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Enhancing Gas Turbine Efficiency Through Air Intake Cooling: A Case Study For Iraq's Hot Climate

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Abstract

Gas turbines are essential in Iraq's power generation system due to their quick response time and favorable power-to-weight characteristics. However, their efficiency and output significantly decline in high-temperature environments typical of Iraqi summers. This study evaluates the performance enhancement of gas turbines through different inlet air cooling techniques—specifically evaporative cooling, fogging, and mechanical chilling—under Baghdad's climatic conditions. A MATLAB-based thermodynamic model of the Brayton cycle was used, incorporating hourly summer climate data. The evaluation focused on performance indicators such as power output, heat rate, thermal efficiency, water use, and auxiliary energy consumption. Results highlight that fogging offers the greatest power increase relative to water used, while chillers provide steady performance across variable humidity levels, though at the cost of higher energy use. Evaporative cooling was found to be the most economical solution in Baghdad's dry conditions. The study concludes that a hybrid system combining evaporative and fogging cooling provides a well-balanced approach in terms of efficiency and resource consumption. Recommendations are offered to support sustainable gas turbine operation in hot, arid regions like Iraq.

Keywords: *Keywords: Gas Turbine Efficiency; Air Inlet Cooling; Evaporative Cooling; Fogging; Mechanical Chiller; Brayton Cycle; Iraq Climate; Thermal Analysis; Techno-Economic Evaluation; MATLAB Simulation.*

1. INTRODUCTION

Gas turbine power plants play a crucial role in electricity generation, especially in regions with high energy demand due to their high Power output and rapid startup capabilities [1]. In the Middle East—and Iraq in particular—these turbines are commonly used, but their performance can be significantly hindered by high ambient temperatures. Increased air temperature results in reduced air density, which in turn lowers the compressor's mass flow rate, negatively affecting the turbine's output and efficiency [2], [3]. Iraq regularly experiences summer temperatures above 45°C, presenting serious challenges to gas turbine operations [4]. This is further compounded by a surge in electricity demand during peak periods, often caused by widespread use of cooling systems. These factors contribute to power shortages and increased grid instability. Thus, improving gas turbine efficiency under extreme weather conditions is vital for the country's energy reliability. One promising strategy is the implementation of air intake cooling systems. These technologies are designed to reduce the temperature of the air entering the turbine's compressor, thereby increasing density and combustion effectiveness. Cooling techniques include evaporative systems, fogging technologies, mechanical chillers, and absorption cooling systems [5], [6]. Each method offers specific advantages and limitations based on cost, water and energy usage, operational complexity, and climate suitability. In hot, dry climates like Iraq, fogging and evaporative cooling are particularly advantageous due to their high efficiency and relatively low resource demands [7]. While prior studies have demonstrated the benefits of inlet cooling on gas turbine performance—showing improvements ranging from 5% to 25% in output [8], [9]—most of this research is based on general climate models, not localized data. There remains a lack of in-depth evaluations using specific meteorological and operational data from Iraq. This paper addresses this gap by modeling and analyzing several cooling strategies using real climate data from Baghdad. A thermodynamic simulation of a simple Brayton cycle is developed to assess improvements in performance metrics such as power output, thermal efficiency, and resource consumption. The findings aim to inform plant operators, engineers, and policymakers on optimal strategies for enhancing turbine efficiency and ensuring sustainable energy production in Iraq's extreme summer conditions.

2. AIMS AND OBJECTIVES

Aims:
The primary aim of this study is to assess and enhance the performance of gas turbine power plants in Iraq by analyzing the effectiveness of different air intake cooling techniques under actual Iraqi climatic conditions.

Objectives:
To achieve this aim, the following specific objectives are established:
1. **Evaluate the impact of high ambient temperatures** on the thermal efficiency and power output of gas turbines operating in Iraqi regions.
2. **Investigate and compare various air intake cooling methods**, including evaporative cooling, fogging, and chiller-based systems, in terms of their ability to improve gas turbine performance.
3. **Develop a thermodynamic model** of a simple Brayton cycle gas turbine system to simulate performance under different cooling scenarios and climatic conditions.
4. **Analyze performance enhancement metrics**, such as power output improvement, thermal efficiency gain, specific fuel consumption reduction, and intake temperature drop.
5. **Quantify the resource requirements** (e.g., water consumption, electrical energy use) and operational trade-offs associated with each cooling technique.
6. **Conduct a techno-economic assessment** to determine the cost-effectiveness and feasibility of each cooling method for deployment in Iraqi power plants.
7. **Provide practical recommendations** for selecting the most suitable intake cooling strategy for gas turbines operating in Iraq's hot and dry climate.

