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Thermal Efficiency Optimization for A Natural-Gas Power Plant

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ABSTRACT

Energy production from fossil fuels has been regarded as the main source of the climate change. The reason for that is the oxidation of carbon in fossil fuels to carbon dioxide during combustion and the highest percentage of greenhouse gases in atmosphere belongs to carbon dioxide. Amongst the fossil fuels natural gas is preferred due to its low emission of greenhouse gases and having no particulate matter after combustion. While the other fossil fuels emit mainly carbon dioxide during the combustion process; natural gas emits mostly water together with carbon dioxide. Around 22 % of the world's electricity is produced by natural gas and this share is expected to increase in near future. The power plants operating with natural gas as a gas cycle consisting of a compressor, a combustion chamber and gas turbine are combined with a vapor cycle in order to increase the efficiency. A heat recovery steam generator is used to reach this aim in recent years in generating steam by the heat received from the combustion gases leaving the gas turbine. It is very important to design and operate such energy conversion systems fired by natural gas in optimal conditions. If the efficiency can be increased, it can be said that the energetic, economic, and environmental aspects also improve. The modeling and optimization studies for a combined gas-vapor power plant are studied and the most important parameters which influence the efficiency are determined. The results indicate that the most effective parameters from the viewpoint of efficiency are air/fuel ratio, gas/steam ratio and the pressure ratios of the compressor and, thus, the gas turbine. The thermal efficiency increases by 18.25 % and, in the meantime, the exergy destroyed decreases by 9.84 % using optimum design parameters determined by the optimization algorithm proposed.

Keywords:
Optimization, Combined gas-steam, Thermal efficiency

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INTRODUCTION

As the term implies, natural gas is a gas mixture naturally occurred and consists mainly of methane (CH_4) between the limits 87-97 mole %. The worldwide natural gas consumption for electricity generation will be growing by an average of 2.7 % per year since 2012 to the last estimation year of 2040. The natural gas share was 22 % of the total world electricity production in 2012 and it is expected to reach 28 % in 2040. The usage of natural gas in electricity generation is encouraged in USA from the viewpoint of low prices and low greenhouse gas emission [1]. During combustion, carbon oxidize to carbon dioxide and natural gas emits carbon dioxide like all the other fossil fuels, however considerably in fewer amounts and the main product of the combustion is water and has no harm to the environment. Furthermore, in electricity generation, the technology for natural gas is more efficient than coal. So, CO_2 reduction required by Kyoto Protocol can be met for many countries simply by using natural gas instead of coal. In order to meet the world's increasing energy demand, natural gas will continue to be used in the future depending on global expectations. For this reason, it is very important to design and operate such systems in optimal conditions. The most crucial factor for the evaluation of a power plant is thermal efficiency. Every increase in the percentage of thermal efficiency means an increase in the amount of power production and a decrease in the cost of production. Due to this reason, the present study is on the optimization of the efficiency of the power plants operated by natural gas. The most efficient power plants operate on gas-vapor cycles, where combustion gases are used in gas turbines and steam is used in steam turbines to produce additional power. The expanded gas leaving the gas turbine is used to provide steam in

a heat exchanger called heat recovery steam generator. So, the energy of the combustion gases leaving the gas turbine is utilized as the energy source of the steam turbine.

