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Hybrid solar flameless combustion system: Modeling and thermodynamic analysis

Seyed Ehsan Hosseini[a,*], Hasan Barzegaravval[b], Bruce Chehroudi[a], Mazlan Abdul Wahid[b]

[a] *Combustion and Sustainable Energy Laboratory (ComSEL), Department of Mechanical Engineering, Arkansas Tech University, 1811 N Boulder Ave, Russellville, AR 72801, USA*

[b] *High-Speed Reacting Flow Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia*

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ABSTRACT

In this paper, the idea of using flameless combustion in a hybrid solar combustion system is investigated by modeling and thermodynamically analyzing a gas turbine system. In this regard, a gas turbine system coupling with hybrid solar flameless combustion including heliostat solar field, central receiver, flameless combustor and power generation system are modeled. In conditions that sun power is not adequate to heat up the combustion air over auto-ignition temperature of the fuel, air is passed through the first stage combustor. To provide a basic cycle for comparison, a common gas turbine with preheater is modeled as well. Energy and exergitic-based analyses of various systems are evaluated and environmental footprints reduction of proposed optimum cycle is assessed and compared to the basic case. The results illustrate that Nitrogen Oxides formation in hybrid solar flameless combustion is significantly lower than common gas turbine system. While the gas turbine with preheater generates 67 μg Nitrogen Oxides per kWh, hybrid solar combustion system produces less than 7 μg Nitrogen Oxides per kWh. In comparison to gas turbine system, fuel consumption decreases in hybrid solar flameless combustion system from 0.1875 kg/s to 0.16 kg/s (about 14.7%) when solar share is considered just 40%. Since the inlet air of flameless combustor is charged from solar heater outlet, increasing air temperature enhances the share of solar energy in the system which results in overall exergy reduction in the system. The proposed system shows significant environmental benefits and based on the available technologies, it is suitable for high temperature solar towers.

1. Introduction

Renewable energy sources have great potential to reduce Greenhouse gases (GHG) emission from power generation systems [1]. Currently, the contribution of solar, wind and geothermal energy is estimated about 0.4% of the global energy demand, while conventional fossil fuel resources account for around 80% [2]. Statistics illustrate that more than 78% of CO_2 emission is generated by fossil fuel power plants [3]. In addition to the growing global concerns about climate change due to increasing rate of energy consumption, arising of the exploitation of finite fossil fuel resources menaces the energy security of the world [4]. It is projected that the world energy consumption will increase by 70–100% before 2050 [5]. Among renewable and sustainable energy sources, development of clean and abundant solar energy is perceived to be a promising solution to mitigate the negative effects of climate change and ensuring energy security [6]. However, solar power generation without thermal storage systems provides only a diurnal power due to its intermittent nature [7]. Furthermore, the addition of electrical or thermal energy storage increases the overall cost of the electricity. Nevertheless, more investigations are still underway to decrease the investment costs and technical constraints of adopting solar power generation. The main goal of these endeavors is to generate up to 11% of the global electricity demand by solar energy by 2050 [8]. As a promising method of the efficient and low cast solar power generation, the solar thermochemical process is developed widely where the solar energy is upgraded to the high-quality chemical energy of the

Abbreviations: AHPS, advanced oxy-fuel hybrid power system; AC, air compressor; AP, air preheater; CCPP, combined cycle power plant; CDC, Colorless Distributed Combustion; CFD, Computational Fluid Dynamic; DNI, direct normal irradiance; EEC, Excess Enthalpy Combustion; EGM, entropy generation minimization; FLOX, Flameless Oxidation; GHG, greenhouse gas; GT, gas turbine; GTPRE, Gas turbine with preheater; HiTAC, High Temperature Air Combustion; HSC, hybrid solar combustion; HSGT, hybrid solar gas turbine; ISCC, Integrated Solar Combined Cycle; LHV, lower heating value; MILD, Moderate and Intense Low oxygen Dilution; NG, natural gas; PV, photovoltaic; PRP, primary air enrichment and preheating; RSS, Real Solar Share; SFC, Solar Flameless Combustion; SHR, Sun Hours Ratio; ST, steam turbine; STHS, Solar Thermal Hybrid Steam; SEGS, Solar Electric Generating System; TSC, Two Stage Combustion

* Corresponding author.
E-mail addresses: seyed.ehsan.hosseini@gmail.com, shosseini@atu.edu (S.E. Hosseini).

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Nomenclature

c_p	specific heat at constant pressure [kJ/kg·K]
$\dot{E}_x$	exergy flow rate [MW]
$\dot{E}x_D$	exergy destruction rate [MW]
Ex_{ph}	physical exergy [MW]
ex^{ch}_{mix}	mixture chemical exergy [MW]
G^E	the excess free Gibbs energy
H_{in}	stream enthalpy of inlet
H_{out}	stream enthalpy of outlet
$\dot{m}_a$	air mass flow rate [kg/s]
$\dot{m}_f$	fuel mass flow rate [kg/s]
$\dot{n}_f$	the mole of fuel
$\dot{n}_p$	the mole of products
$\dot{Q}_{rec}$	the heat transfer rate from irradiations into central receiver
$\dot{Q}_f$	the supplied heat by fuel
r_c	compressor pressure ratio
T_{pz}	temperature of the primary zone at combustion
T_{sun}	sunny hours per day
T_{AP}	temperature of preheated air
T_{FL}	temperature of flue gases
τ	the residence time in the combustion zone
$\bar{\lambda}$	fuel-air ratio on a molar basis
η_{rec}	efficiency of receiver
θ	dimensionless temperature

