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Simulation And Optimization of The Sulaymaniyah Combined Cycle Power Plant 1500 MW in Chamchamal, Kurdistan

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Abstract: Combined cycle power plants are crucial for the production of electric power. They are becoming increasingly necessary for electric power generation. This study modeled the Sulaymaniyah Combined Cycle Power Plant 1500 MW in Chamchamal for three combinations of C_6^+ (C_6, C_7, C_8) by energy and material balance in Excel and then simulated by Aspen HYSYS. Additionally, the effects of the mass flow rates of natural gas and air on gas turbine power, as well as the mass flow rate of water on steam turbine power, were investigated. The calculation results in Excel for the combination (47% C_6, 36 % C_7, 17 % C_8) showed a strong correlation with real data collected from the power plant. According to optimum results, the combined-cycle efficiency is 58.91%. The optimum gas turbine power was achieved at a natural gas flow rate of 7.65 kg/s and an air flow rate of 423 kg/s. The optimum steam turbine power is obtained for more than 28 kg/s of water.

Keywords: *Steam Turbine; Combined Cycle Power Plant; Aspen HYSYS; Simulation; Optimization.*

1. Introduction

Concerns about energy supply and environmental degradation caused by excessive energy consumption have become critical to global warming, which is caused primarily by excessive greenhouse gas emissions [1]. The combustion of fossil fuels for the electrical power generation system, industrial processes, and transportation has led to significant increases in atmospheric concentrations of carbon dioxide (CO_2), Nitrogen oxides (NO_x), and methane (CH_4) [2]. Consequently, more attention is directed toward identifying energy sources that ensure highly efficient electricity production with minimum environmental impact to relieve the untoward effects of global warming [3-6]. Among these, combined cycle power plants (CCPP) are considered the optimal solution for electricity generation due to their high thermal efficiency, cost-effectiveness of construction, operational flexibility, low environmental emissions, and reduced fuel consumption compared to conventional power plants [7, 8]. CCPPs integrate a gas turbine engine and a steam turbine, utilizing the waste heat from the gas turbine engine to generate additional electricity through the steam turbine cycle, thereby enhancing overall efficiency. Notwithstanding the essential advantages of gas turbine engines integrated with steam turbines, their efficiency still depends on several thermodynamic and operational parameters, including turbine inlet temperature, pressure compressor, cooling technology, and heat recovery ratio [8-10]. Optimizing these factors is crucial to improving the overall performance of the CCPPs.

The Organic Rankine Cycle (ORC) cycle's energy efficiency is increased from 9.3% to 47.3% by the use of a LiBr absorption chiller. However, it reduces the exergy efficiency from 15.6% to 4.6%, mainly due to the increase in the exergy destruction of the system. The results reveal that when the LiBr absorption chiller cycle is included, a new parameter termed the electricity and cooling cost for this hybrid system drops from 0.0552 to 0.0028 $/kWh. It is discovered that, in terms of thermodynamic performance, the double-stage reheated organic Rankine cycle configuration has surpassed previous arrangements [11]. Utilizing R141b as the working fluid presented in the work, the result of the study shows that the triple cycle (high pressure, low pressure, and intermediate pressure) for the double-stage reheated organic Rankine cycle's thermal efficiency increased by 1.40% while the specific fuel and water consumption reduced by 1.28% and 3.35%, respectively [12].

Franco and Casarosa studied the Heat Exchanger Configurations of a Heat Recovery Steam Generator. The different configurations of Heat Recovery Steam Generators (HRSGs) are examined to improve the energy efficiency of a Combined CCPP. Increasing the efficiency of combined cycle plants to more than 60% without requiring the gas turbine's new technology can be achieved by optimizing HRSG, using gas turbine reheating (after burning), and implementing gas-to-gas recuperation. This configuration has the potential to increase the overall efficiency of the power plant by up to 65% [13].

Moreover, advances in simulation and computer-aided modeling have made it possible to predict and optimize CCPP performance with higher accuracy. However, the researchers continued their investigation on accurately verifying simulation results using actual CCPP data and identifying key factors influencing performance deviations. They can further optimize CCPP performance, minimizing energy losses and improving power generation systems' overall efficiency by integrating advanced modeling techniques such as Cycle-tempo, MATLAB, Aspen HYSYS, and Gate Cycle [14].

