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Analysis of combined cycle efficiency by simulation and optimization

Şaziye Balku

Atilim University, Department of Energy Systems Engineering, Ankara, Turkey

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ABSTRACT

Natural gas has been regarded as the cleanest fuel when compared to the other fossil fuels because of its low emission of greenhouse gases and no particulate matter after combustion. Around 22% of the world's power production is based on natural gas. Combined gas-steam power plants operating with natural gas are preferred in recent years due to their high efficiency and less emission. To meet the world's increasing energy demand, natural gas will continue to be used in the future in increasing amounts. For this reason, it is very important to design and operate such systems in optimal conditions. Energy conversion systems can be analyzed in terms of energetic, exergetic, economic, and environmental aspects for a good management. When the overall efficiency is increased, it can be said that these four aspects will also improve. In the present study, the modeling, simulation and optimization studies on the combined gas-steam power plants are performed. The most important parameters which influence the efficiency of such plants are determined. The simulation results indicate that the crucial unit is the combustion chamber. The optimization results show that the most effective parameters in the power production are air/fuel ratio, gas/steam ratio and the pressure ratio for the compressor and, thus, the gas turbine. The thermal efficiency of the plant increases by 22.55% and the exergy destroyed decreases by 22.65% using optimal design variables determined by the optimization algorithm in which the objective function is the thermal efficiency. The study demonstrates that the modeling, simulation and optimization can be used for the optimal design of the plants before invested, for operating the present plants at optimal conditions and for analyzing the systems. The minimum detrimental effect on the environment can be provided by optimal design and operation under optimal conditions. The originality of the study is to use an objective function by defining a new efficiency term for the maximum power production with the minimum exergy destruction which results 23.49% increase in the thermal efficiency and, in the meantime, 23.61% decrease in the exergy destruction. This new efficiency term can be used as an objective function in the solution of the optimization problems related with the efficiency of power generating in order to achieve better results.

1. Introduction

As the term implies, natural gas is a 'naturally' occurring gas mixture consisting mainly of methane (CH_4) between the limits 87–97% (on mole basis). Natural gas is the least carbon-intensive fossil fuel; like all the other fossil fuels, the natural gas combustion emits carbon dioxide, but at about half the rate of coal. In addition, the natural gas technologies are more efficient than the coal technologies in generating electricity. Thus, it can help in meeting CO_2 (carbon dioxide) reduction goals for many countries [1–3]. The worldwide natural gas consumption for electricity generation will be growing by an average of 2.7% per year from 2012 to 2040. The natural gas share of total world electricity generation is expected to reach 28% in 2040 whereas it was 22% in 2012. In the United States, natural gas-fired generation is encouraged by low prices and favorable greenhouse gas emission requirements. The natural gas production is 3460.6 billion cubic meters in 2014, and of this production 21.4%, 16.7% and 5.1% belong to the USA, Russian Federation and Qatar respectively [3]. The natural gas has accounted for 24% of the primary energy consumption globally [4]. 187.1 trillion cubic meters of natural gas total proved reserves are present in the world at the end of 2014. Russian Federation, Turkmenistan, Iran, Qatar, and the USA have the shares of 17.4%, 9.3%, 18.2%, 13.1 and 5.2% of total, respectively [5]. The ranking is given differently in 2012 as Iran, Russia and Qatar in the first three in another source [6]. The data differs according to the source or the year of the references, for example BP (British Petroleum) and OPEC (Organization of Petroleum Export Countries) data is different for 2014 [7], anyhow it gives some idea on the situation of the natural gas worldwide in the energy sector. Although Turkey does not appear in any rank in the natural gas reserve and production of the world,

E-mail addresses: saziye.balku@atilim.edu.tr, sazbalku@gmail.com

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Nomenclature

h	specific enthalpy (kJ/kg)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
η	isentropic efficiency
η_C	isentropic efficiency for compressor
η_{CC}	efficiency of combustion chamber
η_{HRGS}	efficiency of heat recovery steam generator
$\eta_{T,g}$	isentropic efficiency for gas turbine
η_{th}	overall thermal efficiency of the power plant
η_{enex}	overall energy-exergy efficiency of the power plant
P	pressure (kPa)
P_r	relative pressure
q	heat transfer per mass (kJ/kg)
$\dot{Q}_{in}$	rate of thermal energy entering into the power plant (kW)
R	ideal gas constant (kPa·m^3/kg·K)
s	specific entropy (kJ/kg·K)
s^o	specific entropy of an ideal gas at a given temperature (kJ/kg·K)
s_f	specific entropy of saturated liquid (kJ/kg·K)
s_{fg}	specific entropy difference between saturated vapor and saturated liquid (kJ/kg·K)
$\dot{S}_{gen}$	entropy generation rate (kW/K)
$\dot{W}_{net,plant}$	net power produced by the power plant (kW)
x	quality of the saturated liquid and saturated vapor mixture leaving low pressure turbine
$\dot{X}$	rate of exergy (kW)
ψ	specific exergy (kJ/kg)