Recent studies on the performance of the combined gas steam power plants published in the literature depend on energy and exergy-based analysis and then optimization algorithms. The available part of energy which can be converted to work, or in other words, the maximum energy that can be obtained from a system is defined as "exergy". In order to determine the irreversibilities, entropy generation and the effective use of an energy source, the best way is exergy-based analysis. Exergy-based analyses are very convenient methods for assessing the performance of energy conversion systems. One of these studies presented a method for simulation of a model developed in Modelica and based on ThermoPower [2]. Kaviri et.al. [3] estimated the heat exchange between steam and gas side in a HRSG (heat recovery steam generator) configuration using a genetic algorithm technique. They concluded that the exergy destruction for HP-EVP (high pressure turbine-evaporator) was the highest amongst the other components, and, that increasing the inlet temperature of the steam generator more than 650^0C had no better effect on both the thermal and exergy efficiencies of the vapor cycle. Ahmedi and Dinçer [4] chose an objective function related to cost including fuel, exergy destruction and purchase, and in order to minimize the objective function they used a genetic algorithm embedded in MATLAB. In their study on multi- objective optimization, Kaviri, Jaafar and Lazim [5] utilized two objective functions, the first one related with the costs consisting of component costs, the fuel cost, the duct burner cost and the exergy destruction cost. The second one was related with the exergy efficiency. In order to solve this multi-objective optimization problem a genetic algorithm approach was used. The temperature of the gas turbine, the pressure ratio of the compressor and the pinch point temperatures were determined as the most important parameters which affected the objective functions. It meant that small changes in these variables could cause large changes in the objective functions. In another study, Kaviri, Jaafar and Hosseini worked on an optimization algorithm having multi objective functions to find the most effective variables in a combined gas steam power plant [6]. Nadir and Ghenaiet [7] used a particle swarm algorithm as an optimization method and considered different configurations for heat recovery steam generator. A combined cycle with triple pressure and reheat was considered in a study by Bakhshmand et. al. [8] and an exergy and economic analysis were performed. The objective function was a cost function consisting of fuel, investment and destroyed exergy. A genetic algorithm was used as an optimization method developed in MATLAB. The authors concluded that the energy and exergy efficiencies were increased by 3 % using optimal variables, and the total cost was decreased by 9 %. Furthermore, using optimal values for the decision variables brought a 0.58 €/h specific cost decrease when it was compared to the base values. The results of a case study performed in Montazar Ghaem power plant, Iran showed that using a cooling system for compressor inlet air caused a 3.2 % temperature drop which led 1.136 % increase in both thermal efficiency and a net output power in the warmest month. The exergy destroyed in the combustion chamber was decreased in considerable amount when the cooling system is operated [9].

Energy generation from fossil fuels has been regarded as the main source of CO_2 emission and has a significant effect on a global warming. As a result, natural gas can be considered as the best fossil fuel when compared to coal and petroleum oil from the environmental viewpoint since its hydrogen content is greater than the others. There are also some simulations and optimization studies related with environmental concerns, such as CO_2 capture which is a very important point. A natural gas fired power plant and a post combustion CO_2 capture unit were simulated in Aspen Plus V8.4 by Rezazadeh et. al. [10]. Simulations were performed at full and 90, 80, 70 and 60% part loads. They considered two processes one with CO_2 capture and the other was without CO_2 capture and the results confirmed performance viability. On the other hand, Pan et. al. [11] proposed some strategies to minimize the detrimental effects of carbon capture such as applying better heat transfer techniques, extracting some amount of steam from the HRSG and exhaust gas circulation,. Açıkkalp et.al. (2014) determined the exergy efficiency of a natural gas power plant in Eskişehir, Turkey to be 40.2 %, pointing out that the most important components for improving the system were the gas turbine and the combustion unit based on the real data [12]. A complex model including 1300 variables was developed and tested using a sequential quadratic programming for a cogeneration plant in the studies of Rodriguez-Toral, Morton and Mitchell [13]. In another similar study [14], twelve parameters were selected as decision variables affecting the exergetic efficiency, total cost and CO_2 emission which were the objective functions. The exergetic efficiency was increased by 6 % and in the same time CO_2 emission decreased by 5.63% using the optimum values for these variables.

In the present study, initially a basic model is developed using mass, energy and entropy balances for a combined gas vapor power system and in the second step the basic model is simulated under an optimization algorithm in order to find the optimum design parameters which yield maximum thermal efficiency.

