

Systematic Review on Improving Performance of a Single-Spool Gas Turbine System Using Combustion Chamber Direct Water Injection

Azubuike John Chuku¹; David Abraham Moses²

¹ Department of Marine & Offshore Engineering, Faculty of Engineering, Rivers State University, Port-Harourt

² NNPC/Renaissance JV Centre of Excellence in Marine & Offshore Engineering, Rivers State University, Port-Harcourt

*Correspondents Author

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ABSTRACT

This study synthesizes prior research on performance enhancement of single-spool gas turbine systems through direct water injection in the combustion chamber. The review establishes that water injection effectively reduces nitrogen oxides (NO_x) emissions by suppressing peak flame temperatures and modifying combustion kinetics. Numerical and experimental investigations indicate that increasing water-to-fuel ratios improves combustion stability, augments mass flow rate, and enhances power output, albeit with a corresponding rise in specific fuel consumption. Comparative assessment of alternative optimization strategies, including regeneration, combined cycles, and inlet air cooling, reveals inherent trade-offs between efficiency gains, environmental performance, and operational constraints. Despite extensive studies, a critical gap remains in defining optimal injection parameters under varying operating conditions. This work therefore proposes a simulation-based framework for optimizing water injection in a 135 MW single-spool gas turbine, targeting improved thermal efficiency, reduced emissions, and enhanced overall performance.

Key words: Gas turbine; Single spool; Combustion chamber; Direct water injection, etc

INTRODUCTION

The growing escalation of energy needs has forced numerous scientists and researchers to conduct extensive research in the energy and power production especially in the inventions and optimization of the gas turbines. Their studies yielded exceptional results that form the basis of strength behind the energy industry. This chapter will explain the works of renowned scholars and technical professionals who have been involved in the performance analysis and evaluation of the energy systems in line with the proven engineering principles and practices. Energy is a basic requirement when it comes to different activities because it is one of the key ingredients that power people to existence and civilization. The increase in the human population has resulted to the need to increase energy demands and as a result this has been achieved by improving the use of energy and its efficiency irrespective of limited resources (Rao et al., 2007).

Ruly et al. (2023) performed a critical evaluation of the efficiency of a gas turbine power plant in Jambi, Indonesia, to establish the underlying causes of the reduction in power production and the growth of fuel consumption. They perform necessary checks of the control systems in the plant to measure their operation and do parametric analysis of the working data to determine the thermodynamic performance of the gas

turbine. It was found that the efficiency of the plants had reduced because compressor blades were clogged and that other turbine flow channels were blocked and thus could only be completely cleaned by cleaning the turbine internals. The system was reinstalled but the optimum operating parameters of the plant were not considered when restoring the system. Moreover, the changes in the air filtration system in the compressor inlet will be done to reduce the external pollutants that cause blade contamination in the turbine.

Agbadede et al. (2020) conducted a comprehensive experiment of the impact of water injection on the emissions of nitrogen oxide (NO_x) to the combustor of an aero-derivative gas turbine. The focus of their study was to counter the environmental problems that are caused by NO_x molecules which are typically generated at high levels of combustion and are considered to be some of the key pollutants in the atmosphere. Over the years, many methods of minimizing NO_x emissions by gas turbines have been explored and water injection is one of the methods that can be considered effective.

The investigators used numerical modeling to model the behavior of a twin-shaft aero-derivative gas turbine in which GasTurb simulation software was used to simulate the performance of an engine. The RTA turbine model was based on GE LM2500 series which is a widely established type of gas turbines. To evaluate the effectiveness of water injection, they did various ratios of water/fuels 0.0-0.8 in small steps of 0.2 directly in the combustion chamber.

As the results of the simulation showed, there was a clear tendency, the higher the water-to-fuel ratio, the less the severity index of the NO_x emissions, which means the successful decrease in the harmful substances. The lowering was attributed to a lower flame temperature because of the injected water which disrupts the thermal environment necessary to generate NO_x. The paper has observed that the rate of heat and the power output to the shaft of the turbine increased as the level of water injection increased. This improvement in performance came at the cost of high fuel consumption and there is a need to balance between pollution control and energy effectiveness.

Dayyabu et al. (2018) conducted an extensive analysis of the effect of the water droplet injection on the functioning of a complete gas turbine system with Computational Fluid Dynamics (CFD) as their primary modeling tool. Their study attempted to examine the possibility of altering the thermodynamic characteristics and efficiency of the turbine by water addition into its working cycle. By comparing the conditions with water injection and the ones when the dry compression is used, the researchers have managed to detect a significant performance difference that is connected to the presence of the water droplets.

The rate of water injection applied in the simulation was 0.5 to 3.0 to assess the level of impact at the different levels of operation. The results had significant effect on the engine performance even when minor water was added. The presence of water droplets also led to a higher inlet mass flow rate which enhanced pressure ratios during the compression as well as the expansion cycle of the turbine. This had an improvement in terms of a measurable increase in engine performance and thermal efficiency, which was mainly due to the ability of water to absorb heat and reduce the severity of radiative energy inside the combustion chamber.

