Performance Evaluation of a Combined Gas Turbine Power Cycle and Absorption Chiller in Design and Off-Design Operation under Different Control Strategies

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ABSTRACT

This work aims to evaluate the effect of compressor inlet air temperature on the power cycle performance of gas turbines, employing different control operation techniques. Therefore the power cycle of the combination of a Gas Turbine (GT) with a single effect H_2O-BrLi absorption refrigeration is examined. GT power cycle simulations are carried out based on the full and partial load model of power and cooling systems, deploying the Thermo-flow and Engineering Equation Solver (EES). Moreover, Turbine Inlet Temperature (TIT), Inlet Guide Vane (IGV), and the combined IGV and TIT control strategies, are employed to evaluate the advantages of applying various GT power cycles and off-design operations. The results exhibit that the combined IGV and TIT method is the appropriate one, offering higher integrated cooling and power system efficiency compared to the TIT control approach alone. When the compressor intake air temperature rises, it negatively influences cycle effectiveness. The air mass flow rate and pressure ratio decrease, thus, leading to a decrease in the power output and thermal efficiency of the gas turbine. Finally, the absorption cooling system implementation improves power generation and thermal efficiency in a GT power plant, by 20.68% and 5.32%, respectively.

Keywords-thermodynamic analysis; power output; thermal efficiency; ambient temperature impact; combined cooling and power; design and off-design conditions

I. INTRODUCTION

A power plant-based GT contingent on the Bryton cycle faces two primary challenges. Initially, that of electrical energy demand rise, since both industrial and residential customers utilize air conditioning systems at the same time. In addition, this power plant's effectiveness and production ability for electrical energy decrease during hot days. In general, GT performance worsens when the compressor inlet air temperature increases.

Various methods have been proposed to lower compressor intake air temperature in the GT power systems. The most important of them comprise absorption chillers, swirl-flash, fogging, ice storage, and media cooling. Among these methods, the absorption cooling system does not initiate moisture or water droplets into the air, thus preventing negative impacts, like corrosion and erosion on GT blades and other components. Furthermore, the energy required by the absorption cooling system can be attained from the waste heat at the turbine exit. A large, high-capacity absorption chiller is vital for this purpose. Multiple interconnected large-capacity absorption cooling systems should operate instantaneously, to achieve ISO inlet conditions for commercial uses [1].

However, gas turbines have certain weaknesses, with the most significant being their decreased power output in hot climates, caused by their sensitivity to environmental temperature. To improve power generation in these conditions, the air temperature flowing into the compressor should be decreased. The cooling systems of the inlet air are among the best cost-effective solutions for enhancing GT performance [1, 2]. Consequently, a number of cooling methods have been evolved to cool intake air, such as inlet fogging, absorption chiller, mechanical chiller, wet compression, and evaporative cooling.

Ambient intake-air to the power plant compressor can be cooled by utilizing an absorption chiller or evaporative cooler. The evaporative cooling technology, however, has provided a limited reduction in inlet air temperature, being affected by the wet bulb temperature when compared with the absorption cooling system [3]. Authors in [4] assessed the impact of fog inlet air cooling on integrated power cycle performance. They specified the optimum design factors based on a genetic algorithm apart from economic and exergy analyses.

It was shown that a thermodynamics analysis along with an economic study of a combined GT power plant, incorporated with fogging means to cool the compressor, improved the specific power output. This is due to a decrease in the inflowing air temperature and an increase in the mass flow rate [5-8]. Highly competent mechanical coolers possess a Coefficient Of Performance (COP) above 6.0, such as those in [9]. Besides the important cooling effects they offer, the electrical energy needed for them to run, leads to losses related to the power cycle.

In contrast, absorption cooling systems need electrical energy to power their pumps, using a trivial amount most of the times. Additionally, effective absorption cooling systems based on a double-effect type, have a COP of about 1.5 [10]. Authors in [11] employed an absorption chiller to enhance combined power cycle performance. It was found that the power output was augmented by approximately 10.5%, with a payback period of about 3.8 years for an air temperature of 15 °C (ISO) and 100% relative humidity at the compressor inlet.

Authors in [12] evaluated the influence of a hybrid turbine power cycle and cooling unit in dry weather. They proposed a hybrid system capable of improving the power output by 10%. Authors in [13] presented a thermodynamics analysis in order to use the rejected heat from the GT power cycle exhaust, to increase efficiency and power, while decreasing inlet air temperature. Their combination consisted of a gas refrigeration cycle and a propane organic Rankine cycle. It was found that efficiency and power increased by 50% and 35%, respectively.

Authors in [14] proposed coolant inter-cooling to raise power cycle performance and decrease coolant temperature. Their method resulted in higher power output and effectiveness (in an integrated power cycle) compared to the coolant pre-cooling technique. Authors in [15] performed a comparative investigation between a mechanical and an absorption chiller to analyze the influence of twin cooling in a combined power cycle. They claimed that cooling based on an absorption cooling system, enhanced the power output of the integrated power cycle by 8.2%.

In [16], efficiency-enhancing prospects in standing GT plants were assessed via the cooling of inlet air. The electrical efficiency was increased from 32.0% to 34.2%, and the power output of the Gas Turbine Cycle (GTC) improved from 24.1 MW to 28.1 MW, while the intake air temperature dropped from 45 °C to 15 °C.

Authors in [17] analyzed the influence of cooling inlet air on the performance enhancement of a GTC based on a vapor compression system. They indicated that a greater power output of 20.769 kJ/kg was achieved compared with the simple cycle. Moreover, when the absorption chiller was employed to cool the intake air, the obtained values were improved by 16.41%, as shown in [18].

Authors in [19] evaluated the performance of a combined vapor compression system and an evaporative system to cool the intake air of the GTC in terms of different operating parameters. It was found that the inlet air cooling systems enhanced GTC efficiency in higher ambient temperatures.

Authors in [20-22] carried out a thermodynamic analysis of the integrated GT with an H2O-LiBr absorption cooling system to cool the intake air temperature in the GT compressor, having concluded that the energy efficiency and power output of the GTC, enhanced by 13% and 23.2%, respectively.

