel viscosity requires a higher pumping power for viscous oil compared to diesel. Moreover, biodiesel's high fuel viscosity can also adversely affect the atomisation of fuel, an effect that is later quantified by estimating the size of the droplet. Fuels with such a high viscosity do not generate suitable atomisation, so it is possible to introduce alternative strategies such as fuel mixing, preheating before injecting the fuel through the fuel supply line to minimise viscosity and pressure drop.

3.4. Oxygen Content

Low energy density (a related effect of high water content), corrosivity, and chemical instability of fuels with high oxygen content are immiscible in fossil fuels. Pyrolysis bio-oils have a higher oxygen content of about 30–40 wt% since most of its oxygen content is from biomass feedstock [8,66]. This is where fossil fuels and bio-oils differ since the former are not oxygenated as shown in Table 2. By reducing the oxidizer required for stoichiometric conditions, the higher oxygen content is responsible for reducing the air-to-fuel combustion ratio there. This in turn raises the flame temperature and leads to an increase in the prompt formation of NO_x.

It is evident from Table 2 that pyrolysis bio-oils have several unfavourable fuel properties that are not acceptable for efficient atomisation as compared to fossil fuels. These oils can then be blended/physically upgraded to enhance the physical and chemical properties of fuel and spray combustion [67]. Since pyrolysis oils are high in solid residue within the fuel itself especially during storage, fuel filtering can be useful if but there is a risk that filters can clog more frequently [68,69]. Additionally, when pumping through a filter, the unheated high viscosity fuel presents important challenges. It has been widely documented that the pyrolysis bio-oils are also combined with alcohol-based solvents such as ethanol, methanol, or butanol to boost the combustion efficiency, further contributing to fuel stabilisation, which decreases the rate of fuel ageing [54,70].

4. Fuel Spray Atomisation Using Pyrolysis Bio-Oil

In the design of any combustion system, the fuel atomiser or fuel injector is of vital importance. One of the most important aspects of any liquid fuel combustion is the formation of an effective spray. An atomizer should be able to produce fine droplets with larger surface area, thereby allowing rapid heat transfer and increased evaporation. The droplet vaporisation is inversely proportional to the square of droplet diameter for spray combustion [54]. Better vaporisation leads to improved mixing and combustion of fuel/air thus decreasing the residence time of the droplet and consequently reducing the length of the flame. The atomisation process with complex fluid dynamics and transport phenomena has a crucial effect on heat and mass transfer, momentum and energy between fluid phases, based on the characteristics of the fuel spray, and thus enhances the overall combustion process to ensure that pollutant emissions are reduced [70]. Kinematic viscosity, surface

tension and density are some of the main parameters influencing atomisation, and viscosity is one of the most critical fuel properties with the most effect on atomisation [71,72]. The effects of atomisation become of prime importance when dealing with highly viscous fuels like pyrolysis bio-oils. A pressure swirl nozzle is used for less viscous fuels such as light oils, which produces droplets in the range of 15–60 microns compared to high viscous heavy fuel oils, where an air-assisted nozzle is preferred. Many light fuel oils can operate effectively without fuel preheating, whereas more viscous fuels need a high nozzle pressure and 85–140 °C fuel preheating to form droplets in the 50–70 micron range [67,73]. In the literature, it has been stated that excess preheating in the case of pyrolysis bio-oils compared to that of other viscous fuel oils results in degradation of fuel quality, nozzle clogging, and change in chemical composition due to polymerisation, which in turn requires thorough understanding of the physics of atomisation of fuel spray.

Droplet Formation

Conceptually, droplets are produced by a liquid jet or liquid sheet breakup or disassociation due to disrupting forces. According to Lefebvre, [52] spray formation is mainly classified as classical and prompt primary atomisation. In classical atomisation, instabilities are created within the liquid sheet surface thereby promoting formation of waves leading to disintegration into ligaments and droplets. Higher surface tension, viscosity and thickness of liquid jet, lower spray turbulence, and relative velocity of droplets result in greater distribution of droplet size and larger droplet diameter, generally known as Sauter mean diameter (SMD). The ratio of volume to surface area of an average droplet within a given spray is known as SMD [8,52].

