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Exergetic Investigation of a Combined Cycle Power Plant: A Case Study

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ABSTRACT

Nowadays, energy demand continuously rises while energy stocks are dwindling. Discovering new energy resources in addition to using current resources more effectively are crucial for the world this century. One of the methods to utilize energy resources effectively is to generate electricity from thermal combined cycle power plants (CCPP). Conducting performance analysis is a necessity to achieve effective operating conditions of thermal plants. The current paper offers a theoretical analysis of exergy losses of a typical CCPP over at various temperature and relative humidity ranges. Exergy destruction and the exergy efficiencies of each component of a thermal plant are calculated as well as subjecting them to parametric analysis. Energy and exergy efficiencies of the CCPP in the current study were 48.19% and 46.49%, respectively. Exergy destruction of a CCPP decreases with increasing ambient temperature and relative humidity. Exergy efficiency of a CCPP drops with increased ambient temperature. It is found that the combustion chamber is responsible for most of the exergy destruction amongst the system components.

Keywords:
Efficiency; combined cycle; ambient conditions; energy; exergy

1. Introduction

Effective use of various energy resources is highly important, since the Earth’s population continuously increases and intense industrialization rates demand much energy, straining our resources. At some point, energy resources will be inadequate to meet demand [1-7]. Combined cycle thermal power plants (CCPPs), examined in this paper, are useful for effective utilization of energy. In these thermal plants, fuel is utilized for generating electricity from two power production cycles. Therefore, CCPPs have higher thermodynamic efficiencies compared to traditional thermal plants that generate electricity from a single power cycle [8-12]. CCPPs comprise many components including a gas turbine (GT), air compressor (AC), combustion chamber (CC), steam turbine (ST) condenser (C) and heat recovery steam generator (HRSG).

CCPP plants are used extensively around the world for power generation, especially to meet peak load demand [13-17]. A gas turbine is a constant volume flow machine that uses ambient air as a

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working fluid [10]. Therefore, ambient parameters (temperature, relative humidity as well as pressure) greatly impact the performance of these power plants. GT generation capacity is evaluated by the ISO [18, 19]. It specifies reference ambient air inlet conditions including an air temperature of 15 °C (59 °F), relative humidity of 60% at an absolute (sea level) pressure of 101.325 kPa (14.7 psia) [20-25]. Exergy analysis assesses system efficiency and offers guidelines for reaching optimal system performance. Furthermore, Second Law considerations can precisely pinpoint the sources of thermodynamic losses. Hence, exergy analysis can be used to optimize power systems and enhance their functionality. Exergy analysis allows us to draw conclusions about specific energy uses. The exergy concept has been widely used by academics as a method to evaluate, improve, and optimize gas turbine systems.

Daoud *et al.,* [26] used exergy analyses of a gas turbine plant utilizing fuzzy logic control. They found that up to 80% of the extreme and lowest exergy losses took place in the combustion chamber and approximately 8% occurred in the compressor. Baghernejad and Moghaddam [27] conducted an exergoeconomic study in addition to an environmental investigation of a regenerative cycle. They documented that the inlet air temperature as well as pressure ratio significantly influence the exergy rate. Exergetic evaluation of a natural gas enhancing station utilizing an actual model and real data was done by Salimi *et al.,* [28]. They observed that hot weather accounted for 64.6% of the exergy destruction caused by a combustion process. Ogunedo and Okoro [29] documented the exergetic efficiency of a compressor at 99%, a combustor at 76%, and a turbine at 96%. According to these results, the cycle loses of energy were about 2.23 kJ for each 1 MW of power output in the CC. Ivan *et al.,* [30] examined the exergy and energy efficiency of a closed-cycle gas turbine cycle. Bassily [31] analyzed techniques for decreasing the HRSG irreversibilities of combined cycles and also investigated modern cooling methods for commercial CCPPs. The results reveal that reducing the temperature differences of the pinch points and decreased flow rates of steam drums decreases the irreversibilities.

According to Majdi *et al.,* [32] exergy efficiency can be enhanced by using a heat pump as it increased by about 1.2%. Exergy analysis of a gas turbine power plants utilizing real data was done by Mohammad Reza Majdi *et al.,* [33]. They observed that decreasing ambient air temperature at the compressor inlet results in improving the exergy efficiency. Abuelnuor *et al.,* [34] performed a destructive exergy investigation at the Garri “2” thermal power plant. According to their results, exergy destruction in the CC was 63%, while that in the GT was 13.6%. Mahto and Pal examined the effect of using a fogging system on the performance of a CCPP system. They also carried out a thermodynamic analysis of the system [35]. Additionally, they carried out thermoeconomic, exergy and energy analyses for each system [36]. Tiwari *et al.,* [37] provided an exergy analysis of a thermal power plant in India. They reported that the exergy destruction taking place in CC is 35% of the total. Petrakopoulou *et al.,* [38] examined a CCPP using both advanced and conventional exergetic evaluation methods. Besides the common exergy efficiency evaluation, they also carried out an exergy investigation by dividing the exergy destruction into unavoidable, avoidable and endogenous as well as exogenous portions. Several important thoughts arise from the literature. They are:

i. The influence of humidity on CCPP performance, especially exergy calculations, was neither not clarified nor negligible.
ii. Investigation of Grassmann diagram was not provided.
iii. The specific chemical exergy values of flows were negligible.

Using a different approach than previous work, the current study of the performance of an actual CCPP is done with the actual operating records of a real thermal plant. Additionally, the exergy destruction and exergy efficiency of each section was determined. The current paper offers a theoretical analysis of exergy losses of a typical CCPP to enhance optimization of the thermal plant. This was done for an actual plant located in Syria, the Jandar facility. ISO and actual value differences are evaluated and analyzed. A theoretical model outlining fundamental assumptions adopted in this work is presented. The results of the research can be used to modify cycle components aiming to enhance efficiency. This decreases the consumption of natural gas, air, and water pollution as well as global warming.

2. CCPP System Description

In this paper, actual operating data of a working CCPP, the Jandar Thermal Power Plant, is used. This facility is one of the most significant electric power plants in Syria. It comprises four gas turbine units, which operate on natural gas with two steam turbines. The power plant meets about 20% of Syria's needs for electric power [1]. It is located near the City of Homs, 35 km away from the city center. The Jandar Energy Corp. was founded in 1993 and began to produce electricity in October 1994. The last ST was put into service in June 1995. The major purpose of the plant is to meet the electrical power and energy demands of central Syria while providing a specific amount of electricity to the national electricity network as well to the shareholders of the Hassiaa Industrial Zone.The Jandar Thermal Power Plant consists of two blocks. Each block comprises two GT units, two HRSGs, one ST unit and an air-cooled condenser. A plant schematic is given in Figure 1.