The impact of off-design operating strategies for combined gas turbines combined with cooling systems was explored in [23, 24]. A comparative investigation based on mass and energy balances was carried out, having integrated an economic study of various cooling techniques for a conventional GT power cycle, under dry climate conditions, such as the weather in Riyadh. It was proposed that the single-effect absorption refrigeration system be endorsed under Riyadh weather conditions. Moreover, the combined inlet cooling technology and the standing GT power cycle could be effective in warm periods for Arab Gulf countries [25].

It has been demonstrated that decreasing the intake air temperature of the GTC compressor, can improve power cycle performance in terms of efficiency and power output. The current work evaluates the design and off-design performance of a combined GTC with absorption refrigeration system, using low grade exhaust heat for cooling the inlet air temperature of the GT in a hot and dry climate. It also examines the influence of ambient air conditions, pressure ratio, and TIT on the GT power cycle performance, using absorption refrigeration chiller to cool the intake air into the compressor of the power cycle. Moreover, different control strategies of the operation methods are incorporated.

It can be seen that limited studies considered the influences of the off-design conditions on the performance of the integrated power and cooling systems. In this work, the off-design performance of a combined power and cooling system is assessed. Finally, we find the impacts of different working and control approaches for the GTC, on the off-design characteristics of the whole system.

II. COMBINED SYSTEM DESCRIPTIONS

The Combined Power and Cooling (CPC) system is presented in Figure 1. The investigated CPC system combines a single-shaft GTC with a single-effect absorption refrigeration system. The GT power cycle, which operates using natural gas as fuel, is utilized to satisfy the need for electrical power. The elevated-temperature exhaust gases produced by the gas turbine are used to run the absorption refrigeration system in order to assist in fulfilling the cooling load. The single-effect configuration is integrated within the CPC system, because of its elevated COP.

A. Gas Turbine Power Cycle

To improve the performance of the CPC system, the GT model is investigated in cooperation design and off-design situations. However, it is not feasible to initiate the off-design scheme for the GT power cycle to precisely forecast the performance of different off-design GT power cycles, as each GT reveals unique features.

The impact of the deployed strategies for the GTC on the CPC system can be considered depending on parametric studies. Both design and off-design models of the GE Frame 9E GT power cycle (Al Khairat Power Plant, 10×125 MW) are developed to forecast the full and part loads' performance. In the current study, the GE Frame 9E GT power cycle (Al Khairat Power Plant, 10×125 MW) is implemented in the CPC system. The GE Frame 9E GT power cycle includes a single-stage compressor and single-stage turbine and combustor, without any cooling system.

In the investigated system, the air enters the axial compressor and is compressed through a compression process from state 1 and state 2, as displayed in Figure 1. Then, the compressed air goes into the combustor component, where the fuel undergoes combustion, thus generating high-temperature gas at state 3. After that, the gas from the combustor in the high temperature is subsequently allowed to expand to state 4 within the GT stage, leading to a decrease in both pressure and temperature. Natural gas is burnt in the combustor, to increase the gas temperature up to the required temperature at the turbine inlet. In the expansion process, the hot gas energy is utilized to run the compressor and increase air pressure. Finally, a generator is employed to generate electrical energy.

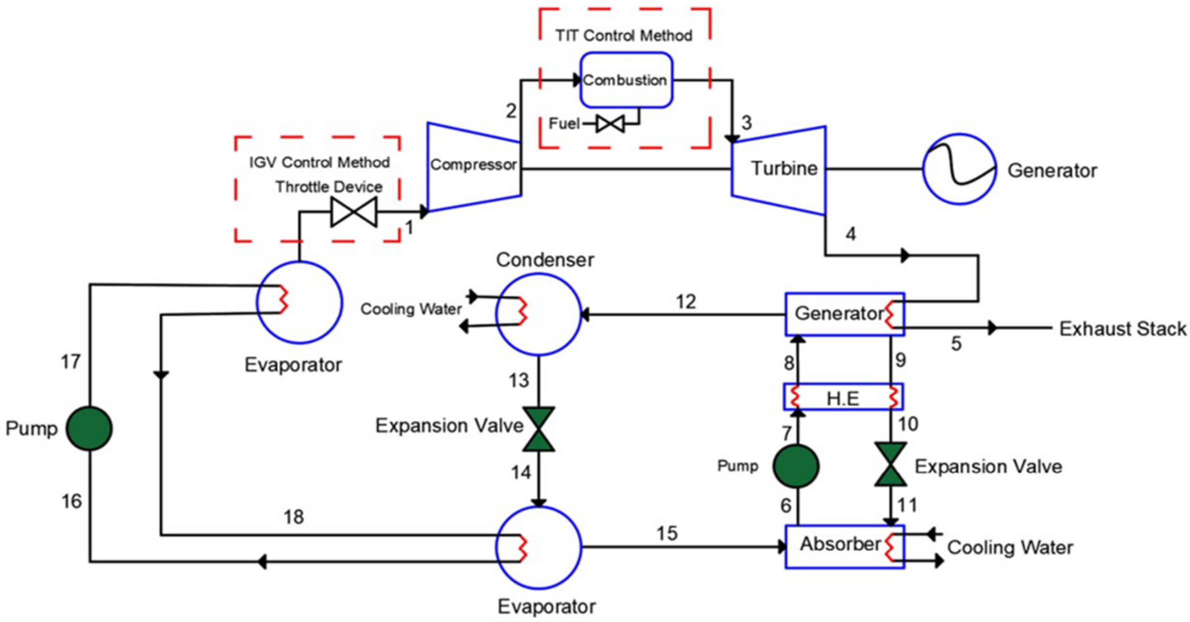


Fig. 1. Schematic diagram of the developed combined power and cooling systems.

B. H_2O-LiBr Absorption Refrigeration System

As depicted in Figure 1, at state 4, the gas exiting from the turbine stages is guided to the generator component of the single-effect absorption cooling system. After that, it is released into the ambient at state 5. The generator component of the absorption system is driven by the hot exhaust gases in terms of thermal energy, where the main refrigerant water vapor is split from the strong solution of the lithium-bromide/water. Then, the refrigerant moves into the condenser, which is associated with heat rejection.

