Exergy and exergoeconomic analyses of a novel integration of a 1000 MW pressurized water reactor power plant and a gas turbine cycle through a superheater

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Abstract
Combined cycles are used for various reasons, including to increase the efficiency of power generation system. In this study, a gas turbine cycle is combined with a pressurized water reactor (PWR) power plant to increase the total plant efficiency. In this novel cycle, saturated steam produced in the steam generators of the nuclear power plant is superheated by the hot combustion gases exiting the gas turbine. An exergoeconomic analysis is carried out and the effects of compressor pressure ratio and gas turbine inlet temperature are investigated on the net power output, the first and second law efficiencies, the total cost rate and the specific cost of the produced work. The results show that there is an optimum pressure ratio for each gas turbine inlet temperature. The combined cycle total cost rate and the specific cost of the produced work for a gas turbine inlet temperature of 1500 K and a compressor pressure ratio of 13 are determined to be 41,882 $/h and 31.63 $/MWh, respectively.

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1. Introduction

To move toward energy sustainability and to address limitations for many conventional energy resources, increased efficiency is usually desirable for power generation systems. Combined cycles can help achieve such aims, as they can help increase the net electrical power output, decrease the fuel consumption and increase the efficiency. The most common combined cycles include Rankine and Brayton cycles (i.e., an integration of a steam turbine cycle and a gas turbine cycle). For the combined cycle considered here, the exhaust gas from the Brayton gas cycle passes through a heat recovery steam generator (HRSG) to produce steam. A Rankine steam cycle uses the produced steam as working fluid.

Exergy is an important concept related to the second law of thermodynamics and is defined as the maximum useful work that can be obtained from a flow of matter or energy in a reference environment. Exergy analysis characterizes the thermodynamic performance of an energy system and determines the efficiency of system components by quantifying their entropy generation (Kwak et al., 2003). The combination of exergy analysis with economics is the branch in engineering known as exergoeconomic or thermoeconomic analysis. This technique helps the designer to provide information that is not available through economic evaluation and conventional energy analysis (Sahoo, 2008). Many researchers have analyzed combined cycles. Erlach et al. (1999) proposed a structural theory of thermoeconomics and applied it to a 305 MW combined cycle power plant. Kwak et al. (2003) thermo-economically analyzed a 500-MW combined cycle plant. Two criteria for allocations of residue costs of combined cycles have been proposed by Torres et al. (2008) and Seyyedi et al. (2010a). Critical reviews of exergy and exergoeconomic analyses have been reported by Vieira et al. (2004, 2005, 2006), Torres et al. (2008), Sahoo (2008), Zhang et al. (2006), Lazzaretto and Tsatsaronis (2006).

However, exergoeconomic analysis and optimization have been utilized in limited ways on nuclear power plants. Using the second law of thermodynamics, the irreversibility of nuclear reactors has been calculated by Gyftopoulos and Beretta (1991). The irreversibility of a fast breeder reactor (FBR) nuclear power plant has also been investigated by Seigel (1970). Dunber et al. (1995) analyzed the exergy of a boiling water reactor (BWR) nuclear power generation plant. A typical pressurized water reactor (PWR) nuclear power plant has been exegetically analyzed by Sayyadi et al. (2007). Sayyadi and Sabzaligoll (2009) thermo-economically analyzed a typical 1000 MW pressurized water reactor nuclear...
power plant and then proposed some optimization approaches for the plant. An intelligent optimization algorithm has been used for multi-objective thermo-economic optimization of a PWR power plant which has been integrated with a multi-stage desalination facility (Khoshgoftar Manesh and Amidpour, 2009). A similar thermo-economic optimization was applied to a desalination system coupled with a typical 1000 MW PWR nuclear power plant (Ansari et al., 2010). Chandeg et al. (2014) proposed and analyzed an ammonia water power/refrigeration co-generation system incorporating a high-temperature gas cooled reactor and a gas turbine cycle, integrated with reverse osmosis for desalination. On the basis of overall plant exergy efficiency, the sodium-cooled fast reactor based system is found to be more efficient. Stanek et al. (2016) analyzed the multiple design criteria of various power technologies, taking into account thermo-ecological cost, direct and cumulative emissions, and economic evaluation. The environmental and ecological comparison of the nuclear power plant with the existing conventional coal and gas plants requires the evaluation of the overall life cycle of electricity generation. Using exergy analysis, the nuclear power plants are competitive technologies for coal or gas installation and should be taken into account in energy planning and policy development for energy generation. Energy and exergy analyses of a VVER type nuclear power plant have been carried out by (Terzi et al., 2016). The thermodynamic efficiency of this reactor is found as 30%. The leading irreversibilities are encountered in the pressure vessel and the steam generator, which represent 49% and 13% of the total irreversibilities, respectively. Edwards et al. (2016) proposed various thermal energy storage methods for small modular nuclear reactors, in part based on exergy and energy density analyses of the thermal energy storage integration with nuclear power plants. Thermal energy storage options such as synthetic heat transfer fluids perform well for light-water-cooled nuclear power plants, whereas liquid storage salts exhibit better performance with advanced nuclear power plants.

An assessment of the economy of combined nuclear–gas power plants was performed by Florido et al. (2000). Combining an AP600 nuclear power plant steam cycle with gas turbines has been performed by Darwish et al. (2010). The power cost of the modified AP600 was predicted to be $49.83/MWh where they considered fuel cost per unit thermal exergy of reactor ($/kJ), capital recovery factor, annual number of operation hours (h), mass flow rate (kg/s), pressure (kPa), pressure ratio, pressure of steam turbine (MPa), specific enthapy (kJ/kg), specific exergy (kJ/kg), steam turbine inlet temperature (K), specific entropy (kJ/kg.K), temperature (“C or K), gas turbine inlet temperature (K), net power output of combined cycle (MW), net power output of gas turbine cycle (MW), net power output of steam turbine cycle (MW), investment cost rate ($/h), and first law efficiency.

Greek letters:
- \( \eta \): isentropic efficiency
- \( \psi \): exergy efficiency of cycle
- \( \epsilon \): effectiveness of superheater
- \( \varepsilon \): exergy efficiency
- \( \tau \): annual number of operation hours (h)

Subscripts:
- 0: reference environment (reference state)
- AC: air compressor
- CC: combustion chamber
- cond: condenser
- f: fuel
- GT: gas turbine
- In: inlet
- Out: outlet
- P1: condensate pump
- P2: boiler feed water pump
- SG: steam generator
- SH: superheater
- ST: steam turbine
- T: total

Superscript:
- OM: operation and maintenance
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