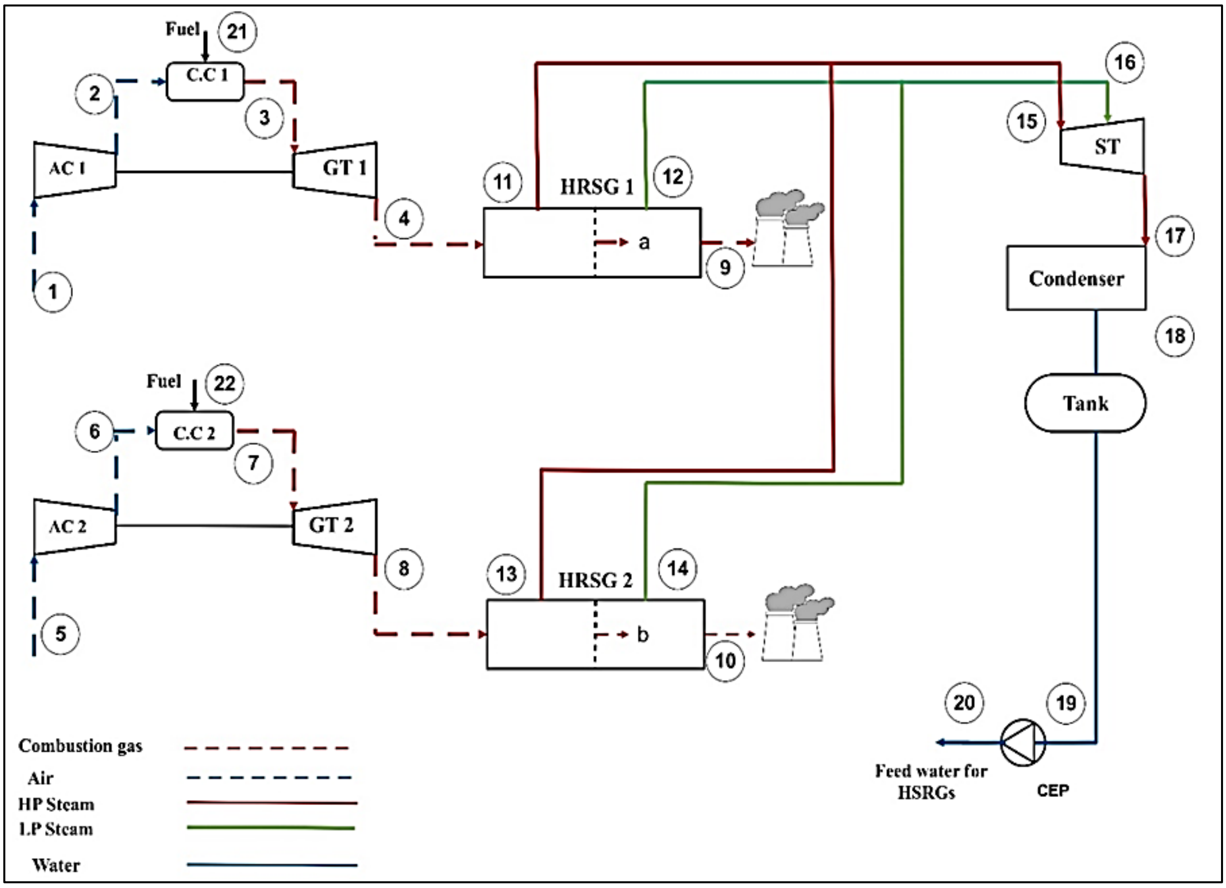

Fig. 1. Schematic representation of a CCPP

According to Figure 1, the topping cycle operates on the basic Brayton cycle. Ambient air is drawn through an air filter at State 1 to protect the blades and other components from dust particles. After a compression stage, the air reaches State 2. This compressed air is then directed with natural gas into a combustion chamber. Combustion produces hot gases at State 3. The combustion gas temperature varies between 1100 and 1120 K. The gases expand while leaving the GT and the combustion gas temperature decreases to a level between 780 and 795 K. An HRSG is employed in the plant to benefit from the high enthalpy and energy rates of the flue gases leaving the GT. The HRSG is a dual pressure level unit, with a high-pressure section (HP) at 55 bars and a low-pressure section (LP) at 5 bars. A portion of the heat is utilized in the HRSG to produce steam. This steam enters the ST at State 15 as HP steam and 16 as a LP steam which expands to the condenser pressure at State 17 to drive a generator. The ST comprises two sections, a HP section and LP section. The HP unit of HRSG is used to feed the HP section of the ST. HP steam expands to the LP section value. The steam is then mixed at the pressure produced by the LP unit of HRSG and expands in the ST LP section. Inside the condenser, the ST exhaust is condensed to a saturation at State 17 and moved by condensate extraction pumps (CEP) to the preheater sections of HRSG1 and HRSG2. The main parameters used characters of the CCPP are presented in Table 1.

Table 1
Main parameters used in calculations [1]

	Parameters		Units
GT	Turbine inlet temperature TIT	1100	°C
	Compressor volumetric flow rate	243	M^3/sec
	Inlet and outlet pressure loss	$0.01P_2$	Pa
	Pressure loss in the combustor	$0.03P_2$	Pa
	Isentropic compressor efficiency	80	%
HRSG	Pinch point temperature	7	°C
	Approach point temperature	9	°C
	HP steam	55	Bar
	LP steam	5	Bar
	HRSG efficiency	97	%
ST	Condenser pressure	8000	Pa
	Isentropic efficiency of the pump	90	%
	Mechanical efficiency	97	%

2.1 Performance Analysis

In this paper, exergy investigation of a thermal plant is conducted using the operating records of the control units of a functioning plant. Additionally, a parametrical investigation is carried out under various conditions. For the performance evaluation of the thermal plant, energy analysis, in addition to exergy analysis associated with the Second Law, are done. Some assumptions are made for the calculations, which include:

i. The flow is assumed steady state.
ii. Air as well as combustion gas are considered an ideal gas.
iii. Conditions of the dead state are T = 298.15 K, P = 1 atm.

To fulfill the performance analysis, calculation of the thermophysical characteristics of the CCPP working fluids and the values of thermophysical characteristics are given in Table 2. In the next section, performance evaluation equations and the thermophysical characteristics of the working fluids are explained.

Table 2
Thermodynamic characteristics of each flux of the CCPP at ISO conditions

Point	Type of the stream	Mass flow (kg/s)	Temperature (℃)	Pressure (bars)	Enthalpy (kJ/kg)
1	Air	296.7	15	1	288.4
2	Air	296.7	360.4	10.593	641.3
3	Combustion gas	303.15	1100	10.272	1483
4	Combustion gas	303.15	523.7	1	821.5
5	Air	296.7	15	1	288.4
6	Air	296.7	364.4	10.593	644.5
7	Combustion gas	303.182	1100	10.272	1481
8	Combustion gas	303.182	522.1	1	822
9	Flue gas	303.15	119.2	1	393.4
10	Flue gas	303.182	120	1	394.3
11	Steam	41.71	493	55	3411.4
12	Steam	8.58	153	4.91	2751
13	Steam	41.76	497	55.1	3421.3
14	Steam	8.61	155.2	4.9	2753.1
15	Steam	83.47	493	54.9	3419.3
16	Steam	17.2	153.5	4.9	2752.3
17	Steam/water	100.66	40.5	0.08	2195
18	Water	100.66	39.4	0.08	164.4
19	Water	100.66	39.5	0.08	164.8
20	Water	100.66	45	2.51	188
21	Fuel	6.447	25	2.6	47100
22	Fuel	6.482	25	2.6	47100

2.2 Exergy Analysis

Superior useful work can be achieved from a system considering the dead state conditions determined as exergy [39]. Recently, exergy evaluation has been extensively used for thermodynamic investigation of many systems since exergetic analysis highlights potential performance improvements of the cycle. A steady state exergy balance equation can be applied [31]:

$$\sum(1-\frac{T_o}{T})Q + \dot{W} + \sum_{in}\dot{m}_{in}\,\psi_{in} - \sum_{out}\dot{m}_{out}\,\psi_{out} = \dot{\Psi}_D \tag{1}$$

The subscripts in and out denote inlet and outlet conditions, respectively, where $\sum(1-\frac{T_o}{T})Q$ is the exergy transfer by heat, $\dot{W}$ represents the exergy transfer by work, $\sum_{in}\dot{m}_{in}\,\psi_{in}$ stands for exergy transfer by mass into the system, $\sum_{out}\dot{m}_{out}\,\psi_{out}$ represents the exergy transferred by mass departing the system and $\dot{\Psi}_D$ is the exergy destruction rate. Q is the heat transferred through the boundary at ambient temperature T. $\dot{m}_{in}$ and $\dot{m}_{out}$ are the mass flowrates of the working fluids at the inlets and outlets of the system. ψ is the exergetic content for a stream given as [40]:

$$\psi = \psi_{ph} + \psi_{ch} \tag{2}$$

In the simulated system, there are various working fluids with different phases. Therefore, equations for computing the exergies of fluids differ. Water/steam phase physical exergy can be calculated as:

$$\psi_{ph} = (h - h_0) - T_0(S - S_0) \tag{3}$$

where s is the specific entropy and subscript 0 represents the dead state conditions. Ideal gases physical exergy can be estimated as [41]:

$$\psi_{ph} = C_p\left[(T - T_0) - T_0 \ln\left(\frac{T}{T_0}\right)\right] + R_a T_0 \ln\left(\frac{P}{P_0}\right) \tag{4}$$

The physical exergy of humid air is calculated using Eq. (5) [34, 37]:

$$\psi_{ph} = \left(C_{pa} + \omega C_{pv}\right)T_0\left(\frac{T}{T_0} - 1 - ln\left(\frac{T}{T_0}\right)\right) + \left(1 + \frac{\omega}{0{\cdot}622}\right)\frac{T_0 R}{M_{d.a}} ln\left(\frac{P}{P_0}\right) \tag{5}$$

Here, R refers to universal gas constant 8.314 (J/ mol·K), $M_{d.a}$ stands for the dry air molar mass and ω is specific humidity.

