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Biomass Derived Fuels for Gas Turbine Application

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Abstract. The use of biomass-derived fuels as an alternative energy has become a key solution to solve fossil fuels shortage and reduce greenhouse gas emission. With the development on biomass energy conversion, biofuels show great improvement in product yield, fuel quality and combustion characteristics, making it possible for gas turbine applications. The stable combustion flame of the gas turbine makes it adaptable to various biofuels. The main research of utilizing biomass-derived fuels in gas turbine in recent years was summarized. Characteristics and combustion feasibility of typical biofuels were discussed including both liquid phase biofuels and gas phase biofuels. The combustion performance, pollutant emission and combustion optimization of biofuels combustion in gas turbines was analysed. The main problems and effective solutions for biofuel applications were summarized, providing guidance for clean and efficient use of biofuels in gas turbines.

1. Introduction
Currently, besides coal, oil and natural gas, biomass is the fourth largest energy source in the world, showing abundant source, great sustainability and good greenhouse gas reduction effect. Therefore, biomass can be used as a substitute for fossil fuels. As a new type of internal combustion engine, gas turbine shows stable combustion flames, fast start-up and high thermal efficiency. The strong mechanical structure, wide power range and flexible combustion system of gas turbine all contribute to the application of biofuels. The application of alternative biofuel on gas turbine can not only control CO_2 emissions but also limit NO_x and soot emissions, achieving dual benefits of environmental protection and economy. However, due to the difference of biofuels with conventional fossil fuels in viscosity, composition and heating value, the use of biofuels on gas turbines still faces problems such as ignition difficulty, poor atomization effect and coking and corrosion of equipment. In this paper, the typical biomass-derived fuels used in gas turbines in recent years are summarized for analyzing the main characteristics, application status and key technical problems in biofuel application.

2. Liquid Phase Biofuel
Liquid biofuels could be mainly classified as vegetable oil and bio-oil. A typical liquid biofuel production path is shown in Figure 1.

2.1. Vegetable Oil
Pure vegetable oil is low in sulfur content, non-toxic and biodegraded. The combustion of vegetable oil is benefited to reduce sulfur oxides, CO and polycyclic aromatic hydrocarbons (PAH). Cavarzere et al. [1] analyzed the characteristics of rapeseed oil, sunflower oil and soybean oil and verified the application of vegetable oil on gas turbine. However, pure vegetable oil combustion would increase fuel injection pressure exponentially, resulting in poor atomization and burner ash accumulation. Fuel

pre-heating, dilution/pre-mixing, micro-emulsification and transesterification can reduce vegetable oil viscosity. F. Chiariello et al. [2] mixed kerosene with sunflower oil and rapeseed oil respectively, and tested the combustion and emission of them in a micro-turbine. It was found that low addition of vegetable oil could increase particulate matters emission with little effect in CO and NO emission. A. Hoxie et al. [3] mixed soybean oil with low-sulfur diesel at a maximum volume ratio of 75%. They confirmed composite fuel oil can be stably and efficiently burned in gas turbines.

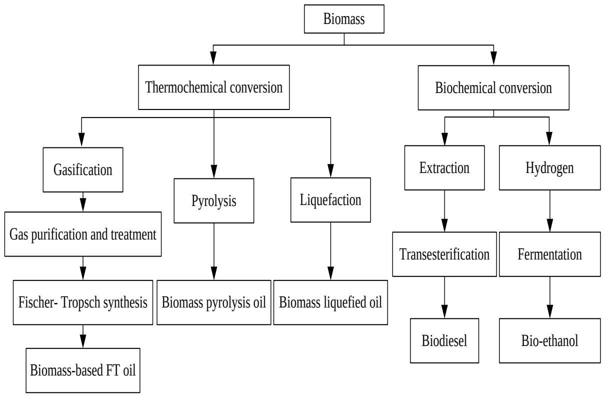

Figure 1. Liquid biofuels production [4].

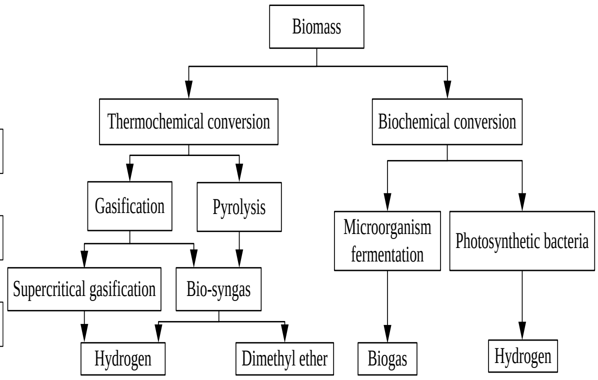

Figure 2. Gas biofuels production.