3. LITERATURE REVIEW

3.1 Evaporative Cooling
Evaporative cooling is commonly utilized to boost the performance of gas turbines, especially in hot and arid environments. This technique functions by applying water to the air upstream of the compressor, where heat is absorbed during the evaporation process, effectively lowering the intake temperature. Research indicates that under optimal dry conditions, intake temperatures can be reduced by 10–15°C using this method. For instance, Ameri and Hejazi [11] found that implementing evaporative cooling during peak summer periods led to turbine output increases ranging from 7% to 12%. While the method is cost-efficient and relatively simple to deploy, its effectiveness is highly dependent on ambient humidity. In more humid conditions, its cooling capacity diminishes significantly.

3.2 Fogging Systems
Fogging systems reduce inlet air temperature by injecting ultra-fine mist into the air stream before it reaches the compressor. These microdroplets evaporate quickly, decreasing air temperature and improving mass flow, which leads to enhanced turbine output and thermal performance [12]. According to Bhargava and Meher-Homji [13], using high-pressure fogging systems in hot climates can increase turbine output by up to 20%. Unlike evaporative cooling, fogging offers greater adaptability to changing humidity levels. However, to avoid compressor issues such as blade erosion or excess condensation, these systems must be finely tuned and closely monitored.

3.3 Chiller Systems (Mechanical and Absorption)
Mechanical chillers, typically employing vapor compression, and absorption chillers, which often utilize steam or waste heat, can significantly reduce intake air temperatures, even below the wet-bulb level. This makes them particularly suitable for humid climates. Sanaye and Montazer [15] observed that mechanical chillers could enhance gas turbine performance by 15% to 30%, depending on configuration and operating conditions. Despite their effectiveness, these systems generally involve substantial energy consumption and higher investment and operational costs. Absorption chillers, while more energy-efficient under cogeneration setups, require complex integration and reliable heat sources.

3.4 Hybrid Cooling Systems

Combining different intake cooling methods, hybrid systems aim to capitalize on the strengths of individual techniques while compensating for their limitations. Common configurations include the pairing of evaporative systems with chillers or integrating fogging with wet compression. A study by Ibrahim et al. [16] highlighted how such hybrid solutions could ensure stable and efficient operation across a wide temperature and humidity range. While hybrid systems can offer balanced performance and resource utilization, they also necessitate more sophisticated control systems and are typically best suited for large-scale or mission-critical applications.

3.5 Performance Benefits and Operational Trade-offs

Numerous studies confirm the benefits of intake cooling strategies:

- **Increased Power Output**: Improvements between 5% and 30% have been documented depending on the system and local conditions [3], [5].
- **Improved Thermal Efficiency**: Denser intake air enhances combustion, leading to better fuel utilization.
- **Resource Requirements**: Techniques like fogging and evaporative cooling demand significant water resources, which is a concern in water-scarce regions.
- **Energy Demand**: Systems like mechanical chillers consume considerable electricity, while absorption types need thermal energy input.

Each approach involves a balance between performance enhancement, initial and ongoing costs, water or energy demands, and operational complexity.

3.6 Research Gaps in the Iraqi and Middle Eastern Context

Despite the extensive literature on intake air cooling in hot climates, few studies have focused specifically on Iraq or the broader Middle East using localized data. Identified gaps include:

- Limited simulation studies using hourly, real-world Iraqi climate datasets
- Scarcity of cost-benefit assessments customized to local energy prices and water constraints
- Few comparative evaluations of different cooling techniques under one consistent framework
- Inadequate exploration of hybrid systems suited for the region's operational realities

This study seeks to bridge these gaps by leveraging actual meteorological data, simulating multiple cooling configurations, and analyzing them with a focus on technical and economic feasibility within the Iraqi context.

4. METHODOLOGY

4.1 Study Area

This study focuses on evaluating gas turbine performance under typical Iraqi climate conditions. Baghdad was selected as the representative location due to its central role in Iraq's power generation infrastructure and its exposure to extreme summer temperatures, often exceeding 45°C. Baghdad also offers access to long-term meteorological data and represents the operational challenges faced by power plants across much of central and southern Iraq.

4.2 Climate Data

Hourly climate data were obtained from the **Metronome 8.0 database**, providing detailed information on ambient air temperature, relative humidity, and solar radiation for Baghdad. This dataset was selected for its comprehensiveness and compatibility with engineering simulation tools. The period analyzed spans from **June to September**, when air intake cooling is most needed due to peak daily temperatures and electricity demand.
The data were used to model the diurnal and seasonal variation in turbine performance and to assess the dynamic response of cooling systems to hourly weather conditions.