Natural gas is utilized in the Jandar power plant. The composition as well as heating values of the fuel are presented in Table 3. Chemical exergies of combustion gases play a significant role in exergy analysis of the studied system. During analysis, combustion products are treated as an ideal gas mixture. Eq. (6) is used to calculate the exergy of a chemical mixture [4, 38]:

$$\psi_{ch.g} = \sum X_n \bar{\psi}_{ch_n} + \bar{R}T_0 \sum X_n \ln(X_n) + \bar{g}_E \tag{6}$$

where $\bar{\psi}_{ch_n}$ is the molar chemical exergy, X_n is the mol fraction of each gas in the mixture and $\bar{g}_E$ stands for Gibbs free energy. When the gas mixture pressure is relatively low, $\bar{g}_E$ is negligible [33, 42]. The molar composition of the combustion gases is important for estimating the chemical exergy of this mixture. Eqs. (7) to (11) are used to determine the combustion gas molar fractions [42].

$$\lambda = \frac{o.058\ \dot{m}_{humid\ air}}{\dot{m}_f} \tag{7}$$

$$\chi_{O2} = \frac{2(\lambda - 1)}{1 + (9{\cdot}6254)\lambda} \tag{8}$$

$$\chi_{N2} = \frac{7{\cdot}524\lambda}{1 + (9{\cdot}6254)\lambda} \tag{9}$$

$$\chi_{CO2} = \frac{1 + (0{\cdot}0028)\lambda}{1 + (9{\cdot}6254)\lambda} \tag{10}$$

$$\chi_{H2O} = \frac{2 + (0{\cdot}0972)\lambda}{1 + (9{\cdot}6254)\lambda} \tag{11}$$

Table 3
Properties and composition of natural gas [43,44]

Component	Mass (%)	LHV (Mj/kg)	HHV (Mj/Kg)
$\mathbf{CH_4}$	74	50	55.5
$\mathbf{C_2H_6}$	13.1	47.80	51.9
$\mathbf{C_3H_8}$	5.1	46.35	50.35
$\mathbf{C_4H_{10}}$	3.2	45.75	49.5
$\mathbf{N_2}$	4.1	0	0
$\mathbf{CO_2}$	0.5	0	0
Total/average	100	47.1	52.02

The chemical exergies of common hydrocarbons C_aH_b can be determined in terms of their lower heating value, LHV, using an expression of the form [45]:

$$\psi_{ch.f} = \left(C_1 + C_2\left(\frac{b}{a}\right) - \frac{C_3}{a}\right) LHV \tag{12}$$

where $C_1 . C_2$ and C_3 are constants equal 1.033, 0.0169 and 0.0698, respectively. The constants, a and b are the numbers of Carbon and Hydrogen atoms in the fuel [38]. Exergy analysis and equations of the CCPP components (Figures 2 to 8) are expressed as:

$$\dot{\Psi}_{D.AC} = W_c + \dot{\Psi}_1 - \dot{\Psi}_2 \tag{13}$$

$$\eta_{II.AC} = \frac{\dot{\Psi}_2 - \dot{\Psi}_1}{W_c} = 1 - \frac{\dot{\Psi}_{D.AC}}{W_c} \tag{14}$$

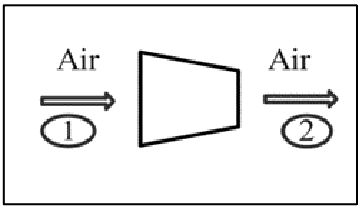

Fig. 2. Compressor

$$\dot{\Psi}_{D.cc} = \dot{\Psi}_{fuel} + \dot{\Psi}_2 - \dot{\Psi}_3 \tag{15}$$

$$\eta_{II.cc} = \frac{\dot{\Psi}_3}{\dot{\Psi}_{fuel} + \dot{\Psi}_2} = 1 - \frac{\dot{\Psi}_{D.cc}}{\dot{\Psi}_{fuel} + \dot{\Psi}_2} \tag{16}$$

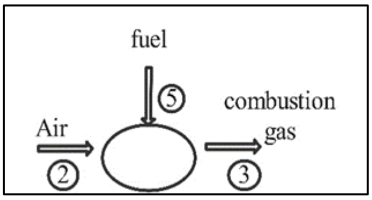

Fig. 3. Combustion chamber

$$\dot{\Psi}_{D.GT} = \dot{\Psi}_3 - \dot{\Psi}_4 - W_{GT} \tag{17}$$

$$\eta_{II.GT} = 1 - \frac{\dot{\Psi}_{D.GT}}{\dot{\Psi}_3 - \dot{\Psi}_4} \tag{18}$$

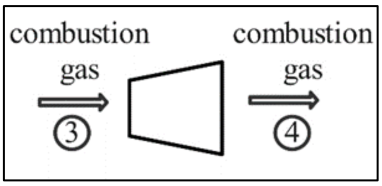

Fig. 4. Gas turbine

$$\dot{\Psi}_{D.ST} = \dot{\Psi}_{15} + \dot{\Psi}_{16} - + \dot{\Psi}_{17} - W_{ST} \tag{19}$$

$$\eta_{II.ST} = 1 - \frac{\dot{\Psi}_{D.ST}}{\dot{\Psi}_{16}+\dot{\Psi}_{15}-\dot{\Psi}_{17}} \tag{20}$$

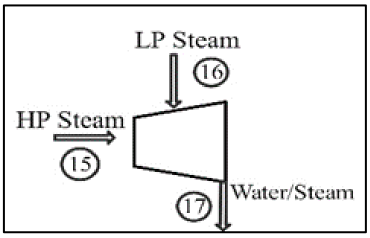

Fig. 5. Steam turbine

$$\dot{\Psi}_{D.C} = \dot{\Psi}_{17} - \dot{\Psi}_{18} \tag{21}$$

$$\eta_{II.C} = \frac{\dot{\Psi}_{18}}{\dot{\Psi}_{17}} = 1 - \frac{\dot{\Psi}_{D.C}}{\dot{\Psi}_{17}} \tag{22}$$

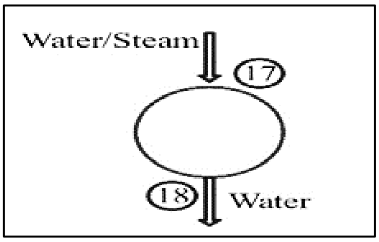

Fig. 6. Condenser

$$\dot{\Psi}_{D.HRSG} = \dot{\Psi}_4 + \dot{\Psi}_{20} - \dot{\Psi}_{11} - \dot{\Psi}_{12} - \dot{\Psi}_9 \tag{23}$$

$$\eta_{II.HRSG} = 1 - \frac{\dot{\Psi}_{D.HRSG}}{\dot{\Psi}_4 + \dot{\Psi}_{20}} \tag{24}$$

