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Research paper

Performance analysis of a partial oxidation steam injected gas turbine cycle

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HIGHLIGHTS

- Thermodynamic performance of a POSTIG cycle was evaluated.
- The combustor outlet temperature has a great impact on the cycle efficiency.
- There exist optimal bottoming gas turbine cycle pressure ratios.
- The exergy efficiency of the POSTIG cycle is about 50.648%.
- The POSTIG cycle has a higher efficiency than the STIG cycle by at least 2%.

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ABSTRACT

Partial oxidation gas turbine (POGT) has great potential in improving efficiency because of staged releasing of the chemical energy of fuel. Several researchers have studied the applications of POGT in repowering of different existing power plants. In this study, the POGT is integrated with a steam injected gas turbine (STIG) cycle. This research evaluated the overall thermodynamic performance of a partial oxidation steam injected gas turbine (POSTIG) cycle and investigated the influences of key variables. In addition, comparisons with the STIG cycle were conducted based on exergy analysis. Results show that the combustor outlet temperature of the bottoming gas turbine cycle, the pressure ratio of the bottoming gas turbine cycle compressor, and the temperature of partial oxidation affected the efficiency and specific work output of the POSTIG cycle obviously. Compared with the simple gas turbine cycle, the oxygen concentration in the combustor outlet gas of the POSTIG cycle decreases significantly, and the cooling flow rate increases. Efficiency of the POSTIG cycle is at least two percentage points higher than that of the STIG cycle because of the production and utilization of higher quality steam, along with lower exergy destruction during the graded release of the fuel's chemical energy.

1. Introduction

Under the background of limited potential of the Brayton cycle in efficiency improvement and emission reduction, cycle innovations are essential for the development of gas turbines [1]. Researchers have made continuous efforts to improve cycle performance by introducing additional features, such as recuperation, intercooling, reheating and water/steam injection [1]. The nature of complete fuel combustion does not change in these advanced cycles. Other research efforts involve designing cycles to reveal all possible contributions of the fuel conversion process. One of these designs is the partial oxidation gas turbine (POGT), which promises high electrical efficiency, high specific power output and low NO_x emission. In the POGT, a partial oxidation reactor replaces the traditional combustor, in which the quality of air is less than that of the stoichiometric value that is required for complete fuel combustion. The partial oxidation reactor produces a synthesis gas (mainly carbon and hydrogen) with higher specific heat than complete combustion gas. Thus, more energy per unit mass of fluid

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can be extracted by the POGT expander than is the conventional case [2]. Meanwhile, when the synthesis gas fuel is burned in a bottoming cycle, the combined cycle would provide high efficiency and ultra-low NO_x emission [2,3].

The Institute of High Temperature in the former Soviet Union first applied POGT concepts for power generation [3]. Since the 1990s, colleges and research institutes in America, the Netherlands, and Belgium have performed feasibility studies on potential POGT applications [2,4–7]. Heyen and Kalitventzeff investigated the thermodynamic performance of an existing steam cycle that was repowered through topping with a POGT [4]. Results showed that the repowering cycle had a higher efficiency than topping with a conventional gas turbine. Korobitsyn utilized the POGT in the repowering of a direct-fired power plant and concluded that the repowering increases efficiency by 3.7 percentage points and power output by 60% [6]. Research by IVTAN showed that the retrofit modification of existing natural-gas-fired steam turbine power plants by the POGT would improve fuel efficiencies to between 70 and 80% and reduce NO_x emissions by a factor of 10 or more [2]. Cornelissena et al. explored the application of a POGT in the production of synthesis gas for methanol [5]. Calculation results showed that the system has a 12% gain in thermal efficiency and 7% decrease in product cost compared with the conventional case. The Gas Technology Institute (GTI) has been actively working on the POGT concept since 1995 and performed system studies of POGT applications in repowering of conventional gas turbine, combined cycle, coal-fired power plants, and integrated gasification combined cycle plants [8]. In 2007, the GTI tested a 7 MW pressured partial oxidation reactor [8]. On the basis of this reactor, a 200 kW POGT prototype based on a Spartan T-350 gas turbine was designed, constructed, and operated in 2009, which verified the engineering feasibility [3,9]. In addition, studies on fuel flexibility, combustion instability, and partial oxidation reactor modeling have been conducted [5,10].