The condensed water at the exit of the condenser component flows through the throttle device towards the evaporator component at low pressure. The liquid of the refrigerant (water) is vaporized at low pressure by absorbing the heat of the space in order to be cooled, thus leading to cooling energy production. The weak solution passes into the generator to regenerate the strong solution. Inside the absorber, the vapor exchanges with the strong solution delivered from the generator via the low-temperature solution heat exchanger. The regenerated weak solution is then pumped back to the generator, passing through both the solution heat exchangers.

III. ANALYSIS METHODOLOGY

Thermodynamic modeling of the CPC system is performed based on mass and energy, balancing control volume, except for the GT combustion chamber where gas pressure reductions are considered, given by:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

The phrase for the first-law of thermodynamics pertaining to each part is:

$$Q + \sum(\dot{m}h)_{in} = \sum W + (\dot{m}h)_{out} \quad (2)$$

GTC thermal efficiency is obtained by [7]:

$$\eta_{overall} = \frac{W_{net}}{Q_{add}} \quad (3)$$

The generated net power output (Wnet) is given by [7]:

$$W_{net} = (W_{GT} - W_C)\,\eta_m\,\eta_g \quad (4)$$

The added heat (Q_{fuel}) from the fuel is obtained from:

$$Q_{fuel} = \dot{m}_{fuel} \times LH \quad (5)$$

A. GTC Modeling

The governing equations of each GTC module are clarified as follows:

1) Compressors

The actual temperature of the compressor discharged air during an isentropic compression process [26] can be determined by:

$$T_2 = T_1 * (PR_{ao})^{\frac{\gamma a-1}{\gamma a * \eta p,c}} \quad (6)$$

where T_1 is the ISO inlet temperature of the compressor (15 °C), PR_a is the compression ratio, and $\eta_{p,c}$ is the compressor polytropic efficiency.

The air specific heat (Cp_a) is identified as a function of temperature that can be represented by a fourth-degree polynomial:

$$Cp_a = A_0 + A_1T + A_2T^2 + A_3T^3 + A_4T^4 \quad (7)$$

where T refers to the average compression in Kelvin and the polynomial with coefficients A_0, A_1, A_2, A_3 and A_4.

The compressor's consumed power is determined as:

$$W_c = \dot{m}_{ao} * Cp_a * (T_2 - T_1) \quad (8)$$

2) Combustion chamber

The air enters the combustion zone, mixes with the fuel injected into the combustor component and rises the temperature of the gases entering the GTC at state 3, as portrayed in Figure 1. A second-degree polynomial is employed in this analysis to approximate the gas specific heat value (CP_{gi}) for each gas present in the combustion products (CO_2, H_2O, N_2, O_2 , and Air) within the temperature range of 273-3000 K:

$$CP_{gi} = F_0 + F_1T + F_2T^2 \quad (9)$$

The main gas specific heat is obtained by:

$$CP_g = \sum_{i=5}^{5} y_i CP_{gi} \quad (10)$$

The calculation of the turbine entering temperature (T_3) is based on the energy balance of the combustor component and is obtained by [27]:

$$T_3 = \frac{\dot{M}_{ao}CP_a\,T_2 + \dot{M}_{ao}\,LHV\,\eta_{cc}}{\dot{M}_{go}\,CP_g} \quad (11)$$

The combustion chamber's heat input can be calculated as:

$$\dot{Q}_{add} = \dot{M}_{fo} * LHV * \eta_{cc} \quad (12)$$

3) Gas Turbine

After the combustion process, the hot gases depart the combustor's component at state 3 and flow through the axial flow gas turbine, expanding at state 4 with a pressure higher than atmospheric pressure. The actual temperature of the GT exhaust during an expansion process can be found by:

$$T_4 = T_3 * \left(\frac{1}{PR_{go}}\right)^{\frac{\gamma g-1}{\gamma g}\eta_{p,t}} \quad (13)$$

The power output from the power cycle is obtained by [27]:

$$W_{GT} = \dot{m}_{go}\,CP_g\,(T_3 - T_4) \quad (14)$$

B. Module of Absorption Cooling System

The rate of the heat absorbed from the compressor intake air temperature of the power cycle represents the evaporator cooling load, which can be expressed as:

$$\dot{Q}_{cooling} = C_{pa} * \dot{m}_a * (T_{ambient} - T_{iso}) \quad (15)$$

$$\dot{Q}_{cooling} = \dot{Q}_{evap}$$

In the evaporator part, the refrigerant mass flow rate (i.e., coolant) is determined by:

$$\dot{m}_{ref} = \frac{Q_{evap}}{h_{10} - h_9} \quad (16)$$

The weak and strong solutions mass flow rates of lithium-bromide (Li-Br) are obtained using:

$$\dot{m}_{ws} = \dot{m}_{ss} + \dot{m}_{ref} \quad (17)$$

$$\dot{m}_{ws}x_{ws} = \dot{m}_{ss}x_{ss} \quad (18)$$

$$X = \frac{\dot{m}_{ws}}{\dot{m}_{ref}} \quad (19)$$

$$X = \frac{x_{ss}}{x_{ss} - x_{ws}} \quad (20)$$

1) Generator Component

$$\dot{m}_4 + \dot{m}_8 = \dot{m}_9 \quad (21)$$

$$\dot{m}_8x_8 = \dot{m}_{12}x_{12} + \dot{m}_9\,x_9 \quad (22)$$

$$\dot{m}_8h_8 + Q_g = \dot{m}_{12}h_{12} + \dot{m}_9\,h_9 \quad (23)$$

2) Absorber Component

$$\dot{m}_{11} + \dot{m}_{15} = \dot{m}_6 \quad (24)$$

$$\dot{m}_{11}x_{11} + \dot{m}_{15}x_{15} = \dot{m}_6\,x_6 \quad (25)$$

$$\dot{m}_8h_8 + Q_g = \dot{m}_{12}h_{12} + \dot{m}_9\,h_9 \quad (26)$$

3) Condenser Component

$$\dot{m}_{12} = \dot{m}_{13} \quad (27)$$

$$x_{12} = x_{13} \quad (28)$$

$$\dot{m}_{12}h_{12} + Q_c = \dot{m}_{13}h_{13} \quad (29)$$

4) Evaporator Component

$$\dot{m}_{14} = \dot{m}_{15} \quad (30)$$

$$x_{14} = x_{15} \quad (31)$$

$$\dot{m}_{14}h_{14} + Q_{evap} = \dot{m}_{15}h_{15} \quad (32)$$

5) Solution Heat Exchanger Component

$$\dot{m}_7 = \dot{m}_8\ ; x_7 = x_8; \dot{m}_9 = \dot{m}_{10}; x_9 = x_{10} \quad (33)$$

$$\dot{m}_7h_7 + \dot{m}_9h_9 = \dot{m}_8h_8 + \dot{m}_{10}h_{10} \quad (34)$$

6) Refrigerant Expansion Valve

$$\dot{m}_{13} = \dot{m}_{14}\ ; \quad x_{13} = x_{14}\ ; \quad h_{13} = h_{14} \quad (35)$$

