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Effect of producer gas staged combustion on the performance and emissions of a single shaft micro-gas turbine running in a dual fuel mode

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A B S T R A C T

Producer gas from biomass gasification has a potential to cover a considerable part of power production in the future, the availability and variety of biomass put it as the fourth energy resource. The use of producer gas fuels in gas turbine engines can help mitigating problems related to fossil fuels depletion, emissions and biomass waste disposal. In this work, the effect of the staged combustion of a simulated low calorific value producer gas fuels on the performance and emissions of a single shaft micro gas turbine was investigated experimentally. In order to perform the experiments, the micro gas turbine system was characterized first with the liquefied petroleum gas (LPG) and then tested with two producer gas fuels, producer gas1 (10.53% H_2, 24.94% CO, 2.03% CH_4, 12.80% CO_2, and 49.70% N_2) and producer gas2 (21.62% H_2, 32.48% CO, 3.72% CH_4, 19.69% CO_2, and 22.49% N_2) in a dual fuel mode. Two injection methods were proposed and tested for producer gases including radially and axially injection. The tests were examined in terms of LPG fuel replacement, turbine entrance temperature, combustor efficiency, turbine efficiency, and emission characteristics at different LPG fuel replacement ratios. The study showed stable operation with a maximum LPG replacement of 42% and 56% for the radially injected producer gas1 and producer gas2, respectively. While for the axially injected producer gas fuels, the maximum achieved LPG replacement ratio was 38% and 52% for producer gas1 and producer gas2, respectively. A relatively higher efficiencies for the combustor and turbine with a remarkable reduction in NOx emissions were achieved when LPG fuel was replaced with producer gas fuels. On the other hand CO emissions were increased for both injection methods.

1. Introduction

Biomass is an essential energy source for mankind throughout the history. The availability and variety of biomass put it as the fourth energy resource after coal, oil and natural gas [1]. Since the amount of carbon which can be released from biomass is equivalent to the amount of carbon that can be absorbed during biomass lifetime, biomass is considered as carbon neutral [2]. Due to growing concerns on the environmental issues and fossil fuel depletion, a renewed attention has been given to extract energy from biomass. Substituting part of the traditional fuels with biomass have been considered as a promising way to meet the urgent environmental targets. Among all available renewable resources, biomass is the only resource that can be converted to gas, liquid and solid product by various conversion processes [3]. In Malaysia, the availability and variety of biomass make this type of fuel as one of the most promising solutions for power production in the future. In addition to the huge forest resources, Malaysia is the second largest producer and exporter of palm oil with 43% of total world supply [4]. Shown in Table 1 is the collected biomass from palm oil in Malaysia in 2005. Oil palm fronds (OPF) is the major component of palm oil residues, it basically consists of petiole and leaflets [4]. Researches show that the morphological structure of the frond fibers is comparable to those of hardwood. In the recent few years, an extensive research on oil palm fronds gasification was conducted in the

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Table 1
Collected biomass from palm oil in malayasis in 2005 [4].

Biomass component	Quantity available (million tons)
Empty fruit brunches	17.00
Fiber	9.60
Shell	5.92
Fronds and trunks	21.10
Palm kernel	2.11
Total	55.73

Biomass Energy Laboratory of Universiti Teknologi PETRONAS [5–7]. The results showed that the produced gas of OPF gasification is comparable to that of hardwood [5].

The main challenge of utilization of producer gas from gasification in energy production is due to its low energy density [8,9]. For the same amount of power, the flow rate of the low calorific value producer gas from biomass gasification may reach seven times that of natural gas on volume basis [10]. Thus, combustion of low calorific value producer gas requires combustors that provide high mixing quality with long residence time [11,12]. In order to improve the producer gas calorific value, different methods were investigated and applied such as using steam, oxygen and hot air as a gasification agent. In addition, the combination of biomass and other material which capable to produce higher combustible gases is another option. Co-gasification of coal and biomass can be considered as a mixed way for energy production from fossil fuels and renewable resources. Coal gasification is a process of producing a fuel-rich product. It has some advantage related to availability and low cost of coal, but still it has the same fossil fuels disadvantages. Extracting energy from biomass by gasification has an advantage as compared to coal gasification because it's environmentally friendly, but at the same time the produced gas has a low calorific value and it affected by wastes seasonal shortage [13]. The combination of coal and biomass in gasification is more attractive than their individual gasification. In recent years, some researchers have reported that the combination of both coal and biomass is more advantageous than their individual effects [13]. Biomass–coal gasification can allow using biomass and coal commercially with an environmentally friendly technique. In addition, it makes feasible utilization of biomass in energy production in larger scale, higher efficiency, and low specific operating costs [14]. Moreover, the use of Biomass and coal for gasification could help to provide a stable gasification condition and hence stable production of producer gas with a higher calorific value.