In prompt atomisation, the jet disintegrates immediately upon exiting the nozzle with small observable intact length on which disturbances quickly form, grow, and breakdown. The rapid and violent liquid breakdown in a spray mechanism ensures that the produced droplet sizes remain independent of the jet or foil diameter or fuel viscosity [74]. The distribution of droplet volume is therefore primarily regulated by air velocity, air mass flow to liquid ratio (ALR), and surface tension components, [75]; atomisation process for both sheet formation and liquid jet breakup is very similar. The generated droplets break up into smaller finer droplets with higher pressure or density when applied inside the spray [52,75]. This essentially means that until magnitude of forces within the atomisation are balanced, the spray droplets continue to disintegrate into smaller droplets.

5. Common Fuel Atomisers Used in Combustion Applications

Pressure swirls and twin-fluid nozzles are the most common fuel atomizers used in liquid fuel combustion applications [74]. Depending on the type of nozzle and its application, liquid fuel is pumped in either jet or sheet form. Liquid jet disintegrating is of primary importance for atomisers such as single orifice pressure nozzles or dual fluid nozzles, while liquid sheet breakage is important for the design of simple or pressure nozzles or dual fluid prefilm nozzles. Figure 2 shows the schematic of fuel nozzles which have been reprinted from [75] by permission of Elsevier. In pressure atomisation, the liquid is forced through a small opening, resulting in a narrow or strong conical spray that causes the liquid to form a radially expanding annular liquid layer in the form of a solid spray or a hollow cone with a comparatively wider conical angle [9,52]. Pressure atomisers are used in light fuel oil combustion applications at comparatively higher pressures, which can cause wear, corrosion, and performance degradation [63,76]. The kinetic energy of moving air is used by twin fluid atomizers to split a jet or sheet of liquid into ribbons and then into fine droplets. The most popular atomizers include Air Blast and Air Assit. The key difference is the volume and the flow rate of the air used. Using a relatively small amount of high velocity air, air assist atomizers are characterised. On the other hand, air blast atomizers use huge volumes of atomising air continuously flowing at relatively low velocities (20–120 m/s) [77]. Compared to pressured atomisers, the air blast atomisers require low fuel injection pressure to produce a fine droplet spray. In

addition, since the atomisation process ensures a homogeneous mixture of fuel and air, the resulting combustion process produces a low amount of soot, low flame radiation, and clean combustion products. Higher air-to-fuel ratios (ALR) suggest a higher relative air-to-liquid velocity, leading to more energy being delivered to break up liquid fuels. Twin fluid nozzles with viscous fuels are relatively easy to operate because they are less susceptible to liquid viscosity than pressure atomizers (as viscosity had a very little effect on fuel atomisation in two studies up to 100–120 cP) [78,79].

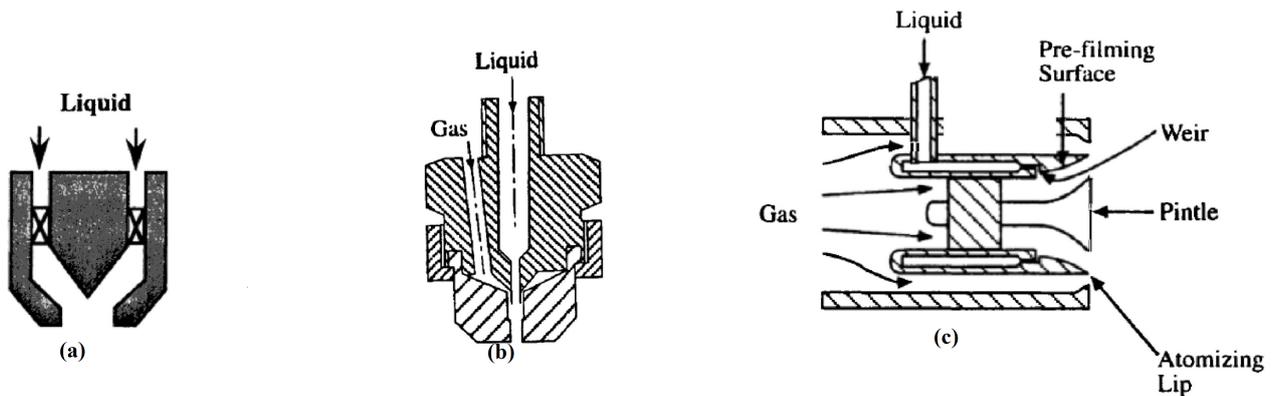


Figure 2. Schematic of (a) simplex pressure nozzle, (b) internally-mixed twin-fluid nozzle, and (c) prefilming twin-fluid nozzle [9,75].