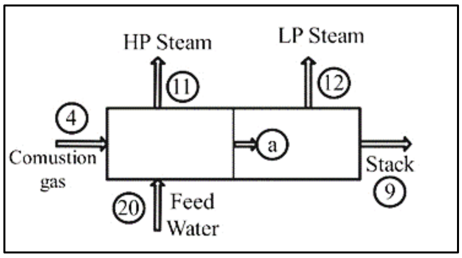

Fig. 7. Heat recovery steam generator

$$\dot{\Psi}_{D.Pump} = \dot{\Psi}_{19} - \dot{\Psi}_{20} + W_{Pump} \tag{25}$$

$$\eta_{II.Pump} = 1 - \frac{\dot{\Psi}_{D.Pump}}{W_{Pump}} \tag{26}$$

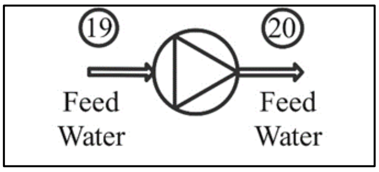

Fig. 8. Pumps

The following equations can be used to estimate the exergetic efficiency of the entire system:

$$\eta_{II.Top\ Cycle} = \frac{W_{GT,net}}{\dot{\Psi}_{fuel}} \tag{27}$$

$$\eta_{II.CCPP} = \frac{W_{CCPP,net}}{\dot{\Psi}_{fuel}} \tag{28}$$

3. Results

A parametric investigation of CCPP is conducted with the equations above using information from Tables 1 and 2. The outcomes are presented in Table 4. The chemical, physical as well as total exergy rates of air, combustion gases, natural gas, steam, and water at different points were calculated and presented in Table 5.

Table 4
CCPP summary

Parameter	Value	Unit
Generated power by GTs	185	(MW)
Generated power by ST	111.4	(MW)
Total fuel consumption	12.93	(kg/s)
Net energy efficiency	48.19	%
Net exergy efficiency	46.49	%

Table 5
Chemical, physical, and total exergy of each flow

Point	Type of the stream	$\dot{\Psi}_{ph}$ [MW]	$\dot{\Psi}_{ch}$ [MW]	$\dot{\Psi}_{Total}$ [MW]	S [kJ/kg K]
1	Air	0	0	0	5.66
2	Air	94.22	0	94.22	5.846
3	Combustion gas	290.11	2.23	292.34	6.66
4	Combustion gas	72.6	2.23	74.83	6.716
5	Air	0	0	0	5.66
6	Air	95.31	0	95.31	5.85
7	Combustion gas	291.78	2.227	294.01	6.67
8	Combustion gas	73.5	2.227	75.72	6.71
9	Flue gas	5.07	2.23	7.3	5.974
10	Flue gas	5.183	2.227	7.41	5.976
11	Steam	59.48	0.1	59.58	6.9
12	Steam	6.74	0.021	6.76	6.83
13	Steam	59.8	0.104	60	6.912
14	Steam	6.776	0.022	6.8	6.841
15	Steam	118.31	0.21	118.52	6.906
16	Steam	13.38	0.043	13.42	6.83
17	Steam/water	18.2	0.252	18.4	6.984
18	Water	0.402	0.251	0.653	0.562
19	Water	0.405	0.251	0.656	0.564
20	Water	0.63	0.251	0.881	0.636
21	Fuel	1.75	311.78	313.53	-
22	Fuel	1.76	313.4	315.2	-

The largest value of exergetic destruction for the CCPP, 117.33 MW (80.6%), occurs in the combustion chamber, followed by the gas turbine, 21 MW (14.25%), as shown in Figure 9. The least exergy destruction occurs in the boiler feed pumps (BFP), 0.9 MW. The reasons for the large exergy destruction rate and low exergetic efficiency in the combustion chamber are unburnt fuels, heat losses during the process, and incomplete combustion. The chemical reactions are the most important source of exergy destruction in the combustion chamber. Irreversibilities occur because heat transfer, friction, and mixing decreases the thermodynamic performance of parameters such as exergy efficiency.

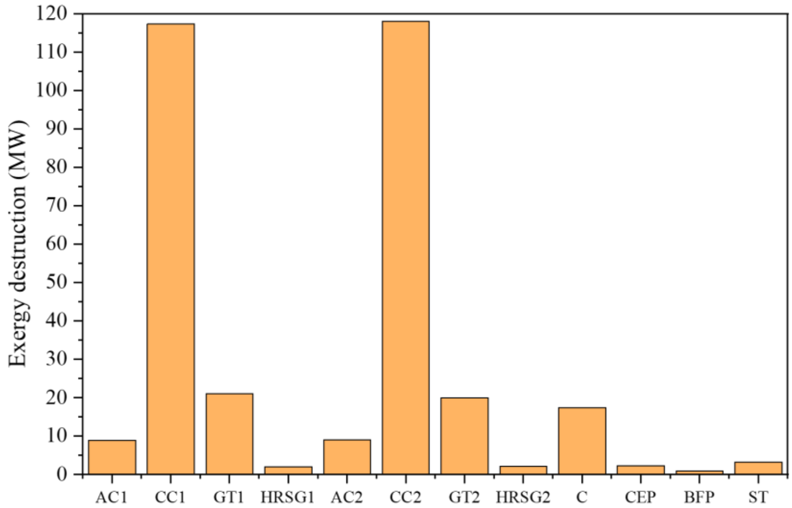

Fig. 9. Exergy destruction for the each CCPP component

The values the exergetic efficiency indicated in this paper are shown in Figure 10 for various components. It is observed that the steam turbine, HRSGs and GTs have high exergetic efficiencies, 98.2, 97.4, and 93%, and that the condenser, CEP pumps and CCs have the lowest exergetic efficiencies, 18.4, 21.3, 71.3%. The plant exergetic efficiency is 46.52%. Compared to the energy efficiency of the plant, 48.22%, the exergy efficiency is lower than the energetic efficiency. According to the results of the exergy analysis, the combustion chambers, CEP pumps and condenser should be designed to reduce exergy destruction and improve exergetic efficiency. Figure 11 shows a Grassmann diagram of the gas turbine unit demonstrating the exergy destruction and percentages of each component in the unit based on the obtained results. It is notable that about 14 MW of the overall fuel exergy is destroyed and rejected to the environment in the exhaust.