Gholam Reza and Davood simulated CCPP in three by Cycle-tempo. The first, a low-pressure heat recovery heat exchanger and a gas turbine, were utilized, and the efficiency and exergy improved by about 4%. In the second configuration using high pressure, the efficiency and exergy were increased by close to 7%. In the third configuration, both high pressure and low pressure were present at the same time, and the efficiency and exergy increased to 9%, respectively. It should be mentioned that the type of gas turbine used was different in all three configurations [15].

Ibrahim et al. presented a simulation program in MATLAB software to study the Thermodynamic parameters analysis of combined cycle gas turbines (CCGT) with various gas turbine configurations, which provides valuable information on performance optimization under various operating conditions. This study highlights the effects of ambient temperature and compression ratio in determining the most efficient gas turbine configuration by utilizing MATLAB software for performance analysis and simulation improves the accuracy of the results, demonstrating that while simple gas turbine configurations provide higher power output, regenerative gas turbine configurations achieve greater efficiency, especially under varying ambient temperatures [16].

Chang et al. investigated the integration of various computational tools for multiscale modeling and dynamic simulation of a combined cycle power plant (CCPP) with a two-tank thermal energy storage system (TES). The study provides Excel as an interactive bridge for data exchange between gPROMS and SimCentral. This approach allows for a comprehensive analysis of both TES performance and its feasibility in improving a combined cycle power plant [7]. Although the models in MATLAB [16] and Excel [7] provide flexibility in formulation and are cost-effective; however, they are inconvenient for the user and require extensive programming and approximations. Moreover, the complexity of simulating the model can lead to errors and numerical convergence challenges.

Li et al. used Aspen HYSYS to simulate the performance of a combined cycle gas turbine power plant. They compared the results with a GateCycle model. The differences obtained from comparing the two models were less than two percent. However, Aspen HYSYS may have some advantages over GateCycle, such as the use of the well-proven real gas Peng-Robinson fluid package and easy integration with various energy systems [17].

Harutyunyan et al. analyzed various reinforcement methods for a 300 MW steam cycle power plant using GateCycle software, focusing on improving energy efficiency and reducing carbon emissions. The analysis was carried out to study thermodynamic parameters and emissions and evaluate the plant's performance at various load levels (from 100% to 50%), focusing on increasing power output, and the other on improving plant efficiency by reducing fuel consumption, especially in regions such as Armenia, where altitude and climatic conditions can affect efficiency [18].

Aminov et al., [2], conducted a simulation model of the Tashkent Thermal Power Plant in the EBSILON Professional tool to improve the efficiency of the combined cycle gas turbine (CCGT) and evaluate the use of CCGT technology in a conventional power station for saving fossil fuels and reducing CO_2 and NO_x emissions.

In this paper, the 1500 MW Sulaymaniyah combined cycle power plant in Iraqi Kurdistan was investigated, and the aim was to find out the methods and assumptions on which this power plant was designed. In this work, the required information was obtained by using mass and energy balance in Excel and simulating the power plant using Aspen Hysys software. Finally, the parameters affecting the efficiency of the combined cycle power plant are discussed.

2. Process Description

Figure 1 shows the production of steam from four heat recovery steam generators (HRSG) to produce electricity from the combined cycle power plant. First, air enters a compressor with 17 stages and about 945 filters that remove dust particles, after which the air is compressed to 10 bar at approximately constant temperature. The compressed air is then sent to the combustion chamber, where it is mixed and burned with natural gas (NG) from the Khor Moor field.

The exhaust gas temperature from the combustion chamber is approximately 550°C, and its energy is utilized to heat the boiler from the bottom to the top through two flows: high pressure (HP) and low pressure (LP). In the boiler, water is heated to its boiling point. The temperature at which the water boils may be much higher than 100°C because the system is operated under pressure.

At the top of the evaporator is a steam drum where water and steam are separated. The water cycles back through the evaporator while steam is collected and taken to the third module, called the superheated. This step dries the steam and raises its temperature above the boiling point, before piping it to the steam turbine.

The steam produced from four boilers is mixed by two flows, HP and LP, and sent to produce power from one steam turbine. When the steam reaches the steam turbine, at first, HP rotates the turbine, then the residue of HP joins the LP flow, and the mixture of both flows rotates the turbine again. Turbines convert kinetic energy into mechanical energy, which then turns into generators, which then turn mechanical energy into electrical energy [19].