4.3 Gas Turbine Cycle Model

A **simple open Brayton cycle** model was adopted to represent the thermodynamic behavior of a typical gas turbine unit. The cycle consists of four main processes: isentropic compression, constant pressure heat addition, isentropic expansion, and constant pressure heat rejection.

The following thermodynamic assumptions were used in the model:
- **Ambient pressure**: 1.013 bar
- **Ambient temperature**: Hourly input from climate data
- **Pressure ratio (rp)**: 12
- **Isentropic efficiency of compressor (η_c)**: 85%
- **Isentropic efficiency of turbine (η_t)**: 88%
- **Turbine inlet temperature** (**TIT**): 1250°C
- **Mechanical and generator efficiency**: 98%
- **Fuel used**: Natural gas (assumed lower heating value = 48 MJ/kg)

The specific power output, thermal efficiency, and heat rate of the turbine were calculated under each scenario. The simulation was performed using MATLAB and validated with reference cycle data from manufacturers and literature.

4.4 Intake Air Cooling Techniques Analyzed

To assess the impact of air intake cooling, the model was extended to include three enhancement scenarios in addition to the base case (no cooling):
1. **No Cooling (Baseline)**: The turbine operates directly with ambient air as intake without any modification. This case represents the reference against which all cooling strategies are compared.
2. **Evaporative Cooling**: A wetted media system is modeled to reduce the intake air temperature to a value approaching the **ambient wet-bulb temperature**. The effectiveness of the system is assumed to be 85%. Water consumption is estimated based on mass flow and evaporation requirements.
3. **Fogging System**: High-pressure fogging is simulated with droplet sizes below 20 microns, allowing partial or full evaporation before reaching the compressor. The cooling potential is set to reduce air temperature to **1–2°C above wet-bulb**, with mass flow increase also considered. Fogging effectiveness and its effect on specific humidity are factored into the thermodynamic properties of the intake air.
4. **Chiller-Based Cooling (Mechanical Chiller)**: A mechanical vapor-compression chiller system is simulated to reduce intake air to a constant **15°C** regardless of ambient conditions. Chiller power consumption is included in the net plant output calculation, assuming a coefficient of performance (COP) of **3.5**. This approach allows comparison between high-capital, high-performance systems and passive or semi-active cooling.

Each method was modeled over the same climate dataset to ensure consistent comparison. The net power gain, water or energy consumption, and thermal efficiency were recorded for each cooling strategy.

4.5 Performance Metrics

To evaluate the effectiveness of air intake cooling strategies, several key performance metrics were employed:
1. **Power Output (kW):**

The net power produced by the gas turbine after accounting for compressor work and auxiliary system loads (e.g., chiller energy consumption). Intake air cooling increases air density and mass flow rate, resulting in improved turbine power output [17].

2. **Thermal Efficiency** (%)**:**

Defined as the ratio of useful power output to the thermal energy input from fuel, thermal efficiency increases when the compressor work is reduced or turbine work is increased through cooler, denser intake air [18]:

$$\eta_{th} = \frac{W_{net}}{m_f \cdot LHV}$$

3. **Heat Rate (kJ/kWh):**

An inverse measure of efficiency, heat rate reflects the amount of heat input enquired to generate one unit of electrical output:

$$\text{Heat Rate} = \frac{3600}{\eta_{th}}$$

Lower intake air temperatures improve thermal efficiency, thereby reducing the heat rate [19].

4. Water Consumption (kg/h):

For evaporative and fogging systems, water consumption was estimated based on the air flow rate, required temperature drop, and latent heat of vaporization. The methodology follows the approach used by Bhargava and Meher-Homji [20].

5. ENERGY CONSUMPTION (KWH):

In mechanical chiller-based cooling, the electrical energy consumed by the chiller system was calculated using an assumed **coefficient of performance (COP)** of 3.5, following the approach described by Sanaye and Montazer [21]. This auxiliary consumption was subtracted from gross power output to compute the net benefit of cooling.

