Design Considerations for Improving the Resilience of Combined-Cycle Power Plants to Temperature Fluctuations

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Abstract. As global energy demand rises and environmental concerns intensify, the efficiency and sustainability of power generation systems have become paramount. Combined-cycle power plants (CCPPs) are a widely adopted solution, offering high efficiency through the utilization of both gas and steam turbines. However, temperature fluctuations significantly affect the performance of CCPPs, leading to reduced efficiency and increased operational costs. This paper explores the impact of ambient temperature variations on the thermodynamic cycles of CCPPs and investigates various design considerations to mitigate these effects. Key strategies include the implementation of advanced cooling technologies, hybrid integration with renewable energy sources, and adaptive control systems utilizing real-time monitoring and AI-based predictive controls. Simulation methods, such as Computational Fluid Dynamics (CFD) and Monte Carlo simulations, are highlighted as essential tools for optimizing plant performance. Future trends in CCPP design are also discussed, with a focus on high-temperature-resistant materials, the integration of IoT and smart grid technologies, and the adoption of carbon capture and storage (CCS) for low-emission energy production. This paper demonstrates that enhancing the resilience of CCPPs to temperature fluctuations through these innovations will ensure their continued role in efficient and sustainable power generation.

Keywords: Combined Cycle Power Plant; Temperature Fluctuations; Cooling Technologies; Hybrid Design with Renewable Energy Integration; Adaptive Control Systems and Monitoring.

1. Introduction

The CCPP represents a promising solution to address these issues. As one of the most efficient methods for generating electricity using fossil fuels, CCPPs have been widely adopted globally to meet rising energy demands. These power plants maximize the chemical energy of fuel, minimizing energy waste. Particularly notable is the high utilization efficiency of clean fuels such as natural gas, which can significantly lower fuel consumption per unit of electricity generated. CCPPs not only provide reliable electrical power but also have the advantage of rapid start-up, making them ideal for meeting energy shortages during peak demand periods.

However, numerous parameters influence the performance of CCPPs. Environmental factors include site-specific conditions such as ambient air temperature (AAT), atmospheric pressure, and relative humidity. Non-environmental factors encompass issues such as component failure, fuel quality, and design parameters, including the compressor pressure ratio and pinch point temperatures.

Sanjay's study [1] highlights the impact of fluctuations in cycle process parameters on CCPP efficiency. Similarly, Adumene and Nitonye [2] investigate the effects of ambient air temperature, relative humidity, and site altitude. These studies emphasize the financial losses incurred due to AAT fluctuations, which directly affect the power generation capacity of CCPPs. Thus, developing resilient power plant designs is crucial to ensure stable performance under varying environmental conditions. The aim of the paper is to explore and propose design considerations to enhance the resilience of CCPPs to ambient temperature fluctuations.

2. Impact of Temperature Fluctuations on Combined-Cycle Power Plant Performance

2.1. Temperature Sensitivity of Gas and Steam Turbines

The thermodynamic cycles of CCPPs, specifically the Brayton and Rankine cycles, are sensitive to temperature variations, particularly ambient temperature. In the Brayton cycle, which is employed by gas turbines, the efficiency of the cycle depends on the temperature difference between the turbine inlet air and the exhaust. As ambient temperature increases, the temperature of the air entering the gas turbine rises, reducing the thermodynamic efficiency of the cycle. Higher inlet air temperatures cause a decrease in air density, which reduces the mass flow rate of air entering the turbine. This directly impacts the turbine's ability to produce mechanical work, leading to a drop in power output.

Similarly, in the Rankine cycle, which governs steam turbines, ambient temperature fluctuations affect the heat exchange processes. When the temperature of the air entering the steam turbine rises, the energy available for steam expansion diminishes, further reducing overall thermal efficiency. According to the law of conservation of energy, with a constant steam flow rate, less energy enters the steam turbine, resulting in lower output power.

Furthermore, the reduction in air density due to increased temperatures means that turbines must work harder to maintain the same power output. This decrease in efficiency is especially pronounced during peak summer months when ambient temperatures are at their highest. High-temperature environments, such as those experienced in the summer, not only reduce turbine efficiency but also compromise the unit's peak-shaving capacity, severely limiting the overall output of gas turbines [3]. Overall, temperature-induced inefficiencies in both gas and steam turbines highlight the importance of temperature-sensitive design considerations in CCPPs to ensure stable performance under varying environmental conditions.