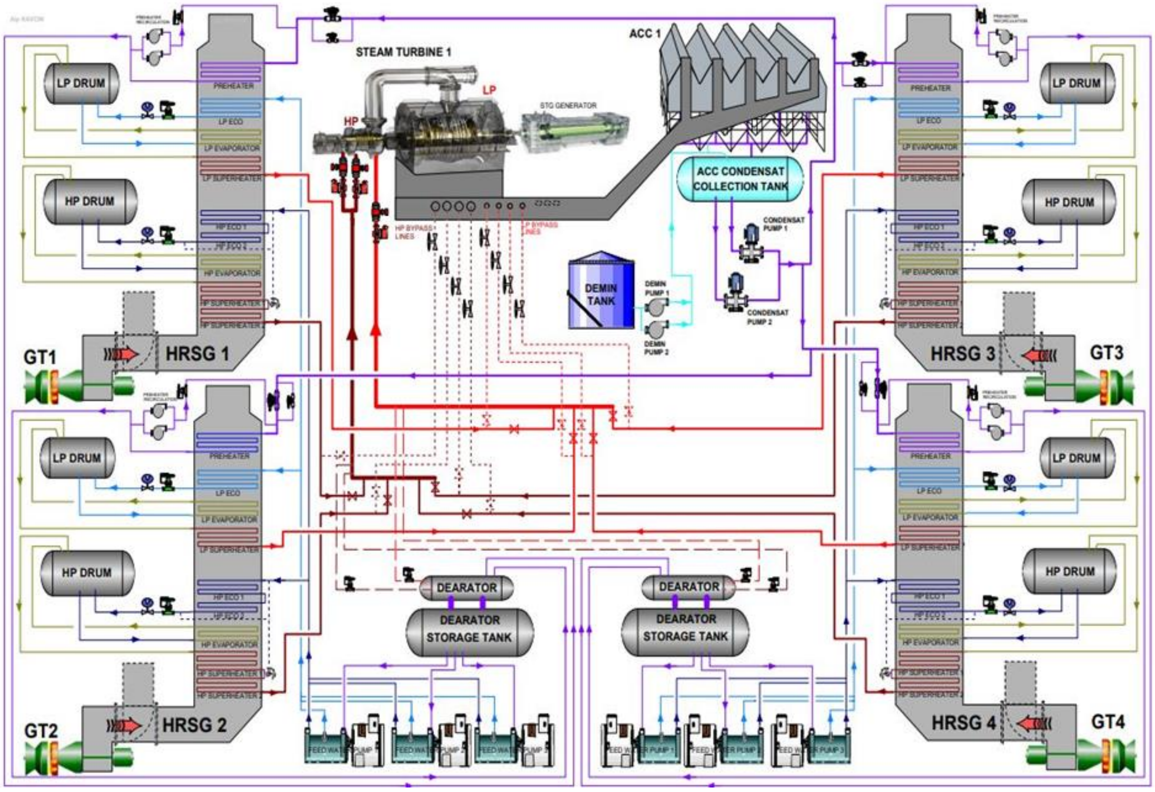

Figure 1: Production of electricity from the combined cycle power plant [19].

3. Methodology

The combined cycle power plant is modeled based on the mass and energy balance equations, which are initially formulated and structured using Microsoft Excel. Subsequently, the combined cycle power plant is modeled and analyzed using Aspen HYSYS software to provide an accurate thermodynamic and performance evaluation (Figure 2).