2.2. *Biodiesel*

Biodiesel is a fatty acid methyl ester or ethyl ester formed from animal or vegetable oil through ester conversion with methanol or ethanol. KK.Gupta et al. [5] found by blending 20% biodiesel in diesel, CO and particulate matters could be decreased by 12% and unburned hydrocarbon could be declined by 20%. Although the addition of biodiesel decreases combustor temperature, the high oxygen content of biodiesel could lead to lean combustion and improve thermal efficiency. Zhang et al. [6] found the combustion efficiency could still reach more than 99% with biodiesel and the influence of biodiesel could be limited with increasing oil/gas ratio. Habib et al. [7] found biodiesel reduced static thrust of gas turbine and CO and NO emission. Chong et al. [8] detected a wider flame reaction zone, higher spray droplet density and higher spray volume flow rate in the combustion of rapeseed biodiesel than ordinary diesel. Thus, soot and NO_x could be reduced by combustion. Besides, the blending ratio could be enhanced to 50% and the thermal efficiency could reach about 26% by biodiesel preheating [9, 10].

2.3. *Bioethanol*

Bioethanol refers to alcohol produced by microbial fermentation or thermochemical conversion. It has a low flash point and cetane number, making it easy to ignite for clean combustion. There are no atomization problems for bioethanol [11].

Lupandin et al. [12] carried out multiple biofuels combustion on an OGT2500 gas turbine. The modified gas turbine can adapt to bio-oil, bioethanol and biodiesel. Among these biofuels, bioethanol resulted low NO_x, CO, and SO_x emissions below the government limits. J.A. Alfaro-Ayala et al. [13] compared the combustion of natural gas and bioethanol in gas turbines. The inlet temperature, power generation and efficiency of gas turbines for bioethanol were slightly lower with same amount of fuel. Therefore, under the same load, bioethanol fuel consumption is higher than natural gas. But NO_x emission of bioethanol was only 65% of natural gas. Sallevelt et al. [14] carried out combustion of bioethanol and diesel in a 2MW OP16 gas turbine, and simulated the atomization of bioethanol combustion. The results show that CO emissions of bioethanol are comparable to diesel and the NO_x emissions are low.

2.4. *Bio-oil*

Bio-oil is liquid fuel made from biomass thermochemical conversion. The chemical composition of bio-oil is relatively complicated with high oxygen and impurity content, high viscosity and corrosivity, making it difficult for gas turbine application [15].

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Pedro L. Cruz et al. [16] evaluated biomass gasification-Fischer-Tropsch synthesis combined cycle by exergy analysis. They studied the behavior of bio-oils derived from Fischer-Tropsch synthetic in gas turbines, and proposed optimum design for improving exergy efficiency. M.E Boucher et al. [17] evaluated the viscosity, stability, combustion reactivity and aging characteristics of biomass pyrolysis oil. They added methanol to the pyrolysis oil to promote its application in gas turbines. Marco Buffi et al. [18] prepared a low-viscosity, high-organic bio-oil based on the liquefaction with an acidified glycol solvent. They used it in a 25kW micro gas turbine by mixing bio-oil with ethanol, increasing CO emission and decreasing NO_x emission. The components and fuel characteristics of diesel, aviation kerosene, and typical liquid phase biomass-derived fuels are shown in Table 1.

Table 1. Liquid biofuel properties [19-20].

Properties	Diesel	JET-A	Straight vegetable oils	Bio-diesel	Bio-ethanol	Pyrolysis oil
Density (kg/m³)	827.4	807	900~940	860~900	794~810	984~1250
Kinetic viscosity (Cst, 40 °C)	1.7283	0.88	30~40	3.5~5	1.4~1.7	32~45
Flash point (°C)	44~50	38	230~280	120~180	13	56~130
Cloud point (°C)	-6	——	-4~14	-3~-12	——	——
Pour point (°C)	-16	-47	12~10	-15~5	-117	-35~-10
Lower calorific value (MJ/kg)	43	43.23	38~39	39~41	25~26	13~18
Ignition temperature (°C)	250	220	325~370	177	423	580
Cetane no.	45~55	55	37~42	48~60	8	10
Stoichiometric air/fuel ratio	14.6	14	13.8	13.8	9.79	34:1

3. Gas Phase Biofuel

As shown in Figure 2, gas phase biofuels which are produced by biochemical or thermochemical conversion, mainly contain biogas, biomass syngas, dimethyl ether and hydrogen.