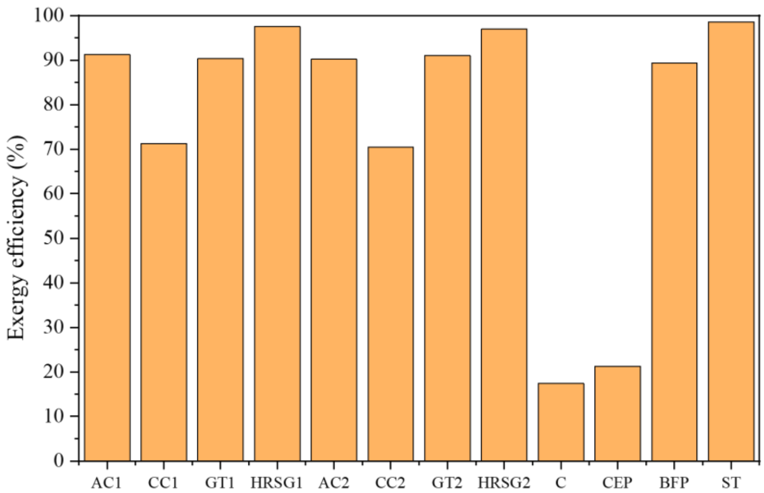

Fig. 10. Exergy efficiency of various CCPP components

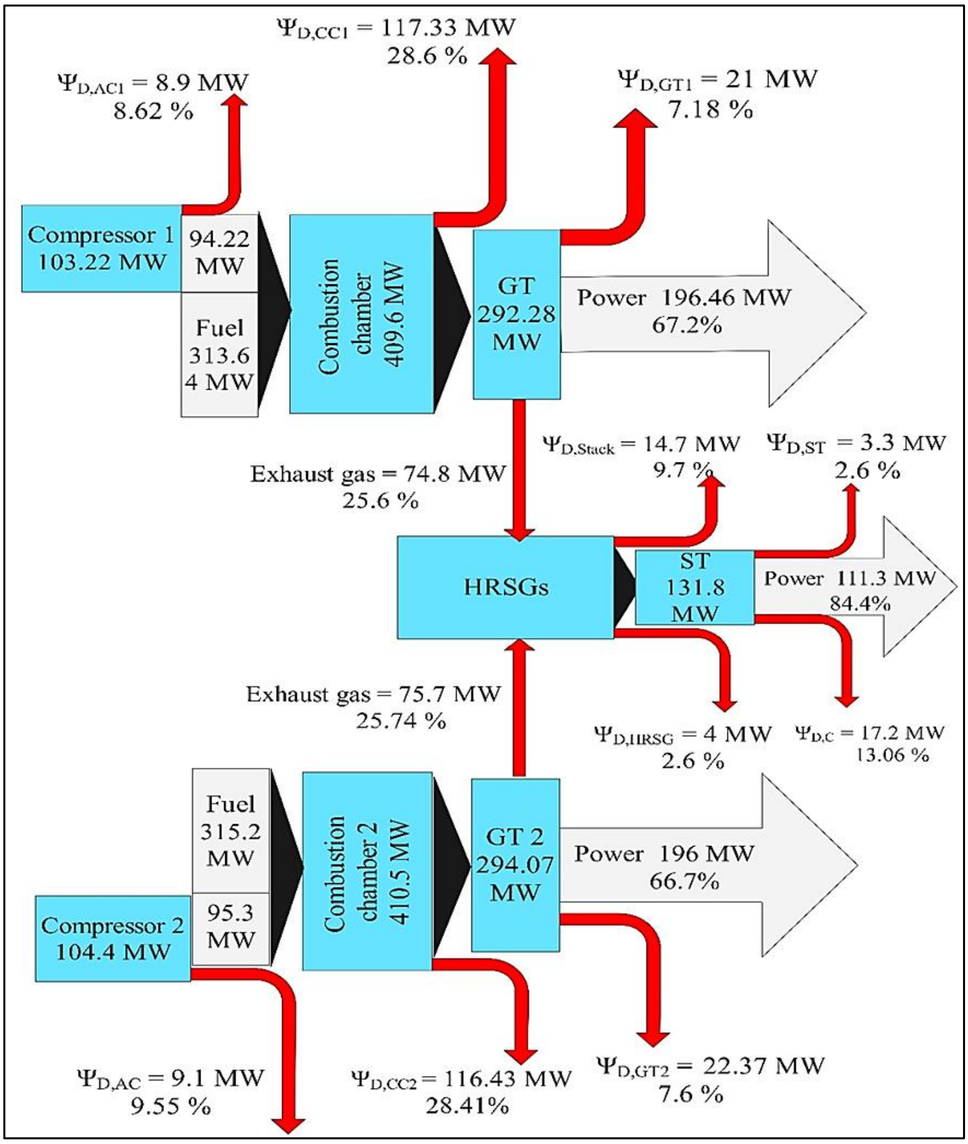

Fig. 11. Grassmann diagram of the CCPP

Figure 12 shows a correlation between exergy efficiencies and destruction at the compressor with various air temperatures and humidity levels. With increased ambient temperature, the AC exergy destruction declines. Elevated air inlet temperatures make air less dense, lowering the mass flowrate into the compressor, according to Eq. (13). Since the decreased compressor power is greater than the decrease in $\dot{\Psi}_2$, in addition to a slightly increased $\dot{\Psi}_1$, the compressor exergy destruction decreases as ambient air temperature increases. The results reveal that at 60% relative humidity and between 15 °C and 35 °C, a temperature difference of 20 °C, there is a 5.2% decrease in compressor power. When the intake temperature is 45 °C, the exergy rate of compressed air is reduced to 91.48 MW and the compressor power decreases to 93.3 MW. Relative humidity has a positive impact on the exergy destruction ratio. $\dot{\Psi}_{D.C}$ decreases with increased relative humidity, especially at higher ambient temperatures. Although increased relative humidity makes the ambient air less dense and consequently reduces its mass flowrate, it reduces the air temperature leaving the compressor, resulting in a reduction of specific compressor work.

AC exergy efficiency increases with ambient air temperature since the decreased exergy destruction $\dot{\Psi}_{D.c}$ is less than the decrease in Wc. This results in increased efficiency (Eq. (14)). Relative humidity has a negative impact on efficiency. The influence of humidity is clear at higher ambient temperatures. The reason is that the exergy rate of compressed air is more affected by ambient air humidity than is compressor power. At 30 °C, an increase in relative humidity to 60% results in an increased $\dot{\Psi}_{D.C}$ of 1.43 MW, while $\dot{W}_c$ decreases by 4.2 MW. Consequently the $\frac{\Psi_{D.c}}{W_c}$ ratio increases, leading to better exergy efficiency.

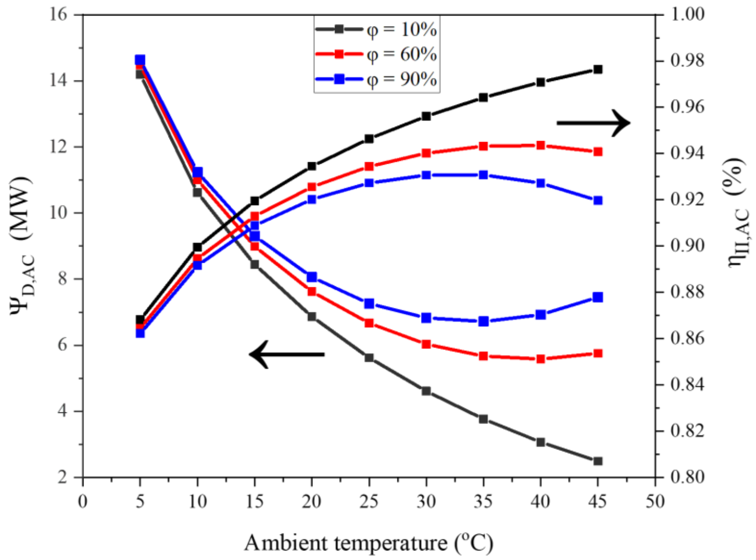

Fig. 12. Exergy efficiency and destruction in the air compressor

Figure 13 demonstrates the temperature dependency of CC exergy destruction. Exergy destruction decreases with the ambient air temperature. It decreased by 2.4% with a 20% increase in temperature at a constant 60% relative humidity. Additionally, it was found that relative humidity has a negative role in decreasing exergy destruction. At a 30 °C ambient air temperature, the exergy destruction for 10%, 60% and 90% relative humidity was 106.34 MW, 110.4 MW and 113.07 MW, respectively. Increasing the relative humidity at a constant ambient air temperature results in an increased fuel mass flowrate. The results revealed that the CC exergy efficiency increases with the ambient air temperature for low relative humidities. In contrast, at elevated relative humidities, efficiency is reduced at high ambient temperatures due to an increased fuel mass flowrate.