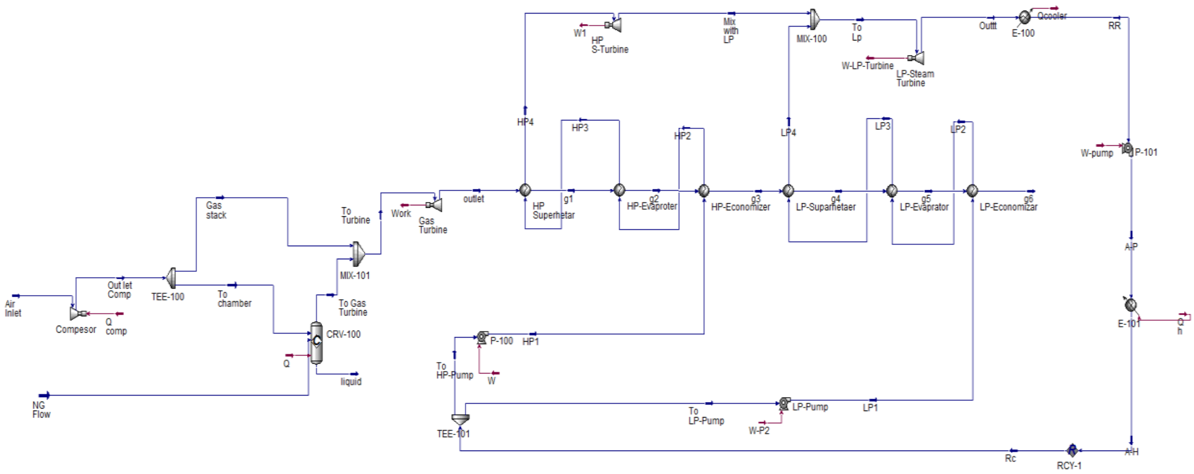

Figure 2: Simulation of CCGT by Aspen Hysys.

The composition of the raw materials (natural gas) is shown in Table 1. It contains C_{6+}, which includes a fixed ratio of n-hexane (C_6H_{14}), n-heptane (C_7H_{16}), and n-octane (C_8H_{18}), that have been studied based on three cases published in case 1: (50 % C_6, 25 % C_7, 25 % C_8), case 2: (47% C_6, 36 % C_7, 17 % C_8), and case 3: (37.3 % C_6, 36.6 % C_7, 26.1% C_8) [20].

Table 1: Natural gas composition in the Sulaymaniyah combined cycle power plant 1500 MW in Chamchamal

No.	Component	Mole Fraction (%)
1	CH_4	88.76
2	C_2H_6	8.92
3	C_3H_8	1.2
4	n-C_4H_{10}	0.35
5	i - C_4H_{10}	0.17
6	n-C_5H_{12}	0.1
7	i - C_5H_{12}	0.11
8	C_{6+}	0.14
9	N_2	0.18
10	CO_2	0.07
Total		100

The following assumptions were made during the simulation of a combined cycle power plant:

1. The CCPP system operates in steady-state conditions.
2. The combustion reaction is complete.
3. The air compressor, gas turbine, LP, and HP steam turbines are considered adiabatic.
4. The energies of kinetic and potential are neglected.

Based on the assumption that natural gas is completely reacted, the chemical reactions that happen during combustion are flowing [21]:

(1) $$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

(2) $$C_2H_6 + \frac{7}{2}\, O_2 \rightarrow 2CO_2 + 3H_2O$$

(3) $$C_3H_8 + 5\, O_2 \rightarrow 3CO_2 + 4H_2O$$

(4) $$C_4H_{10} + \frac{13}{2} O_2 \rightarrow 4CO_2 + 5H_2O$$

(5) $$C_5H_{12} + 8\, O_2 \rightarrow 5CO_2 + 6H_2O$$

(6) $$C_6H_{14} + \frac{19}{2}\, O_2 \rightarrow 6CO_2 + 7H_2O$$

(7) $$C_7H_{16} + 11\ \ O_2 \rightarrow 7CO_2 + 8H_2O$$

(8) $$C_8H_{18} + \frac{25}{2}\, O_2 \rightarrow 8CO_2 + 9H_2O$$

3.1 Material and Energy Balance

In a system, a conservation of materials and energy balance may be written as,

$$Input - \text{output} + Generation - Consumption = Accumulation \quad (9)$$

Inputs and outputs here refer to quantities entering or leaving through system boundaries, generation and consumption refer to quantities produced and consumed within the system, and accumulation is the accumulation of quantities in the system (positive or negative).

The mass equation for a general steady-state, steady-flow process can be written in rating form as;

$$\sum \dot{m}_{input} = \sum \dot{m}_{output} \quad (10)$$

Where ṁ is mass flow rate in kg/s. For CCPP systems and their components, mass balance equations are derived for steady-state, steady-flow, and constant-flow systems.

Figure 3 shows a schematic of a combined cycle power plant. The system consists of an air compressor (AC), a combustion chamber (CC), a gas turbine (GT), a heat recovery steam generator (HRSG), a steam turbine (HPST/LPST), a condenser (CON), a water treatment plant (WTP), and a pump. According to Figure 3, the streams are indicated by numbers 1 to 13 or by the letters air and fuel.