The POGT could also be integrated with the steam injected gas turbine (STIG) cycle, which is known to have high efficiency, low emission, and low cost [1,2]. In such a cycle, steam from a heat recovery steam generator (HRSG) is injected into the topping cycle. The novel partial oxidation steam injected gas turbine (POSTIG) cycle combines advantages of both the POGT and the STIG cycle. This particular approach using steam injection increases the power output of the POGT [2]. Moreover, for the POSTIG cycle, the injection of steam could reduce or eliminate the formation of soot in the partial oxidation reactor [10]. However, up to now, the study on the POSTIG is not enough. Firstly, the performance curve of the POSTIG cycle, which is of great importance for the system design and operation, has not been brought out yet. Secondly, it is necessary to identify the key parameters that affect the system performance most and find out how they influence the performance and the interplay of these parameters. Thirdly, the addition of POGT will cause noticeable changes in working fluids in combustor and turbine compared with the simple gas turbine cycle. There is a need to quantize these changes and influences. Fourthly, several studies have demonstrated that, for a POGT cycle, staged releasing of fuel chemical energy will bring about the increase of cycle efficiency. However, nobody has concluded whether the advantage still exists in the POSTIG cycle and how big the benefit is.

This study investigated the overall thermodynamic performance of a typical POSTIG cycle and analyzed the impact of partial oxidation reaction temperature. Comparisons were conducted with a STIG cycle based on exergy analysis. Study results could contribute to the answers to the above questions and will lead to a better understanding of the POSTIG cycle.

2. System description and models

2.1. System description

A flowsheet of a POSTIG cycle is shown in Fig. 1. Ambient air is compressed by the compressor of the bottoming gas turbine cycle. Part of the air is then further compressed to approximately 6 MPa and enters the partial oxidizer. In contrast to the STIG cycle (Fig. 2), where the steam is injected into the combustor, steam injection occurred in the partial oxidizer and mixer of the topping gas turbine cycle in the POGT cycle. In the partial oxidizer, the fuel reacts with air and the injected steam under high pressure and temperature to generate a secondary fuel gas. The secondary fuel gas is mixed with steam and enters the expander. Then the secondary fuel gas from the exit of the expander is delivered to the combustor of the bottoming gas turbine cycle. The recovered heat from the gas turbine exhaustion is utilized to generate steam for the topping gas turbine cycle.

Since the product gas from the partial oxidation reactor contains no oxygen, the turbine is designed to employ blades that are made of special materials, which could withstand high temperatures of approximately 1800 °C [11]. Thus, turbine cooling is not considered in the topping gas turbine cycle of POSTIG, as showed in Fig. 1.

2.2. Models

Compressors, combustors, turbines, and pumps are modeled based on the principles of mass and energy balance. Superheaters, evaporators and heat exchangers models are referred to other studies [12]. Typically, the partial oxidation reactor operates at high temperatures of 1200 °C–1500 °C. Thus, modeling this reactor under chemical equilibrium assumptions is reasonable.

Performance prediction of gas turbine (GT) cycles requires accurate modeling of turbine cooling. In this study, the flow rate of cooling air is estimated through a simple and generic cooling model by using open-loop cooling, as showed in Fig. 3 [13].

In this model, the cooling fluid, which is extracted from the compressor exit, is mixed with the hot combustion gas before the turbine inlet. The model could reflect the influence of cooling medium and gas composition change on the coolant flow rate estimation, as well as calculate the reduction of the turbine polytropic efficiency from the mixing of coolant and hot gas based on the following equations [13]:

$$\frac{m_c c_{p,c}}{m_g c_{p,g}} = b\left(\frac{T_{g,cmbexit} - T_b}{T_b - T_{c,cmprexit}}\right)^s \tag{1}$$

$$\frac{\Delta p}{p_{tbn,inlet}} = \frac{m_c}{m_g} K; \quad \Delta p < 0 \tag{2}$$

$$\frac{\eta_{p,uctbn} + \Delta\eta}{\eta_{p,uctbn}} = \frac{\ln\left(p_{tbn,exit} \big/ p_{tbn,inlet}\right)}{\ln\left(p_{tbn,exit} \big/ \left(p_{tbn,inlet} + \Delta p\right)\right)} \tag{3}$$

$$\eta_{p,ctbn} = \eta_{p,uctub} - \Delta\eta; \quad \Delta\eta > 0 \tag{4}$$

In this equation, T_b is the maximum sustainable blade surface metal temperature. m_c and m_g are the mass flow rate of cooling air and gas from combustion, respectively. $c_{p,c}$ and $c_{p,g}$ are the heat capacity of the cooling air and hot gas from the gas turbine. $T_{g,cmbexit}$ and $T_{c,cmprexit}$ are the temperatures of hot gas from the combustor and the cooling air, respectively. $p_{tbn,inlet}$ and $p_{tbn,exit}$ are