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PART-LOAD PERFORMANCE ANALYSIS OF A COMBINED CYCLE PLANT CO-FIRING BIOGAS AND NATURAL GAS

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ABSTRACT

In this paper, the influence of co-firing natural gas and biogas on part-load performance of a natural gas combined cycle (NGCC) plant is investigated from thermodynamics perspective. Simulations of the plant, of which design fuel is natural gas, are developed. Performance of the plant fueled by natural gas is determined as a benchmark. Part-load performance of the plant running with different mixtures of natural gas and biogas is calculated and compared with the benchmark. Results show that co-firing mixed fuel leads a reduction in energy utilization efficiency at low gas turbine load, and leads an increase at high gas turbine load. When the gas turbine is fueled by mixed fuel, exergy efficiency decreases at every condition, and the most reduction is around 6% from benchmark. It is not efficient to use biogas at low power load from both energy and exergy efficiency perspectives for the plant in this study.

Keywords: biofuel, natural gas combined cycle, combined heat and power, part-load operation

NONMENCLATURE

Abbreviations	
NGCC	Natural Gas Combined Cycle
LHV	Lower Heating Value (kJ/kg)
Symbols	
R	ratio
n	molar quantity (mol)
N	power output (MW)
$\dot{m}$	mass flow rate (kg/s)
ex	exergy (kJ/kg)
V	volume flow (m^3/s)
η	efficiency
H	total enthalpy (MW)

1. INTRODUCTION

In the last decades, the continuous rise in world population has led to growing energy demand with excessive use of fossil fuels and increasing greenhouse gas concentration in the atmosphere. Research focuses on using alternative energy sources is therefore under urgent demand to combat this trend. As a renewable energy source, biogas can be produced from various resources, such as wood, agricultural residue and municipal organic waste.

Among energy industries, the gas turbine combined cycle systems are considered as the most effective and suitable technology to use biogas for providing power, due to their high fuel flexibility [1]. Extensive studies on the effective utilization of biogas in gas turbine systems have been presented in the recent literature. However, these studies are mainly focused on the performance of the plant under design condition or full-load condition. Besides the variation of base-load performance, the variation of part-load performance is also of great importance for the operation of an NGCC plant [2]. In addition, with high prevalence of intermittent renewable energy, such as solar and wind energy, the demand for peaking on NGCC plants from electricity market has been increasing. Consequently, the plants often run under off-design conditions. To the best of the authors' knowledge, there is not a reported work that presents the variation of part-load performance of NGCC plants, after the fuel is shifted to a mixture of natural gas and biogas.

Therefore, the influence of co-firing natural gas and biogas on the part-load performance of an NGCC plant is investigated from the perspective of thermodynamics in this study. Simulations of the NGCC plant, of which design fuel is natural gas, are developed. Performance of the plant fueled by natural gas is determined as a benchmark. Part-load performance of the plant running with different mixtures of natural gas and biogas is calculated and compared with the benchmark. The variations of part-load performance are quantified and analyzed.

2. MIXED FUEL AND AN NGCC PLANT

In many power generation systems, the biogas is generally used to co-fire with natural gas. On the one hand, the production capacity of biogas may not be large enough or stable enough to feed large-scale power plants during different time and seasons. On the other hand, the production of biogas may suffer from some fluctuations in quality and composition due to different resources. In such cases, the co-firing of natural gas and biogas is a good solution for steady operation of NGCC plants. The properties of natural gas and biogas used in this study are shown in Table 1. The CH_4 and CO_2 concentration of biogas are set to be 60% and 40% respectively, and other substances are not considered for their little quantity [3].

Table 1

Natural gas and biogas properties

	Natural gas	Biogas
Composition (mole %)		
H_2O	0.006	-
CO_2	3.000	40
CH_4	95.949	60
C_2H_6	0.908	-
C_3H_8	0.137	-
LHV (kJ/kg)	46085	17680

In this study, a large-scale NGCC plant based on a Siemens SGT5-4000F gas turbine is modelled. The exhaust gas from gas turbine passes through a reheat sub-critical HRSG. There are three pressure levels of water-steam circuit in the bottoming cycle: high pressure (HP), intermediate pressure (IP) and low pressure (LP) systems. The HP, IP and LP turbine sections compose the condensing steam turbine. A direct water cooled condenser is used. The cold reheat steam consists of the exhaust steam from HP turbine, and the IP steam from IP superheater, becoming hot reheat steam after reheaters and passes into IP turbine section.