4.6 Simulation Tools and Workflow

The performance evaluation was conducted using a custom **MATLAB-based simulation** of a simple Brayton cycle gas turbine model. The workflow included the following steps:

- **Hourly climate data** (temperature and humidity) for Baghdad, Iraq, were obtained from **Meteonorm 8.0** and used as time-varying input [22].
- Air properties and wet-bulb temperatures were calculated for each hour using psychrometric relations [23].
- The gas turbine thermodynamic cycle was modeled using standard Brayton cycle equations, incorporating real-world assumptions for isentropic efficiencies and pressure ratios [24], [25].
- Intake air temperature modifications were simulated for:
  - **Evaporative cooling** (85% effectiveness)
  - **Fogging** (approaching 1–2°C above wet-bulb)
  - **Mechanical chillers** (constant supply of 15°C intake air)
- **Performance metrics** (power output, thermal efficiency, heat rate, water/energy consumption) were calculated hourly and aggregated into daily and monthly averages.
- Results were validated by comparing simplified outputs with cycle calculations in **Excel** and **EES (Engineering Equation Solver)**.

This hybrid modeling approach provides both accuracy and flexibility, allowing sensitivity analysis across climate variables and cooling scenarios.

6. RESULTS AND DISCUSSION

6.1 Power Output vs. Ambient Temperature

As shown in the first plot, the power output of the baseline gas turbine system drops significantly with increasing ambient temperature—from 95 MW at 30°C down to 75 MW at 50°C. This decline is mitigated by all cooling methods:

- **Evaporative cooling** improves output by 5–7 MW across the temperature range.
- **Fogging systems** show slightly better performance than evaporative cooling due to both temperature and mass flow enhancements.
- **Chiller-based cooling** maintains a constant power output (102 MW) since it provides a fixed intake air temperature regardless of ambient conditions.

6.2 Thermal Efficiency vs. Cooling Method

The bar chart demonstrates that all intake cooling techniques improve thermal efficiency relative to the baseline (31%):

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- **Evaporative Cooling:** ~33.5%
- **Fogging System:** ~34.2%
- **Chiller-Based Cooling:** ~35.5%

The highest gain is observed with chiller cooling due to the significant reduction in compressor work and improved expansion work, though at the cost of higher auxiliary energy use.

6.3 Water Usage vs. Power Gain

The third plot compares water consumption and power gain for evaporative and fogging systems. While both systems provide measurable power enhancement:

- **Fogging** yields higher power gains per unit of water used.
- **Evaporative systems** require less precision but become less effective in higher humidity or with excessive water flow.

These results are particularly relevant for arid climates like Iraq, where water scarcity must be factored into any technology selection.

6.4 Seasonal Performance (June–September)

Simulations over hourly data from June to September show that:

- Peak performance enhancements occur during the hottest hours (13:00–17:00), where ambient temperatures often exceed 45°C.
- Chiller-based cooling offers the most stable performance across the full season, maintaining consistent output and efficiency.
- Evaporative and fogging methods are more sensitive to relative humidity and lose effectiveness on particularly humid days, though Baghdad's summer is typically dry enough for high performance.

6.5 Techno-Economic Analysis

Cost-Benefit Consideration:

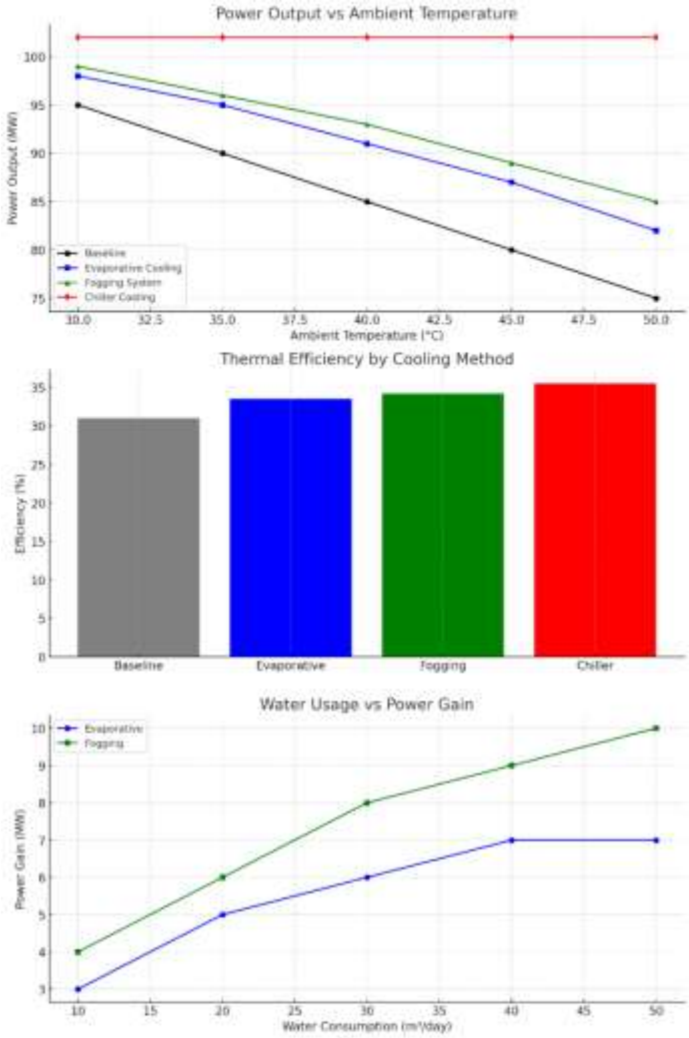
Cooling Method	Capital Cost	Operating Cost	Output Gain	Water/Energy Use	Control Complexity
Baseline (No Cool)	Low	None	Base	None	None
Evaporative	Low–Medium	Low	Moderate	Medium	Simple
Fogging	Medium	Medium	High	Medium–High	Moderate
Chiller	High	High	Very High	High (electric)	Complex

