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Effect of air-fuel ratio and pressure ratio on the exergetic performance of combined cycle gas turbine plant components

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Abstract

The performance of a combined cycle gas turbine power plant depends on multiple operating parameters, which are influential in distinct ways. These parameters are classified as gas turbine parameters and steam turbine parameters. This paper deals with the influence of two gas turbine operating parameters, i.e., pressure ratio and air-fuel ratio. The 2nd law of thermodynamics has been taken into consideration along with energy analysis to measure the performance of several components of a combined cycle gas turbine plant. Therefore, a comprehensive exergy analysis for each element and the plant has been carried out to overserve the trend of the given range of aforementioned parameters. It is observed from the results that exergy destruction increases in the compressor at a higher-pressure ratio if the compressor is subjected to increased airflow, but exergetic efficiency remains unchanged. Moreover, a similar increment has been observed in the combustion chamber, but the rate of change varies along with the increase in the Air-fuel ratio. For the lower pressure ratios (5-10), the exergy destruction rate for the steam turbine decreases along with increasing in air-fuel proportion, but the effect becomes nearly opposite for the higher-pressure ratios.

Keywords: Combined cycle gas turbine; Exergy analysis; Exergetic efficiency; Compressor; Combustion chamber; Steam turbine

1. Introduction

The energy demand is increasing day by day at a significant rate. This demand is majorly fulfilled by thermal-based power-generating units [1]. The combined cycle gas turbine (CCGT) plants are one of the advanced powers solving multiple available power plant technologies [2]. As a CCGT plant possesses an upgraded efficiency than a standalone coal-based steam power plant, it also shows lesser emission from plant exhaust [3].

The performance of these plants relies on the complex combination of several parameters. These parameters can be described as environmental parameters and user-based parameters. The user-based parameters are further classified as gas and steam turbine parameters. The gas turbine parameters are the ones that influence the performance of CCGT significantly [4]. The major influencing gas turbine parameters are compressor pressure ratio, air-fuel ratio, turbine inlet temperature, and isentropic efficiencies of compressor and gas turbine [5, 6]. The performance speculation of any energy system is carried out by thermodynamics means.

The most popular and simple technique available is 1st law analysis. Though it is easy to implicate the 1st law concept in the aforesaid system, the study does not show the complete performance information. Here comes the role of the 2nd law of thermodynamics as the manifestation of exergy analysis. The exergy analysis takes the various irreversibilities

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into account, which are getting generated at different locations of the energy system. Moreover, this technique helps in finding those locations and providing the scope of improvement in a particular component. Hence identifying the individual components with high potential for improvement provides an efficient system [7]. An exergetically improved system is said to have lesser energy wastage with better utilization of fuel. The common terms studied under the exergy analysis are known as exergy destruction rate and exergetic efficiency. Few researchers have studied the effect of the aforementioned gas turbine parameters on this exergy-based performance factor.

Ankit et al. [6] studied the effect of compressor pressure ratio and isentropic efficiency on the thermal efficiency of the gas turbine cycle. It was observed that increasing the pressure ratio and isentropic efficiency increases the thermal efficiency as per a higher value of the air-fuel ratio. Also, increasing the air-fuel ratio and keeping the compressor inlet temperature constant resulted in decreased thermal efficiency. Horlock et al. [8] also presented the influence of these operating parameters on the energy performance of natural gas-based gas turbine cycles. Abdollahian et al. [9] studied the effect of supplementary firing on the energy performance factors of a combined cycle power plant. Implementing the supplementary firing caused an increase of 26.3 MW and 2.43% in power generation and cycle efficiency, respectively.

The literature work discussed above is associated with an energy analysis of gas turbine cycles and combined cycle gas turbine systems. The emphasis on the 2nd law of thermodynamics has not been observed. The present study considers the same operating parameters, but the performance of CCGT will be observed through an exergetic perspective. With the help of available literature work regarding the CCGT, the two parameters considered for the analysis are pressure ratio and air-fuel ratio.

1.1. System Description

The combined cycle gas turbine plant consists of a topping cycle (i.e., Gas turbine working on the principle of Brayton Cycle), Heat recovery steam generator (HRSG), and Bottoming Cycle (i.e., Steam Turbine working on the principle of Rankine Cycle). Figure 1 exhibits the schematic arrangement of a combined cycle gas turbine plant. The Exhaust of the gas turbine is utilized as a heat source for the steam cycle. Therefore, this arrangement is more efficient and environmentally friendly as a power-generating facility.

