



The optimal design and 4E analysis of double pressure HRSG utilizing steam injection for Damavand power plant



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ABSTRACT

Energy, Exergy, Exergoeconomic and Environmental (4E) analysis of combined cycle power plant utilizing the method of steam injection into the combustion chamber is performed in the current study. Steam is supplied from low pressure (LP) side of the heat recovery steam generator (HRSG). According to genetic algorithm's results, the steam injection elevates the total combined cycle power by 2 MW while lowers the design costs considerably at optimum state. Some parameters restrict the steam injection usage within combined cycles that could be noted as Gas turbine power decline; Gas turbine loss increase due to pressure loss; HRSG's manufacturing costs growth; opposition between high and low pressure flow rate variations; NO_x and CO emission costs dependency on optimum conditions. This paper discusses the above limitations for implementation of such technology in combined cycles. At the optimum point, Exergy and thermal efficiencies values increased from 42% and 47.6% to 47.28% and 48.94% respectively. Optimum pinch and approach temperatures for HP and LP sides were computed to be 35, 20, 17 and 37.5, respectively. Also, the optimum value of X parameter is 23.28%; X is defined as the ratio of steam to the inlet air flow rate divided by the other fraction which is the ratio of fuel to input air flow rate while there is no steam injection into the combustion chamber.

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1. Introduction

Most researches about steam injection into the combustion chamber are experimental and numerical and it could be claimed that there are few researches on 4E ((1) Energy, (2) Exergy, (3) Exergo-economic and (4) Environmental) analysis of combined cycles which utilize steam injection. 4E assessment of non-steam injection combined cycle was performed by Ahmadi et al. [1] and is currently being developed. Quality improvement of steam turbine output vapor is recently analyzed by Ganjehkaviri et al. [2]. The optimization process in this work is not related to a particular type of steam turbine. Some parameters such as compressor pressure ratio, compressor, and turbine isentropic efficiencies and gas turbine inlet temperature are included in their calculation. Their triple-objective optimization led to the determination of 15 parameters of the combined cycle operation.

Normally, HRGS is designed in non-steam injection condition for combined cycles. There is no investigation on the influences of HRSG new configuration and design on the combined cycle operation in the case the combustion chamber is steam-injected. The required amendments in HRSG to have the best performance for combined cycle in this situation are also uncharted. In this area, many articles could be exemplified which have paid attention to HRSG design in non-steam injection condition. Casarosa and Franco [3] are from HRSG design pioneers. From other researchers who have contributed in HRSG design and optimization, Pasha and Sanjeev [4], Esmaeili et al. [5], Behbahaninia et al. [6] and Ganjehkaviri et al. [7] could be mentioned. To determine the optimum fuel flow rate in duct burners for Damavand combined cycle power plant, Mokhtari et al. [8] modeled HRSG in order to decrease gas turbine losses in various temperatures. In 2015, Mokhtari et al. [9] designed HRSG as a part of their investigations on solar water desalination to select the appropriate working fluid in power generation section of the cycle.

There are several configurations of Humidified Gas Turbines (HGT) cycles including the Steam-Injected Gas Turbine (SIGT), Humid Air Turbine (HAT) and Evaporative Gas Turbine (EvGT) [10].

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In an SIGT system, steam is generated using a HRSG, injected into the gas turbine combustion chamber and utilized as working fluid with air [11]. Recently, several studies have examined injected-steam gas turbines [12–22]. Paepe and Dick [14] analyzed the water recovery in steam injected gas turbines in terms of the technology and economy. Nishida et al. [11] analyzed the performance characteristics of two types of regenerative steam injection gas turbines and compared their performance with characteristics associated with simple, regenerative, water injection and steam injected gas turbine cycles. They presented that the steam injection configuration can be applied in a flexible heat-and-power cogeneration system. Wang and Lior [10] investigated the performance of an SIGT-based combined system with thermal desalination systems. Their analysis improved authors' understanding of the combined SIGT power and water desalination process and opened their ways to improve and optimize it.

Hassan Kayhan et al. [21], investigated the steam injection into the combustion chamber of a gas turbine cycle. In their study the amount of steam injection, thermal efficiency and environmental impacts (production of NO_x and CO) were investigated. There is no consideration of the pressure drop, HRSG design and economic analysis in their research. From other valuable works, Tufalo and et al. [22] study could be mentioned. They dedicated their researches to obtain mathematical equations in the case in which steam is injected into the combustion chamber. The installed control system results in their investigated gas turbine (LM2500-PEO) led to a semi-experimental relation for emission analysis. The system adjusted its coefficients with experimental data in order to predict CO and NO_x amounts.