3.1. Biogas

Biogas is a kind of gas mainly composed of CH_4 and CO_2 produced by microbial fermentation under anaerobic conditions. Its calorific value is lower than natural gas. Bruno et al. [21] used a biogas-burning micro-turbine to build a sludge treatment tri-generation system. Many researchers have further confirmed the economic and environmental benefits of gas turbine biogas combustion [22, 23]. Nikpey et al. [24] conducted a mixed combustion test of biogas and natural gas based on a regenerative micro gas turbine, verifying that biogas can be stably burned with natural gas in an unmodified micro gas turbine. Compared with natural gas, the electrical efficiency and operating parameters are almost unchanged. Besides, CO_2 emissions can be reduced by 19% at full load. Somehsaraei et al. [25] built a thermodynamic model to analyse the effects of biogas combustion on gas turbine performance based on a 100kW micro gas turbine. Biogas combustion decreases gas turbine mass flow, pressure ratio and surge margin compared with nature gas. Electrical efficiency and heat recovery efficiency of heat exchangers decreased as the CH_4 content of biogas decreased.

3.2. Biomass Syngas

Syngas containing H_2, CO, CO_2, CH_4, etc. can be obtained by biomass pyrolysis or gasification at high temperature, requiring independent compressors for air and gas compression during combustion. Design and modification of gas mass flow measurement system, gas delivery and injection system, fuel nozzle and combustion chamber are needed. The power consumption of gas turbine shafts also increases accordingly [26, 27]. Adouane et al. [28] used a 1.5MW pressurized fluidized bed to prepare biomass syngas and achieved stable turbulent combustion in a gas turbine. The conversion efficiency of fuel NH_3 to NO_x was 10-60%. Sukumaran et al. [29] simulated the combustion of different biomass syngas and analyzed the key factors affecting the NO_x emissions and the mechanism, guiding the design of low NO_x syngas burners. Cameretti et al. [30] calculated the combustion efficiency and pollutant emissions of biomass syngas in micro gas turbines, proposing a coordinated improvement for combustion efficiency and NO reduction. Walter et al. [31] achieve stable co-combustion of biomass syngas and natural gas in gas turbines based on the reformation of the fuel supply system.

3.3. Dimethyl Ether

Dimethyl ether (CH_3OCH_3) has a simple structure, non-toxicity, high cetane number and strong environmental friendliness. Dimethyl can quickly evaporate and form a good fuel-air mixture to accelerate combustion. Lee et al. [32, 33] used GE7EA gas turbines to perform dimethyl ether combustion. They verified dimethyl ether can be used as clean gas turbine fuel. The NO_x emission is significantly lower than methane. Compared with methane, dimethyl ether has a lower spontaneous combustion temperature, a higher flame propagation speed and a greater risk of spontaneous combustion during premixing. Saitou et al. [34] developed a multi-cluster burner, which can significantly reduce the risk of spontaneous ignition and tempering of dimethyl ether. Lee et al. [35] designed and manufactured a new type of dimethyl ether combustion nozzle, which can not only prevent spontaneous combustion and tempering, but also reduce NO_x and CO emissions. Namasivayam et al. [36] used dimethyl ether as the ignition fuel for gas turbines. Results showed that dimethyl ether can reduce NO_x by about 20% at low load. Kang et al. [37] studied the effect of dimethyl ether addition on the combustion of turbulent methane/air jet diffusion flames and found the addition of dimethyl ether changed the flame structure and reduce soot and NO_x emissions.

Table 2. Gas biofuel properties.

Properties	**Methane**	**Propane**	**Biogas**	**Biomass syngas**	**DME**	**Hydrogen**
Chemical composition	CH_4	C_3H_8	CH_4, CO_2	CO, H_2, CH_4, CO_2, N_2	C_2H_6O	H_2
15°CDensity (kg/m^3)	717	490	0.65-0.91	765~785	670	70.8
Boiling point (°C)	-161	-42	-126~-162	-192	-25	-252.8
0°CVapor pressure at 0°C (MPa)	24.6	0.93	——	——	0.61	——
Flammable limits in air (%)	5~15	2.1~9.4	7~26	5~32	3.4~17	4~75
Ignition temperature (°C)	537	470	632~813	——	235	500
Max. burning velocity (cm/s)	37	43	——	——	50	289
Stoichiometric air/fuel ratio	16.9	15.7	10~17	9.1	9.0	34.1
Lower calorific value (MJ/kg)	49	46.3	20~28	10~18	28.8	120
Cetane no.	0	5	——	70	55~60	——

3.4. Hydrogen

Hydrogen can be produced by biomass pyrolysis, gasification and microbial fermentation. Only thermal NO_x is formed due to the presence of air. Hydrogen combustion has a high combustion speed and extremely high diffusivity. Hydrogen can be fully mixed with air, reaching a combustion temperature of 2300 K and a combustion efficiency of 100% [38]. Due to the rapid combustion reaction, premixed combustion is still the main use of hydrogen on gas turbines. Lee et al. [39, 40] tested H_2 and CO combustion in gas turbines. They found the gas turbine requires only a small amount of modification to stabilize combustion. The ratio of H_2 and CO directly affects syngas combustion. Premixing H_2 had an effect on the gas turbine operating amplitude, frequency and instability pattern. After premixing, the flame speed stage temperature changed and formed a variety of instability modes. York et al. [41] carried out experiments on premixed combustion of high-hydrogen fuel in gas turbines based on self-designed premixed combustion nozzles. Hydrogen fuel can achieve stable combustion without tempering and generate carbon-free flue gas. Taamallah et al. [42] and Kahraman et al. [43] evaluated hydrogen premixed combustion stability and NO_x emission based on simulation. The results were compared with conventional fuels to support optimizing flame structure and combustion dynamics.