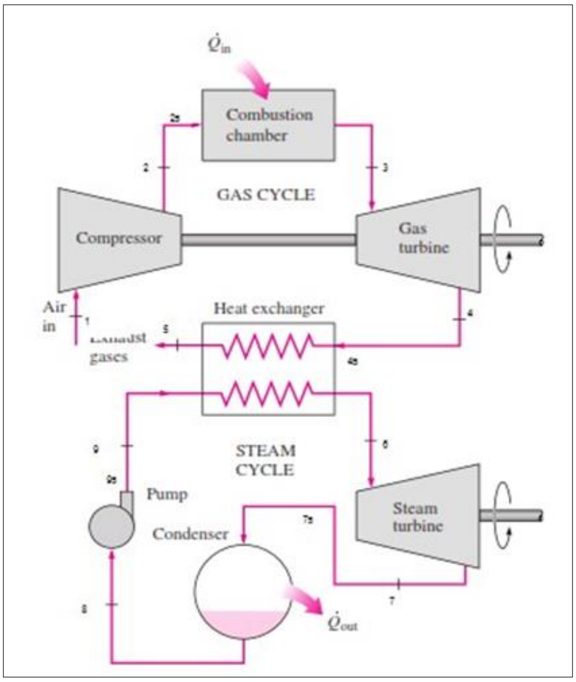

Figure 1 Schematic of combined cycle gas turbine plant

Steam is generated with the help of HRSG as it comprises three heat exchanger packages (Economizer, evaporator, and superheater). Figure 2 displays the heat transfer between exhaust gas and the water/steam line.

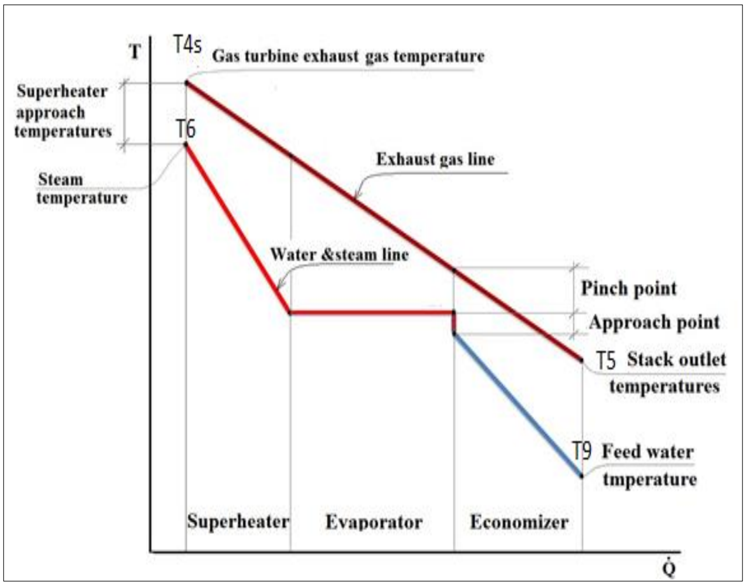

Figure 2 T-Q diagram of HRSG

2. Methodology

The equations for energy analysis of combined cycle gas turbine plants have been taken from Ahmadi et al. [10]. The basic equation employed in the exergy analysis performed on the selected combined cycle power plant is presented in this section. As with the energy analysis, exergy balances for individual components are written, and exergy flows and irreversibilities for each component are found. Then, overall exergy efficiency and exergy destruction are found for the whole system.

The equation for exergy destruction for an energy system can be written as[11]

$$\dot{Ex}_Q + \sum_i \dot{m}_i e_i = \sum_e \dot{m}_e e_e + \dot{Ex}_W + \dot{Ex}_D \qquad 1$$

The combustion chamber is the only component where both physical and chemical forms of exergies are considered. The equation for the chemical exergy is given below:

$$X_{ch} = \dot{m}_f e_{ch} \text{ ……………2}$$

where,

$$e_{ch} = \dot{x}_i e_{chi} + RT_0 \sum x_i ln x_i + G_e \text{………… 3}$$

Where Ge is Gibbs free energy which is a negligible quantity in a gas mixture operated at low pressure. So, for the calculation of fuel exergy, the given expression does not hold well. Thus, the fuel exergy can be calculated as the ratio of fuel exergy to the lower heating value of the fuel.

$$\Omega = \frac{e_f}{LCV} \text{………………4}$$

$\boldsymbol{ef}$ is the specific exergy of the fuel.