One of the problems of combined cycles and power generation cycles which operate with gas turbine is their unexpected power decrease. This decline is caused by site environmental conditions which can also disrupt the preparation of other units. For a power plant, two important points are required to be considered:

1. Supply the network-base load by maximum nominal power.
2. Power generation standby regarding the network load variations.

Governmental power plants in Iran profit from two responsibilities taken by ministry of energy:

1. Energy conversion
2. Circuit existence standby

In this paper, circuit existence standby of the combined cycle is remarked. The only controlling system in the combined cycle is combustion chamber fuel rate. The usage of duct burner increases the fuel consumption which causes separation of the upstream cycle (top cycle) from the downstream (bottom cycle) one. The fin tips temperature in heat exchangers especially superheaters should not exceed 600 °C. As a result, this system can be used in limited circumstances even though this approach reduces the cycle efficiency. As noted previously, several investigations considered this method, which [1,8] and [23–25] can be referred.

1.1. Why steam injection for Damavand combined cycle power plant?

Damavand power plant is located near Tehran, at the elevation of 1300 m above sea level with the annual mean temperature and humidity of 16.6 °C and 52%, respectively. It comprises 12 gas turbines (V94.2) with 160 MW nominal power for each one. The modeling data is presented in Table 1.

In this study, only one block of this power plant including a gas

turbine, a steam turbine and a HRSG is studied (Fig. 1). Average annual temperature and ISO-temperature (15 °C) don't differ sensibly. Compressor inlet volumetric flow rate is assumed to be fixed while mass flow rate varies with temperature and pressure. Therefore, the decrease in the pressure and also air mass flow rates are the reason for power decline.

The plant is assumed to operate in two states of having and lacking duct burners. Owing to the fact that the power is better to be improved without additional fuel consumption, the process is modeled without utilizing duct burners.

Table 1, indicates three main air properties deflection from the ISO mode. For example, moisture content change represents the variation from 60% to 52% while temperature and pressure of ISO state remain constant. It well helps to trace the related effects of each parameter variations on gas turbine cycle parameters.

As can be observed, cycle working pressure change is a factor that heavily influences the cycle operational parameters. As a result, one method is required to be chosen to increase the power generation in the downstream cycle.

One way is cooling compressor inlet air which is reasonable due to the high temperature difference in ISO mode. However, when compared to Table 1, it seems as an inappropriate method because of the low difference between yearly mean temperature and ISO mode temperature.

One of the constraints which lead to power production dissipations in gas turbine is its inlet temperature which should not exceed defined boundaries [1,26,27]. Since cycle operation increases CO_2 and environmental negative effects, steam injection into combustion chamber is proposed for power generation growth and environmental negative effects diminution. Current research, assesses the cycle from 4E points of view.

1.2. The importance of HRSG design for steam injection situation

In this study, it can be realized that the steam injection into the combustion chamber increases the gas side pressure drop within HRSG. Hence, the purpose of this paper is to optimally design HRSG configuration regarding the application of steam injection.

Fig. 1 illustrates schematically how HRSG and gas turbine parameters affect the gas turbine power generation. Due to the sensitive dependence of pressure drop to HRSG's configuration, HRSG should be designed how that the minimum power loss occurs in the gas turbine. Thus, it cannot be definitely reported that whether the increase in steam injection leads to net power decrease or not. This phenomenon depends on HRSG design which is going to be addressed in this study.

The equation which is introduced in Fig. 2, demonstrates the power loss relation. Supplementary descriptions about it can be met in the HRSG modeling section; but the dependence of power dissipations to steam injection should be noted here. There is a direct relationship between gas turbine exhaust mass flow rate ($\dot{m}_g$) and power loss. The more exhaust mass flow rate due to steam injection, the more pressure drop and power loss. It seems to be an unavoidable process. Hence, to decrease the power loss, some improvements should be executed for the systems in which power dissipation parameters may play an important role. According to Fig. 2, HRSG and gas turbine are influential parts of the cycle. Thus, HRSG design and configuration and associated power dissipations during steam injection process are analyzed in this article.

1.3. Scenario definition and assumptions

The scenario here attends these objectives: increasing the upstream generated power by changing pinch and approach

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