fuel. In this method, the solar thermochemical process utilizes the concentrated solar radiation as a source of heat to drive an endothermic chemical conversion [9]. Solar steam reforming of Natural gas (NG) was experimented and a steam injected gas turbine power plant were integrated for solar syngas production and application [10]. The use of photocatalysts to split water into stoichiometric amounts of Hydrogen and Oxygen (overall water splitting) without the use of external bias is of particular interest due to its simplicity and potential low cost of operation [11]. The steam-gasification of coal into syngas was developed using concentrated solar energy as the source of high-temperature process heat [12]. Experimental investigation of a 5 kW solar chemical reactor for the steam-gasification of petcoke in a high-flux solar furnace was performed and the effects of varying the particle size and slurry stoichiometry on the degree of chemical conversion and energy conversion efficiency were examined [13]. Solar hydrogen production was investigated as an endothermic process which is applied for efficient and low cost solar power generation [14].

1.1. Hybrid solar combustion power plants

Investigations confirm that hybrid plants have remarkable advantages over solar only plants, especially for near term markets. These advantages include lower capital investment as well as lower energy costs, the opportunity for higher energy conversion efficiency and higher valued energy due to dispatchability [15]. The Photovoltaic technology (PV) as the direct way of power generation from solar energy is extending its focus from decentralized small-scale power generation systems towards large-area bulk electricity generation [16].

Hybrid solar combustion (HSC) technology has been recently developed to achieve cost-competitive power generation, especially in the regions that direct sunlight is abundant [17]. As the major option to accelerate market introduction of solar power generation, HSC systems has illustrated so many advantages compared to solar-only systems. Reduction of technical and economic risks, higher efficiency of the system, fewer start-up and shutdown-losses and reduction of part load operation are the main advantages of HSC systems. Moreover HSC system guarantees the required power delivery to the grid and combustion system can be kept stand-by to compensate the fluctuating power supply of solar system [18]. In the Hybrid solar gas turbine (HSGT) system, solar power is used to preheat the pressurized air before injection to the combustion chamber. In HSGT system, since the temperature of the pressurized air is about 800–1000 °C after passing the solar tower, lower amount of fossil fuel is consumed in combustion chamber to maintain the inlet temperature of the turbine in optimum temperatures (950–1300 °C) [19]. The high efficient and cost effective of HSGT implies a great potential for cost reduction of environmentally friendly HSC power plants [20]. Thermoeconomic concept was applied using genetic algorithm for optimization of an Integrated Solar Combined Cycle (ISCC) system that produces 400 MW of electricity. It was found that the cost of electricity generated by steam turbine and gas turbine in the optimum design of the ISCCS are about 7.1% and 1.17% lower with respect to the base case [21].

In the ISCC systems, waste heat of the exhaust gases of Gas turbine (GT) is applied to preheat water and to superheating steam, while solar energy is employed to make additional steam. Electricity generation by ISCC also results in significant reduction of carbon dioxide emissions compared to the fossil fuel power plants and, therefore, less environmental impacts [22]. ISCC system as the modern combined cycle power generation with GT and Steam turbines (ST) and additional thermal input of solar power was initially proposed in 1993 [23]. Since then, several schemes have been suggested for integration of solar power to supply low temperature energy into top and bottoming sections of Combined cycle power plant (CCPP). The performance of an ISCC system and justified the preferences of this system in comparison with a Solar Electric Generating System (SEGS) was evaluated [24]. In this research, thermal power from parabolic troughs was integrated to the Rankine cycle (bottom cycle) of a combined cycle power plant and it was found that the generation cost of electricity (kW h) is significantly low in ISCC system. High temperature air provided by solar system which is fed into the Brayton cycle of a CCPP could increase the efficiency of the system around 30% and decrease the cost of electricity about 6 cent per kWh in such CCPP [18]. The thermodynamic characteristics of an Advanced oxy-fuel hybrid power system (AHPS) using the advanced process simulator Aspen Plus and compared their results with a Solar Thermal Hybrid Steam (STHS) turbine power generation system as the reference was analyzed [25]. It was concluded that the efficiency of the AHPS is 95.90%, which is 21.61% higher than that of the STHS. Also, exergy efficiency of the AHPS was recorded 55.88%, which is 2.13% higher than that of the STHS.

Although, valuable attempts have been made to develop power generation technology by hybrid solar combustion systems, limited scientific sources can be found about combustion method in HSC system. The performance of a hybrid solar receiver combustor operating with Moderate and Intense Low oxygen Dilution (MILD) and conventional combustion was compared [26]. The effects of the dominant geometrical parameters, burner configuration and flux distribution of the incident solar radiation on the heat transfer mechanisms, heat losses, thermal efficiency and heat flux distribution were investigated with a three-dimensional Computational Fluid Dynamics (CFD) model of the device. Two different burners were considered; non-premixed and partially premixed flames; one with and the other without swirl. It was stipulated that the device can obtain a similar thermal performance in each mode of operations. Moreover, the thermal efficiency of the system increased with the length-to-diameter cavity ratio and/or solar peak flux at the focal plane [26]. It was pointed out that the rate of fuel consumption as well as cost of electricity can be reduced up to 41% and 6% respectively if MILD combustion is employed in HSC [27].

Since conventional combustion or flame mode is usually used in the gas turbine cycle and solar energy is used to preheat the combustion air,