For gaseous fuel with composition $\boldsymbol{CxHy}$, the value of Ω can be calculated as

$$\Omega = 1.033 + 0.0169\frac{Y}{X} - \frac{0.0698}{X} \text{ …………… 5}$$

For Methane (CH_4) X=1, Y=4

Then Ω=1.06

$$\boldsymbol{X_f} = \dot{m}_f(\mathbf{1.06}*\text{LCV}) \text{ ....6}$$

The two exergy-based performance factors are considered for the analysis of various components of the CCGT plant. These factors are knowns as exergy destruction rate and exergetic efficiency. The equations for these components are given in Table 1. The input parameters considered for comprehensive exergy analysis are listed in Table 2.

Table 1 Equations for exergy destruction rate and exergetic efficiency

Components	Exergy Destruction Rate	Exergetic Efficiency
Compressor	$X_1 - X_{2s} + W_c$	$\frac{X_1 - X_{2S}}{W_C}$
Combustion Chamber	$X_{2s} + X_f - X_3$	$\frac{X_3}{X_{2S} + X_f}$
Gas Turbine	$X_3 - X_{4s} - W_{GT}$	$\frac{W_{GT}}{X_3 - X_{4S}}$
HRSG	$(X_{4s} + X_{9s}) - (X_5 + X_6)$	$\frac{X_{9S} - X_6}{X_{4S} - X_5}$
Steam Turbine	$X_6 - X_{7s}$	$\frac{W_{st}}{X_6 - X_{7s}}$
Condenser	$X_{in} - X_{out}$	$1\text{-}\frac{\triangle Xdest.,Cond}{\text{Xin}}$
Pump	$X_8 - X_{9s} + W_P$	$\frac{X_8 - X_{9S}}{W_P}$

Table 2 Input parameters consider for analysis

Parameter	**Value (Unit)**	**Parameter**	**Value (Unit)**
Ambient Temp.	298 K	Pressure Ratio	5-30
Ambient Pressure	1.01325 bar	LCV of Fuel	43500 kJ/kg
γ_a	1.4	$\eta_{is,GT}$, $\eta_{is,ST}$	90 %
γ_g	1.33	$\eta_{is,C}$	88%
C_{pa}	1.002 kJ/kg.K	Dryness fraction	0.88
C_{pg}	1.115 kJ/kg.K	Condenser pressure	0.07 bar
Air-Fuel Ratio	50-130	Pinch point temp. difference	13 ^{0}C

3. Results and Discussion

A MATLAB code has been generated to calculate the factors showing the pattern of varying the multiple operating parameters. The main parameters selected for the study are the air-fuel ratio and pressure ratio. The performance factors for exergetic evaluation are exergy destruction and exergetic efficiency.

Fig. 3 portrays the exergy destruction of the air compressor as a function of the air-fuel ratio at various pressure ratios. The pressure ratio varied from 5 to 30 in a step of 5, while the air-fuel ratio varied from 50 to 130 in a step of 10; with the increase in the air-fuel ratio, the exergy destruction rate of the air compressor increased. Here, the mass of fuel remains constant at 1 kg, and the mass of air increases, so the air-fuel ratio. To compress more air, the compressor has to work more, and it results in an increased exergy destruction rate. At a particular ratio, as the pressure ratio increases exergy destruction rate increases too. This is because more work is required by the compressor and work done required by the compressor is directly proportional to the pressure ratio.