2.2. Seasonal and Regional Variations

Air temperature varies significantly throughout the year. From January to July, the power output of CCPPs decreases as the temperature rises, while from July to December, it increases as the temperature falls [4]. A study on a natural gas combined cycle (NGCC) power plant in Hangzhou, China, indicates that when ambient temperature increases from 5 °C to 35 °C, the power output of the NGCC system decreases by 22.6%, and energy efficiency drops from 57.28% to 56.3% [5]. Additionally, as the ambient temperature rises from 5 °C to 35 °C, the total power output of gas turbines and steam turbines decreases by 17.0% and 16.2%, respectively [5]. Another study on a CCPP in Mato Grosso do Sul, Brazil, highlights that the efficiency and maximum generation of CCPPs are adversely affected in tropical regions [6].

2.3. Financial and Operational Impacts

Fluctuations in AAT lead to a decrease in the efficiency of CCPPs. As a result, more fuel is required to generate the same amount of electricity, thereby increasing fuel costs. Furthermore, the amount of electricity the power plant can sell within the same time frame decreases, leading to a reduction in revenue. Additionally, high-temperature environments can negatively impact the lifespan of equipment, increasing the frequency of repairs and replacements, which further drives up operational costs.

3. Design Considerations for Enhancing Resilience to Temperature Fluctuations

3.1. Advanced Cooling Technologies

The performance of gas turbines is significantly affected by ambient temperature, especially during peak electricity consumption in summer, when power demand rises. Inlet cooling technologies are an effective solution to this issue, as they stabilize the air intake temperature, ensuring more consistent turbine performance. One commonly used method is the traditional evaporative cooling system, which reduces ambient temperature by absorbing heat through water evaporation. This method is widely adopted due to its simplicity, but it has limitations, such as a limited cooling effect and a potential decrease in turbine output due to pressure drop. Additionally, evaporative systems have a relatively low requirement for water quality, which can also affect overall efficiency [7].

In contrast, more advanced methods, such as inlet fogging systems, use atomizing nozzles to convert water into a fine mist or fog at the turbine inlet. As the fog evaporates in the intake duct, it cools the air effectively, enhancing turbine performance. This method provides better cooling efficiency compared to traditional evaporative systems, as it addresses the issue of pressure drop and improves the air density entering the turbine [7].

Absorption chillers are another advanced cooling technology that can be integrated into gas turbines. These systems utilize waste heat from exhaust gases to provide the necessary cooling, thus improving the overall energy efficiency of the power plant. Absorption chillers have been shown to increase gas turbine capacity by up to 25%, making them a valuable addition to power plants operating in high-temperature environments [8].

Another promising technology is the ejector refrigeration system, which uses a portion of the turbine exhaust heat to drive the refrigeration cycle. This system offers an advantage over traditional cooling methods due to its lower power consumption. By utilizing waste heat more efficiently, ejector refrigeration systems can provide effective cooling without imposing a significant energy burden on the power plant [9].

In addition to air inlet cooling systems, both air-cooled and water-cooled condensers are employed to manage the heat dissipation process in power plants. Water-cooled condensers, while more efficient in heat removal, require substantial water resources, which can limit their use in regions with water scarcity. In contrast, air-cooled condensers offer a more sustainable solution but are less efficient in terms of heat transfer, which may affect the overall cooling capability in high-temperature environments.

3.2. Hybrid Design with Renewable Energy Integration

The integration of renewable energy sources into CCPPs offers a promising solution to offset temperature-induced inefficiencies, particularly during peak summer months when ambient temperatures rise and power output declines. By combining CCPPs with renewable energy sources such as solar and wind power, hybrid systems can stabilize energy production, reduce reliance on fossil fuels, and improve overall system stability. These hybrid designs allow for energy source flexibility, ensuring that when one source is insufficient, others can supplement the energy demand.

For instance, a solar-wind-diesel generator hybrid system has proven effective in mitigating the inefficiencies caused by rising air temperatures, maintaining a stable power output during periods of increased ambient temperature [10]. Hybrid systems like these leverage the complementary nature of renewable energy sources—when solar power generation is reduced due to cloud cover, wind power can compensate, and vice versa. This dynamic reduces the overall vulnerability of the power plant to temperature fluctuations and seasonal changes.

