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Energy optimization analysis of a thermochemical exhaust gas recuperation system of a gas turbine unit

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ABSTRACT

This article considers the scheme of a gas turbine unit (GTU) with a thermochemical exhaust heat recuperation system by using steam methane reforming. The main concept of thermochemical recuperation (TCR) is the transformation of exhaust gases heat into chemical energy of a new synthetic fuel that has higher calorimetric properties such as low-heating value. As an example, the gas turbine plants with turbines where the exhaust gas temperature exceeds 900 K are considered. To determine the optimum operating parameters of the thermochemical exhaust recuperation system, the influence of temperature, pressure, and inlet reaction mixture composition on the recuperation rate are determined. Based on thermodynamic analysis, the amount of exhaust heat that is transformed into chemical energy of the new synthetic fuel for various operating parameters is calculated. The thermodynamic analysis is performed by minimizing Gibbs energy via the programs IVTANTHERMO and Aspen HYSYS. The results of the thermodynamic analysis are verified with the results obtained by the analytical calculation of other authors based on the law of mass action and the law of mass and energy conservation. As a result of the calculation, it was established that in the temperature range (900–1000) K the recuperation rate reaches a maximum value for the inlet reaction mixture composition of H_2O: CH_4 = 2; in the temperature range of above 1200 K, at H_2O:CH_4 = 1. It is also established that when the pressure in the reaction space increases, the energy efficiency of the use of TCR is reduced; the optimum pressure is in the range of (5–10) bar. The maximum recuperation rate of the TCR system (R = 0.693) is observed at T = 900 K, β = 2, p = 5 bar.

1. Introduction

In the coming decades, fossil fuels, in particular natural gas, will remain as the primary energy sources for the world‘s heat-power engineering. According to the report of the International Energy Agency, the 21st century can be considered the “Golden Age of Gas” [1]. In addition, despite the latest advances in the use of renewable energy sources, the global demand share for natural gas will increase from 20% in 2011 to (26–28)% by 2030. [1,2].

Some of the most important consumers of natural gas are the gas turbine units (GTU) designed for the generation of electrical energy or mechanical work (shaft work of gas-pumping units) [3–5]. According to the second law of thermodynamics, one of the ways to improve the energy efficiency of the GTUs is to increase the temperature of the combustion gases at the gas turbine inlet [6,7]. Therefore, the modern versions of gas turbines have a temperature of combustion gases at the turbine inlet above 1300 K [8,9]. On the other hand, an increase in the temperature of the combustion products leads to an increase in the temperature of the exhaust flue gases. For example, for turbines SGT5-8000H and SGT6-8000H produced by Siemens, the temperature of the exhaust flue gases is more than 900 K at an efficiency of about 40% [8,9].

To improve energy efficiency, GTUs are often combined with waste-heat recuperation systems. Usually, the waste-heat recuperation systems are presented as efficient solutions because the exhaust gas at the gas turbine outlet still has a moderately high temperature and contains much heat. The traditional approaches to improve the energy efficiency of GTUs are the integration with the steam power units, including the standard Rankine cycles (RCs) or the organic Rankine cycles (ORCs) [10–16]. Moreover, to improve energy efficiency in large GTUs, air and fuel are preheated by the exhaust gases before they enters the combustion chamber [17–19]. In GTUs, both additional RCs or ORCs and air/fuel preheaters are used as the exhaust gas recuperation system.

In recent years, the recuperation approach based on thermochemical transformation of the exhaust gases enthalpy to the chemical energy of a new synthetic fuel has found increasing interest among engineers and specialists [20–25]. This method of waste-heat recovery is called thermochemical recuperation (TCR) [26]. TCR can be a promising method to improve the energy efficiency of GTUs and other fuel-consuming equipment.

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TCR of exhaust gases heat takes place when chemical endothermic reactions are used, for example, steam methane reforming [20,23,27], combined steam-dry methane reforming [23–25,28], steam ethanol reforming [21], propane reforming [22], etc. The concept of increasing energy efficiency of fuel-consuming equipment by thermochemical waste-heat recuperation was discussed as early as 1972 [26]. Generally, various chemical endothermic reactions could be used for thermochemical waste-heat recuperation, but it is evident that the most advantageous is when reforming hydrocarbon gases are used, for example, steam methane reforming, which is described by the following chemical reactions:

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 + 206.1\ kJ; \tag{1}$$

$$CH_4 + 2H_2O \Leftrightarrow CO_2 + 4H_2 + 165.0\ kJ; \tag{2}$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2 - 41.1\ kJ. \tag{3}$$

The many thermochemical heat recuperation investigations have focused on gas turbine applications [20,29–31]. All of these papers highlighted the increase in lower heating value (LHV) of the new synthetic fuel compared to the initial (primary) fuel, as well as the increase of energy efficiency of this fuel-consuming equipment by using thermochemical waste-heat recuperation. Carapellucci and Milazzo compared the energy efficiency of GTUs with TCR and without TCR, and they concluded that the gas turbine with the steam methane reformer had better performance, for example, the coefficient of efficiency (52.4%) and power (288.4 MW) compared to the GTU performance without it (38.3% and 183 MW) [29]. Moreover, they suggested upgrading the original schematic diagram of TCR with one steam methane reformer to TCR with two reformers. By this upgrading, GTU with the thermochemical waste-heat recuperation system can reach the following performances: η = 53.8%; P = 292.9 MW. This performance is fairly good compared with those of the GTU with Rankine cycles. This recuperation method is promising as it allows improved performances of GTU without a bottoming Rankine cycle.