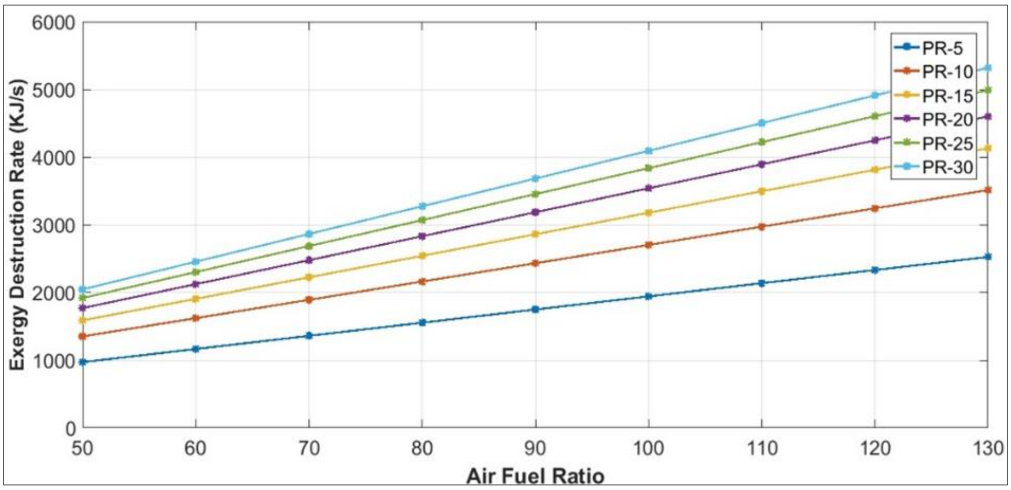

Figure 3 Effect of air-fuel ratio and pressure ratio on the exergy destruction rate of the compressor

Fig. 4 demonstrates the variation of the Exergetic Efficiency of Air Compressor as a function of the air-fuel ratio at various pressure ratios. The air-fuel ratio varied from 50 to 130 in a step of 10. The pressure ratio varied from 5 to 30 in a step of 5. At a particular air-fuel ratio, the exergetic efficiency of the air compressor continuously decreases with an increase in pressure ratio. This is due to the reason that increasing the pressure ratio increases the compressor work. As the air-fuel ratio increases, exergetic efficiency remains constant. This is because exergetic efficiency is not a function of the air-fuel ratio.

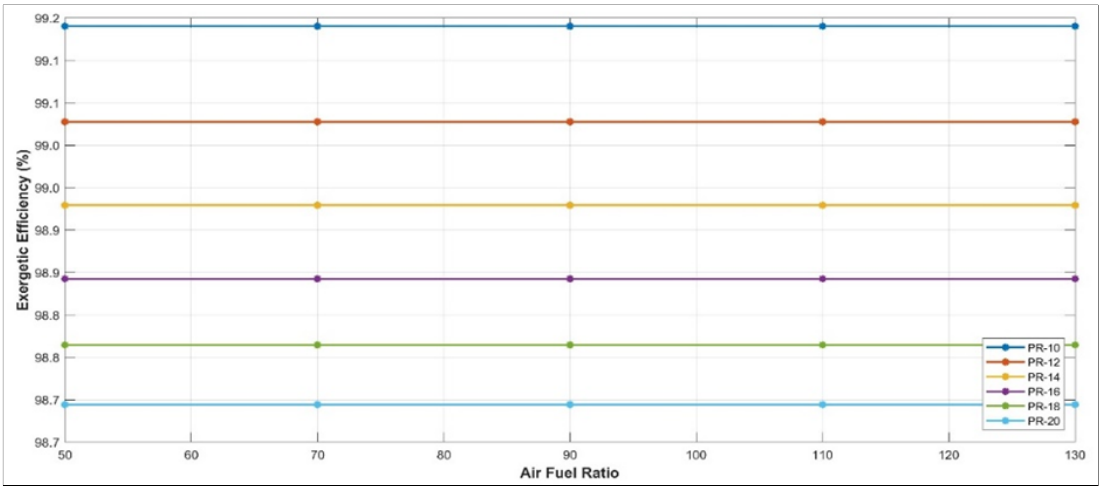

Figure 4 Effect of air-fuel ratio and pressure ratio on the exergetic efficiency of the compressor

Fig 5 demonstrates the variation of the Exergy destruction rate of the combustion chamber as a function of the air-fuel ratio at various pressure ratios. The air-fuel ratio varied from 50 to 130 in a step of 20. The pressure ratio varied from 5 to 30 in a step of 5.

With the increase in the air-fuel ratio, the exergy destruction rate increases too. This is due to the increased amount of heat addition in the combustion chamber, and it results in an increment of exergy destruction rate.