One notable case study involves a hybrid system implemented in a remote rural area of Ethiopia. This large-scale renewable energy system integrates wind turbines, photovoltaic panels, and diesel generators. By blending these energy sources, the system successfully meets the local power demand while maintaining a relatively low energy cost, demonstrating the economic and operational viability of hybrid designs [10].

Another innovative design is the Solar Chimney Power Plant, which generates both electricity and fresh water, providing a dual benefit in arid regions where water scarcity is a concern. The design utilizes solar energy to create a temperature difference that drives airflow through the chimney, generating electricity while simultaneously facilitating water production [11].

In New Zealand, a hypothetical biomass-geothermal hybrid system based on the Rotokawa I geothermal plant demonstrated the potential for increased power output. By integrating biomass with geothermal energy, the hybrid plant generated an additional 8548 kilowatts of power, representing a 32% increase over the standard geothermal plant. This case illustrates how hybrid designs can enhance energy production efficiency by leveraging diverse renewable energy sources [12].

Moreover, Kohler Engines has partnered with Grastim to establish a hybrid self-generating power plant at their diesel engine production facility in Reggio Emilia, Italy. This plant, designed to run on hydrogen, will further reduce dependence on traditional fossil fuels and lower carbon emissions. The inclusion of hydrogen as a power source in hybrid systems offers significant environmental benefits and enhances energy resilience in industrial applications [13].

3.3. Adaptive Control Systems and Monitoring

The implementation of real-time monitoring systems and AI-based predictive controls has become essential in modern power plant operations, particularly in response to temperature fluctuations. These technologies enable adaptive control, adjusting operational parameters dynamically to ensure stable power output, even under varying environmental conditions.

AI-based predictive controls can analyze vast amounts of real-time data, using advanced algorithms to forecast temperature changes and optimize plant operations accordingly. For example, a sliding mode controller applied to a wave power plant with a doubly-fed induction generator has demonstrated improved system stability through simulation, showcasing how adaptive controls can enhance performance under fluctuating conditions [14].

In addition to predictive controls, advanced adaptive algorithms are being utilized to automatically adjust parameters such as turbine speed, fuel flow, and cooling system operation in response to changing temperatures. One such innovation is a distributed adaptive real-time learning framework designed for wide-area power system monitoring, particularly in systems that integrate distributed generation. This framework uses distributed agents, such as synchronous phasors, for autonomous local state monitoring and fault detection, while a central unit provides a global view of the system, enabling improved situational awareness and decision-making [15]. This kind of system ensures that even under extreme temperature fluctuations, power generation remains efficient and reliable.

Furthermore, the use of unmanned aerial vehicles (UAVs) for power plant monitoring has introduced new levels of flexibility and precision in data collection. UAVs equipped with Geiger counters and temperature sensors can measure radiation levels and ambient temperature in real-time, providing crucial insights that can be fed into AI-based control systems. This combination of real-time monitoring and AI-driven control mechanisms ensures that operational adjustments can be made swiftly and accurately, minimizing efficiency losses and extending the operational lifespan of equipment [16].

Adaptive control systems, through the integration of AI and real-time monitoring, represent a significant advancement in managing the challenges posed by temperature variability. These technologies not only enhance operational stability but also reduce maintenance costs by proactively adjusting systems to avoid temperature-induced wear and inefficiencies.

4. Simulation Methods for Process Optimization

4.1. Role of Simulation in Power Plant Design

Simulation plays a critical role in power plant design, enabling engineers and researchers to analyze and optimize various aspects before construction or operation. By simulating different operating conditions and scenarios, engineers can enhance the performance of power plants, reduce costs, improve efficiency, and ensure safety.

Computational Fluid Dynamics (CFD) software is commonly used to simulate the thermal environment of power plant boilers. CFD simulations provide insights into flow patterns, temperature distributions, and pressure drops in boilers. Additionally, IPSEpro software performs thermal balance simulations for thermal power plants, serving as an engineering tool for calculating heat and mass balance and simulating processes. In a study by Sukra, Permana, and Adriansyah, a simple analysis tool was developed specifically for geothermal power plants [17]. Furthermore, Monte Carlo Simulation can estimate the average power generation of CCPPs, with the results used for economic analysis [4].

