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Parametric sensitivity analysis of a SOLRGT system with the indirect upgrading of low/mid-temperature solar heat

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ABSTRACT

Development of novel solar–fossil fuel hybrid system is important for the efficient utilization of low temperature solar heat. A solar-assisted methane chemically recuperated gas turbine (SOLRGT) system was proposed by Zhang and co-worker, which integrated solar heat into a high efficiency power system. The low temperature solar heat is first converted into vapor latent heat provided for a reformer, and then indirectly upgraded to high-grade generated syngas chemical energy by the reformation reaction. In this paper, based on the above mentioned cycle, a parametric analysis is performed using ASPEN PLUS code to further evaluate the effect of key thermodynamics parameters on the SOLRGT performance. It can be shown that solar collector temperature, steam/air mass ratio, turbine inlet pressure, and turbine inlet temperature have significant effects on system efficiency, solar-to-electricity efficiency, fossil fuel saving ratio, specific CO_2 emission and so on. The solar collector temperature is varied between 140 and 240 °C and the maximum net solar-to-electricity efficiency and system efficiency for a given turbine inlet condition (turbine inlet temperature of 1308 °C and pressure ratio of 15) is 30.2% and 52.9%, respectively. The fossil fuel saving ratio can reach up to 21.8% and the reduction of specific CO_2 emission is also 21.8% compared to the reference system. The system performance is promising for an optimum pressure ratio at a given turbine inlet temperature.

1. Introduction

Solar energy plays an important role in meeting people's energy consumption and reducing greenhouse gas emissions. Solar thermal power generation is considered to be an efficient way to utilize solar heat. Solar heat collected at high temperature undoubtedly leads to a significant increase in solar plant costs [1]. On the other hand, the power subsystems usually need high-temperature working fluid for good thermal performance of the whole cycle. For low temperatures of 200 °C or less, solar power generation results in low efficiency [2–6]. For instance, the efficiency of Rankine cycle systems using organic working fluids is generally lower than 10%. To elevate the thermo-economic efficiency, solar hybrid systems are introduced, which use multiple energy sources at different temperature levels in a way that low/mid-temperature energy are used when they are inexpensive, and higher temperature energy sources are integrated according to their cost to raise the energy efficiency. An earlier such hybrid system was proposed by Lior and co-workers [2–6], named SSPRE (solar steam powered Rankine Engine), in which flat-plate solar collectors were introduced to produce solar heat at a temperature below ~100 °C for steam generation. The remaining heat was supplied from higher temperature energy sources for superheating the steam (act as working fluid). The solar heat takes up nearly 80% of the input energy, and the cycle efficiency achieves about 18%. Later, other solar thermal power systems were proposed according to the same hybrid principle (but using concentrating solar collectors for higher temperatures). However, due to cost consideration, relatively low top temperatures and pressures had been chosen, still resulting to low efficiency [7–12].

Besides thermal integration of solar heat into some heat absorption process, some scholars also explored the idea that making use of the low/mid-temperature solar heat (below 300 °C) both thermally and chemically in some power generation systems, which include the endothermic reactions such as reformation and decomposition. Jin and co-workers proposed a solar combined cycle (Solar CC) that originally integrates mid-temperature solar heat with methanol decomposition [13,14]. The low-level solar heat used in this system can be upgraded and finally released as high temperature thermal energy for electricity via the high conversion rate of methanol decomposition into syngas at temperatures of 200–300 °C. Another hybrid combined cycle proposed by Jin employed methane-fuel chemical-looping combustion [15], where

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Nomenclature

A	energy level $\Delta E/\Delta H$
CR	methane conversion ratio
E	exergy (kW)
EM_{CO2}	specific CO_2 emission (g/kWh)
H	enthalpy (kW)
LHV	lower heating value of fuel (kJ/kg)
m	mass flow rate (kg/s)
Q	heat (kW)
R_f	fossil fuel replacement per kJ solar energy input (kJ fossil fuel/kJ solar heat)
R_{fe}	fossil fuel replacement per kJ solar exergy input (kJ fossil fuel/kJ solar heat exergy)
SR_f	fossil fuel saving ratio
T	temperature (°C)
TIT	turbine inlet temperature (°C)
W_{net}	net power output (kW)
W_{sp}	specific power output (kJ/kg air)
X_s	steam–air mass ratio
X_{sol}	solar heat input share
η_{col}	collector efficiency (%)
η_e	system efficiency (%)
η_{sol}	solar-to-electricity efficiency (%)
η_{th}	Thermal efficiency (%)

Subscripts

f	fuel
g	gas
ref	reference system
rad	solar radiation
s	steam
sol	solar heat
syn	syngas
th	thermal
0	environment state
1, 2 … 19	states on the cycle flow sheet

solar heat at the temperature range of 450–550 °C is applied to drive the endothermic reaction. This method also achieved CO_2 capture with low energy penalties. Many other novel systems based on upgrading energy levels from low to high have been successfully proposed and investigated [16–20].