3. MODELLING AND METHODOLOGY

In this study, the NGCC plant is modelled with Ebsilon Professional [4]. Based on the design condition data, the off-design modelling and simulation are performed. Details of the modelling methodology is adopted from our previous work [5]. A field data set that covers a wide range of operating conditions has been selected for validation, and errors are within a tolerance interval of 1.4%.

In what follows the main parameters for evaluating the performance of a NGCC plant is presented. The biogas mixing ratio R_{bg} is defined as the molar fraction of biogas in mixed fuel:

$$R_{bg} = \frac{n_{bg}}{n_{ng} + n_{bg}} \tag{1}$$

The energy utilization efficiency of the plant $\eta_{en,cc}$ is defined as the ratio of power output to the fuel energy input of the plant:

$$\eta_{en,cc} = \frac{N_{gt} + N_{st}}{\dot{m}_{mf} \cdot LHV_{mf}} \tag{2}$$

The system exergy efficiency of the plant $\eta_{ex,cc}$ is defined as the ratio of power output to the chemical exergy of the mixed fuel:

$$\eta_{ex,cc} = \frac{N_{gt} + N_{st}}{m_{mf} \cdot ex_{mf}^{ch}} \tag{3}$$

$$ex_{mf}^{ch} = \beta \cdot LHV_{mf} \tag{4}$$

where β is a multiplication factor of chemical exergy on LHV [6].

4. RESULTS AND DISCUSSION

In order to present the variation of part-load performance clearly, the difference between parameters of NGCC plants fueled by mixed fuel and natural gas are calculated under the same gas turbine load. The part-load performance of the plant fueled by natural gas is set as the benchmark.

The variations of difference in energy utilization efficiency at various gas turbine loads are shown in Fig 1. It can be seen that with decreased gas turbine load, the effects of co-firing mixed fuel on energy utilization efficiency changes from positive to negative. To explain the reason for the variation trend, the energy utilization efficiency is analyzed from the perspective of definition, Equation (1). Under the same gas turbine load, it is mainly related to the heat consumption of system and steam turbine load. The heat consumption of the system is determined by the gas turbine efficiency. As shown in Fig 2, co-firing mixed fuel leads an increase in gas turbine efficiency at high gas turbine load, and a reduction at low gas turbine load.