The following is a list of the mass balances of the components of a CCPP system;

Air Compressor:

$$\dot{m}_{\text{air}} = \dot{m}_1 \quad (11)$$

Combustion Chamber:

$$\dot{m}_1 + \dot{m}_{fuel} = \dot{m}_2 \quad (12)$$

Gas Turbine:

$$\dot{m}_2 = \dot{m}_4 \quad (13)$$

Heat recovery steam generator:

$$\dot{m}_3 + \dot{m}_{12} + \dot{m}_{13} = \dot{m}_4 + \dot{m}_5 + \dot{m}_6 + \dot{m}_{losses} \quad (14)$$

Where $\dot{m}_{\text{losses}}$ is the amount of mass leaked out of the equipment.

High-pressure steam turbine:

$$\dot{m}_5 = \dot{m}_7 + \dot{m}_{\text{losses}} \quad (15)$$

Low-pressure steam turbine:

$$\dot{m}_7 = \dot{m}_8 + \dot{m}_{\text{losses}} \quad (16)$$

Condenser:

$$\dot{m}_8 = \dot{m}_9 \quad (17)$$

Pump:

$$\dot{m}_{11} = \dot{m}_{12} + \dot{m}_{13} \quad (18)$$

The energy equation for each step of the process can be obtained from the following equation;

(19) $$Q + W - \Delta(H + KE + PE) = \Delta E$$

Where the accumulation term (ΔE) in a steady-state system is zero, the kinetic energy (ΔKE) and potential energy (ΔPE) are neglected. Q and W are the net heat transferred and work transferred as Joules, respectively. ΔH is the energy change of fluid flow as Jules.

An approximate combined-cycle efficiency (η_{cc}) is given as

(20) $$\eta_{cc} = \eta_B + \eta_R - (\eta_B * \eta_R)$$

where
η_{cc} : Combined cycle efficiency
η_B : Gas turbine efficiency (Brayton)
η_R : Steam turbine efficiency (Rankine)

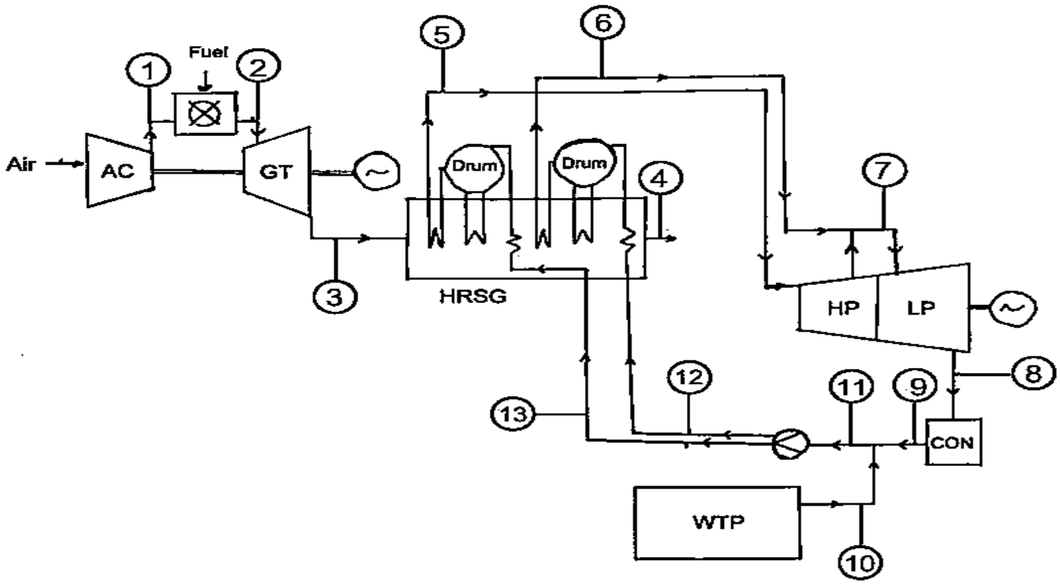

Figure 3. Schematic of a combined cycle power plant [21]

3.2 Simulation using Aspen Hysys

The 1500 MW Sulaymaniyah combined cycle power plant in Chamchamal was simulated by Aspen Hysys software (Figure 2) to investigate the effect of several parameters on the total efficiency.

4. Findings and Discussion

Table 2 shows the mass flow rates of each stream, determined using the mass conservation equation. The calculated results illustrated close correlation with the operational data obtained from the Sulaymaniyah combined cycle power plant 1500 MW in Chamchamal. This close correlation between the measured and calculated values confirms the accuracy of the modeling approach and provides a reliable basis for subsequent analysis of the energy balance using the data obtained.