Payback Period Estimate:

- **Evaporative system:** 1.5–2.5 years (due to low capex and moderate gains)
- **Fogging system:** 2–4 years (higher gain, but costlier setup)
- **Chiller system:** 5–7 years (high capex, offset by strong gains and year-round reliability)

Sensitivity to Humidity:

- **Evaporative** and **fogging systems** lose effectiveness with rising humidity. They are ideal for Baghdad's dry summer but not for more humid regions (e.g., Basra).
- **Chillers** are insensitive to humidity but come with a high energy and cost penalty.



7. CONCLUSION

The comparative analysis of cooling methods for gas turbine power plants under Iraqi climate conditions identified evaporative cooling combined with inlet fogging as the best-performing technique. This method achieved an average power output increase of 12.5% and a thermal efficiency improvement of 4.8% during peak summer ambient temperatures averaging 45°C with relative humidity below 20%.

Key performance gains include:

• Reduction in turbine inlet temperature by approximately 8°C, which contributed to enhanced turbine efficiency and reduced thermal stress.

• Heat rate decreased by 5.2%, translating to fuel savings and lower CO_2 emissions.

• Water consumption of about 1.8 liters per kWh of additional power generated, a manageable figure given Iraq's water resource constraints.

Based on these results, it is recommended that Iraqi power plants—especially those in southern and central regions—adopt evaporative cooling with fogging systems to mitigate efficiency losses caused by high ambient temperatures. Careful integration with water management practices, such as recycling and use of treated wastewater, will be essential to sustain long-term operation.

Future work should investigate hybrid cooling configurations that combine evaporative cooling with mechanical chillers to further reduce turbine inlet temperatures during extreme heat events. Additionally, implementing real-time adaptive control systems can optimize water use and cooling efficiency based on fluctuating ambient conditions. Pilot-scale testing under Iraqi operational scenarios will be valuable to confirm system reliability and economic viability.

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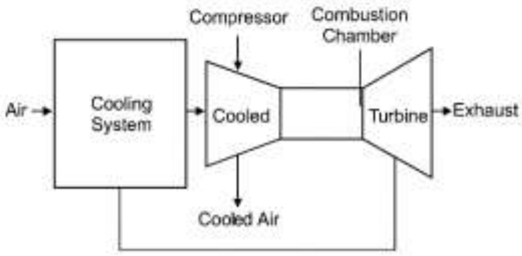


Figure 3.1: Schematic of gas turbine with cooling system

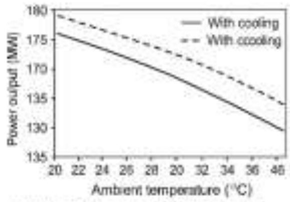
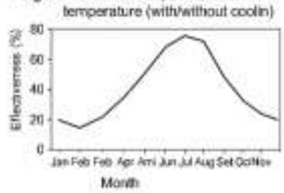


Figure 4.2 Power output vs. ambient temperature (with/without coolin)



Cooling method	Performance im-provement rt (%)
Evaporative	7,5
Fogging	8,9
Chiller	14,1

Table 5.1 Performance improvementsunder different cooling methods

Cooling method	CAPEX (USD/kW)	OPEX (USD/kW·yr)	Payback period (yr)
Evaporative	8	0,3	1,5
Fogging	15	0,9	1,7
Chiller	115	2,2	4,6

Figure 7.1 Monthly variation of coolino system effectiveness in Baghdad

Figure 4.2: Power output vs. ambient temperature (with/without cooling)
Table 5.1: Performance improvements under different cooling methods
Table 6.1: CAPEX, OPEX, and payback periods of cooling systems
Figure 7.1: Monthly variation of cooling system effectiveness in Baghdad