Methane is a more widely used fuel than methanol. Furthermore, the enthalpy rise of the methane-steam reformation reaction is 165 kJ/mol, higher than the 49.5 kJ/mol of methanol-steam reformation and the 90.7 kJ/mol of methanol decomposition, which means larger heat absorption potential. However, the methane-steam reformation reaction requires a much high temperature, above 800 °C with Ni-based catalyst, to obtain notable methane conversion; below 327 °C (600 K) the reformation reaction does not even occur. Therefore, the current research of solar thermo-chemical technology with methane is mainly focused on high temperature solar heat (900–1000 °C) [1]. To integrate low/mid-temperature solar heat (below 300 °C) with methane-steam reformation and achieve the chemical conversion of the solar thermal energy, an indirect way was worked out. A solar-assisted methane chemically recuperated gas turbine system (SOLRGT) was proposed by Zhang and co-worker [21]. Instead of using the conventional solar steam reformation of methane at high collecting temperatures, low temperature solar heat was used to generate the steam needed for methane reformation. Thus low/middle temperature solar heat collected at ~220 °C is first transformed into vapor latent heat, and then further transformed into syngas chemical energy via the reformation reactions. Transformation enables this upgraded fuel to be burned with compressed air and used in a highly efficient power system. The solar-driven steam production helps to improve both the chemical and thermal recuperation of the system. As shown in previous work [22], SOLRGT system can save up to 20–30% fuel compared with conventional chemically recuperated gas turbine (CRGT) system [23] without solar heat contribution. Also, the overall efficiency of such a system is about 5.7% higher than a comparable intercooling CRGT system without solar assistance.

In this paper, sensitivity analysis is performed on an SOLRGT system to further investigate the performance of the cycle comprehensively. Solar collector temperature, steam/air mass ratio, turbine inlet pressure, and turbine inlet temperature are chosen to be the parameters to analyze their effect on system performance. To further assess the system performance from multiple aspects, besides the system efficiencies, some other performance criteria were introduced, such as fossil fuel saving ratio, fossil fuel replacement per kJ solar energy/exergy input and specific CO_2 emission. The results obtained exhibit the comparability of the SOLRGT system with other hybrid solar/fuel combined cycle power systems [13,14].

2. Description of the cycle

Fig. 1 shows a simplified diagram of the solar heat improved chemically recuperated gas turbine (SOLRGT) cycle. The solar heat collected at 220 °C is used to generate steam supplied to a reformer. Together with methane and the cold compressed air, heating by the exhaust gas in the recuperator was undertaken. Instead of being directly fed into the combustor, the natural gas and steam also take heat from the exhaust to produce syngas via reformation. Thus, some of the low temperature solar heat and turbine exhaust heat are converted into the heating value of reformation products.

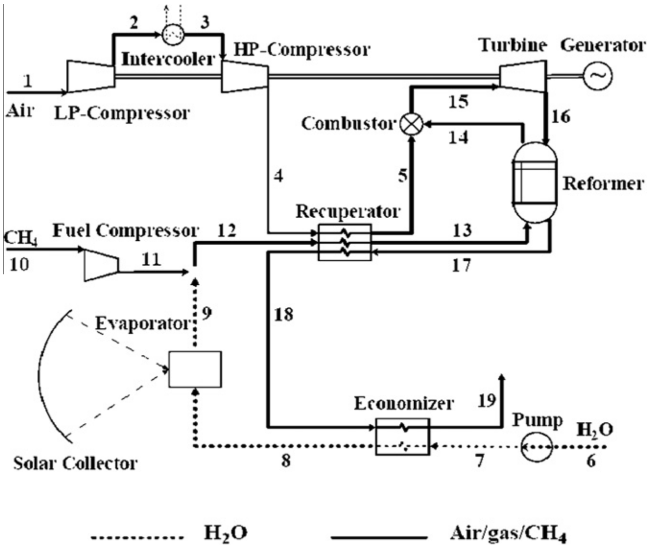

Fig. 1. Schematic of the SOLRGT cycle.