At a particular air-fuel ratio, as the pressure ratio increases, the exergy destruction rate decreases. This happens because, due to the increased pressure ratio, the combustion chamber receives the air with high temperature, so it requires less chemical energy addition.

At a particular air-fuel ratio, with an increasing pressure ratio, the marginal exergy destruction rate decreases. This is due to the reason; the available exergy after the compressor is less for higher pressure ratios owing to the higher destruction rate in the compressor.

At lower air-fuel ratios, the marginal increment in the exergy destruction rate is more rapid as compared to that at higher air-fuel ratios. This is due to the reason at a lower air-fuel ratio, the available exergy is higher since the average temperature of available heat is higher, which goes on decreasing with an increase in the air-fuel ratio.

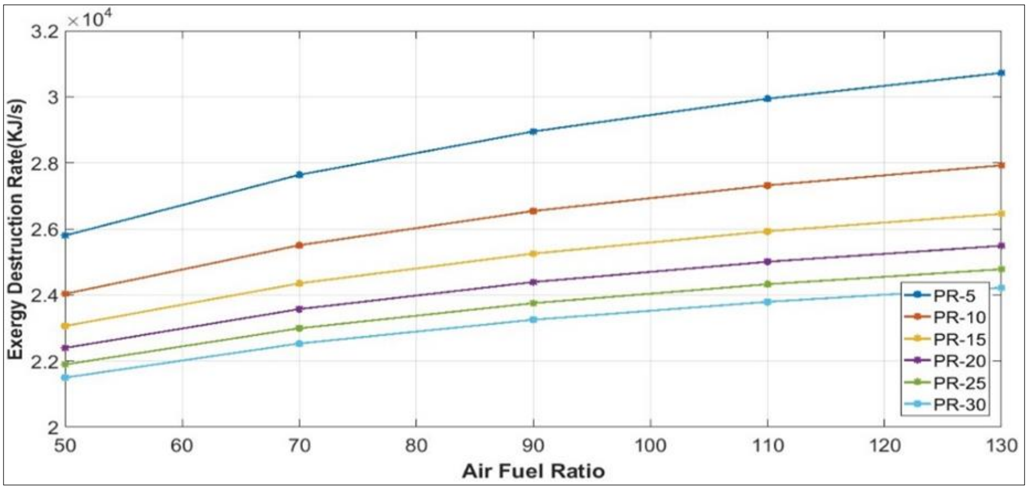

Figure 4 Effect of air-fuel ratio and pressure ratio on the exergy destruction rate of the combustion chamber

Figure 6 displays the Exergy Destruction Rate of the steam turbine at Various Pressure Ratios versus Air Fuel Ratio. The temperature increased by the compressor at a low-pressure ratio is not dominant as compared to the temperature decreased due to the addition of the air-fuel ratio. That's why a specific decreasing trend is visible at the low-pressure ratio. On increasing the pressure ratio, the temperature increase is very much high as compared to the temperature decrease by increasing the air-fuel ratio. That's why the exergy destruction rate continuously increases on increasing air-fuel ratio and at higher pressure ratio.

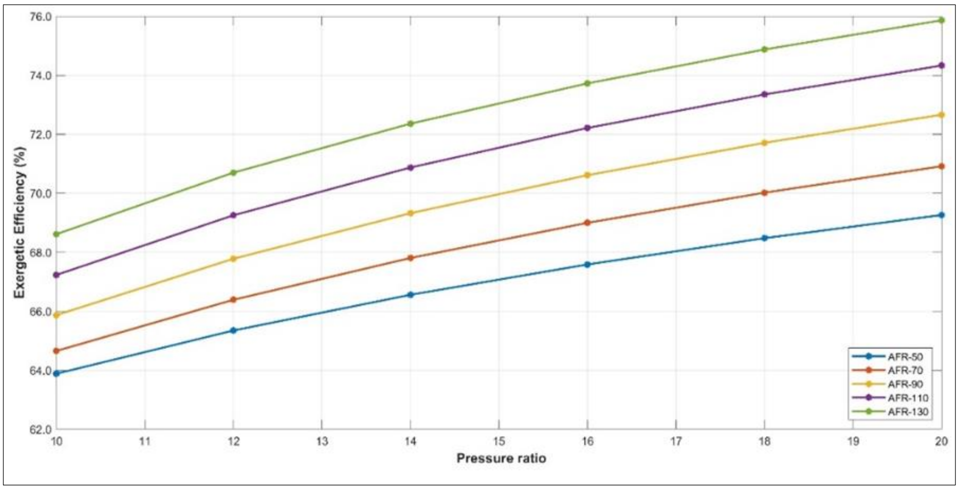

Figure 6 Effect of air-fuel ratio and pressure ratio on the exergetic efficiency of the combustion chamber