4.2. Monte Carlo Simulation for Temperature Variability

Monte Carlo simulation is a numerical calculation method based on random sampling, used to simulate and analyze complex systems by generating a large number of random samples. It has wide applications in fields such as engineering, finance, and physics. In power systems, Monte Carlo simulation is employed to evaluate factors such as system reliability, performance, and risk. Specifically, it can be used to compute thermal efficiency while accounting for AAT variations [4]. In the power sector, particularly when considering the impact of temperature variability on power plants, Monte Carlo simulation plays a crucial role.

4.3. CFD for Design Optimization

With the rapid advancement of computer technology and the development of CFD, numerical research methods have achieved a high level of accuracy, often replacing experimental research. For complex two-dimensional or three-dimensional single-phase viscous Newtonian fluid problems in structures such as curved pipes, CFD can be employed to solve the equations of mass, momentum, and energy conservation. Compared to traditional experimental methods, CFD can analyze complex fluid systems in a shorter time, significantly reducing the time required for design and optimization. Additionally, CFD simulations eliminate the need for physical experiments, thus lowering testing costs. For instance, using fluent software to simulate the turning vanes in the selective catalytic reduction (SCR) reactor of a 600 MW power plant helped determine a more suitable vane shape and an optimized flow field [18].

4.4. Energy Modeling and Scenario Analysis

Energy modeling is crucial for power plants, particularly in the context of growing global energy demand and increasing emphasis on environmental protection. Accurate energy modeling helps optimize energy production, enhance efficiency, and reduce costs. Additionally, modeling provides valuable insights into the performance of power plants under varying operating conditions, offering robust support for planning and decision-making. In thermal power plants, energy modeling considers factors such as fuel costs and equipment performance, enabling optimization of the power generation process and improving energy conversion efficiency [19].

5. Future Trends in Combined-Cycle Power Plant Design

One key future trend in CCPP design is the integration of high-temperature-resistant materials in critical components such as turbine blades and heat exchangers. These advanced materials, capable of withstanding higher operating temperatures, will significantly enhance the durability and efficiency of CCPPs. By improving heat tolerance, these materials allow turbines to operate at higher thermal efficiencies, reducing the overall fuel consumption per unit of electricity produced. In addition, advanced coatings and superalloys are being developed to extend the lifespan of turbine components, ultimately lowering maintenance costs and improving the reliability of power plants. The integration of Internet of Things (IoT) and smart grid technologies is poised to play an increasingly critical role in the future of CCPPs. IoT devices, equipped with sensors and real-time data collection capabilities, will provide continuous monitoring of plant performance, environmental conditions, and equipment health. Smart grids, in conjunction with IoT, will facilitate more efficient energy distribution by adjusting power output based on real-time demand, thus optimizing plant performance. This interconnected system will enable predictive maintenance, minimizing downtime and ensuring that power plants operate at peak efficiency. As a result, overall plant efficiency will be improved, reducing operational costs and energy losses. The development of low-emission CCPPs is another significant trend driven by the global focus on sustainability and emissions reduction. A critical advancement in this area is the incorporation of CCS technologies. CCS allows CCPPs to capture carbon dioxide emissions before they are released into the atmosphere, storing them underground or utilizing them in other industrial processes. This technology ensures that CCPPs can maintain high efficiency while drastically reducing greenhouse gas emissions, even under variable temperature conditions. By integrating CCS into power plants, operators can meet stringent environmental regulations without compromising on performance, making CCPPs a more viable solution for the future of low-carbon energy production.

6. Conclusion

CCPP remains one of the most efficient solutions for addressing the global energy demand while mitigating the environmental impacts of fossil fuel usage. This paper has examined the challenges CCPPs face due to temperature fluctuations, particularly their effects on turbine efficiency and overall plant performance. By exploring various design considerations such as advanced cooling technologies, hybrid integration with renewable energy, and adaptive control systems, we have identified practical solutions to enhance the resilience of CCPPs under varying environmental conditions.

The use of real-time monitoring systems, AI-based predictive controls, and advanced cooling methods such as absorption chillers and inlet fogging, provides significant improvements in performance stability and efficiency. Hybrid designs, combining CCPPs with renewable energy sources like solar and wind power, further bolster energy security and operational flexibility, reducing the reliance on fossil fuels and mitigating the negative effects of temperature variability. Additionally, simulation methods such as CFD and Monte Carlo simulations play a critical role in optimizing power plant design, enabling more accurate forecasting of plant behavior under different scenarios and conditions. Energy modeling further supports this by offering insights into cost-saving measures and performance optimization.

