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Investigating the effect of duct burner fuel mass flow rate on exergy destruction of a real combined cycle power plant components based on advanced exergy analysis

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ABSTRACT

In this research, an advanced exergy analysis of a real combined cycle power plant (CCPP) with supplementary firing is investigated. The endogenous/exogenous irreversibilities of each component and their combination with avoidable/unavoidable irreversibilities are identified. Furthermore, parametric study of the total exergy destruction, thermal and exergetic efficiencies and different parts of exergy destruction of each component are examined as a function of duct burner fuel mass flow rate ($\dot{m}_{DB}$). It is revealed that the avoidable exergy destruction of CCPP decreases within 23.9% while its unavoidable part increases by about 50% as $\dot{m}_{DB}$ increases. In addition, the endogenous avoidable exergy destruction of CCPP gets 3 times while its exogenous part of avoidable is reduced within 86% by increasing $\dot{m}_{DB}$. It is found that the growth of $\dot{m}_{DB}$ elevates the potential improvement of high pressure superheater (HP.SUP), low pressure evaporator (LP.EVAP) and low pressure steam turbine (LP.ST), and decreases the avoidable exergy destruction of the high pressure evaporator (HP.EVAP) and duct burner (DB). Moreover, the increment of $\dot{m}_{DB}$, decreases the unavoidable exergy destruction just in high pressure steam turbine (HP.ST) and dearator (DEAR) by about 8.2% and 5%, respectively, and increases the exogenous of avoidable exergy destruction of DB ($\dot{E}^{AV}_{D,DB}$) within 166%. It means that the effect of other components irreversibilities on avoidable exergy destruction of DB is increased while inefficiency of this component has considerable decrement on its avoidable exergy destruction.

1. Introduction

One way to increase net power output in combined cycle power plant (CCPP) is the usage of duct burner (DB) in warm days. This component is placed after gas turbine to increase the inlet gas temperature of heat recovery steam generator (HRSG) and improve the power generation of steam turbine. Other advantages of DB include the increase of HRSG efficiency, utilizing of some fuels that cannot be used for gas turbine cycle and keeping constant the net power output when gas turbine power output is reduced or environmental conditions change. On the contrary, the decrease of CCPP efficiency and the increase of total exergy destruction, in addition to economic costs, are among the disadvantages of using this component.

Totally, the usage of DB is justified through the price of the produced electricity; especially in summers when the electricity price in some countries increases drastically. Thus, investigating the effect of adding this component as well as other components on the performance of CCPP is important.

Fiaschi and Manfrida [1] investigated pressure ratio and temperature approach on the performance of the semi-closed combined cycle power plant. Ameri et al. [2] analyzed exergy components of a real CCPP. They showed that DB was one of the main sources of exergy destruction. Although, this component decreased thermal and exergy efficiencies of related CCPP but increased the output power of that cycle by about 7.4%. Bassily [3] applied the gas reheat with recuperation to the regular triple-pressure steam-reheat combined cycle. He discussed the effects of varying turbine inlet temperature (TIT) on the net power, cycle efficiency and the amount of irreversibilities. Ahmadi and Dincer [4] optimized an objective function representing the total cost of CCPP with supplementary firing. They analyzed different decision variables in terms of objective function. They also found out that the increase of duct burner fuel mass flow rate not only increased the output power but also decreased the unit total cost of the fuel. Ahmadi et al. [5] analyzed the effect of TIT changes and compressor

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Nomenclature

CCPP	combined cycle power plant
HRSG	heat recovery steam generator
TIT	turbine inlet temperature (°C)
$\dot{E}$	exergy flow rate, (MW)
HP	high pressure
LP	low pressure
HR	heat rate (MJ/MW h)
HPR	heat to power ratio
T	temperature (°C)
P	pressure (bar)
$\dot{W}$	work (power rate) (MW)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat rate (MW)

Components abbreviations

AC	air compressor
CC	combustion chamber
GT	gas turbine
DB	duct burner
SUP	super heater
EVAP	evaporator
ECO	economizer
DEAR	dearator
PRE	preheater
ST	steam turbine
GEN	generator
COND	condenser
CEP	condensate extraction pump
BFP	boiler feed pump