MODELING AND OPTIMIZATION

In the present study, a combined gas-vapor power generation plant is taken into consideration. The mass, energy

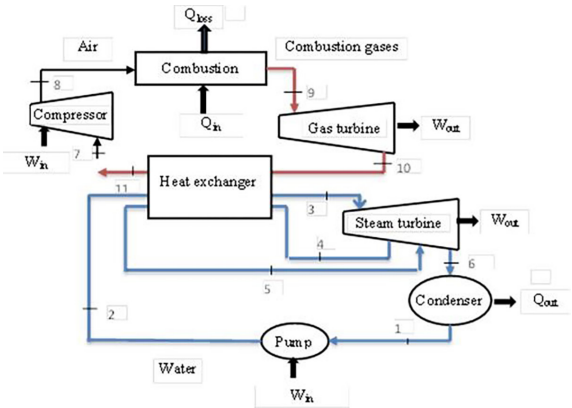

Figure 1. Flow diagram of the combined power plant

and entropy-based thermodynamic modeling of the plant [15, 16, 17] is simulated under an optimization algorithm.

The topping cycle is a gas-turbine power plant. A compressor, a combustion unit and a gas turbine are present in the gas cycle. The bottoming cycle is a non-ideal reheat Rankine cycle, which consists of a steam turbine, a boiler, a condenser and a pump. Steam turbine includes two stages as high pressure and low pressure, and the boiler is the heat recovery steam generator type. The flow diagram of the power plant simulated is given in Fig.1

The optimization problem has been formulated in order to determine the decision variables which maximize the objective function that is the thermal efficiency of a gas-vapor power generation plant.

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,plant}}}{\dot{Q}_{\text{in}}}$$

The thermal efficiency is described (η_{th}) as the total net power achieved from the plant ($\dot{W}_{\text{net,plant}}$) divided by the inlet thermal energy ($\dot{Q}_{\text{in}}$). The objective function is subject to some other functions which describe the power plant by mass, energy and entropy balances. The functions can be expressed as equality constraints $h(x,y)=0$ linear and/or nonlinear functions.The decision variables in the optimization algorithm are the followings;

- inlet temperature to compressor
- pressure ratios for compressor and gas turbine
- pump inlet pressure
- pump exit pressure
- exhaust gas temperature exiting HRGS system
- steam pressure entering LP turbine
- temperature of steam entering HP turbine
- gas-steam ratio
- air-fuel ratio

Therefore, we have 9 decision variables for the combined gas-vapor turbine cycle, and efforts are made to find the optimum quantities of these parameters which maximize the efficiency of the described plant. The decision variables have upper and lower limits.

$$x^L \le x \le x^U$$

where x is the vector of decision variables.

Mass, energy and entropy balances around the combined gas-steam turbine cycle

In the modeling of the plant, the following assumptions are accepted:

1. The operating conditions are steady.
2. Kinetic and potential energy changes between the inlet and the exit of the units are neglected.
3. Air is an ideal gas and enthalpy changes with temperature are taken into account.
4. The thermodynamic properties of combustion gases are equal to the properties of air.

Since the operation conditions are assumed to be steady, all the mass entering the units is equal to the mass leaving the units. Therefore, there is no need to show the mass balances around the system units. However, the energy and the exergy balances around all the most important units are taken into consideration and their bases are shown as follows:

Air Compressor and Gas Turbine

Under these conditions, air is assumed as an ideal gas and the enthalpy, entropy and relative pressure (P_r) values can be determined using ideal gas tables for air. For any process of ideal gases, the entropy change can be written as a function of temperature and pressure as follows;

$$s_{out} - s_{in} = \left(s^{\circ}_{out} - s^{\circ}_{in} \right) - R \ln \frac{P_{out}}{P_{in}} \tag{1}$$

where s is entropy, R is ideal gas constant, P is pressure. For any isentropic process for an ideal gas,

$$s_{out} = s_{in} \tag{2}$$

$$s^{\circ}_{out} = s^{\circ}_{in} + R \ln \frac{P_{out}}{P_{in}} \tag{3}$$

$$\frac{P_{out}}{P_{in}} = \frac{\exp(s^{\circ}_{out} / R)}{\exp(s^{\circ}_{in} / R)} \tag{4}$$

$$\left(\frac{P_{out}}{P_{in}}\right)_{s=const.} = \frac{P_{r,out}}{P_{r,in}} \tag{5}$$