Looking forward, the integration of high-temperature-resistant materials, IoT, and smart grid technologies, along with advancements in CCS, represent key trends in future CCPP design. These innovations will ensure that CCPPs remain a viable and sustainable solution for power generation, capable of meeting the challenges of increasing energy demand and stringent environmental regulations. In conclusion, the ongoing enhancement of CCPP technology, combined with strategic integration of renewable energy and advanced monitoring systems, will play a vital role in achieving efficient, low-emission, and resilient energy production in the future.

References

[1] Sanjay. Investigation of effect of variation of cycle parameters on thermodynamic performance of gas-steam combined cycle. Energy, 2011, 36(1): 157-167.

[2] Adumene S, Nitonye S. Assessment of site parameters and heat recovery characteristics on combined cycle performance in an equatorial environment. World Journal of Engineering and Technology, 2016, 4(2): 313-324.

[3] Liu Y, Banerjee A, Kumar A, et al. Effect of Ambient Temperature on Performance of Gas Turbine Engine//Annual Conference of the PHM Society. 2017, 9(1).

[4] Yeganeh A H J, Behbahaninia A, Ghadamabadi P. Monte Carlo Simulation of a Combined-Cycle Power Plant Considering Ambient Temperature Fluctuations. Journal of Power and Energy Engineering, 2022, 10(5): 116-131.

[5] Wan A, Chen T. Performance degradation analysis of combined cycle power plant under high ambient temperature. Thermal Science, 2022, 26(2 Part C): 1897-1906.

[6] Junior N P, Gazoli J R, Sete A, et al. Climate impact on combined cycle thermoelectric power plant in hot and humid regions. Results in Engineering, 2023, 19: 101342.

[7] Chaker M, Meher-Homji C B, Mee III T, et al. Inlet fogging of gas turbine engines detailed climatic analysis of gas turbine evaporation cooling potential in the USA. J. Eng. Gas Turbines Power, 2003, 125(1): 300-309.

[8] Ansari M, Bazargan P E M. Improvement of Gas Turbine Performance by Cooling the Intake Air by Absorption Chiller 2019.

[9] Al-Ansary H A. The use of ejector refrigeration systems for turbine inlet air cooling: a thermodynamic and CFD study//Energy sustainability. 2007, 47977: 231-238.

[10] Khalil L, Bhatti K L, Awan M A I, et al. Optimization and designing of hybrid power system using HOMER pro. Materials Today: Proceedings, 2021, 47: S110-S115.

[11] Abdelsalam E, Almomani F, Kafiah F, et al. A new sustainable and novel hybrid solar chimney power plant design for power generation and seawater desalination. Sustainability, 2021, 13(21): 12100.

[12] Thain I, DiPippo R. Hybrid geothermal-biomass power plants: applications, designs and performance analysis//Proceedings world geothermal congress, Melbourne, Australia. 2015: 19-25.

[13] Autonomous assembly: designing for a new era of collective construction. John Wiley & Sons, 2017.

[14] Barambones O, Cortajarena J A, Alkorta P, et al. Adaptive sliding mode control scheme for a wave power generation plant//2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). IEEE, 2017: 1-6.

[15] Li K, Guo Y, Laverty D, et al. Distributed adaptive learning framework for wide area monitoring of power systems integrated with distributed generations. Energy and Power Engineering, 2013, 5(4B): 962-969.

[16] Seo J W, Han S H, Shin S Y. Deep learning based nuclear power plant monitoring system using uav//2021 International Conference on Electronics, Information, and Communication (ICEIC). IEEE, 2021: 1-4.

[17] Sukra K F A, Permana D, Adriansyah W. Modelling and Simulation of Existing Geothermal Power Plant: A Case Study of Darajat Geothermal Power Plant. International Journal of Thermodynamics, 2023, 26(2): 13-20.

[18] Shen D, Zhong Z. Computational fluid dynamics-based simulation of optimal design in power plant flue gas denitrification//2011 International Conference on Electronics, Communications and Control (ICECC). IEEE, 2011: 2591-2593.

[19] Coura D P, Leal E M. 4e Analysis of the Thermal Power Plant of a Coke Integrated Steelmaking Process. Available at SSRN 4065406.