Figure 7 displays the Exergy Destruction Rate of the steam turbine at Various Pressure Ratios versus Air Fuel Ratio. The temperature increased by the compressor at a low-pressure ratio is not dominant as compared to the temperature decreased due to the addition of the air-fuel ratio. That's why a specific decreasing trend is visible at the low-pressure ratio. On increasing the pressure ratio, the temperature increase is very much high as compared to the temperature decrease by increasing the air-fuel ratio. That's why the exergy destruction rate continuously increases on increasing air-fuel ratio and at higher pressure ratio.

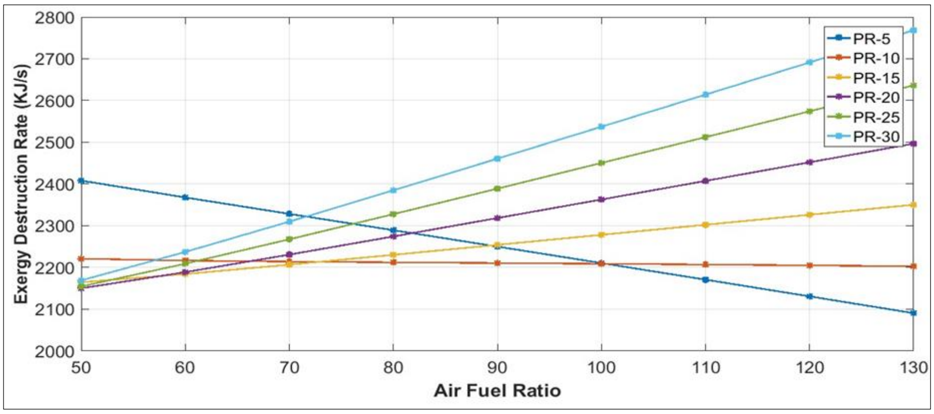

Figure 7 Effect of air-fuel ratio and pressure ratio on the exergy destruction rate of steam turbine

Nomenclature

Symbol	**Description**	**Unit**
X, E	Exergy	KJ
γ	Heat capacity ratio	-
ψ	Specific exergy	kJ/kg
η	Efficiency	-
H, h	Specific Enthalpy	kJ/kg
m	Mass flow rate	Kg/s
C_p	Specific Heat Capacity	kJ/Kg K
T	Temperature	K
Q	Heat supplied	kJ
W	Work	kW
P	Pressure	bar
s	Specific Entropy	kJ/kg.K
Subscript	**Description**	
i, in	Inlet	
e, out	Outlet	
D	Destruction	
f	Fuel	
a	Air	
g	Gas	
is	Isentropic	
0	Ambient condition	
c	compressor	
Abbreviation	**Description**	
LCV	Lower Calorific Value	
GT	Gas Turbine	
HRSG	Heat Recovery Steam Generator	
ST	Steam Turbine	
PR	Pressure ratio	

4. Conclusion

An exergy-based comprehensive analysis is carried out on a CCGT plant. The main parameters selected for the analysis are pressure ratio and air-fuel ratio. The performance has been evaluated in terms of the exergy destruction rate and exergetic efficiency of selected components. The following key points have been concluded from the above analysis are detailed.

- The rate of increment in exergy destruction in the compressor is more at a higher-pressure ratio when associated with an increasing Air-fuel ratio. Moreover, the exergetic efficiency of the compressor remains constant over the range of the air-fuel ratio implying as it is not the function of the air-fuel ratio.
- In the combustion chamber, the marginal increment in exergy destruction rate increases at a greater rate as the pressure ratio is increased. The exergetic efficiency of the combustion chamber is observed to increase with the increase in pressure ratio.
- With the increase in the air-fuel ratio, the exergy destruction rate of the steam turbine decreases for a lower pressure ratio (pressure ratio 5-10). For the pressure ratio of 15 and more, it starts increasing as the pressure ratio increases.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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