Energy Reports 4 (2018) 497–506

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Innovative thermodynamic parametric investigation of gas and steam bottoming cycles with heat exchanger and heat recovery steam generator: Energy and exergy analysis

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ARTICLE INFO

Article history:
Received 8 April 2018
Received in revised form 27 June 2018
Accepted 30 July 2018

Keywords:
Parametric analysis
Energy
Exergy
Bottoming cycles
Heat recovery steam generator
Heat exchanger
Efficiency

ABSTRACT

In this study, gas and steam bottoming cycles, driven by the exhaust gas of Gas turbine cycle, are analyzed thermodynamically. The waste heat of the Gas turbine topping cycle (GT) exhaust gas is used partially to heat the air in the air bottoming cycle and partially to generate steam by passing it through HRSG in the steam bottoming cycle. The topping Gas turbine and air bottoming cycles are coupled with the heat exchanger, whereas the topping and steam bottoming cycles are coupled with Heat Recovery Steam Generator (HRSG). The effects of turbine inlet temperature (1100 K $\leqslant$ TIT $\leqslant$ 1500 K), pressure ratio ($6 \leqslant r_{pt} \leqslant 12$) and flow rate of exhaust gas on the Net work and combined thermal efficiency and exergy loss of exhaust gas are investigated. It is observed that the Net work of steam bottoming cycle is higher than the Net work of gas bottoming cycle and for higher values of turbine inlet temperature TIT = 1500 K, 90% of power is recovered through the bottoming cycle at lower pressure ratio. The combined thermal efficiency increases by 10% with an increase in the turbine inlet temperature from 1100 to 1500 K. It is found that the combined thermal efficiency increases with all pertinent parameters.

1. Introduction

The availability of great amounts of energy is a crucial requirement for the well-being and development of our modern industrial societies (Angerer et al., 2017). The global consumption of energy rises continuously in parallel with population increase and economic growth (MacPhee and Beyene, 2017). To afford this ever-increasing demand, the main energy sources are fossil fuels. Due to the sustainability of oil resources and their heavy disadvantages such as air pollution including sulfur dioxides, greenhouse gases, solid particulates emission and environmental hazards, there is an urgent need to optimize energy conversion systems to promote fuel efficiencies and increase energy savings (Ibrahim and Rahman, 2015). Advanced power scenarios aim to improve performance and to operate with a wide range of fuels and with high tolerance to fuel variability, reduced pollution, and low energy cost. Thus, the development of old power plant relying on conventional cycles can be made steadily (Herrmann et al., 2017). Due to high-efficiency improvement that can be achieved by combining conventional cycles inadequate conditions such as the grouping of a gas turbine with a steam bottoming cycle pressed many engineers and researchers to investigate in this field (Masci and Sciubba, 2017; Haseli, 2017; Fu et al., 2015).

Mahmoudi et al. (2016) recommended a new combined system composed of a Gas Turbine-Modular Helium Reactor and an augmented Kalina cycle which is found after simulations to have reduced dimensions and high economic efficiency. Wu et al. (2017) studied stand-alone triple combined cycle systems based on calcium looping technology and demonstrated after carrying on simulations that the total power efficiency of this off-the-grid electricity system reaches 60.56% and its CO_2 emissions per kWh of electricity is less than 7.18 g CO_2. Yaglıet al. (2016) considered a subcritical and supercritical organic Rankine cycle (ORC) which recovers exhaust gas waste heat of biogas-fueled combined heat and power engine and conducted a parametric optimization and found that the supercritical ORC has better net work, energy efficiency, and exergy efficiency than the subcritical ORC. Benato and Maco (2017) recommended an organic Rankine cycle (ORC) technology to recuperate the discarded heat enclosed in the exhaust gases of a 1 MWel biogas engine, using an "in-house" optimization tool, fluid and the plant configuration are optimized amongst 115 pure and mixtures fluids. Results display that proposed ORC with real data assures a 30% higher net electric power compared to one with ICE nameplate conditions. Pierobon et al. (2014) investigate by multi-objective optimization approach the furthermost

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https://doi.org/10.1016/j.egyr.2018.07.007

Nomenclature

W	Net work (W)
h	Specific enthalpy (J/kg)
$\dot{m}$	Mass flow rate (kg/s)
q	Heat supplied
η	Thermal efficiency
ϵ	Effectiveness of HE
P	Pressure
v	Specific volume
HE	Heat Exchanger
HRSG	Heat Recovery Steam Generator
T	Temperature (K)
r_p	Pressure ratio
s	Specific entropy (J/kg K)
C_p	Specific heat (kJ/kg.K)
LCV	Lower Calorific Value of Fuel
I	Exergy Loss (W)
TIT	Topping cycle Turbine Inlet Temperature (K)