Producer gas from gasification can be utilized in running internal-combustion engines. However, the main challenge of using it in SI and CI engines that these engines are very sensitive to tar and dust presence, which can affect the maintenance cost [12]. Moreover, using producer gas in such engines needs a lot of modifications, especially in the fuel system [15]. Another option for producer gas utilization for power generation is in fuel cells and Stirling engines, however, these technologies are not well established and still under development [16].

Gas turbines are a continuous combustion engines, which develop a continuous flame during operation. It is designed to run mainly on natural gas and oil. The attractive feature of gas turbine as compared to the other engines that it is capable to run with various types of fuels [17,18]. Micro-turbines are a small electricity generator with rated capacities of 25–300 kW [10]. Micro-gas turbines running on producer gas are an applicable option for distributed power generation, especially in rural areas where electricity is lacking. Compared to other internal combustion engines, micro gas turbine offers several advantages such as: high power to weight ratio, less complexity, low emissions and fuel flexibility [10,19,20].

Of all factors influencing gas turbine emissions, the most important factor is the temperature of the combustion zone. One way to reduce the gas turbine emissions is by controlling flame temperature. This can be achieved by using a combustors with variable geometry or by implementation of staged combustion. In the variable geometry systems, the combustion temperature can be controlled within narrower limits by switching air from one zone to another with the change in the engine power [21]. By contrast, the air flow distribution within staged combustors remain constant, the fuel flow is switched from one zone to another in order to maintain a constant combustion temperature [21]. A significant feature of producer gas fuels that they often have a high dilution level, lower flame temperatures and lower flame speeds than natural gas or other medium calorific value fuels which is good from standpoint of thermal NOx emissions [11]. The implementation of staged combustion techniques for producer gas fuels in gas turbine engines has advantages over other fuels from NOx emissions point of view since the temperature levels in producer gas fuels are lower as compared to gas turbine conventional fuels. Moreover, using of more than one injector to introduce the fuels into gas turbine combustor would improve the turbulence which is good for the combustion.

Studies on running micro gas turbines on producer gas fuels were conducted by number of researchers [9,12,22–24]. The studies showed a stable operation with acceptable thermal efficiencies for gas turbine systems when producer gas fuels were used instead of the conventional fuels. The Department of Aerospace Engineering in the Indian institute of Science [22] conducted an experimental study to run a small scale Rovers gas turbine with producer gas. The study showed no difficulty in the start up the gas turbine system with producer gas fuel. Other studies were conducted by Rabou et al. [23,24] to investigate the performance of a micro gas turbine operating on biomass producer gas and mixtures of biomass producer gas with natural gas. They reported that the full nominal power of the turbine could be achieved when the calorific value of the producer gas and natural gas mixture reaches 15 MJ/Nm^3 where the contribution of producer gas was two thirds by volume basis and only one third by energy basis. In order to improve the producer gas combustion characteristics by increasing the residence time, Al-attab et al. [9] proposed and fabricated a cyclonic combustor with a tangential flow at the inlet and outlet of the combustor. They achieved a 48% LPG replacement when cold producer gas was used while for hot producer gas a 72% LPG replacement was achieved.

The producer gas combustibility, dynamic stability and emissions of the gas turbine combustor when natural gas fuel is replaced with a simulated producer gas were studied by a number of researchers [25,26]. The used test facilities were consisted of only combustor, ignition system and producer gas fuel supply system. They reported that there were no problems regarding dynamic or static instability. In addition, the investigation showed that the gas turbine combustion chamber temperature was in the allowable limits. Since these studies were

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