Besides, the paper highlighted numerous environmental and operational benefits associated with water injection. One such conclusion was that a reduction in relative specific fuel consumption, which indicates improved fuel efficiency at water-assisted conditions. Additionally, the existence of water helped to reduce temperatures on both the combustor and turbine exits that is fundamental to keeping materials intact and prolonging the lifespan of the components. It was found that there was a marked decrease in the level of nitrogen oxide (NO_x) which was one of the major emissions caused during high-temperature combustion. The drop was attributed to the cooling effect of the water that suppressed the thermal environment necessary to produce NO_x.

The paper emphasizes the effectiveness of water droplet injection as a viable attempt to enhance the performance of gas turbines at the same time eliminating the environmental problems. Their findings have

great importance on the thermofluid mechanics of turbine systems, and they can help in the further development of the more efficient and less polluting power generation and technology.

Lebele-Alawa et al. (2015) have implemented a transformational engineering project to enhance the operational performance and energy production of a 25MW gas turbine power plant originally intended to operate on a single-cycle mode and in a dry state. To address the limitation of this arrangement, in terms of energy recovery and total efficiency, the researchers redesigned the plant as a combined cycle system with a steam bottoming cycle. The retrofit was achieved through the installation of Heat Recovery Steam Generator (HRSG) which recovers and re-uses the thermal energy in the waste gases that are emitted by the gas turbine. The design also significantly lacked the use of a duct burner, thus classifying the upgraded system as a cogeneration system that produces electricity and useable heat energy of the same fuel source at once.

This strategic change was pegged on the development of a thorough thermodynamic model that was meant to develop the specific operating conditions and performance parameters of the existing gas turbine. The model was used to model the behavior of the proposed combined cycle setup in the application of the MATLAB, which is a powerful computational instrument of the engineering study. The simulation generated critical thermodynamic information which approved the feasibility and effectiveness of the retrofit. This adaptation led to a significant raise in the power production; 25MW to 37.9MW. This was achieved with no proportional increase in fuel consumption or other pollutants, indicating the efficiency gains achieved due to the use of waste heat of the gas turbine to create steam to run an auxiliary steam turbine. The two-turbo system increased the power conversion and further encouraged a more sustainable and environmentally friendly process of power production.

The paper was aware that adding additional heat by means of external sources like a duct burner could help to increase power production, although it was deliberately not included in the scope of the research. The focus was kept on maximizing performance with the fuel supply and infrastructure that were available, thus demonstrating the effectiveness of combined cycle retrofitting as a cost-effective and energy-efficient approach to the upgrading of the existing gas turbine stations.

Reale et al. (2021) performed a numerical study of the performance characteristics of micro gas turbines that use hydrogen-enriched fuel, specifically the role of water and steam injection on the generation of energy and the environmental impact. Their study aimed at enhancing both operational performance and sustainability of micro gas turbine system by undertaking two simultaneous design changes: enriching the traditional methane-driven fuel with hydrogen and moistening the turbine system by carefully adding water and steam into the turbine system.

The computational fluid dynamics (CFD) was used to model and analyze the dynamics of the combustion in the turbine. The simulation demonstrated that fuels enriched with hydrogen offer great benefit, especially in reducing the amount of greenhouse gases emitted and in improving combustion efficiency especially of fuels with a low Lower Heating Value (LHV). However, the researcher has pointed out a major shortcoming in that most of the micro gas turbines are not inherently designed to use fuels with high concentrations of hydrogen. Unless appropriate structural changes are conducted, these turbines experience difficulty maintaining stable and safe combustion with high concentrations of hydrogen.

The authors examined the effect of humid air and water injection on the stabilization of the combustion process. Their results showed that the addition of moisture to the system, through direct water injection or steam injection, have the potential to significantly increase combustion stability, increase power production, and enhance thermal efficiency of the plant. The water in the combustion chamber cools down the temperatures of the flames and enables a sharper and more controlled combustion rate.

Following CFD studies showed that raising the level of hydrogen proportion in the fuel blend to 30 percent by volume is safely and effectively achievable as long as steam injections are carefully regulated. The

experiment concluded that maintaining mass flow rate of a steam injection up to 125% relative to the flow of fuel was necessary to maintain a consistent and reliable rate of combustion under such circumstances.

The way ensured that the work of the micro gas turbine system is safe and at the same time improved efficiency. The study identifies the opportunities of using hydrogen-enriched fuels in conjunction with the latest humidification technologies to increase the energy and environmental performance of small gas turbines. They also make their findings to be of great importance in design and optimization of the next-generation turbine systems that will run effectively on alternative fuels, as well as covering the pressing need of cleaner and more sustainable energy solutions.