An alternative approach effervescent atomisation (EA) can overcome any inherent limitations of an AB atomiser [80,81]. In the EA method, at a point upstream of the nozzle discharge orifice, low velocity air is directly inserted into the bulk liquid and the injected air forms bubbles that create a two-phase bubble flow at the nozzle exit. As the two-phase mixture exits the atomiser, the pressure decreases, allowing air bubbles to expand and the surrounding mass of fuel to decay into a spray of fine droplets. A relatively high supply pressure is required to produce two-phase instabilities under controlled conditions. In 2005, Calvo [82] the flow blurring (FB) injector operating on the EA concept provided 5 to 50 times more fuel surface area for a fixed atomising air flow rate than a plain-jet air blast atomiser. The flow blurring atomisation shown in Figure 3 is based on a basic geometric design that can generate fine liquid sprays with a broad range of kinematic viscosity. Studies by [80,83,84] have reported successful testing in combustion applications with a wide range of fuels from diesel, kerosene, and pure bio-oils to glycerol.

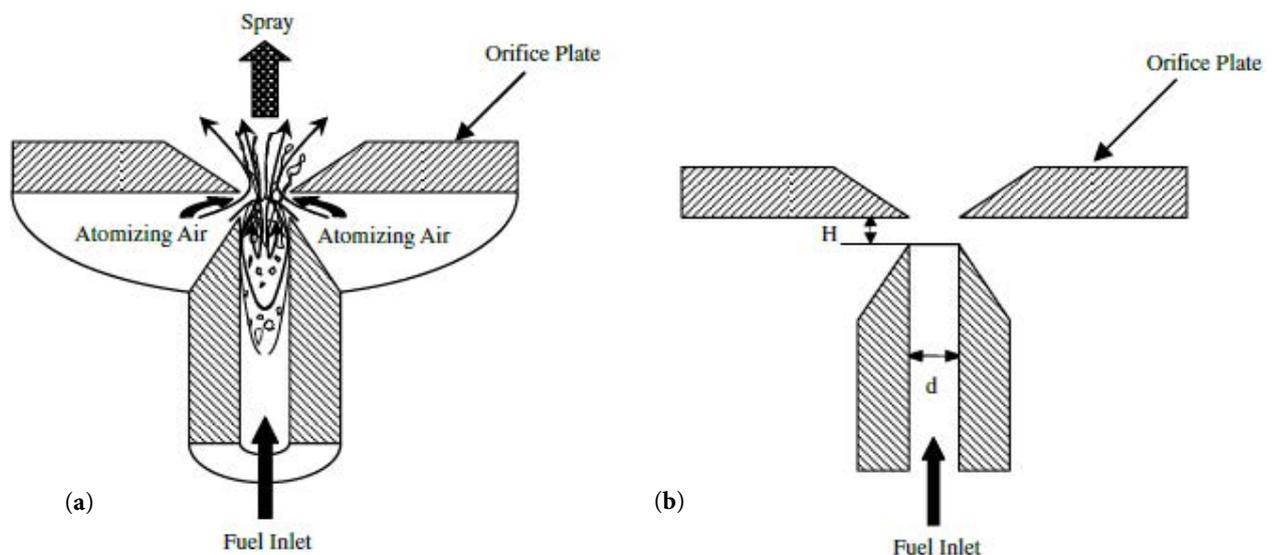


Figure 3. Schematic of the flow-blurring injector: (a) flow structure and (b) geometric details [80].