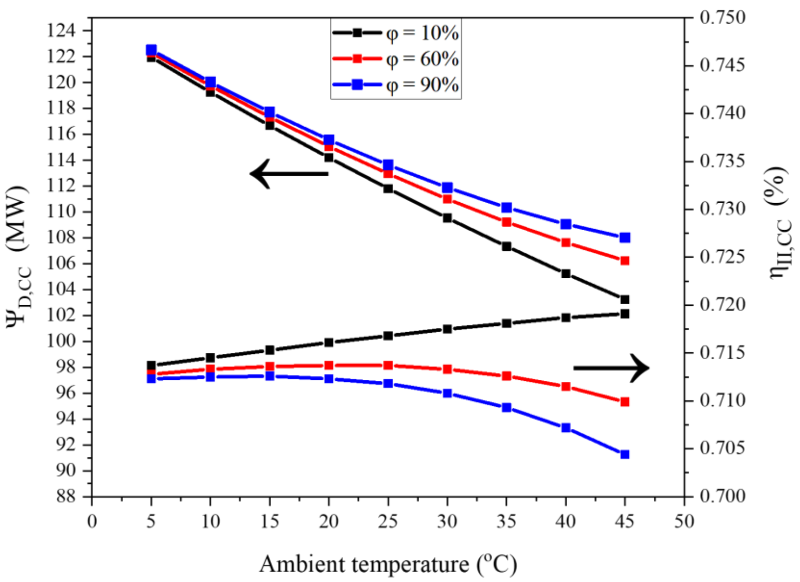

Fig. 13. Exergy efficiency and destruction for combustion chamber

Figure 14 depicts the dependence of GT exergy destruction and efficiency on ambient temperature. An inverse phenomenon is seen when comparing a GT to the compressor and CC. Exergy destruction increases with temperature. According to these results, when the air temperature increases from 5 to 45 °C, the GT exergy destruction increases by 9.86%. This represents an increase of 2214 W. The positive influence of relative humidity can be pronounced as the exergy destruction decreases with increasing relative humidity. The results reveal that GT exergy efficiency decreases with increased ambient temperature. Figure 15 represents the relation between ST exergetic characters with ambient conditions. It was found that increasing ambient temperature has a positive effect on efficiency due to reduced exergy destruction. Relative humidity has a minor influence on ST exergetic characteristics.

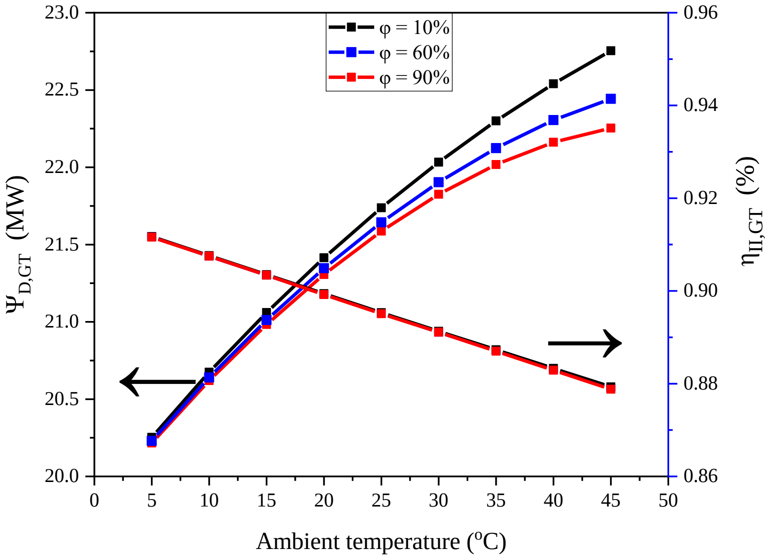

Fig. 14. Exergy efficiency and destruction for gas turbine

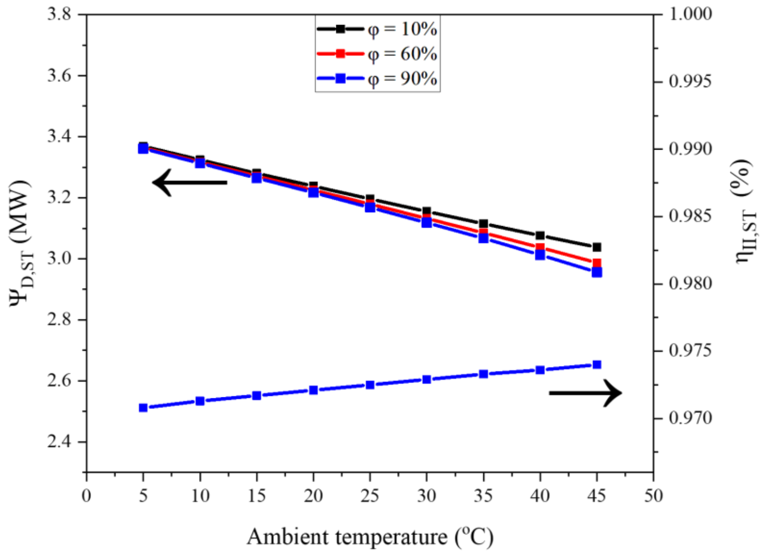

Fig. 15. Exergy efficiency and destruction for a steam turbine

Figures 16 and 17 clearly depict the influence of ambient air temperature and relative humidity on the exergy destruction as well as on the exergy of the top cycle (gas turbine unit) and CCPP. According to these results, exergy destruction as well as the exergy efficiency decrease with increased ambient temperature. For instance, a 40 °C increase in temperature leads to a decreased exergy destruction of the top cycle, from 157 to 134.4 MW and 352.7 to 307.6 MW for the CCPP. The exergetic efficiency of the top cycle is decreased from 31.18% to 25.36% and from 47.13% to 44.74% for the CCPP. However, with increased ambient relative humidity, from 10% to 90%, at an ambient temperature of 30 °C, exergy destruction increases for the top cycle from 136.1 MW to 140.5 MW and from 311.5 MW to 320 MW for the CCPP.

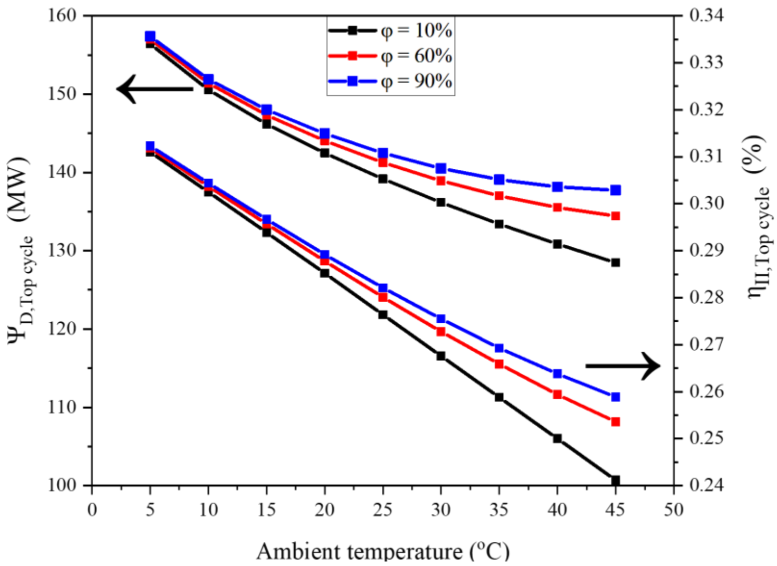

Fig. 16. Exergy efficiency and destruction for the gas turbine cycle

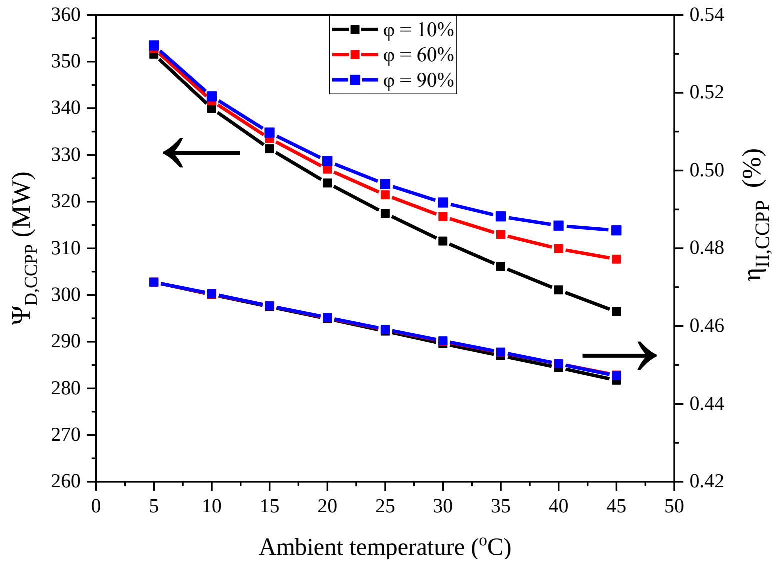

Fig. 17. Exergy efficiency and destruction for a combined cycle thermal power plant