7) Binary Solution Pump

$$\dot{m}_6h_6 + w_p = \dot{m}_7h_7; \ \dot{m}_6 = \dot{m}_7; \ x_6 = x_7 \quad (36)$$

C. Control Strategies for Gas Turbine Power Cycle

Operating a GT power cycle in off-design conditions may significantly affect its performance. Off-design conditions occur when the GT operates beyond its intended design conditions, due to variations in ambient temperature, pressure, humidity, and operational load. Apart from the operating strategies of the integrated power and cooling systems, the part-load performance of the GTC in the combined systems is influenced by numerous control techniques. The latter are the decreasing TIT and IGV, and combined IGV and TIT, as shown in Figure 1. The subsequent two off-design strategies are significant in understanding the setting of stationary gas turbines utilized for electricity generation [27].

1) Effect of Ambient Temperature

A change in ambient air temperature at a constant volumetric gas turbine, usually results in an impact on the air mass entering the compressor, leading to a drop in both thermal efficiency and generated power.

The temperature ratio of the compressor intake-air may be determined using:

$$T^* = \frac{T_1}{T_{ISO}} \quad (37)$$

Moreover, the compressor inlet air temperature ratio enables determining the impact of the air mass flow ratio ($\dot{m}^*$) using:

$$\dot{m}^* = \frac{1}{(T^*)^{1.4}} \quad (38)$$

$$\dot{m}^* = \frac{\dot{m}_{ao}}{\dot{m}_{a1}} \quad (39)$$

where $\dot{m}_{ao}$ is the air mass flow rate in the design condition with variation ambient temperature and $\dot{m}_{a1}$ is the air mass flow rate in the design condition. Since the compressor pressure discharge is proportional to the air flow rate at the inlet, the mass air flow ratio ($\dot{m}^*$) will equal the compressor compression ratio (π^*), as discussed in [27].

2) Variations of the Performance with Load

Another critical aspect of the off-design GT performance is operating at specified boundary conditions under partial load. Variations to a gas turbine's power output are:

a) The Inlet Guide Vane (Opening or Closing)

By implementing this method, air mass flow can be reduced while maintaining a fixed temperature at the turbine inlet. This, in turn, lowers the compressor's compression and raises the exhaust temperature. To avoid a compressor shock, the power output can be reduced by up to 60%, or the exhaust temperature can be increased by about 100 °C, beyond the design value. The ratio of air mass flow (m^{**}) can be determined by:

$$m^{**} = \frac{\dot{m}_a}{\dot{m}_{ao}} \quad (40)$$

where $\dot{m}_{ao}$ is the changed air mass flow rate in the design condition with variation ambient temperature and $\dot{m}_a$ is the air mass flow rate in the off-design state. While the compressor's pressure discharge is proportional to the inlet air flow, the mass air flow ratio (m^{**}) will equal the compressor's compression ratio (π^{**}). This can be expressed as:

$$m^{**} = \pi^{**} \quad (41)$$

$$\pi^{**} = \frac{PR_a}{PR_{ao}} \quad (42)$$

where PR_{ao} is the pressure compression in design state and PR_a is the compressor's compression in off-design state.

b) The Change of Turbine Inlet Temperature

To reduce the power from 100% to 80%, in line with the IGV control method, this approach lowers the mass air flow rate while maintaining TIT constant. This is done for financial reasons. When the power lowers by 80%, the fuel mass flow is reduced, while the mass air flow remains constant. The reduction continues until the power drop approaches 30%. The ratio of fuel mass flow rate (m_f^*) is determined by:

$$m_f^* = \frac{\dot{m}_f}{\dot{m}_{fo}} \quad (43)$$

where $\dot{m}_{fo}$ is the fuel mass flow rate in the off-design condition and $\dot{m}_f$ is the fuel mass flow rate in the off-design conditions.

This final equation can be used to compute the compressor's compression ratio in this control operation approach:

$$\pi^{**} = \frac{m^{**} + m_f^*}{2} \quad (44)$$

c) Combined IGV and TIT

In this approach, the power load will be reduced from 100% to 60%, following the procedure of the IGV control method. Then, the TIT control operation method's strategy will be deployed to decrease the power load to 30%.

IV. RESULTS AND DISCUSSION

The influence of pressure ratio, air inlet temperature, and TIT on the performance of the GTC using absorption chiller, are analyzed in this section. Moreover, the results of different control strategies (TIT, IGV, and combined IGV and TIT) of the GTC in various operating modes, are presented.

The delivered net power output from the GTC is based on the turbine power output and the compressor consumed power. The operation of the compressor and turbine varies with the change in ambient temperature. The variation average network variation is illustrated in Figure 2. In Figure 2, it is also demonstrated that the turbine power output and thermal efficiency are reduced when rising the ambient temperature. For every one-degree rise in an intake air (ambient temperature) temperature, network drops by 0.686 MW and thermal efficiency drops by 0.057%. Figure 3 depicts the impact of the compressor intake air temperature on the cooling capacity of the absorption cycle.