6. Pyrolysis Bio-Oil Combustion in Gas Turbine Engines

Unlike the unpredictable processes of internal combustion engines that put constraints on fuel chemistry in terms of octane and/or cetane quantities, gas turbines are one of the most fuel-flexible engines working in continuous flow. The technological feasibility of running gas turbine engines with fuels such as bio-oil, ethanol, and biodiesel has been shown in field tests in recent years. Kasper et al. performed some early experiments with pyrolysis liquids on the J69-T-29 gas turbine combustion platform at Teledyne CAE (USA) using sluggish pyrolysis fluids [85]. To minimise the engine development cost and ensure efficient performance and durability, fuel quality and price is also of importance when developing pyrolysis bio-oil specifications [86,87]. The key performance and reliability parameters for a gas turbine application are: ignition, lean flame stability, combustion efficiency, liner temperatures, particulate emissions, exhaust emissions (CO, NO_x, HC), corrosion, erosion and deposition, thermal stability, and compatibility with materials. Effect of fuel properties on atomisation and spray formation remains one of the critical aspects that determines and controls the overall combustion performance including the parameters above. While the use of pyrolysis oils in gas turbine engines is difficult, some of the fuel properties can be enhanced by preheating air to at least 80 °C or by using a secondary fuel such as diesel to heat the engine. Fuel preheating is also known to enhance ignition quality by reducing viscosity in-turn improving atomisation, fuel burnout, and emissions. One study by Sallevelt [72] found that poorer spray quality beyond a recommended fuel viscosity for pressure swirl simplex atomiser led to delayed droplet breakup and presence of ligaments which concluded that due to the high viscosity of bio-oils from pyrolysis, dual-fluid atomisers can be used in gas turbine combustion. Another such study by [43], concluded the feasibility of using pressure atomisers by preheating of pyrolysis bio-oils which helped reduce the Sauter Mean Diameter (SMD) below 50 microns. Incomplete combustion, higher emissions, and fuel residue are some of the problems with the use of pyrolysis bio-oils due to short residence periods, which can be managed and minimised by applying fuel filtering [88]. Table 3 shows some of the experimental work reported in literature using biomass pyrolysis oil (PO) for gas turbine engine application. As shown in Table 3, selected work in GT combustors has been presented from literature with their scope of work, outcome, engine specifications, type of fuel used, along with preheating temperature. The table also presents information about combustion and spray test carried out within the literature.

Table 3. Experimental work reported using biomass pyrolysis oil (PO) for gas turbine engine application.

	Ref. [89]	Ref. [90,91]	Ref. [92]	Ref. [93]	Ref. [94,95]
Scope of work	Technical Feasibility of PO in GT	Technical Feasibility of PO,EtOH Biodiesel Bituminous Crude oil in GT	PO power generation experimental study	Combustion studies of PO and ethanol blend (80–20%) (86.45–13.55%) in a standard GT combustor	Spray characteristics of softwood bark PO and rice husk PO using commercial Delavan AB nozzles
Measured Outcome	Feasibility study	Emissions assessed	Combustion optimisation	Combustion study with PO ethanol blends	To verify the Rosin-Rammler model Spray Combustion
Turbine used	Orenda Aerospace GT2500	Orenda Aerospace GT2500	Deutz T 216 micro GT	Lab scale GT combustor	n/a Bench scale combustion system

Table 3. Cont.

	Ref. [89]	Ref. [90,91]	Ref. [92]	Ref. [93]	Ref. [94,95]
Specification	Max Power 2500 kW	Max Power 2500 kW	Single shaft Max power 75 kW	Lab scale	Spray study only, spray and emissions
PO used	Wood waste	Dynamotive	BTG poplar	Softwood bark residue	Softwood bark and Rice husk
PO Preheating (oc)	75	90	50	80(blend) 150(PO)	80
Spray correlation	NO	NO	NO	YES(SMD) not verified	YES
Combustion tests	YES	YES	YES	YES	NO/YES

Preliminary atomisation tests conducted by Orenda [89,90] observed a wider cone angle of both water and pyrolysis bio-oil than diesel. This is attributed to the lower viscosity and surface tension and the association between primary and secondary diesel fuel flows. The SMD for pyrolysis oils was more than double the size of diesel droplets. A detailed understanding of the fuel atomisation process is an essential feature for the efficient operation of any combustion of gas turbines by making necessary adjustments to the combustor or fuel injector. Table 4 shows the spray atomisation test and observations carried out on simulated GT combustor using various biofuels, bio-oils, and reported work using pyrolysis bio-oils.

Table 4. Spray atomisation tests and observations carried out in simulated GT combustor using various biofuels and PO.