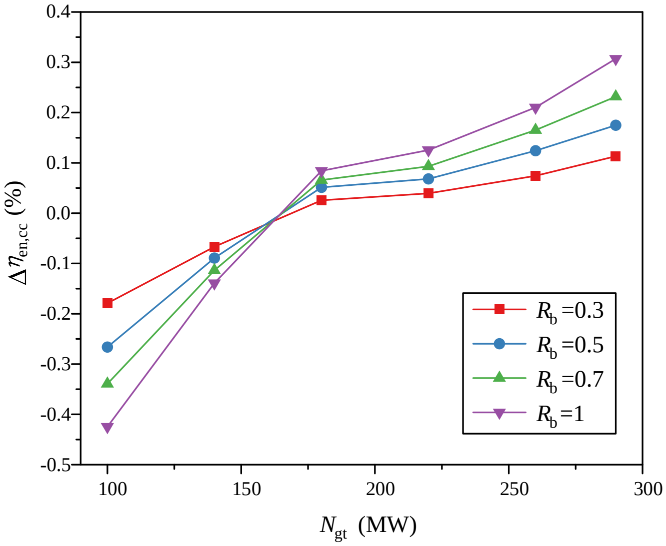

Fig 1 Variations of $\triangle\eta_{en,cc}$ at various gas turbine load

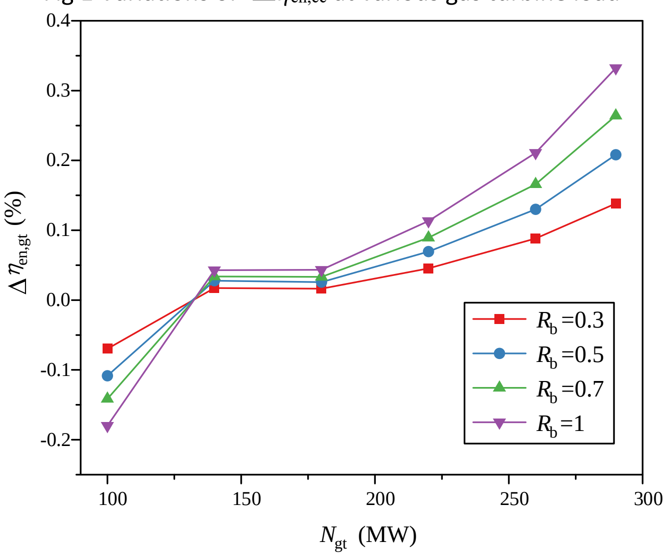

Fig 2 Variations of $\triangle\eta_{en,gt}$ at various gas turbine load

The steam turbine load is determined by the efficiency of waste heat recovery and utilization of bottoming cycle. As gas turbine load decreases, to keep exhaust temperature of a gas turbine equal to a set constant value, the compressor air flow is reduced by closing IGV gradually. When gas turbine load decreases to a certain value (around 50% load), the IGV position is closed to the minimum, which means the compressor air flow also reaches the minimum. Then the compressor air flow is almost constant with the reduction in gas turbine load. As a result, the exhaust temperature of a gas turbine decreases with the reduction in gas turbine load, for lower loads, as shown in Fig 3. Due to a lower heating value of biogas compared to natural gas, the air flow of the gas turbine fueled by mixed fuel is less than that of the gas turbine fueled by natural gas. Therefore, the IGV position reaches the minimum at a higher gas turbine load when co-firing mixed fuel. The variation of the difference in exhaust temperature is shown in the bottom right window of Fig 3. The difference reaches the maximum when the IGV position of the gas turbine fueled by natural gas reaches the minimum. Then as the gas turbine load continues to drop, fuel flow decreases and air flow is close to constant. A higher air-to-fuel ratio results in a decreased exhaust temperature. The exhaust temperature of a gas turbine has a great influence on the efficiency of waste heat recovery and utilization of bottoming cycle, which is evaluated by the bottoming cycle efficiency in this study. The variation of the difference in bottom cycle efficiency is shown in Fig 4. The bottom cycle efficiency $\eta_{en,bc}$ is defined as the ratio of steam turbine load to inlet energy of HRSG:

$$\eta_{en,bc} = \frac{N_{st}}{H_{gt}} \tag{5}$$

Based on the analysis above, co-firing mixed fuel leads an increase in energy utilization efficiency at high gas turbine load, mainly because the gas turbine efficiency rises. At low gas turbine load, due to the reduction of gas turbine efficiency and bottom cycle efficiency, co-firing mixed fuel leads a decrease in energy utilization efficiency.

