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Feasibility study and performance assessment for the integration of a steam-injected gas turbine and thermal desalination system

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HIGHLIGHTS

- Development of thermodynamic, economic, and environmental models for a SIGT–METVC
- Suggestion of performance criteria for retrofitting the SIGT with METVC
- Feasibility study for retrofitting the SIGT plant with a METVC system using RSM
- Multi-objective optimization for minimizing the retrofitted unit product cost

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ABSTRACT

This study proposes a systematic approach for retrofitting a steam-injection gas turbine (SIGT) with a multi-effect thermal vapor compression (METVC) desalination system. The retrofitted unit's product cost of the fresh water (RUPC) was used as a performance criterion, which comprises the thermodynamic, economic, and environmental attributes when calculating the total annual cost of the SIGT–METVC system. For the feasibility study of retrofitting the SIGT plant with the METVC desalination system, the effects of two key parameters were analyzed using response surface methodology (RSM) based on a central composite design (CCD): the steam air ratio (SR) and the temperature difference between the effects of the METVC system (ΔT_{METVC}) on the fresh water production ($Q_{freshwater}$) and the net power generation (W_{net}) of the SIGT–METVC system. Multi-objective optimization (MOO) which minimizes the modified total annual cost (MTAC) and maximizes the fresh water flow rate was performed to optimize the RUPC of the SIGT–METVC system. The best Pareto optimal solution showed that the SIGT–METVC system with five effects is the best one among the systems with 4–6 effects. This system under optimal operating conditions can save 21.07% and 9.54% of the RUPC, compared to the systems with four and six effects, respectively.

1. Introduction

To overcome the scarcity of power and fresh water, thermal desalination plants are usually integrated with power plants as a dual-purpose system for the simultaneous production of power and fresh water. These are generally more profitable, economically, and in terms of energy efficiency compared to standalone power plants and thermal desalination systems [1,2]. Among power plants, humidified gas turbines (HGT), which use a gas water mixture as the working fluid, have higher efficiency and specific power output with lower specific investment costs and NO_x emissions, compared to other power generation cycles. For a given power generation, the injection of steam in the combustion chamber decreases the fuel consumption, which results in an increase in the thermal efficiency and vice versa for a given fuel consumption, resulting in increased power generation. The steam-injection contributes to pollutant emissions from the SIGT system depending on the adiabatic flame temperature. The amount of Carbone monoxide (CO) and nitrogen oxides (NO_x) produced in the combustion chamber and combustion reaction are mainly a function of the adiabatic flame temperature, which is the temperature reached by burning a theoretically correct mixture of fuel and air in an isolated vessel [1,3]. Increasing the adiabatic flame temperature increases the thermal NO_x formed from the oxidation of the free nitrogen in the combustion air or fuel. However, the CO emission decreases when the adiabatic flame temperature increases.

There are several configurations of HGT cycles, including the steam-injected gas turbine (SIGT) cycle, humid air turbine (HAT), and evaporative gas turbine (EvGT) [3]. In a SIGT system, steam is generated using a heat recovery steam generator (HRSG), injected into the gas turbine combustion chamber and utilized as working-fluid with air [4]. Recently, several studies have examined injected-steam gas turbines [2–12].

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Paepe and Dick [6] analyzed the water recovery in steam injected gas turbines in terms of the technology and economy. Nishida et al. [4] analyzed the performance characteristics of two types of regenerative steam-injection gas-turbines and compared their performance with that of simple, regenerative, water injection and steam injected gas-turbine cycles. They showed that the steam-injection configuration can be applied in a flexible heat-and-power cogeneration system. Wang and Lior [3] investigated the performance of a SIGT-based combined system with thermal desalination systems. Their analysis improved our understanding of the combined SIGT power and water desalination process and showed ways to improve and optimize it.

The SIGT systems are available as combined heat and power (CHP) systems, producing heat and power simultaneously. Since the major disadvantage of SIGT systems is their large water consumption, especially in water-short areas, these systems are usually integrated with thermal desalination systems, such as multi-effect thermal-vapor compression (METVC), to produce fresh water for the power cycle and other productions. In order to assess the combination of SIGT systems and thermal desalination systems, several performance criteria, based on thermodynamics and economics, have been defined in the literature [7,13,14]. Agarwal et al. [7] improved the performance of a simple gas turbine cycle through the integration of inlet air evaporative cooling and steam injection using thermal efficiency and exergy efficiency as their two thermodynamic performance criteria. Shakouri et al. [14] studied the feasibility of a dual purpose system using the unit product cost of fresh water as a performance criterion, based on economic analysis. In combined SIGT and desalination systems, since the steam-injection process effects the thermal efficiency (fuel consumption), power generation, pollutant emissions and water production, the thermodynamic, economic and environmental aspects should all be taken into consideration in order to define a performance criterion for assessing the retrofitting of a SIGT plant with a thermal desalination system.