Fuel Tested	Atomiser Type	Kinematic Viscosity N/mm ²	ALR	SMD (microns)	Preheated Fuel Y/N
Diesel [59,60]	Delavan Siphon SNA type AB Nozzle	3.88	2.5 4	22 15	N
Biodiesel#1 [59,60]	Delavan Siphon SNA type AB Nozzle	5.61	2.5 4	28 20	N
Biodiesel#2 [59,60]	Delavan Siphon SNA type AB Nozzle	6.14	2.5 4	29 20	N
Vegetable Oil [59,60]	Delavan Siphon SNA type AB Nozzle	53.74	2.5 4	72 66	N
Vegetable Oil [96]	Delavan Siphon SNA type AB Nozzle	12.5	2.0 4	30 22	N

Table 4. Cont.

Fuel Tested	Atomiser Type	Kinematic Viscosity N/mm ²	ALR	SMD (microns)	Preheated Fuel Y/N
Fast Pyrolysis from Rice Husk [95]	Internal mixed air blast atomiser Nozzle	30	-	50–100	Y (80°)
Wood Derived fast pyrolysis oil [54]	Internally mixed twin fluid nozzles	36 at 40 oc	-	<100 (using water)	Y (40 oc)
Water [97]	Flow Blurring Air Blast	-	2.0	10–13 19–21	N

The above findings concluded that the use of pyrolysis bio-oils in gas turbine combustors is feasible. To achieve acceptable atomisation, it is imperative to reduce viscosity which can be achieved by fuel preheating of about 60–100 °C) for most of the atomisers. One of the other critical aspect of working with pyrolysis oils is the requirement of filtering to reduce ash and solid contents within the fuel. Limited experiments have been conducted on redesigned gas turbine combustors; however, if an atomiser design is tailored according to the range of oils it is feasible to use pyrolysis bio-oils in gas turbine combustor without major modifications. Research findings, [81,97], show successful testing of flow blurring atomisation concept as compared to air blast atomiser which has been successfully implemented to test viscous fuels such as glycerol.

7. Pyrolysis Bio-Oil Combustion in Diesel Engines

Diesel engines are most widely used as engines for generating electricity or transportation, while engines for transport are much smaller. Many diesel engines with medium and slow speeds are versatile in fuel consumption and have been successfully run on lower-grade fuels before and have the ability to be good candidates for pyrolysis biomass oils [98,99], while diesel engines for transportation require a significant fuel upgradation before use. One of the advantages of diesel engines for generating electricity is that they offer portable power solutions that can be useful when dealing with pyrolytic bio-oils made from biomass, as the feedstock is likely to be harvested from remote locations. It is more difficult to use these bio-oils in spark ignition engines because of the need for fast vaporisation and premixing before ignition [99]. Reported work [39,43] on diesel engine operating with pyrolysis bio-oils show that they have a great potential to generate power, but one of the major challenges with such operations is the shorted residence time, intermittent fuel injection, and combustion that need further research to be overcome. Table 5 shows some the experimental work reported in literature using biomass pyrolysis oil (PO) for diesel engine operation. The main aim of these reported studies was to evaluate optimum operating conditions in diesel engines, minimum maintenance requirements, reduced pollutants, minimum levels of erosion-corrosion, maintenance, and reduced costs for diesel engines running on bio-oil.

Table 5. Experimental work reported using biomass pyrolysis oil (PO) for diesel engine operation.

	Ref. [98]	Ref. [100]	Refs. [68,101]	Refs. [102,103]
Scope of work	Test use of Pyrolysis oil in diesel engine	Engine Performance and emissions using PO	Performance of commercial diesel engine with PO and material testing	Compare ignition delay and combustion behaviour of PL, To compare PL and diesel To compare different PL's
Engine Used	Petter AVB0070 test engine 1 cyl., 500 cm ³	Valmet 420 DS engine	Wartsila Vasa 18V32	Ricardo Hydra Mark
Specification	B/S mm: 80/110 CR: 15:3:1 Power: 4.8 kW Rated speed: 2000 rpm	B/S mm: 320/110 CR: 16:5:1 Power: 64kW Rated speed: 2000 rpm	B: 320 CR: 12:1 Power: 410 kW Rated speed: 750 rpm	B/S mm: 80/89 CR: 19:8:1 - Rated speed: 450 rpm
Fuel Used	Ensyn RTP PO	Ensyn RTP, straw derived PO	Ensyn RTP, mixed hardwood derived PO	Diesel No. 2
Major Findings	(1) Unstable engine performance due to clogged nozzle (2) Pyrolysis oil hard to ignite at first	(1) Pyrolysis oil found viable main fuel option for a pilot engine (2) Fast combustion of Pyrolysis oil (3) Fairly high CO and HC emissions	(1) Pilot injection needed (2) Acceptable emissions (3) Fast heat release (4) 44.9% Thermal efficiency	Fuel injection