it takes 13th rank in the consumption by 1.4% of the total world consumption of 3393.0 billion cubic meters in 2014. The consumption percentages are 22.7, 12.0, and 5.0 for the USA, Russian Federation and Iran respectively [5]. Natural gas power plants play an important role in the infrastructure of Turkish electricity system and its role will continue to increase in the near future even though Turkey has a very limited reserve. The consumption of natural gas in Turkey in 1985 was negligible; however it became 48.6 billion cubic meters in 2014. The natural gas based electricity generation was 0.2% in 1985 and its share increased rapidly and reached to 48% of total electricity generation in 2014 whereas the share of natural gas in total thermal power is 60% [8]. Combined gas steam power plants operating with natural gas consisting of a gas turbine, a few steam turbines and a heat recovery steam generator are preferred in Turkey in the recent years since they are environmentally friendly when compared to the other systems burning fossil fuels like coal and petroleum, and also have some advantages of investment cost, construction time and high efficiency. In the present situation there are many power plants in Turkey whose capacities and thermal efficiencies vary in a very large scale. In order to meet the increasing energy demand, the need for the usage of natural gas seems to continue. For this reason, it is very important to design and operate such systems in optimal conditions.

The most important factors for the evaluation of a power plant are the energy and the exergy efficiencies. 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.

Every increase in the thermal efficiency and decrease in exergy destruction mean an increase in the amount of power production and a decrease in the cost of production and benefit for the environment. Due to this reason, the present study is dedicated to the efficiency of the power plants operated by natural gas.

There are many studies on the performance of the combined gas steam power plants published in the literature depend on energy and exergy analysis and optimization. One of these studies presents a method to transform a combined cycle power plant physical model designed for simulation into an optimization-oriented model, which can be further used with efficient algorithms to improve start-up performances. The model has been derived from a complex dynamic simulator developed in Modelica and based on the library for the modeling of thermal power plants, ThermoPower [9].

Kaviri et al. [10] estimated the heat exchange between steam water side and gas side based on the studied HRSG (heat recovery steam generator) configuration from the thermodynamic optimization of the HRSG using a genetic algorithm technique. A main data at base load has been used for a combined gas steam power plant. They concluded the exergy destruction for HP-EVP (high pressure turbine-evaporator) was more than that of the other components. The other result was that increasing the HRSG inlet gas temperature more than 650 °C had less improvement on the thermal efficiency and exergy efficiency of the bottoming cycle. Ahmedi and Dinçer [11] use a genetic algorithm embedded in the MATLAB program for optimization. Their objective function is the total cost which is the sum of the operating and capital cost for a dual pressure combined cycle power plant. In the study on multi-objective optimization by Kaviri, Jaafar and Lazim [12], the first objective function comprises a set of component costs, the cost of fuel injected into the combustion chamber, duct burner cost and the cost of exergy destruction. The second objective function is exergy efficiency. Multi-objective optimization is carried out using a computer code written by using the genetic algorithm approach. Finally, the effect of cycle key parameters on these two objective functions was investigated. It was concluded that the gas turbine temperature, compressor pressure ratio and pinch point temperatures are significant design parameters, and meaning that any changes in these design parameters can lead to a drastic change in the objective functions. Nadir and Ghenaiet [13] considered three configurations of HRSG operating at exhaust gas temperature from 350 °C to 650 °C and concluded that adding another level of pressure led to improving the steam cycle performance independently of turbine outlet temperature using a particle swarm optimization algorithm. An exergo-economic analysis and optimization of a triple-pressure combined cycle plant with one reheat stage was investigated in a study by Bakhshmand et al. [14]. The objective function was the total cost rate of the plant which was the sum of the cost rates of the injected fuel, capital investment and exergy destruction. The simulation code had been developed in MATLAB and genetic algorithm was used as a tool for optimization. The authors concluded that, by using optimal design parameters, the energetic and exergetic efficiencies of the plant increased about 3% and the total cost rate decreased around 9%. In addition, the specific cost was decreased from 21.48 €/h for the base case to 20.9 €/h for the optimum case. The results of a case study performed in MontazarGhaem power plant, Iran showed that using a cooling system for compressor inlet air caused a 3.2% temperature drop which led to 1.138% increment in both thermal efficiency and a net output power in the warmest month. The highest amount of exergy destruction in the combustion chamber decreased after the implementation of the cooling system [15].