Greek letters

η	efficiency
Δ	difference
λ	excess air fraction

Superscripts and subscripts

AP	approach point
AV	avoidable
D	destruction
EN	endogenous
ex	exergetic
EX	exogenous
exh	exhaust
is	isentropic
k	kth component
min	Minimum
P	product
PP	pinch point
R	real condition
T	theory condition
th	thermal
tot	total

pressure ratio with different percentages of duct burner fuel mass flow rate on efficiency and exergy destruction of heat recovery steam generator (HRSG) as well as CCPP, total power of cycle and their costs. Results showed that increasing $\dot{m}_{DB}$ decreased efficiencies and increased exergy destructions. Moreover, $\dot{m}_{DB}$ growth increased the net total power plant while decreased the HRSG efficiency. Tajik Mansouri et al. [6] presented the effect of HRSG pressure levels on exergy efficiency of CCPP. They found that the stack gas exergy and the exergy destruction rate of cycle decreased, but the energetic efficiency of the cycle increased with an increase in the number of pressure levels of HRSG. Ganje Kaviri et al. [7] studied a dual pressure CCPP and observed the TIT, compressor pressure ratio and pinch point (PP) temperatures as the significant design parameters in thermodynamic results. Ghazi et al. [8] carried out the parametric analysis of exergy unit price ($/kW h) depending on the design parameters, such as high and low drum pressures, steam mass flow rate, PP temperature with and without DB. Sanjay and Prasad [9] showed that in an intercooled combustion-turbine based CCPP, the maximum cycle efficiency occurred at a lower value of intercooling pressure ratio while the maximum plant work output happened at a higher value of that. Bassily [10] modified different gas turbine cooling techniques for modern commercial CCPPs. He improved both efficiency and power with the reduction of HRSG irreversibilitiy. In addition, he found out that TIT can be significantly increased by developing some efficient techniques of GT blade cooling. Thus, operation of GT combined cycle at any given TIT and compressor pressure ratio is performed. Ganjehkaviri et al. [11] studied the effect of steam turbine outlet quality on the output power of a CCPP with dual pressure HRSG. Since the steam turbine outlet quality is a restrictive parameter, they discussed optimization of different cases with different steam quality. Their results showed that it is really important to keep the quality of the vapor at turbine outlet constant for the results to be more realistic. Ehyaei et al. [12] optimized the fog inlet air cooling system for CCPPs based on genetic algorithm. They founded that using optimization with inlet air cooling system for the CCPP increases first and second law efficiencies, for warm months of a year. However, conventional analysis does not provide information about components interaction and real potential for improvement of an energy conversion system. Tsatsaronis [13,14] not only evaluated the weaknesses of the conventional exergy analysis, but also discussed the advanced exergy, exergoeconomic and exergoenvironmental analyses; as a solution to those weaknesses. Advanced exergy analysis is an approach that explains and calculates the different parts of exergy destruction (endogenous/exogenous and unavoidable/avoidable) in the components of an energy system. Tsatsaronis and Mang-Ho [15] were the first researchers who presented the concepts of unavoidable and avoidable exergy destruction. Kelly et al. [16,17] defined several methods by using a simple refrigeration cycle and a simple gas turbine cycle to calculate the endogenous and exogenous exergy destruction. Morosuk and Tsatsaronis [18] explained exergy balance approach in detail, which is used for chemically reacting systems such as a gas turbine cycle.

Besides, in advanced exergy analysis of CCPP, several works have been done. Cziesla et al. [19] studied avoidable and unavoidable exergy destruction of components of an externally fired combined cycle. They presented some aspects of system design and improvement. Petrakopoulou et al. [20] analyzed a three pressure level of CCPP with one reheat stage, using conventional and advanced exergy methods. They reported the possibility of a wide range of potential improvement and interaction among components. Petrakopoulou et al. [21] investigated advanced exergy analysis of a CCPP and observed that the plant can be improved potentially by enhancing the performance of the combustion chamber, gas turbine, air compressor and the low-pressure steam turbine. Soltani et al. [22,23] modeled an externally fired CCPP integrated with a biomass gasification unit. They showed that the unavoidable part of exergy destruction in most components is higher than the avoidable part. In addition, using biomass energy for electricity