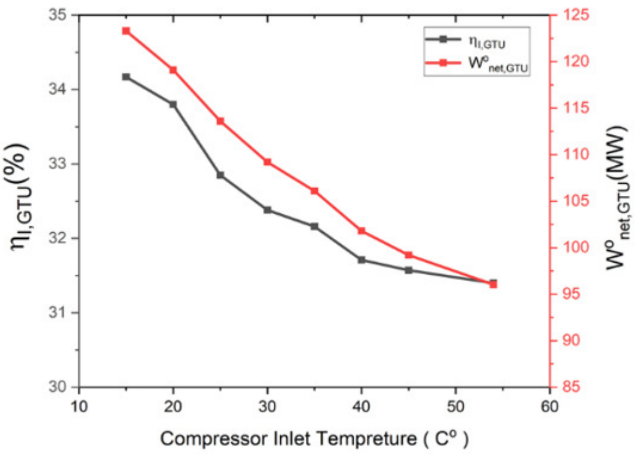


Fig. 2. Influence of intake air temperature on GT performance.

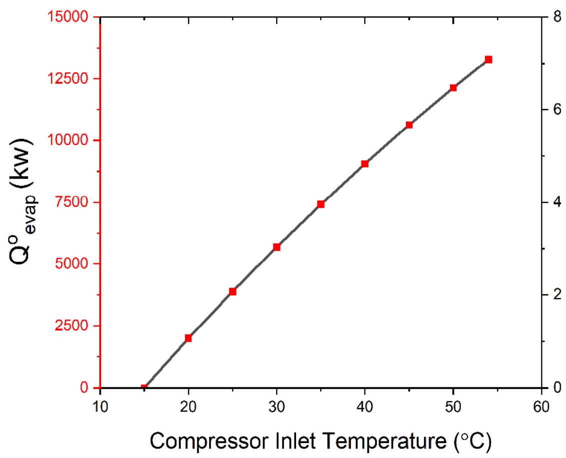


Fig. 3. Impact of compressor intake air temperature on absorption cycle cooling capacity.

Figure 4 shows the change of the heat supplied into the generator component of absorption refrigeration, with air inlet temperature into the compressor, at three different generator temperatures. It is observed that high heat source temperature results in less energy from the generator. At lower heat source temperatures, the combined system's performance becomes more sensitive to variations in the compressor inlet temperature.

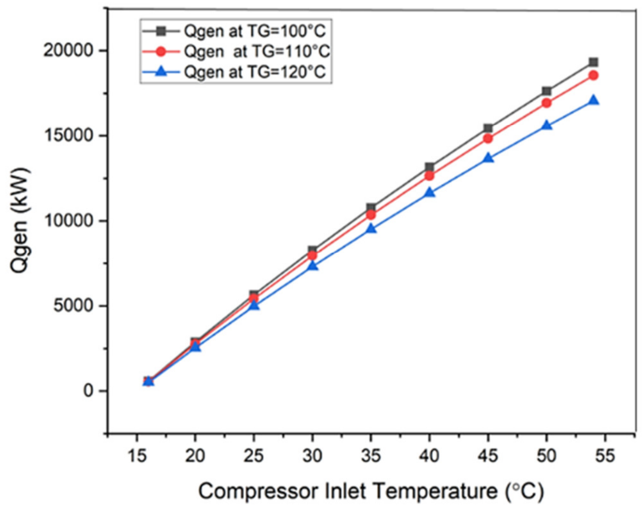


Fig. 4. Variation of heat supplied in absorption refrigeration generator with compressor intake temperature at various heat source temperatures.

Figure 5 presents the change in air mass flow rate and compression pressure ratio, as compressor intake-air temperature varies. The air mass flow rate decreases as the compressor inlet temperature increases, since air density decreases as well. In hot environments or without inlet cooling, the compressor draws less mass for the same volume. The air mass flow rate rises at low compressor intake temperatures due to increased air density when inlet air cooling is utilized. Moreover, high compressor inlet temperatures reduce the air mass flow rate, leading to a decrease in the power output of the GT unit.

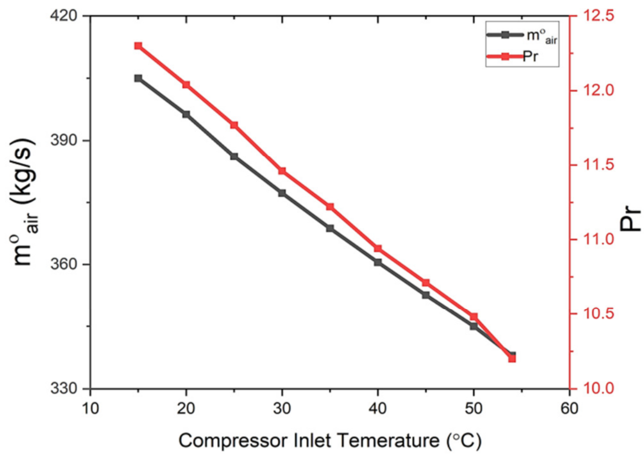
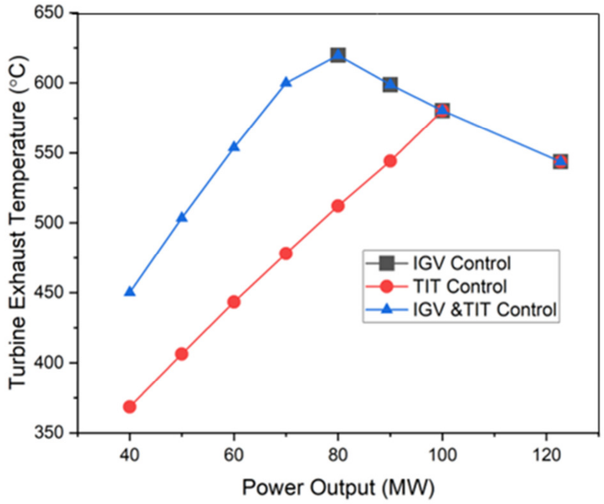


Fig. 5. Variation of mass flow rate and compression pressure ratio with compressor inlet temperature.

Figure 6 illustrates the change of power output with turbine exhaust temperature at various ambient temperatures and using three different control strategies (TIT, IGV, and combined TIT and IGV). TIT control strategy is ranked last in terms of power output. On the contrary, the combined strategy always ranks first.