As seen in our literature review, recent research efforts have focused on defining the performance criteria based on either thermodynamics or economics, without considering the environmental aspect. This study proposes a systematic approach to define a performance criterion for retrofitting a SIGT plant using a thermal desalination system. Since the main purpose of integrating a SIGT plant with a thermal desalination system is to produce fresh water, in this study the integration of the systems is assessed based on the fresh water production costs. In order to consider the thermodynamic and environmental aspects of the SIGT and METVC integration, we defined two costs: the lost opportunity costs and the found opportunity costs. These contribute to decreases in the total annual costs (TAC). The TAC of the retrofitted SIGT with a METVC system was modified by adding the lost opportunity costs and subtracting the found opportunity costs. The retrofitted unit product cost (RUPC) of the fresh water, as an efficient performance criterion for retrofitting a SIGT plant with a METVC system, which considers both the thermodynamic and environmental impacts of the integration process, was defined by dividing the MTAC by the fresh water production.

This paper consists of four major parts. First, we developed theoretical models, including thermodynamic and environmental models, to calculate the power generation and fresh water production of the retrofitted SIGT–METVC system. In addition, we developed an economic model used to calculate the unit product cost of the fresh water, which includes the lost opportunity and found opportunity costs in the total annual costs of the retrofitted SIGT–METVC system. Second, we determined the sensitivity analysis and feasibility study to assess the retrofitting possibility of the SIGT plant with METVC desalination system, specifically investigating the effect of two key parameters: the temperature difference between effects in the METVC system ($\Delta T_{MED\text{-}TVC}$) and steam air ratio (SR) on the fresh water flow rate $Q_{freshwater}$ and the net power generation (W_{net}) of the retrofitted using system response surface methodology (RSM). Third, we optimized the RUPC of the fresh water as a new performance criterion for retrofitting the SIGT plants using multi-objective optimization (MOO), which maximizes the $Q_{freshwater}$ and minimizes the MTAC of the retrofitted system. We obtained Pareto optimal fronts as a set of optimal solutions, selecting the one which best corresponded to the minimum value of the RUPC.

2. Material and methods

2.1. System configuration

Fig. 1 shows a schematic of a retrofitted SIGT plant with a METVC desalination system [3]. The SIGT subsystem includes a gas turbine power plant and a heat recovery steam generator (HRSG). In the GT subsystem, air is compressed by an air compressor. The compressed air is sent to the combustion chamber (CC) where the fuel and steam are injected. The hot gas from the CC is expanded through the GT, where the shaft work is generated to operate an air compressor and a generator. The expanded gas passes through a HRSG to recover the waste heat of the exhaust gas in order to produce saturated steam as motive steam for the METVC system and superheated steam to inject into the combustion chamber.

The detailed schematic of the METVC desalination system with *n* effects is shown in Fig. 2 [13]. The motive steam, generated by HRSG, was used by a steam jet ejector (SJE) to compress some of the water vapor produced by the last effect. The compressed vapor was introduced into the tube side in the first effect and condensed by releasing its latent heat into the feed water for evaporation. A part of the condensate returns to the HRSG, with the other part passing into the first flashing box. Demisted vapor that forms during the first effect and the flashed vapor from the first flashing box are used together as heating sources in the first pre-heater in order to preheat the feed water to the first effect. The combined vapor from the first pre-heater passes into the second effect and is used as the heat source to vaporize the feed water in the second effect. This process is repeated for all of the effects until the last one, where the vapor generated from the last effect is condensed through the condenser.

2.2. Thermodynamic and economic modeling

In this section we detail the equations that form the thermodynamic and economic models for the SIGT–METVC system presented in Figs. 1 and 2. The models, developed by Janghorban Esfahani et al. [13,15], Wang and Lior [16] were used for thermodynamic modeling and the models, developed by Lazzaretto and Toffolo [17], Cardu and Baica [9], Janghorban Esfahani et al. [13] and Rossen et al. [18], were used for our economic model. Several simplifying assumptions, listed below, were used in the development of our thermodynamic model:

- The cogeneration systems are operated under steady-state conditions;
- The principle of the ideal-gas mixture is applied to the air and combustion products;
- The dead state condition is $P_0 = 1.01$ bar and $T_0 = 25\,^{\circ}C$;
- The temperature differences across the feed heaters are equal, in order to achieve the optimum operating conditions in the METVC desalination system;
- The feed flow rate for all of the effects is equal in the METVC desalination system;

The governing equations for the thermodynamic modeling (presented in Tables 1A to 4A) and for the economic modeling (presented in Table 1B and Eqs. (B18) to (B 23)) of the SIGT subsystem and METVC subsystem were developed using Matlab software in order to simulate the combined system. In this study, we considered the system presented in Table 1 as a SIGT plant [2]. The thermodynamic parameter's initial conditions for the METVC desalination system are presented in Table 2. The simulated models were validated by