Table 1. Decision variables: the assigned and optimum values

Parameter	Unit	Assigned Values	Optimum
Compressor inlet temperature	°C	15	15.2
Compressor pressure ratio		7	10.5
Pump inlet pressure	kPa	10	9.4
Pump outlet pressure	kPa	6000	6000
Air/fuel ratio		40	36.7
Gas/steam ratio		8,7	13
Temperature of steam entering HP turbine	°C	468	468
Pressure of steam entering LP turbine	kPa	1000	1000
Exhaust gas temperature leaving HRSG system	°C	200	199.7

where Pr is relative pressure and expressed as $P_r = \exp(s^\circ / R)$

For non-isentropic processes take place in the compressor and the turbine calculated the equations 6 and 7 are used taking isentropic efficiencies into account.

$$\eta_C = \frac{h_{out,s} - h_{in}}{h_{out} - h_{in}} \tag{6}$$

$$h_{out} = h_{in} - \eta_T (h_{in} - h_{out,s}) \tag{7}$$

where h is enthalpy, η is isentropic efficiency.

Combustion Chamber

The enthalpy of the combustion gases exiting the combustion unit is determined by the following equation which is actually an energy based balance including an efficiency factor for the combustion chamber which represents the amount of heat leaving the combustion chamber by exhaust gases and the remaining part is representing the heat loss from combustion chamber.

$$\begin{aligned} &\dot{m}_{\text{air}} (h_{\text{air}})_{in} + \dot{m}_{\text{fuel}} LHV_{\text{fuel}} + \dot{m}_{\text{fuel}} h_{\text{fuel}} = \\ &(\dot{m}_{\text{air}} + \dot{m}_{\text{fuel}}) \left(h_{\text{air}} \right)_{out} + \\ &(1 - \eta_{CC}) \left(\dot{m}_{\text{air}} (h_{\text{air}})_{in} + \dot{m}_{\text{fuel}} \left(LHV_{\text{fuel}} + h_{\text{fuel}} \right) \right) \end{aligned} \tag{8}$$

where LHV_{fuel} is lower heating value and $\dot{m}_{\text{fuel}}$ is the flow rate of fuel in mass.

Heat Recovery Steam Generator (HRSG)

Energy Balance around HRSG

Table 2. The results of optimization algorithm for a simple combined power system

	Unit	Initial	Optimum
Q_{in}	kJ/s	2124900	2124900
W_{net}	kJ/s	648340	766570
n_{th}		30.51	36.08
Total exergy destroyed	kJ/s	1071700	966220

$$\begin{aligned} &\dot{m}_S \left(h_{out} - h_{in} \right)_{forHP} + \dot{m}_S \left(h_{out} - h_{in} \right)_{forLP} = \\ &(\dot{m}_{\text{air}} + \dot{m}_{\text{fuel}}) \eta_{HRSG} \left(h_{in} - h_{out} \right)_{gas} \end{aligned} \tag{9}$$

Overall Energy Balances

$$\dot{Q}_{\text{in}} = \dot{m}_{\text{fuel}} LHV_{\text{fuel}} + \dot{m}_{\text{air}} (h_{\text{air}})_{in} + \dot{m}_{\text{fuel}} h_{\text{fuel}} \tag{10}$$

$$\begin{aligned} &\dot{W}_{\text{net,plant}} = \dot{W}_{\text{net,gas}} + \dot{W}_{\text{net,steam}} = \\ &\dot{W}_{\text{T,gas}} - \dot{W}_{\text{C,gas}} + \dot{W}_{\text{T,steam}} - \dot{W}_{\text{P,steam}} \end{aligned} \tag{11}$$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,plant}}}{\dot{Q}_{\text{in}}} \tag{12}$$

Exergy Balances

Exergy balances for all the units in the power plant can be in the following forms:

$$\underbrace{\dot{X}_{\text{in}} - \dot{X}_{\text{out}}}_{\substack{\text{Rate of net exergy transfer} \\ \text{by heat, work, and mass}}} - \underbrace{\dot{X}_{\text{destroyed}}}_{\substack{\text{Rate of exergy} \\ \text{destruction}}} = \underbrace{\Delta \dot{X}_{\text{system}}}_{\substack{\text{Rate of change} \\ \text{of exergy}}} \tag{13}$$