The composition and fuel characteristics of methane, propane and typical gas phase biomass-derived fuels are shown in Table 2.

4. Optimization of Biofuel Application on Gas Turbine

Compared with conventional fossil fuels, the combustion of biofuels in gas turbines is still in its infancy. Further improvements need to be made in terms of combustion stability, fuel applicability and combustion solutions.

4.1. Fuel Modification and Upgrading

Compared with conventional fuels, biofuels still show differences in evaporative atomization effect, droplet size, flame stability, turbine inlet temperature and pollutant emission concentration. Biofuel upgrading can make biofuel closer to conventional fuels, improving combustion efficiency and avoiding major fuel system changes. Chan et al. [44] used hydrogenated vegetable oil (HVO) on turbofan engines. They found that compared with conventional Jet A-1 fuel, NO_x emissions of HVO combustion decreased significantly. Under 80% and 95% load idling conditions, the NO_x emissions of 50% HVO/Jet A-1 mixed fuel can be reduced by up to 0.3g/kg. Buffi et al. [45] observed through the optical swirl burner that the HVO fuel combustion exothermic temperature is very uniform. Thus the HVO combustion pollutant emissions are low.

4.2. Combustion Equipment Improvement

Due to the differences of biofuels and conventional fuels, the air-fuel ratio, fuel atomization effect and combustion stability of biofuels in gas turbine are different from conventional fuels. The gas turbine fuel supply system, injection system and combustion system need to be designed and modified. Prussi et al. [46] reformed commercial gas turbine fuel pipelines, realizing switch between diesel and pure vegetable oil. Under the same load, the fuel consumption of vegetable oil was only increased by 5%. The output pressure of fuel pump was increased by 30%. Al-attab et al. [47] constructed a dual fuel supply system which can simultaneously use liquefied petroleum gas and biomass syngas, achieving stable combustion for biomass syngas alone or the mixture with liquefied petroleum gas. Asai et al. [48] optimized the structure of burner and combustion chamber by single-nozzle fuel-air mixing experiments and burner combustion experiments for reducing NO_x, CO and unburned hydrocarbon. The stability of the combustion system and emission is optimized greatly.

4.3. Combustion Technology Optimization

Fuel preheating can reduce viscosity to conventional fuel levels and improve evaporative atomization. Sallevelt et al. [49] can significantly reduce vegetable oil viscosity to 1/3 by increasing fuel injection temperature of micro gas turbines, reducing CO emissions by 28% while improving combustion efficiency. Chiaramonti et al. [9] also found the CO emissions of biodiesel were higher than that of diesel without preheating. By preheating biodiesel to 120°C, CO emissions could be reduced by 63-64%.

The premixed and pre-evaporated lean combustion of biofuel could assist atomization and evaporation of fuel by forming a vortex air flow in the premixed tube. Jozsa et al. [50] performed a spectral analysis on the premixed combustion of rapeseed oil in a gas turbine. They found that controlling the number of premixed swirls can achieve stable combustion of rapeseed oil. The levels of NO_x and CO emissions are close to diesel. Chen et al. [51] used lean-burn premixed enhanced combustion nozzles to test the combustion of biogas in gas turbines. PIV observed good biogas flow in the nozzles and strengthened vortex flow.

5. Conclusion

The use of alternative biofuels for gas turbines can not only alleviate the shortage of fossil fuels, but also broaden the scope of biofuels application and improve the overall energy structure. Potential biofuels include vegetable oil, biodiesel, bioethanol, dimethyl ether and hydrogen. Biofuels can be used stably in gas turbines by modification, upgrading or mixing with fossil fuels. The fuel consumption rate is slightly higher than fossil fuels at the same load and the temperature of combustion chamber inlet is lower. The application of most biofuels can reduce SO_x, CO, NO_x and soot in gas turbines. The combustion efficiency is equivalent to that of fossil fuels. Fuel upgrading, combustion system modification, and optimization of combustion technology can all promote the stable application of biofuels in gas turbines. Premixed and pre-evaporated lean combustion are currently effective biofuel combustion application methods.

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