4. Conclusions

Exergy analysis of a CCPP was done with variable inlet air temperatures and relative humidities, yielding the following results:

i. With increased air temperature, exergy destruction for an air compressor and combustion chamber decreased, but the for the gas turbine, it increased.

ii. To decrease high exergy losses in the CC, some changes can be made by modifying the air-fuel ratio of mixture entering the combustor and achieving ideal combustion by reducing excess air.
iii. Exergy efficiency for an air compressor increases with the inlet air temperature.
iv. At low relative humidities, the exergy efficiency of the combustion chamber increases with ambient air temperature. Additionally, for high relative humidities, the efficiency decreases at high ambient temperatures.
v. The effect of relative humidity is particularly noticeable at high inlet air temperatures.
vi. The influence of ambient temperature on CCPP performance is greater than that of relative humidity.
vii. Exergy destruction of a CCPP decreases with increased ambient temperature.
viii. Exergy efficiency of a CCPP decreases as ambient temperature increases.

Therefore, this type of work offers a remarkable opportunity to study and understand the performance of thermal processes through modeling to determine energy and exergy losses. In future work, we will analyze the effects of using cooled inlet air.

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References

[1] Sammour, Alaa Ahmad, Oleg V. Komarov, Mohammed A. Qasim, Samair Almalghouj, Ali Mazen Al Dakkak, and Yang Du. "Ambient conditions impact on combined cycle gas turbine power plant performance." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 45, no. 1 (2023): 557-574. https://doi.org/10.1080/15567036.2023.2172100

[2] Blinov, V. L., I. S. Zubkov, S. V. Bogdanets, O. V. Komarov, and G. A. Deryabin. "Studies of erosive wear of the blading in axial compressors of gas turbines." *Thermal Engineering* 70, no. 6 (2023): 430-442. https://doi.org/10.1134/S0040601523060022

[3] Qasim, Mohammed A., Vladimir I. Velkin, and Sergey E. Shcheklein. "The experimental investigation of a new panel design for thermoelectric power generation to maximize output power using solar radiation." *Energies* 15, no. 9 (2022): 3124. https://doi.org/10.3390/en15093124

[4] Qasim, Mohammed A., and V. I. Velkin. "Experimental investigation of power generation in a microgrid hybrid network." In *Journal of Physics: Conference Series*, 1706, no. 1, p. 012065. IOP Publishing, 2020. https://doi.org/10.1088/1742-6596/1706/1/012065

[5] Qasim, Mohammed A., Vladimir I. Velkin, Sergey E. Shcheklein, Sajjad A. Salih, Baseem A. Aljashaami, and Alaa Ahmad Sammour. "Conversion of heat generated during normal PV panel operation into useful energy via a hybrid PV-TEG connection." *International journal of renewable energy research* 12, no. 4 (2022): 1779-1786.

[6] Yohana, Eflita, Tony Suryo Utomo, Muhammad Ichwan Faried, Mohammad Farkhan Hekmatyar Dwinanda, and Mohamad Endy Yulianto. "Exergy and Energy Analysis of Gas Turbine Generator X Combined Cycle Power Plant Using Cycle-Tempo Software." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 104, no. 1 (2023): 37-46. https://doi.org/10.37934/arfmts.104.1.3746

[7] Kit, Lam Wai, Hassan Mohamed, Ng Yee Luon, Hasril Hasini, and Leon Chan. "Modelling and Simulation of Micro Gas Turbine Performance and Exhaust Gaseous." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 104, no. 2 (2023): 184-195. https://doi.org/10.37934/arfmts.104.2.184195

[8] Martin, Awaludin, and Rahmat Dian Amir. "Exergoeconomic analysis of 21.6 MW gas turbine power plant in Riau, Indonesia." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 84, no. 1 (2021): 126-134. https://doi.org/10.37934/arfmts.84.1.126134

[9] Baakeem, Saleh S., Jamel Orfi, Shaker Alaqel, and Hany Al-Ansary. "Impact of ambient conditions of Arab Gulf countries on the performance of gas turbines using energy and exergy analysis." *Entropy* 19, no. 1 (2017): 32. https://doi.org/10.3390/e19010032

[10] Sammour, Alaa Ahmad, Oleg V. Komarov, Mohammed A. Qasim, and Ahmad Yousef Saleh. "Investigation of the Influence of Ambient Conditions on the Thermodynamic Characteristics of Air as a Working Fluid for Gas Turbines." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 106, no. 1 (2023): 182-196. https://doi.org/10.37934/arfmts.106.1.182196