Subscripts

c	Compressor
gt	Gas turbine
st	Steam turbine
cc	Combustion chamber
p	Pump
a	Air
g	Exhaust gas of gas turbine of topping cycle
s	Steam
f	Fuel
γ	Ratio of specific heat
GB	Gas Bottoming Cycle
SB	Steam Bottoming Cycle
T	Topping cycle
comb	Combined cycle

appropriate waste heat recovery system for offshore services using three technologies steam Rankine cycle, the air bottoming cycle and the organic Rankine cycle. It is found that the organic Rankine cycle system guarantees higher performances more than the steam Rankine cycle. However the application of air bottoming cycle has no effect in economic and environmental viewpoint. Benato et al. (2015) explore and predict the most stressed devices lifetime reduction for power plant contains a gas turbine and a three pressure level Heat Recovery Steam Generator with reheat. Results show that the proposed the power plant dynamic model valuable innovative instrument to improve the plant's flexibility. Benato et al. (2016) inspect new technique capable to forecast the power plant dynamic behavior through running, recognize the furthermost stressed section and assess their lifetime drop, they apply their procedure a 380 MW combined cycle unit, they found that for load variation around 50% faster than the reference case 52.9% reduction in superheater collectors life appears. However, for load variation around 50% a 35.8% lifetime increase is detected in superheater collectors. Benato et al. (0000) develop and test numerical model for case study is the Draugen off-shore oil and gas platform, they found that decreasing the core weight of the recuperator leads to limiting the frequency fluctuations, therefore reducing the hazard of failure of the power structure.

Luk'yanova and Trukhnii (2012) determined the quantitative margins required to improve the economic efficiency of the steam power unit for a given gas turbine unit and studied the flow rate, temperature, and thermophysical properties of gases supplied to the heat recovery boiler. Studies of the thermal efficiency improvement of combined cycle's power plant are of great interest. Several researches have carried out studies to enhance the gas/steam combined cycle performance. Kovalevskii (2011) investigated the impact of initial steam pressure variation on thermal efficiencies of condensing type circuits of binary combined cycle plants containing one, two, and three loops with different pressure levels. They reported that the combined use of steam reheating and the gas assisted air preheater leads to a higher efficiency however it requires an amplification of the heat recovery boiler heating surfaces. Chen et al. (2008) considered a thermodynamic model for open combined Brayton and two parallel inverse Brayton cycles. They improved the model performance by regulating the compressor inlet pressure of the bottom cycles, the mass flow rate and the distribution of pressure losses along the flow path. Mondal and Ghosh (2016) assessed the techno-economic performance and carried on a thermodynamic analysis of a biomass-fired combined cycle plant, employing a topping gas turbine (GT) cycle and a bottoming steam turbine cycle. They found that the total plant efficiency is maximized at topping cycle pressure ratio of 4 and Turbine inlet temperature = 1000 C, where the plant also has the least CO_2 emission. In order to make the results more accurate, Some pertinent and input parameters for the combined cycle power plant are considered around real case value e.g. ambient temperature, mass flow rate of air and steam in different compartments, isentropic efficiency of turbine, compressor and pump (Khan and Tlili, 2018; Khan et al., 2017; Ghazikhani et al., 2014; Tiwari et al., 2013). In order to enhance the combined cycle performance several solutions were studied and proposed such as, augmenting pressure ratio, inserting intercooling and re-heating in the reference cycle, increasing gas turbine inlet temperature (TIT), and decreasing the temperature differences in the heat recovery steam generator (HRSG) as well as minimizing the condenser pressure. Sanjay and Prasad (2008) proposed different scenarios to improve gas–steam combined cycle power plant efficiency beyond 62 percent such as augmenting pressure ratio, temperature inlet temperature, and maximum blade temperature and inserting intercooling and re-heating in the reference cycle. In a classic combined cycle, exhaust heat from the gas turbine is recovered in a HRSG. The major recognized HRSG parameters are the exhaust gas temperature, stack temperature, pinch point and steam generation pressure and temperature. A thermodynamic analysis of a combined cycle with three-pressure reheat HRSG was conducted by Xiang and Chen (2006). They found that the combined cycle power plant efficiency could be enhanced up to 59.05% at base load by combining HRSG optimization and gas to gas heat recuperation. Corchero et al. (2016) conducted a parameter study of a semi-closed combined cycle for CO_2 capture, based on the combined cycle (CC) gas turbine side. They reported that the maximum efficiency can be achieved when inlet temperature is close to the HRSG exit conditions at the gas turbine side. Energy and exergy analysis of a combined cycle power plant includes data required to determine the potential for enhancing system efficiency. Mohtaram et al. (2017) carried on an energy–exergy analysis on the ammonia–water combined cycle and the Rankine cycle in order to assess the impact of compressor pressure ratio on the thermodynamic performance. They found that the exergy destruction of high-pressure compressors, intercooler, and the gas turbine continuously augments in parallel with the rise of the pressure ratio of the compressor. However, the exergy destruction of recuperator declines constantly. Angelino et al. (1999) investigated a procedure where a fraction of the low-pressure steam is extracted and fed to an auxiliary organic Rankine cycle which is considered an alternative way of approaching optimum heat rejection conditions. A thermodynamic and exergo-economic