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Review

Liquid biofuels production and emissions performance in gas turbines: A review

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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 reducing 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.

1. 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

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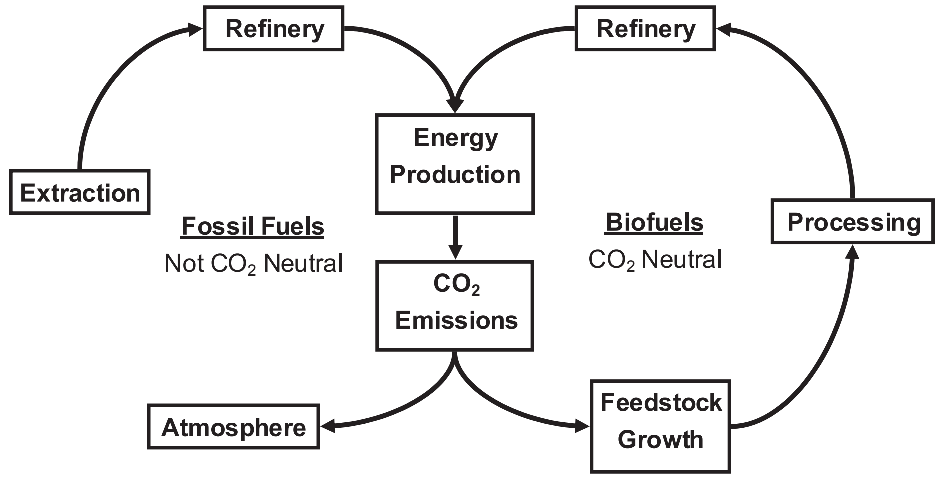

Fig. 1. CO_2 lifecycle comparison between fossil fuels and biofuels.

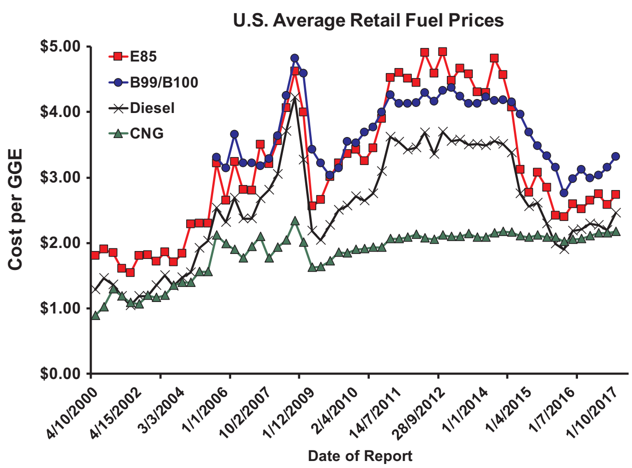

Fig. 2. Fuel prices of E85 bioethanol, B100 Biodiesel, diesel and CNG from year 2000 to 2017 in the U.S. [2].

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 U.S. 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 United Nations 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 U.S. 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. 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