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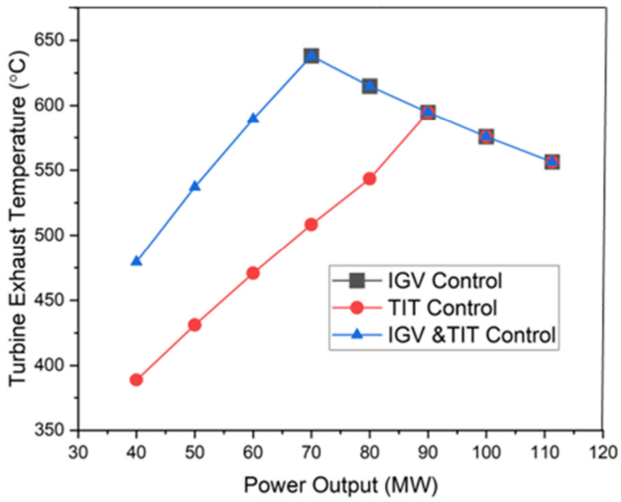

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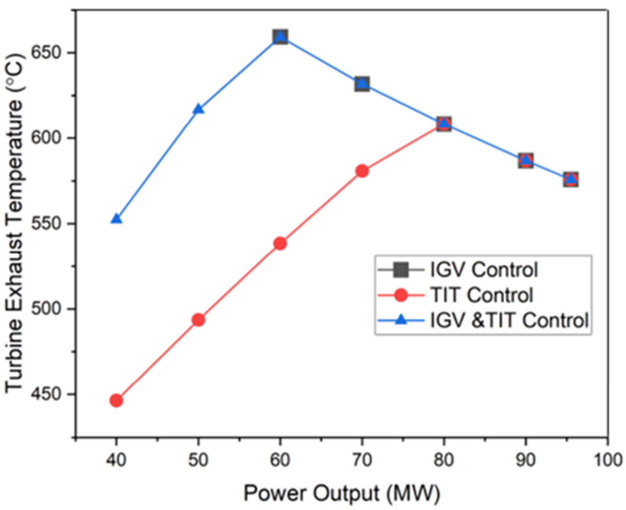
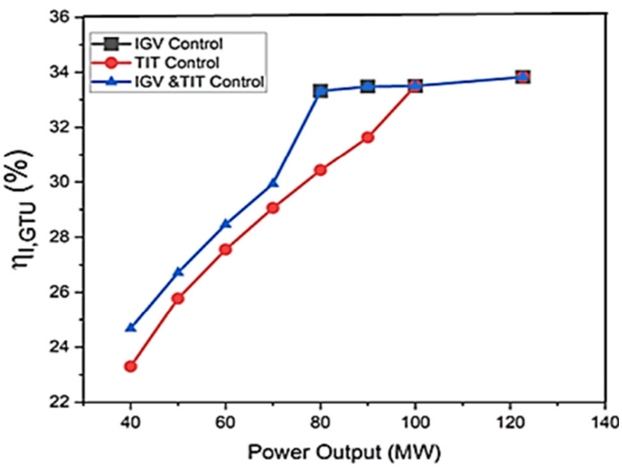


(c)

Fig. 6. (a) Ambient temperature of 15 °C, (b) ambient temperature of 30 °C (c), ambient temperature of 54 °C. Change of power output with turbine exhaust temperature for different ambient temperatures and control strategies.

The rise in turbine exhaust temperature is followed by an increase in power output (up to a limit). Figure 7 portrays the variant of thermal efficiency with power output for different intake air temperatures and three control strategies.



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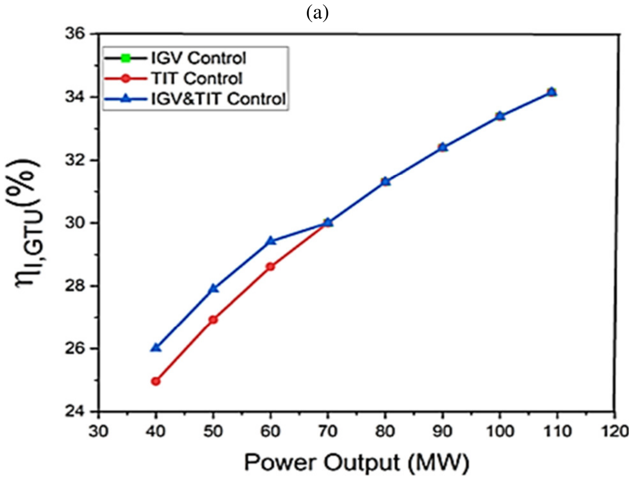

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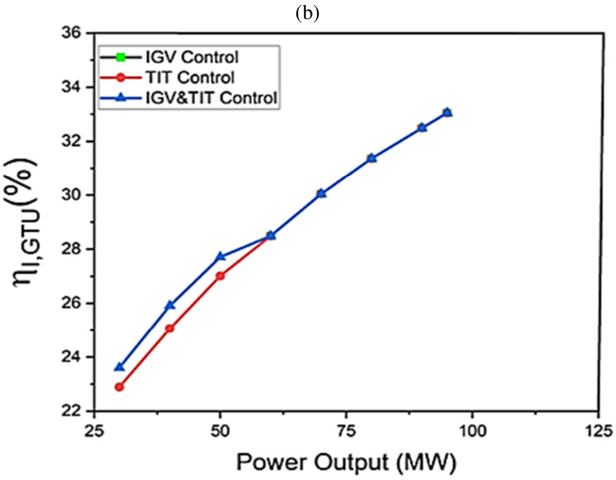

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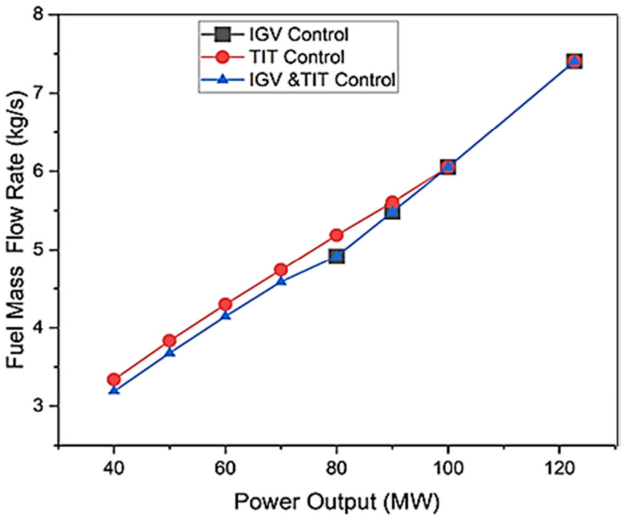
Fig. 7. (a) Ambient temperature 15 °C, (b) ambient temperature 30 °C, (c) ambient temperature 54 ℃. Variant of thermal efficiency with power output for different intake air temperatures and three control strategies.