Atomisation in diesel engines is equally important and critical just like any other combustion applications. Diesel engines normally use simple pressure atomizers where the efficiency of the injector depends primarily on the viscosity of around (10–20 cST) to produce an efficient fuel spray [99,104]. High fuel viscosity is known to create larger droplets with droplets entering the cylinder wall that would penetrate deeper into the combustion cylinder, thereby affecting combustion. However, one study [104] which tested for only about 30 minutes, reported that when highly viscous pyrolysis oil was sprayed in a diesel engine through one and four hole injector, shorter spray angle, and shorter droplet breakup length led to an overall better atomisation, as compared to diesel. A higher fuel rate during and longer injection times is needed for the lower heating value of the fuel, which then leads to modification of the injection system. Ignition is an important property for diesel engines, because the combustion time is typically short in the order of milliseconds. The cetane amount of pyrolysis bio-oil is lower compared with diesel fuel and the ignition efficiency is worse with high water content, high viscosity, and slow fuel chemistry. All these characteristics lead to prolonged ignition, incomplete combustion, and high emissions [102,105].

Several experiments were performed using engine efficiency and emissions pyrolysis oils in a 4.8 kW single-cylinder test engine, a 60 kWe Valmet 420 DS four-cylinder engine, and a 410 kW Vasa 18V32 engine [100,101]. Some of the findings made during such studies were that diesel was needed for pilot injection, pyrolysis oils had faster heat release, and high pyrolysis liquid water content evened out the NOx reduction temperature gradient

and high density. In addition, the low calorific value of pyrolysis oils requires consideration when designing the fuel system. Larger compression engines using pyrolysis oils showed superior fuel flexibility and resisted clogging and longer residence times. While pyrolysis bio-oils enable small, high-speed engine operation, some fuel modifications, such as mixing with methane or cetane enhancers, are typically needed to ultimately achieve the same output as diesel fuel [40]. In one study, [106] tested crude fast pyrolysis oil to evaluate the output effects of a 20 kW engine compared to physically and chemically improved fast pyrolysis oil. The results of the study concluded that the fuels were preheated to around 50 °C and all improved fuels performed better, in particular the difference between the two fuels was significantly reduced at higher loads in terms of emissions from CO. The NO_x was lowest for crude fast pyrolysis oil and highest for blended oil. These studies have shown that the combustion of pyrolysis oil in diesel engines is primarily subject to slow chemistry and not just due to poor atomisation quality compared to the combustion of diesel oil, which limits the mixing of diesel oil. Another observation found that ignition delay is more affected due to thermal cracking during the fuel production process. By preheating the air between 55 and 150 °C to raise combustion temperatures, ignition difficulties in diesel engines can be overcome. It is not possible to initiate combustion from a cold-start especially with pyrolysis bio-oils because of its poor ignition properties, conventional fuels are often used as a starter for the secondary fuel. Like gas turbine engines, because of high viscosity, poor ignition, low cetane number, susceptibility to corrosion and erosion, and clogging of the injection system that requires attention before they can be introduced for long-term service, challenges still remain in the use of pyrolysis bio-oils in diesel engines.