In Table 3, the results of the energy balance are shown in the form of three cases, because the operational data obtained from the Sulaymaniyah combined cycle power plant included C_6^+, and the composition percentage of C_6^+ was needed for the reactions in the combustion chamber. Therefore, the results of the energy balance are shown for three cases, including equipment duties, the efficiency of the turbines, and the overall efficiency. There are perfect overall efficiencies for three cases of 60.32%, 61.68%, and 61.64%, respectively. The total electricity produced is about 216.307 MW, 227.173 MW, and 227 MW, respectively. The calculated results of the first case are inconsistent with the real data, but the second and third cases are in good agreement with the power plant data, especially the second one, which has an error of about 1 to 2%. Therefore, Hysys considered case 2 (47% C_6, 36 % C_7, 17 % C_8) the basis for simulating and optimizing the power plant.

Table 2: Mass flow rates (kg/s)

Stream No.	NG	N_2	O_2	H_2O	CO_2	Total	Pressure (kPa)	Temperature (°C)
1	-	335.7	89.3	-	-	425	1000	350
2	7.5	335.7	89.3	-	-	432.5	1000	1127
3	-	337.8	59.9	15.9	22.1	435.7	110	540
4	-	337.8	59.9	15.9	22.1	435.7	110	115
5	-	-	-	48.2	-	48.2	7700	540
6	-	-	-	10	-	10	800	220
7	-	-	-	58.2	-	58.2	800	220
8	-	-	-	58.2	-	58.2	<100	60 - 75
9	-	-	-	56	-	56	<100	40 - 50
10	-	-	-	3.3	-	3.3	900	30
11	-	-	-	59.3	-	59.3	700	110
12	-	-	-	10.5	-	10.5	2000	110
13	-	-	-	48.8	-	48.8	10000	112

Table 3: Obtained data from energy balance based on three cases

Parameters	Case 1: (50/25/25)	Case 2: (47/36/17)	Case 3: (37.3/36.6/26.1)
Compressor Duty (MW)	142.629	142.629	142.629
Gas Turbine Power (MW)	297.061	307.927	307.703
Combustion Chamber Duty (MW)	405.743	411.823	411.932
HRSG Duty (MW)	169.6	169.6	169.6
Pump Duty (MW)	0.766	0.766	0.766
Steam Turbine Power (MW)	61.875	61.875	61.875
Efficiency Gas turbine (η_B)	38%	40.13%	40.07%
Efficiency Steam turbine (η_R)	36%	36%	36%
Efficiency CCGT (η_{cc})	60.32%	61.68%	61.64%

Table 4 shows the standard data and optimization results of the combined cycle power plant (CCPP) simulation using Aspen Hysys. According to standard data, the gas turbine efficiency was 38.3%, the steam turbine efficiency was 29.29%, and the combined-cycle efficiency was 56.37% [21]. After optimizing, the gas turbine efficiency increases to 39.79%, the steam turbine efficiency rises to 31.77%, and the combined-cycle efficiency improves to 58.91%. However, when comparing the Aspen HYSYS results to the standard data [21]. There were discrepancies of approximately 2.7% in the steam turbines that were observed. The data of the Sulaymaniyah combined cycle power plant in Chamchamal shows that the steam turbine produced 60 to 66 MW, while the optimized Aspen HYSYS results prefer that the optimal power output is 68.294 MW for a high-pressure steam turbine (HP) and