Verkhivker and Kravchenko analyzed the energy efficiency of the combined cycle (gas turbine with steam cycle) with the TCR by steam methane reforming [20]. They concluded that the energy efficiency of the combined GTU with TCR can reach (80–90)%. Also, they reported that the exergy efficiency of the GTU with TCR has reached the level of (85–90)%. For TCR by steam methane reforming, the overall lower heating value of the new synthetic fuel can be 1.25 times higher than LHV of the original methane.

Han et al. developed a new power generation system based on the moderate conversion of coal and natural gas [32]. In this system, the heat of steam produced by the exhaust heat is used for reforming organic fuel (natural gas, coal). The authors calculated that with the same fuel input to power generation single systems, the new system based on the thermochemical principles can generate about 5.8% more electricity. The net efficiency of the new power generation system can achieve 48.6%, that is about 5% higher than that of the conventional combined gas cycles.

Moreover, Popov et al. showed that the energy efficiency of high-temperature plants with the thermochemical waste-heat recuperation was approximately 20 percentage points higher than that of the high-temperature plants without TCR [23]. In addition, Chakravarthy et al. published the results of thermodynamic analysis of an internal combustion engine (ICE) with thermochemical exhaust heat recuperation [25]. The authors concluded that the estimated second law efficiency can be increased for TCR with ethanol and isooctane reforming by 9 and 11%, respectively.

High-energy efficiency as the main advantage of TCR is highlighted for all the papers presented above. In addition, Knoche et al. [33] reported that the combustion irreversibility of the new synthetic fuel is less than that of the primary fuel. In summary, thermochemical exhaust heat recuperation is the promising method to increase the energy efficiency for the various fuel-consuming equipment, in particular, the gas turbine units.

Furthermore, many publications on TCR for GTUs mainly focus on determining the energy efficiency of using this method of heat recovery. However, it is known that the temperature, the inlet gas composition of the initial reaction mixture, and the pressure in the reaction space have a significant effect on the TCR efficiency. This is due to the fact that the degree of conversion of the original fuel, for example, methane (degree of methane conversion), depends on these parameters. Many articles assume that the degree of conversion of the original fuel is 1, and the effect of temperature, pressure and feed gas composition are not accounted for.

The objectives of this paper are (1) to determine the operational conditions (temperature, feed gas composition and pressure) for optimal operation of the thermochemical exhaust gas recuperation system by steam methane reforming in the GTU; (2) to identify the advantages of the TCR in the GTUs.

2. GTU with thermochemical recuperation

The general idea of TCR applying to gas turbines is the increase in the lower heating value of the synthetic fuel (synfuel) compared to the original fuel converting the exhaust heat into chemical energy of a new synfuel. Fig. 1 illustrates the schematic diagram of the GTU with thermochemical exhaust heat recuperation by steam methane reforming. This diagram is based on two fundamental concepts: (1) the increase in the LHV of the synfuel compared to the original fuel; (2) the transformation of the exhaust heat into chemical energy of the new synfuel.

In this schematic diagram there are two subsystems. The first is the power generation subsystem with main components such as a compressor (C), a combustion chamber (CC), a gas turbine (GT) and a generator (G). The second is the thermochemical exhaust heat recuperation subsystem with main components such as a steam methane reformer (SMR) and a steam generator (SG). The exhaust gases from the GT are sequentially passing through the steam methane reformer and the steam generator. The steam methane reformer performs as a shell-and-tube heat exchanger. Heat is transferred through the wall. One side of the wall is filled with the exhaust gases, the other side is filled with the reaction mixture. The reaction mixture at the inlet consists of methane and steam. In the steam methane reformer, methane and steam are converted to the synthesis gas that is called the synthetic fuel or synfuel. The steam methane reforming absorbs a large amount of the high-temperature thermal energy that is extracted from the exhaust

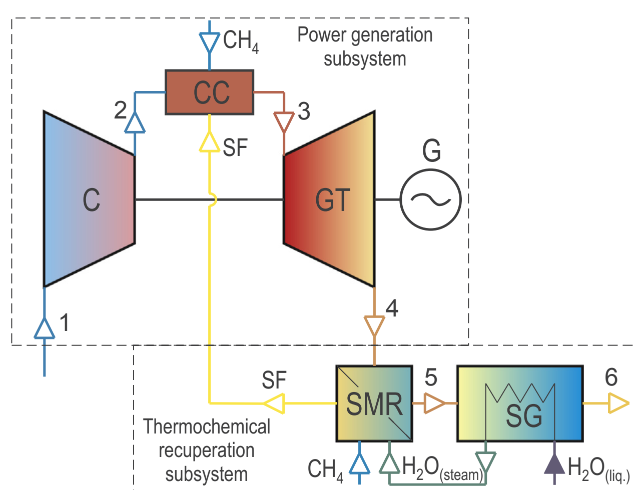

Fig. 1. The schematic diagram of the GTU with thermochemical exhaust heat recuperation by steam methane reforming: C – compressor; CC – combustion chamber; GT – gas turbine; G – generator; SMR – steam methane reformer; SG – steam generator; SF – synthetic fuel.