[11] Ahmed, Ahmed Hasan, Anmmar Mahmoud Ahmed, and Qussay Younis Hamid. "Exergy and energy analysis of 150 MW gas turbine unit: A case study." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 67, no. 1 (2020): 186-192.
[12] Salleh, Hamidon, Amir Khalid, Syabillah Sulaiman, Bukhari Manshoor, Izzuddin Zaman, Shahrin Hisham Amirnordin, Amirul Asyraf, and Wahid Razzaly. "Effects of fluid flow characteristics and heat transfer of integrated impingement cooling structure for micro gas turbine." *CFD Letters* 12, no. 9 (2020): 104-115. https://doi.org/10.37934/cfdl.12.9.104115
[13] Qasim, Mohammed A., Vladimir Ivanovich Velkin, Mustafa Fawzi Mohammed, Alaa Ahmad Sammour, Yang Du, SA-A. Salih, Baseem Abdulkareem Aljashaami, and Sharipov Parviz Gulmurodovich. "Design of a multi-level inverter for solar power systems with a variable number of levels technique." (2023): 1218-1229. https://doi.org/10.11591/ijpeds.v14.i2.pp1218-1229
[14] Qasim, Mohammed A., Vladimir I. Velkin, and Sergey E. Shcheklein. "Experimental and implementation of a 15× 10 teg array of a thermoelectric power generation system using two-pass flow of a tap water pipeline based on renewable energy." *Applied Sciences* 12, no. 15 (2022): 7948. https://doi.org/10.3390/app12157948
[15] Komarov, Oleg V., Viacheslav A. Sedunin, Vitaly L. Blinov, and Alexander V. Skorochodov. "Parametrical diagnostics of gas turbine performance on site at gas pumping plants based on standard measurements." In *Turbo Expo: Power for Land, Sea, and Air*, vol. 45660, p. V03BT25A012. American Society of Mechanical Engineers, 2014. https://doi.org/10.1115/GT2014-25392
[16] Sidik, Nor Azwadi Che, and Ehsan Kianpour. "Effects of row trench holes geometries on an endwall cooling." *CFD Letters* 11, no. 6 (2019): 27-38.
[17] Hassan, Haswira, Kamil Abdullah, Akmal Nizam Mohammed, and Makatar Wae-Hayee. "Asymmetrical compound-angle on combined-hole film cooling." *CFD Letters* 12, no. 3 (2020): 50-57.
[18] Mohammed, Mustafa F., and Mohammed A. Qasim. "Single phase T-type multilevel inverters for renewable energy systems, topology, modulation, and control techniques: A review." *Energies* 15, no. 22 (2022): 8720. https://doi.org/10.3390/en15228720
[19] Blinov, Vitalii L., Oleg V. Komarov, Yurij M. Brodov, and Ilya S. Zubkov. "Technical condition assessment of the gas turbine units with free power turbine." In *International Symposium on Sustainable Energy and Power Engineering*, pp. 161-167. Singapore: Springer Nature Singapore, 2021. https://doi.org/10.1007/978-981-16-9376-2_16
[20] Hassan, Haswira, Kamil Abdullah, Akmal Nizam Mohammed, and Makatar Wae-Hayee. "Asymmetrical compound-angle on combined-hole film cooling." *CFD Letters* 12, no. 3 (2020): 50-57. https://doi.org/10.37934/cfdl.12.3.5057
[21] Ibrahim, Thamir K., Firdaus Basrawi, Omar I. Awad, Ahmed N. Abdullah, G. Najafi, Rizlman Mamat, and F. Y. Hagos. "Thermal performance of gas turbine power plant based on exergy analysis." *Applied thermal engineering* 115 (2017): 977-985. https://doi.org/10.1016/j.applthermaleng.2017.01.032
[22] Bajuri, Muhammad Nur Arham, Djamal Hissein Didane, Mahamat Issa Boukhari, and Bukhari Manshoor. "Computational fluid dynamics (CFD) analysis of different sizes of savonius rotor wind turbine." *Journal of Advanced Research in Applied Mechanics* 94, no. 1 (2022): 7-12. https://doi.org/10.37934/aram.94.1.712
[23] Sammour, Alaa Ahmad, Oleg V. Komarov, Farkad A. Lattieff, Mohammed A. Qasim, and Ahmad Yousef Saleh. "Influence of surrounding air temperature and humidity upon the performance of a gas turbine power plant." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 112, no. 1 (2023): 22-37. https://doi.org/10.37934/arfmts.112.1.2237
[24] Elfeituri, Idris A. "Exergy based performance analysis of a gas turbine unit at various ambient conditions." *International Journal of Energy and Power Engineering* 11, no. 6 (2017): 777-786.
[25] Sidik, Nor Azwadi Che, and Ehsan Kianpour. "Influence of compound spherical trenched holes on film cooling performance at the end of combustor simulator." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 28, no. 1 (2022): 13-24. https://doi.org/10.37934/araset.28.1.1324
[26] Daoud, Raid W., Ahmed H. Ahmed, Wadhah H. Al Doori, Ataalah H. Jassim, Anmmar M. Ahmed, and Zaid H. Ali. "Exergy and energy analyses of 70 MW gas turbine power plant using fuzzy logic control." In *2021 International Conference on Engineering and Emerging Technologies (ICEET)*, pp. 1-6. IEEE, 2021. https://doi.org/10.1109/ICEET53442.2021.9659610
[27] Baghernejad, Ali, and Amjad Anvari-Moghaddam. "Exergoeconomic and environmental analysis and Multi-objective optimization of a new regenerative gas turbine combined cycle." *Applied Sciences* 11, no. 23 (2021): 11554. https://doi.org/10.3390/app112311554
[28] Salimi Delshad, Mohammad, Ali Momenimovahed, Mohammad Sh Mazidi, Mehdi A. Ehyaei, and Marc A. Rosen. "Energy, exergy, exergoenvironmental, and exergoeconomic (4E) analyses of a gas boosting station." *Energy Science & Engineering* 9, no. 11 (2021): 2044-2063. https://doi.org/10.1002/ese3.966
[29] Ogunedo, Briggs Martin, and V. I. Okoro. "Exergy Analysis of Afam IV Gas Turbine Power Plant." *Mechanical Engineering—Elixir International Journal* 105 (2017): 46222-46225.

[30] Ivan, Lorencin, Štifanić Daniel, Musulin Jelena, and Mrzljak Vedran. "Energy and exergy evaluation of co2 closed-cycle gas turbine." *Trans Motauto World* 5, no. 4 (2020): 143-146.
[31] Bassily, A. M. "Modeling, analysis, and modifications of different GT cooling techniques for modern commercial combined cycle power plants with reducing the irreversibility of the HRSG." *Applied Thermal Engineering* 53, no. 1 (2013): 131-146. https://doi.org/10.1016/j.applthermaleng.2013.01.002
[32] Majdi Yazdi, Mohammad Reza, Mehdi Aliehyaei, and Marc A. Rosen. "Exergy, economic and environmental analyses of gas turbine inlet air cooling with a heat pump using a novel system configuration." *Sustainability* 7, no. 10 (2015): 14259-14286. https://doi.org/10.3390/su71014259
[33] Yazdi, Mohammad Reza Majdi, Fathollah Ommi, M. A. Ehyaei, and Marc A. Rosen. "Comparison of gas turbine inlet air cooling systems for several climates in Iran using energy, exergy, economic, and environmental (4E) analyses." *Energy Conversion and Management* 216 (2020): 112944. https://doi.org/10.1016/j.enconman.2020.112944
[34] Komarov, Oleg V., Alaa A. Sammour, Ilya S. Zubkov, and Vitaly L. Blinov. "Exergy analysis of thermodynamic performance of a gas turbine unit." *Izvestiya MGTU MAMI* 17, no. 4 (2023): 321-329. https://doi.org/10.17816/2074-0530-492278
[35] Mahto, D., and Subhasis Pal. "Thermodynamics and thermo-economic analysis of simple combined cycle with inlet fogging." *Applied Thermal Engineering* 51, no. 1-2 (2013): 413-424. https://doi.org/10.1016/j.applthermaleng.2012.09.003
[36] Sammour, Alaa Ahmad, Oleg V. Komarov, Mohammed A. Qasim, Bassam Kassam, and Ali Mazen Al Dakkak. "Studying the effect of compressor ambient operating conditions on gas turbine performance." In *AIP Conference Proceedings*, vol. 2901, no. 1. AIP Publishing, 2023. https://doi.org/10.1063/5.0178698
[37] Tiwari, Arvind, M. Hasan, and Mohd Islam. "Exergy analysis of combined cycle power plant: NTPC Dadri, India." *International Journal of Thermodynamics* 16, no. 1 (2013): 36-42.
[38] Petrakopoulou, Fontina, George Tsatsaronis, Tatiana Morosuk, and Anna Carassai. "Conventional and advanced exergetic analyses applied to a combined cycle power plant." *Energy* 41, no. 1 (2012): 146-152. https://doi.org/10.1016/j.energy.2011.05.028
[39] Aderibigbe, D. A., and G. Osunbor. "Performance of a 270 MW gas power plant using exergy and heat rate." *Energy and Power Engineering* 11, no. 02 (2019): 15. https://doi.org/10.4236/epe.2019.112002
[40] Zevenhoven, Ron, and Özer Arnas. "The effect of air humidity on the exergy efficiency of domestic heat pumps." *Energy Conversion and Management* 221 (2020): 113054. https://doi.org/10.1016/j.enconman.2020.113054
[41] Alpuche, Ma Guadalupe, Christopher Heard, Roberto Best, and Jorge Rojas. "Exergy analysis of air cooling systems in buildings in hot humid climates." *Applied Thermal Engineering* 25, no. 4 (2005): 507-517. https://doi.org/10.1016/j.applthermaleng.2004.07.006
[42] Ersayin, Erdem, and Leyla Ozgener. "Performance analysis of combined cycle power plants: A case study." *Renewable and Sustainable Energy Reviews* 43 (2015): 832-842. https://doi.org/10.1016/j.rser.2014.11.082
[43] Alhosani, O., A. Alhosani, and Z. Dadach. "Exergy analysis of a power plant in Abu Dhabi (UAE)." *International Journal of Energy Engineering* 5, no. 3 (2015): 43-56. https://doi.org/10.5963/ijee0503001
[44] Qasim, Mohammed A., Vladimir I. Velkin, Sergey E. Shcheklein, Abduljabbar O. Hanfesh, Talib Z. Farge, and Fadl A. Essa. "A numerical analysis of fluid flow and torque for hydropower pelton turbine performance using computational fluid dynamics." *Inventions* 7, no. 1 (2022): 22. https://doi.org/10.3390/inventions7010022
[45] Moran, Michael J., Howard N. Shapiro, Daisie D. Boettner, and Margaret B. Bailey. *Fundamentals of engineering thermodynamics*. USA: John Wiley & Sons, 2010.