8. Other Applications: Pyrolysis Bio-Oil Combustion in Burners/Boilers

Pyrolysis bio-oils are currently used with great success in burners, boilers, and furnaces for the production of heat and electricity. Longer residence times and fuel flexible designs capable of operating on a wide range of fuels, including those with a high solid content as well as those with a high solid content, these applications are less susceptible to the requirements of atomisation, fuel/air mixing and combustion properties. They are designed to run on heavier fuels with efficiency >1 MW [103], more like pyrolysis oil properties compared to distillate fuels used in gas turbines or diesel engines. In a FLOX burner coupled with a very small Stirling CHP unit, Bandi and Baumgart [107] tested pure pyrolysis oil. Pyrolysis bio-oils can only work in the burner after sufficient preheating of the burner with emissions below German specifications for diesel engines within the similar load and power range. However, common problems such as blockage of the atomisers and fuel supply line and low efficiency have also been reported. Issues like clogging and blocking of nozzle are ongoing which can lead to further heating of the stagnant pyrolysis oil sitting within the nozzle leading to ageing and polymerization [67,73]. This can be prevented by flushing the injection system with a solvent like ethanol. However, the most appropriate long-term solution would be to work on improving fuel quality thereby reducing the solids content since they hinder the overall combustion process and emissions. These combustion systems can achieve efficient atomisation by reducing fuel viscosity to about 4–25 cSt by preheating fuel between 40 and 100 °C or adding appropriate solvent at about 10–12%.

9. Research Challenges and Conclusions

In various small to medium combustion applications, pyrolysis fuel oils are currently becoming a commercially viable potential fuel option. However, their use within stationary combustion engines like gas turbines, diesel engines, and burner/boilers/furnaces requires further fuel standardization and quality improvement to ensure proper atomisation can be achieved. Further application within the transport engines is still in its early research stages and will require significant upgrading as compared to other applications [43,108]. Emphasis on atomisation is critical when dealing with pyrolysis oil combustion due to its significance on overall efficient combustion and given the unique fuel properties [109]. It would be

much easier to reduce the emissions to acceptable levels once the combustion system is optimised [8,40,67]. For example, [78,110–112], stated that emissions of NO_x and particulate matter could be managed using low NO_x burners or other similar methods by applying staged combustion. However, more advanced combustion techniques, such as flameless combustion or exhaust gas recirculation (EGR) or even low-temperature combustion, have yet to be used to allow the use of bio-oil pyrolysis in combustion [113,114].

9.1. Challenges Using Pyrolysis Oils in Gas Turbine Engines

- Shorter residence time requires some system modification before such oils can be used.
- Fuel filtration is required prior to use, as the turbine and combustion parts can be sensitive towards particulate matter.
- Fuel blending, air, and fuel preheating or even pilot fuel can help initiate ignition of pyrolysis oil.
- Spray atomisers/nozzles must adapt to unique fuel properties of pyrolysis oils. However, [80,81,84,96,97] researchers reported that by tailoring the atomiser without major fuel property modification can also lead to efficient and effective atomisation leading to reduced emissions and increased combustion efficiency.
- Rosin-Rammler SMD equation has been experimentally verified to estimate droplet diameter using pyrolysis oils.
- The large-scale testing of Orenda's power generation using 100% pyrolysis bio-oil resulted in reasonable emissions without damaging the components.
- Micro turbines engines have sparked interest with pyrolysis bio-oils which is likely avenue for future research interest [39,65].
- Previous experimental work reported dual-fuel operation resulting in higher levels of fuel residue and poor combustion quality along with higher emissions [39].
- Overall, gas turbine engines fuelled by pyrolysis bio-oils can be a valuable resource for both centralised and decentralised systems and can provide for a potentially viable option.

9.2. Challenges Using Pyrolysis Oils in Compression Ignition Engines/Diesel Engines

- Better suitable for running in low-speed large engines and moderate speed engines
- Highly tolerable to low grade fuels; blended and upgraded fuels more resistant to high mechanical and thermal stresses and have potential to be used in high-speed smaller engines
- Injection system will require some modifications using pyrolysis oils to achieve comparable combustion efficiency between diesel fuel and pyrolysis bio-oil.
- Preheating and fuel filtering is required. Cold start up can be an issue when dealing with high viscous oils but can be overcome using a pilot fuel for initial ignition. Increased compression ratio can help assist ignition issues.
- High CO, NO_x and UHC emissions are expected, however, and oxidized catalyst can help reduce NO_x.
- Very limited studies demonstrated success of using pyrolysis oils and reporting stable engine performance, hence this remains an area of interest.
- Unless the fuel injection system is modified to be suited for use with such heavy oils, it will remain a challenge to successfully operate on 100% pyrolysis oil.