The rate of change exergy with respect to time is zero by steady flow assumption. Then, the exergy destroyed during any steady flow process will be:

$$\begin{aligned} &\dot{X}_{dest} = \dot{X}_{in} - \dot{X}_{out} = \\ &\sum (1 - \frac{T_0}{T_k}) \dot{Q}_k - \dot{W} + \sum \dot{m} \psi_{in} - \sum \dot{m} \psi_{out} \end{aligned} \tag{14}$$

where is the heat transfer through the boundary at temperature Tk at location k,

$$\psi_{in} - \psi_{out} = [(h_{in} - h_{out}) - T_0 (s_{in} - s_{out}) - \Delta ke - \Delta pe \cancel{\to} 0] \tag{15}$$

$$\begin{aligned} &\dot{X}_{\text{dest}} = \dot{m} [T_0 (s_{out} - s_{in}) - q] \\ &\text{since, from energy balance, } q - w = h_{out} - h_{in} + \Delta ke \end{aligned} \tag{16}$$

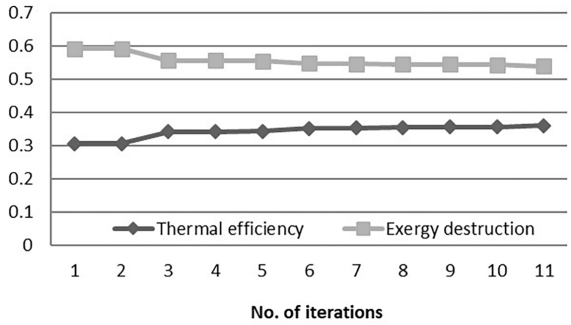

Figure 2. Thermal efficiency and exergy destruction

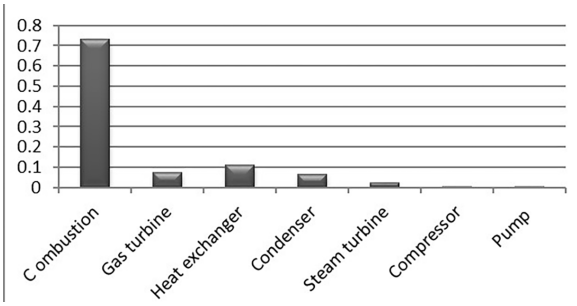

Figure 3. Exergy destruction of process units

$$\dot{X}_{\text{dest}} = T_0\left(\dot{m}(s_{out} - s_{in}) - \dot{m}\frac{q}{T_0}\right) = T_0\dot{S}_{\text{gen}} \qquad (17)$$

Alternatively, the exergy destroyed can be determined by entropy balances as follows:

$$\underbrace{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{\text{gen}}}_{\text{Rate of entropy generation}} = \underbrace{\Delta\dot{S}_{\text{system}}}_{\text{Rate of change of entropy}} \overset{=0 \text{ (steady)}}{} \qquad (18)$$

$$\rightarrow \quad \dot{S}_{\text{gen}} = \dot{S}_{\text{out}} - \dot{S}_{\text{in}}$$

The entropies of the liquid and vapor mixtures for water are determined by

$$s = s_f + xs_{fg} \qquad (19)$$

where x is the quality of the liquid-vapor mixture (mass percent of the steam in the mixture).

In entropy and exergy calculations; the amount of heat loss from the combustion and the condenser units are taken into account.

Optimization

A combined gas-steam turbine cycle model whose details are given above is simulated under an optimization algorithm written using MATLAB® [18, 19]. There are 20 parameters that must be entered initially into the algorithm: compressor inlet air temperature, fuel inlet temperature, pressure ratios for compressor and gas turbine, isentropic efficiencies for compressor, gas turbine, HP turbine and LP turbine, efficiencies for pump, combustion chamber and HRSG, pump inlet and outlet pressure, fuel rate in mass per time, air/fuel ratio, gas/steam ratio, pressure of steam entering LP turbine and the exhaust gas temperature leaving HRSG system, LHV of natural gas and finally, the temperature of steam entering the HP turbine. Amongst these parameters, nine parameters are selected as decision parameters given in Table 1 with their initially assigned values. In order to determine the steam and air properties, the algorithms appeared on Mathworks web [20] and [21] are used respectively.