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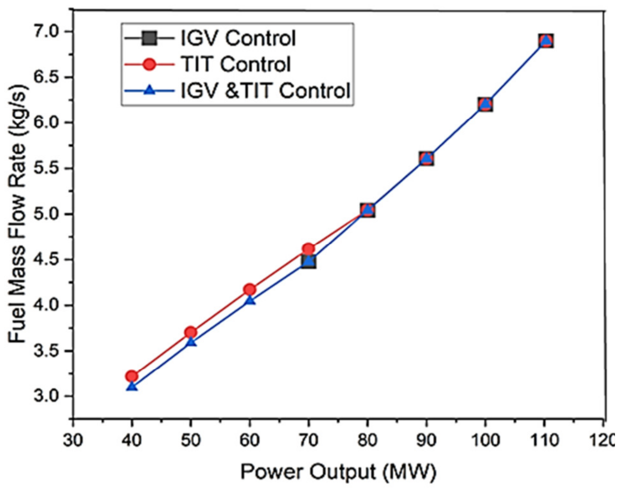

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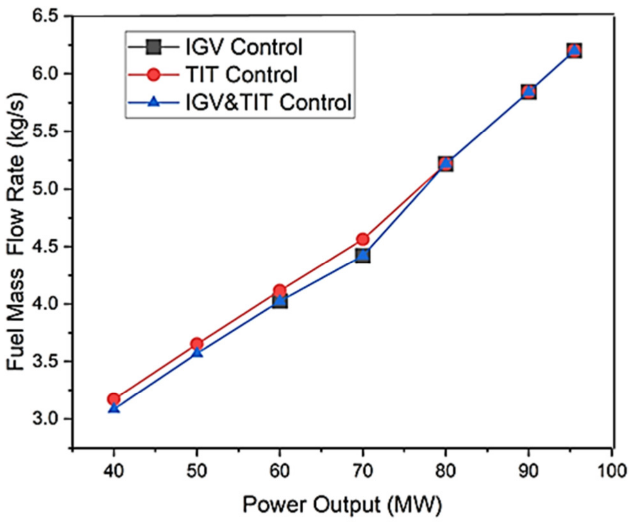
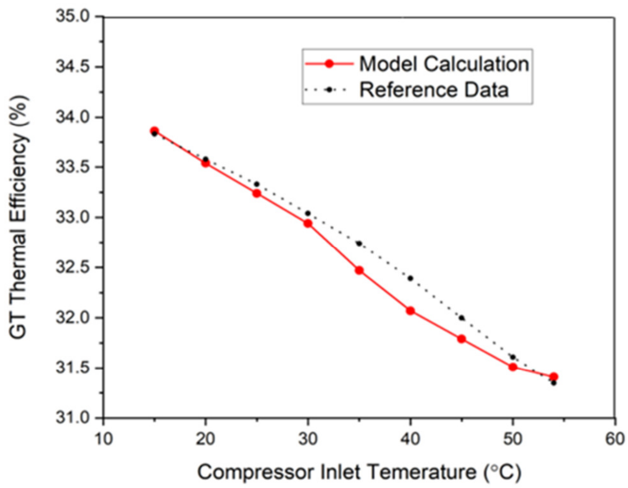


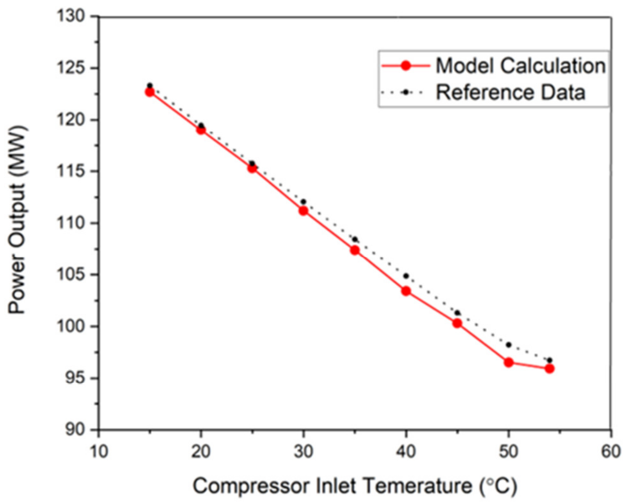
(c)

Fig. 8. (a) Intake air temperature of 15 °C, (b) intake air of temperature of 30°C, (c) intake air temperature of 54 °C. Change of fuel mass flow rate with power output for various ambient temperatures and control strategies.

The relation between the power output of the power cycle and its thermal efficiency for various intake air temperatures is complicated because it is influenced by many parameters, such as the control strategy implemented and the ambient conditions. It is observed that GTC thermal efficiency is reduced at high intake air temperatures. This occurs because the inlet compressor air temperature increases, thus leading to an increased air density, which reduces the air mass flow rate. The IGV and the combined IGV and TIT control strategy are the best methods regarding power output and thermal efficiency. Figure 8 displays the variant of fuel mass flow rate with power output for 3 different ambient temperatures and three control strategies. It was revealed that at lower intake air temperatures, the power output is higher compared with other ambient temperature conditions. The IGV control strategy, along with the combined IGV and TIT, reduce fuel consumption by adjusting airflow, compressor functionality, and combustion efficiency. They are, therefore, the best option for fuel economy.



(a)



(b)

Fig. 9. Comparison of thermal efficiency and power output as the compressor inlet temperature changes.

Figure 9 displays the variant of the power output and thermal efficiency, when compressor intake-air temperature changes. These performance parameters are influenced by the inlet temperature when working at in-design and off-design situations. The rise in the compressor intake air temperature, leads to a drop in the fuel mass flow rate owing to the decrease in air density. This results in lower power output, and therefore lower combustion efficiency.