9.3. Challenges Using Pyrolysis Oils in Burners/Furnaces/Boilers

- Pyrolysis oils are better for engines with longer residence times.
- In boiler applications, pyrolysis oils need only minor improvements to the current infrastructure, as the properties of pyrolysis oils are very close to those of heavy oils.
- Flame stabilisation using primary/combustion air swirl can help minimise ignition issues.
- Particularly for cold start with pyrolysis oils, proper atomisation, effective combustor insulation, air and fuel preheating, and pilot flame will be needed.

- Pyrolysis oils used in boiler/burner have shown promising and successful outcomes; however, research has been active to seek process and design enhancements, increase combustion efficiencies, and attain lower emissions.

Combustion quality of pyrolysis bio-oils is strongly related to fuel properties like high viscosity, presence of solids, and it remains a challenge to achieve standardisation and consistency in this aspect. However, it is critical that pyrolysis oils, despite their raw material and production process, can have the market to be used for various applications. Table 6 shows the status of developmental milestones achieved using pyrolysis oils within different combustion engine. As shown in the below Table 6, no major technical issues exist today concerning the use of pyrolysis bio-oils. It has been observed and reported through various works that pyrolysis bio-oils can be adapted within the existing power generation engine infrastructure without much technical modification; the only obstacle that needs attention remains on the economical side.

Table 6. Status of using pyrolysis oils in different combustion engines.

	Gas Turbine Engines	Diesel Engines	NG and Coal Co-Firing
Status of Development	Commercial development of 2500 kW system ready	No reliable system yet developed	NG cofiring successfully tested successfully tested
Critical Issues/Major Modifications	Fuel atomisers, materials, in-line filtering system, emissions	Injector and Fuel pump material emisisions, filtering	Oil gun material pump and, feeding line
Research and Development needs	Long term reliable commercial demonstration. Modification of fuel injector, GT components	Development of effective/reliable pumping and injection systems, efficient combustion to avoid hot spots	Long term commercial demonstration
Future Work	Use of pyrolysis oil in micro turbines (decentralized power)	Use of emulsions and blends for ignition fuel property and injection improvement	Further fuel cost reduction to make NG and coal co-firing economically possible

9.4. Conclusions

The use of pyrolysis oils and its effects on fuel injection have critical impact on combustion process. This process has been extensively reviewed within the scope of present study. With specific fuel properties, atomising pyrolysis biofuels is difficult and extensive research has been carried out and numerous techniques have been identified to promote the use of liquid biofuel. Studies have shown that although SMD is known to be dominant in controlling fuel injection, the role of shear forces at the injector exit in the near field also have an effect on flame instabilities and emissions. An atomiser such as internally mixed swirl or twin fluid that can generate finer droplets at even low ALR's will be preferred for use with pyrolysis oils. Overall, use of an effective atomisation strategy not only makes the combustion of 100% pyrolysis oils in combustors possible but also helps in reducing harmful emissions while maintaining comparable combustion efficiency as those of fossil fuels. Furthermore, this will help reduce the dependency on blending and upgrading pyrolysis oils with solvents like ethanol that can be expensive and interfere with food production and is unsustainable. From the reported research studies, it is inferred that the pressure atomiser may not be ideally suited to the use of pyrolysis oils, because the narrow internal passage of the nozzle may be blocked and the spraying is mainly based on the viscosity of the fuel, which contributes to a higher SMD. Twin fluid atomisation

has been a widely accepted choice for pyrolysis oil combustion in most engines, except diesel engines and many studies have suggested nozzle design strategies to optimise the use with such bio-oils. Long term testing of pyrolysis bio-oils in demonstrating reliable operation across most industrial application is required, and testing underway regardless of the future of pyrolysis oils from biomass is bright. Several engine experiments have shown a great deal of promise with more developments leading to the introduction of pyrolysis oils in large-scale industrial engines in the near future. While the current review focused on pyrolysis oils mostly from biomass, the results of the research are transferable to other feedstocks such as municipal waste, wine waste, dairy waste, plastic waste, and other heavy viscous fuels such as glycerol, a byproduct of transesterification. Finally, the interest of consumers lies in the overall expense of the combustion process relative to the cost of fossil fuels. Consequently, the cost-effectiveness of the entire product is equally desirable and significant.

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