The algorithm which uses the power plant model described by the mathematical equations, the thermodynamic relations, the physical laws and the laws of thermodynamics is simulated under an optimization algorithm and the optimal values of these nine decision variables which make the objective function maximum are evaluated.

The steps in the optimization algorithm are as follows;

- The initial guesses for the decision parameters are assigned.
- Minimum and maximum constraints for the decision parameters are defined.
- The values of all the other system parameters are entered.
- The stopping criteria are given.
- The model is simulated with the initial guesses.
- Objective function is evaluated.
- The constraints and the stopping criteria are checked, if they are not suitable, new values for the decision parameters are determined by an embedded sub-program "fmincon"
- The iterations continue until the stopping criteria are reached.

RESULTS

The results achieved by the proposed optimization algorithm for a simple combined gas-vapor power system are shown in Table 1. In the algorithm, the initial quantities of the decision parameters are assigned for the defined system which can be seen in the third column on Table 1. The assigned values are taken from Çengel and Boles [15]. Then, an optimization sub-program "fmincon" is used to determine the optimal quantities for the decision parameters which make the thermal efficiency maximum. The fourth column indicates the optimal quantities of the decision parameters which make the objective function, or the thermal efficiency of the plant maximum. In the calculations, the efficiencies of units in the system are assigned to be 80 % (isentropic efficiencies of compressor, gas turbine, LP turbine and HP turbine, pump efficiency, and heat transfer efficiencies for combustion chamber and HRGS). LHV and the temperature of the fuel are taken as 47220 kJ/kg and 25°C, respectively. The fuel mass entering is 45 kg/s. The upper and lower boundaries are

0.5 and 1.5 times of the assigned values.

Table 2 shows the power produced as net power, the thermal efficiency of the plant and the total exergy destroyed by the main units of the plant for the assigned initial values and the optimum quantities of the decision parameters. The thermal efficiency increases from 30.51 % to 36.08 % when the optimum quantities for the decision parameters are used.

DISCUSSION

In the present study a combined gas-steam power cycle is modeled and then simulated by an optimization algorithm. Nine parameters are selected as decision parameters and the optimal values of these parameters are evaluated which give the maximum thermal efficiency. As it can be seen from Fig. 2 as thermal efficiency increases, the exergy destruction decreases as it is expected.

The exergy destruction according to the main units of the cycle is shown in Fig.3. The most important unit from the viewpoint of exergy destruction is the combustion chamber. 73 % of the total exergy destruction belongs to the combustion chamber. The heat exchanger follows it by 11 %. The exergy destruction percentages are determined by the optimal values of the decision parameters.

CONCLUSION

Upon analyzing Table 1 and Table 2 together, it can be concluded that the most important decision variables for the defined plant are air/fuel ratio, gas steam ratio and compressor pressure ratio as well as the gas turbine pressure ratio. Especially the gas-steam ratio and the compressor ratio reach the upper boundaries, implying that if the upper boundaries are increased, they too exceed beyond these figures. The other decision variables do not change much during the course of optimization. The results indicate that, using the same amount of thermal energy input, it is possible to higher the efficiency of the combined cycle by changing the decision variables. The cycle efficiency increases by 18.24 % and, in the meantime the exergy destroyed decreases by 8.92 % using optimum design variables determined by the optimization algorithm proposed. The maximum exergy destruction occurs in the combustion chamber and the heat exchanger follows it. In a future work, in order to satisfy the consistency with the actual power plants, the IP (intermediate pressure) turbine and an additional gas turbine unit are proposed embedded into the algorithm. Another suggestion will be the change of steam mass entering the HP, IP and LP as a decision variable.

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