Figures 10 and 11 display the GT performance with and without the absorption refrigeration system. The power output and thermal efficiency are achieved through compressor inlet air cooling. Without the absorption refrigeration system, the power output and thermal efficiency decrease as the ambient temperature rises. The implementation of the absorption refrigeration system, significantly improves power output and thermal efficiency.

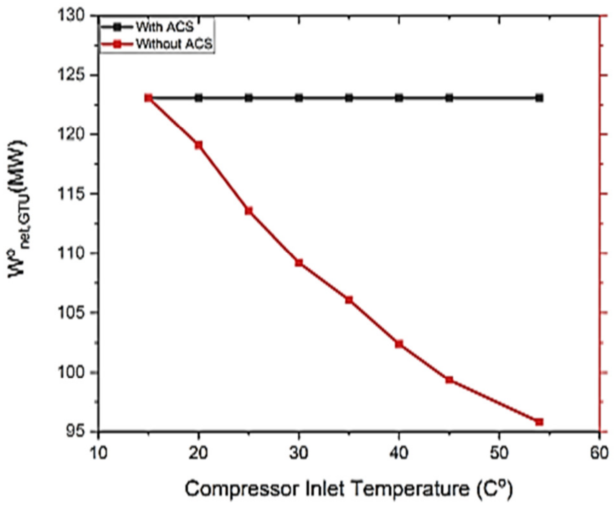


Fig. 10. The effect of ambient air temperature on GT power output.

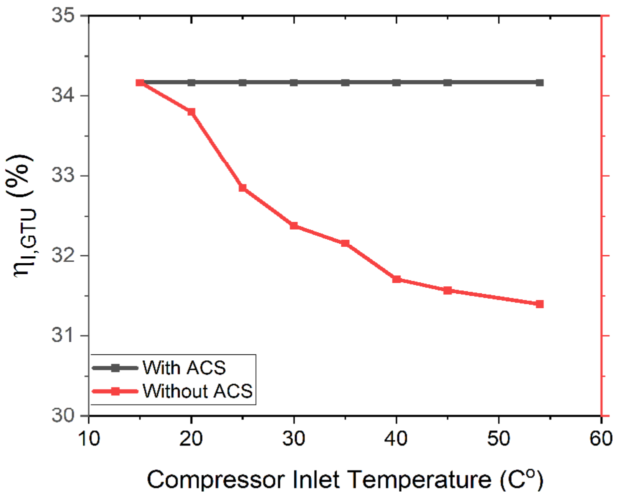


Fig. 11. The effect of ambient air temperature on GT thermal efficiency.

The Operational Characteristic Curve (OCC) is an important tool for assessing a compressor's performance in GT power cycles. It provides a graphic representation of the relationship between control methods and operational parameters, like power output, efficiency, pressure ratio, and mass flow rate. Figure 12 shows the mass flow rate and pressure ratio, with lines corresponding to varied TIT settings, at constant or changing IGV angles, and at fixed TIT values. Full load is achieved when the IGV is at its maximum angle of 84°, while at the minimum open angle of 54°, the load reaches 60%.

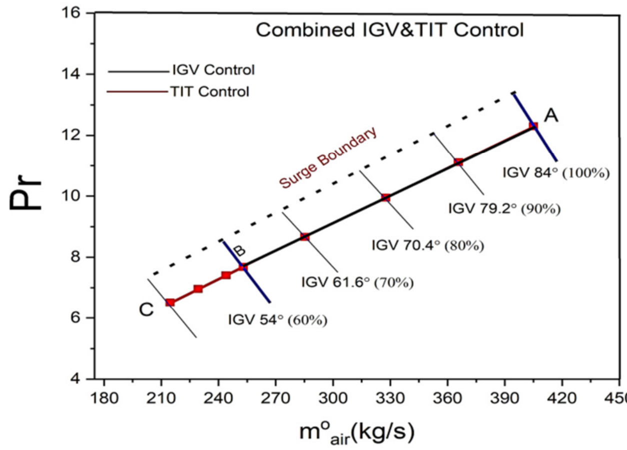


Fig. 12. OCC of a compressor utilizing IGV and TIT control techniques.

V. CONCLUSIONS

In this research, a combined system based on the Gas Turbine Cycle (GTC) and single effect Lithium Bromide–Water absorption cooling system is analyzed. The absorption refrigeration system is operated using the heat energy from the exhaust gas that is considered waste, before it exits the steam generator.

A thermos-flow software is employed to simulate the Gas Turbine (GT) power cycle model. It combines typical compressor and turbine performance parameters, in order to evaluate the full-load operating (i.e. design conditions) and part-load operating (i.e. off-design conditions) performance of the power system, employing various control strategies. The Engineering Equation Solver (EES) software is implemented to simulate the absorption chiller model and identify the impact of the GT power cycle exhaust. The GE Frame 9E GT (Al Khairat Power Plant, 10 × 125 MW), located in Karbala City in central Iraq, is selected and investigated. Parametric investigations are conducted to evaluate the impact of several operating conditions on developed system performance for both full and partial loads. Moreover, different control strategies, namely the Turbine Inlet Temperature (TIT), Inlet Guide Vane (IGV), and combined IGV and TIT, are utilized as performance parameters.

The results exhibited an enhancement of about 20.68% in the generated power output and 5.32% in the thermal efficiency of the GT power plant, when the compressor inlet air was cooled from 54 °C to 15 °C. Additionally, the results indicated that the combined IGV and TIT operating control approach can enhance the performance of the combined power cycle and absorption system, with part-load operating schemes. In general, the IGV and TIT utilized as operating control strategies, are appropriate for various GT power cycles. When different power cycles based on gas turbines are provided in the integrated power and cooling systems, the advantages of the IGV working control scheme should be considered. This analysis may deliver a new working approach for limited-scale gas power cycles to augment the off-design/part-load performance of the Combined Power and Cooling (CPC) system. The GT plant results are compared with those of [28] for the same type of gas turbine, while they were very close to the reference data. The validation of the maximum power output was 2.01%. The H2O-BrLi absorption cooling model is validated by comparing the current model results with those from [28]. The heat rate of the evaporator in the absorption cooling system at an ambient temperature of 50 °C, is compared again with the same reference data using the same gas turbine, considered a case study. The validity of the heated rate of the evaporator was 3.8%.

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