73.113 MW for a low-pressure steam turbine (LP). Moreover, the optimal output power for a gas turbine is 324.7 MW.

Table 4: Optimum data from Aspen Hysys simulation

Equipment	Parameters	Standard	Optimum
Compressor	Efficiency (%)	81.16	81.16
	Duty (MW)	154	153.1
Combustion Chamber	Pressure (kPa)	1000	1050
	Temperature (°C)	1164	1200
	Duty (MW)	399.16	437.7
Gas Turbine	Power (MW)	307	324.7
	η_B (%)	38.3	39.79
	Temperature (°C)	546	555
HP Super Heater	UA (kW/°C)	34694.4	22000
	Pressure Drop in the shell (kPa)	5	5
	Pressure Drop in tubes (kPa)	20	20
	HP4 Temperature (°C)	546	565
	HP3 Temperature (°C)	299.3	299.3
	g1 Temperature (°C)	334.4	356
HP Evaporator	UA (kW/°C)	486.11	280.55
	Pressure Drop in the shell (kPa)	5	5
	Pressure Drop in tubes (kPa)	20	20
	HP2 Temperature (°C)	232.7	232.7
	g2 Temperature (°C)	296.6	319.4
HP Economizer	UA (kW/°C)	369.44	268.61
	Pressure Drop in the shell (kPa)	5	5
	Pressure Drop in tubes (kPa)	20	20
	HP1 Temperature (°C)	111.3	111.3
	g3 Temperature (°C)	237.2	261.9
LP Super Heater	UA (kW/°C)	3105.5	2000
	Pressure Drop in the shell (kPa)	5	5
	Pressure Drop in tubes (kPa)	20	20
	LP4 Temperature (°C)	232.7	260
	g4 Temperature (°C)	188.6	213.6
LP Evaporator	UA (kW/°C)	7.69	3.47
	Pressure Drop in the Shell (kPa)	5	5
	Pressure Drop in tubes (kPa)	20	20
	LP3 Temperature (°C)	177.6	180
	LP2 Temperature (°C)	142	145
	g5 Temperature (°C)	184.9	210
LP Economizer	UA (kW/°C)	26.81	18.36
	Pressure Drop in the Shell (kPa)	5	5
	Pressure Drop in tubes (kPa)	20	20

	LP1 Temperature (°C)	110.2	110.2
	g6 Temperature (°C)	181.7	206.9
HP Steam Turbine	Power (MW)	67.82	68.294
	η_R (%)	29.48	31.65
LP Steam Turbine	Power (MW)	72.886	73.113
	η_R (%)	22.22	25.36
Condenser	Pressure Drop (kPa)	0	0
	Duty (kW)	142416.67	139722.22
Pump	Pressure Drop (kPa)	680	680
	Duty (MW)	0.0548	0.055
CCPP	η_{cc} (%)	56.37	58.91

In Figure 4, the effect of the mass flow rate of NG and air on the power of the gas turbine is investigated. With increasing the mass flow rate of air, the power decreases, but with increasing the mass flow rate of NG, the power increases. Therefore, the optimal values for the mass flow rate of both substances must be determined, which, as shown in the figure, at the intersection point of the two graphs, the optimal value of NG is 7.65 kg/s, and the air value is 423 kg/s, which is the same as the actual and standard values [13, 21]. These results confirm the accuracy of the simulation with Aspen Hysys.