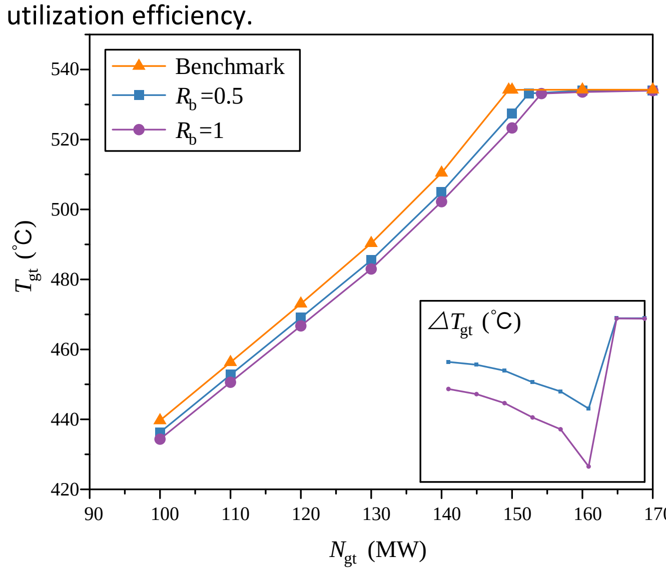

Fig 3 Variations of T_{gt} at various gas turbine load

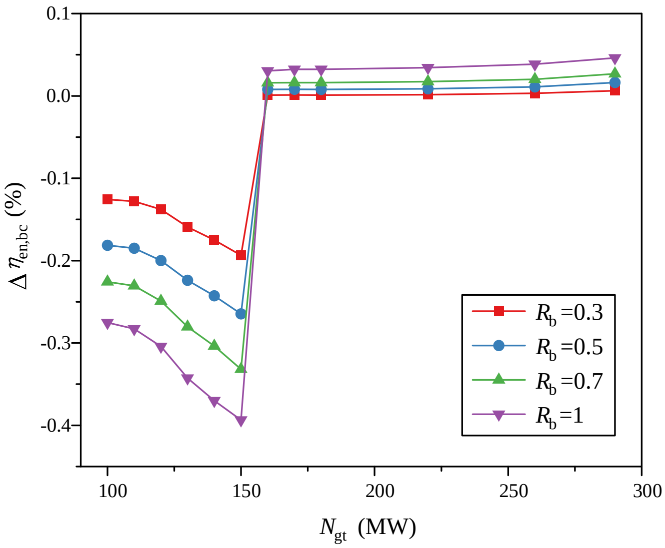

Fig 4 Variations of $\triangle\eta_{en,bc}$ at various gas turbine load

As can be seen from Fig 5, co-firing fuels reduces the exergy efficiency at every condition. The more biogas is mixed into natural gas, the larger the reduction in exergy efficiency is. The most reduction is around 6% from benchmark when the gas turbine fueled by mixed fuel. Combining the above analysis on energy utilization efficiency, it is not efficient to use biogas at low power load from both energy and exergy efficiency perspectives for the plant in this study.

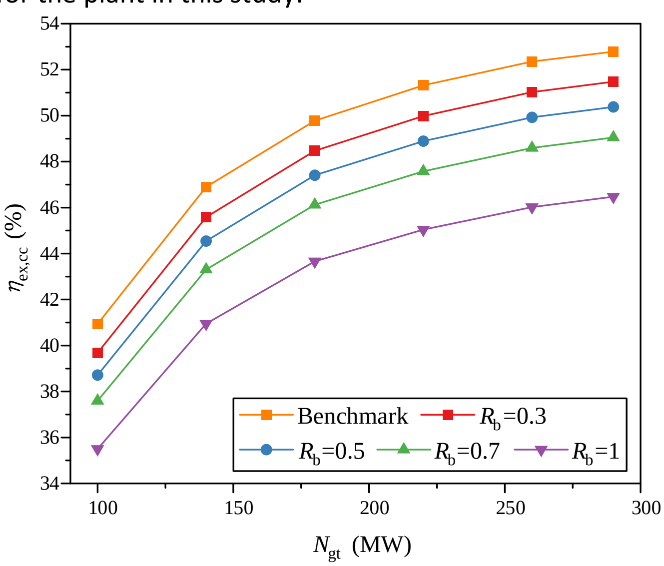

Fig 5 Variations of $\eta_{ex,cc}$ at various gas turbine load

5. CONCLUSIONS

In this work the effects of co-firing natural gas and biogas on the part-load performance of a NGCC plant is investigated based on process simulation. Performance of the plant fueled by natural gas was the benchmark. The difference in part-load performance between plants fueled by mixed fuel and natural gas are calculated. Various biogas mixing ratios are taken into consideration. After the fuel is shifted from natural gas to mixed fuel, the energy utilization efficiency increases at high gas turbine load, and declines at low gas turbine load. The exergy efficiency of the plant decreases at every condition, and the most reduction is around 6% from benchmark. It is not efficient to use biogas at low power load from both energy and exergy efficiency perspectives for the plant in this study.

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