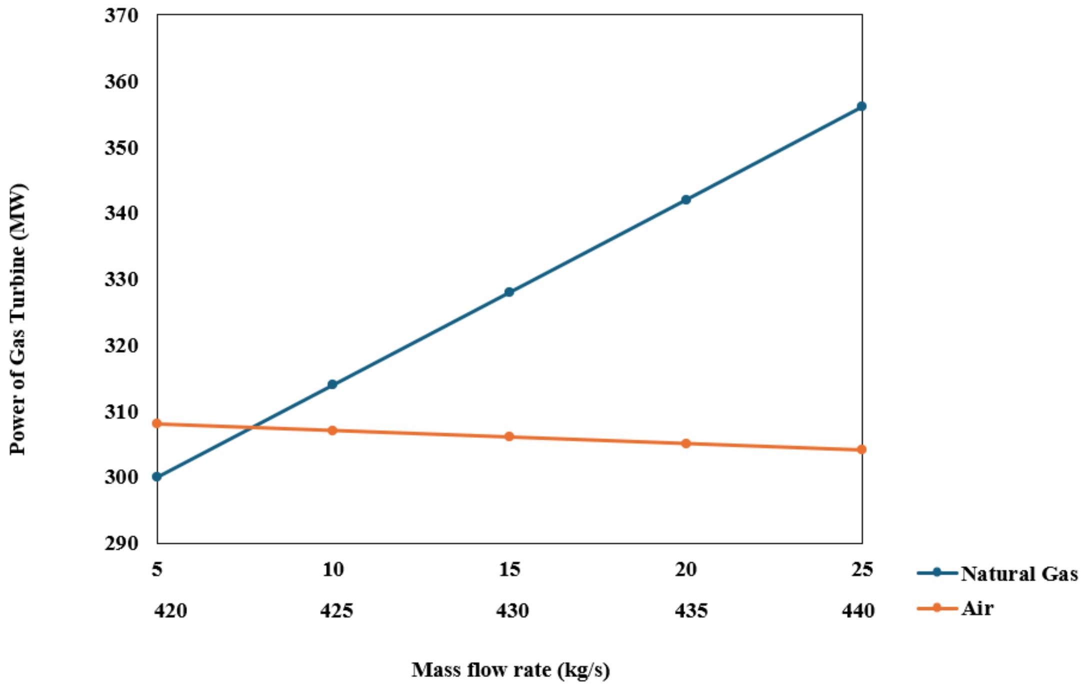

Figure 4: Effect of flow rate on the duty of the gas turbine

The effect of the mass rate of water in the R_C stream (Figure 2) on the power of steam turbines is shown in Figure 5. As the mass rate of water increases, the power also increases. According to the figure, for values less than 28 kg/s, the turbine power is very low. For values greater than 28 kg/s, the power increases, and the power of HP is more than LP, which is by the standard [15, 21]. Therefore, the amount of water should be more than 28 kg/s to obtain the maximum power of the steam turbine.

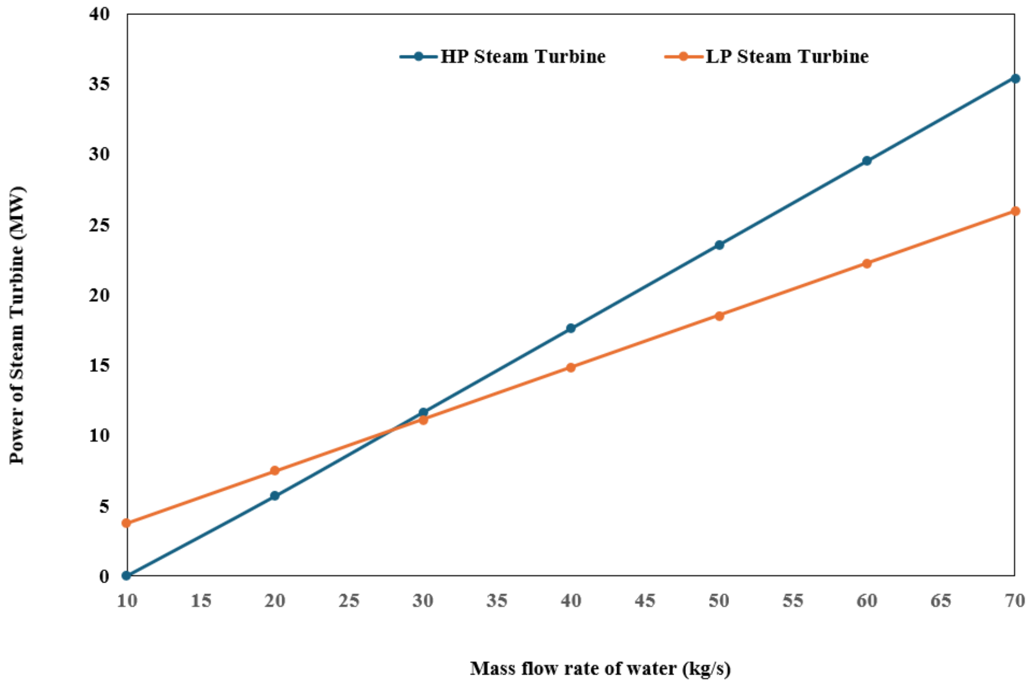

Figure 5: Effect of water flow rate on the duty of steam turbines

5. Conclusion

In this study, the Sulaymaniyah Combined Cycle Power Plant 1500 MW in Chamchamal for three combinations of C_6^+ ((C_6, C_7, C_8) simulated by Excel and Aspen HYSYS. Also, the effect of the mass flow rate of natural gas and air was studied on gas turbine power and water on steam turbine power. The data obtained from Excel calculations had a low difference of 2 to 3 % from the actual data. The optimum combined-cycle efficiency was 58.91%, which is close to the power plant efficiency. The optimum duty of the gas turbine power was obtained at 324.7 MW. The optimum steam turbine power is obtained for a mass flow rate of water higher than 28 kg/s.

Author’s Contribution:

Ahmed Subhi and Hemn Abubakir obtained the results and wrote the first draft. Khadijeh Mirza edited the first draft, including text, tables, and figures, to ensure that the results obtained were in line with international standards. She led the research as the first supervisor. Hewa Hussein, as the second supervisor, carried out the second revision of the paper. He helped to improve the paper by describing the process and analyzing the results obtained.

Conflict of Interest:

The authors declare that there are no competing interests.

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