Galdo et al. (2020) performed a numerical research to investigate the ways of reducing nitrogen oxide (NO_x) emissions in diesel engines, based on comparing ammonia and water injection processes. They used the Wartsila 6L 46 commercial marine diesel engine as the focal point of their studies and applied the simulations available in computational fluid dynamics (CFD) in studying the effects of the different strategies on the formation of NO_x when direct injecting a mixture into the combustion chamber. The primary aim was to determine the effectiveness of ammonia injection as an alternative to water considering its ability to interact with combustion gases and reduce the emission of NO_x.

To isolate and study the mechanism of specific reduction of NO_x, the researchers used an artificial inert species method. In this method, inert substances that resembled the physical characteristics of water, ammonia and air were used and allowed individual analysis of the chemical, thermal and dilution effects of each injection process. In this manner, they would better understand the effect of each variable on emission control in the absence of combustion reactions. This approach was used to explain the different roles that chemical reactivity, thermal absorption, and gas dilution played in the reduction of NO_x.

It was shown that ammonia injection proved to be most effective when introduced in the expansion stroke of the engine cycle. Chemical reaction between ammonia and combustion byproducts is maximized leading to a significant reduction in NO_x. The effects of ammonia heat and dilution were also observed to be insignificant at this stage implying that the major strength of ammonia lies in its chemical reactivity. The given finding indicates the importance of proper timing when using ammonia as an NO_x-reducing agent.

On the other hand, water injection showed an increased reduction in NO_x, which was observed at the top dead center (TDC). Water at this point in the cycle is the main agent in the process of controlling emissions due to a thermal effect that cools the combustion chamber and the second factor of controlling the emissions is through the dilution of the gases of the reactants. It is worth noting that, the heating, as well as the diluting effects of ammonia increase when it is added at TDC, but the overall reduction of NO_x is worse than that of water. Such an analogy highlights the complexity of every fluid and emphasizes the need to tailor the injection time and approach in terms of the specific features and mechanisms of the used drug.

Xue et al. (2015) conducted a comprehensive research to compare the introduction of the steam in an aircraft combustor with internal flow characteristics and the formation of nitrogen oxide (NO_x) during the use of Jet-A fuel. In order to achieve this they provided an integrated strategy of combining performance modeling with computational fluid dynamics (CFD) and chemical reactor network (CRN). Such a mixed technique allowed modeling complex processes in the combustor and the influence of the steam on the properties of combustion and the formation of pollutants.

The CFD simulation showed that when the steam is added to the combustion process, the flame temperature decreases much. The primary reactive species in the production of NO_x on the radical pool also migrated down the combustor due to the cooling action. The researchers incorporated these CFD findings with the CRN model to improve the accuracy of the prediction of the NO_x emissions under a variety of operating and operating conditions. The CRN was used as a critical tool in defining the chemical pathways that are involved in the formation of NO_x and quantifying the effect of steam on the reactions.

Further studies suggested that in cases where steam is mixed with air at very high levels, the region in which NO_x normally forms is moved to the post-flame region. Such spatial change reduces the NO_x emissions significantly, especially in the condition that the steam mass fraction is elevated. The findings further show that steam is an inhibitor of NO_x by altering the thermal and chemical environment within which the pollutants are formed. This effect increases with increase in volume of steam, which highlights its feasibility as an emission cutting method.

It is important to note that though steam injection has a major impact on the combustion temperature and formation of NO_x, its impact on the overall design of the flow field is relatively minimal. The steam that is injected mostly affects regions of high temperature without significantly altering the aerodynamic or structure of the airflow in the combustor. This also means that steam can reduce the pollutants without compromising the aerodynamic efficiency of the engine, which is very important in the aviation propulsion systems.

The comparison analysis conducted by Ighodaro et al. (2021) evaluated the effectiveness of a typical gas turbine cycle in comparison to different modified versions. Their query targeted important performance parameters such as thermal efficiency, specific fuel consumption and power output. These characteristics were modeled and analyzed by the researchers using DWSIM software to be able to model the simple cycle and advanced versions of the simple cycle, such as those with intercooling, warming and regeneration. This form of thermodynamic modeling provided a complete system of analyzing the effect of every change on the overall performance of the system.

The analysis showed that most of the modified cycles had improved thermal efficiency as compared to the simple traditional cycle. However, not every modification resulted in positive results, in some cases the thermal efficiency was lower than in the original system. Similarly, the differences in the use of particular fuel and power generation were observed across different combinations. The differences demonstrate that a complex relationship exists between design of the cycle and performance outcomes that not all the changes are beneficial across the board.

Of the tuned cycles, a number of configurations had gained important performance improvements, and thermal efficiency improvements of up to 65% under certain conditions. These results highlight the ability of integrated cycle designs to significantly increase the efficiency of operations of gas turbine systems. In any case, the study has shown that certain modifications like the use of an intercooler exclusively will lead to an overall drop in performance. This finding indicates that every improvement should not be evaluated in isolation, but as part of a system design process. The analysis comparison gives important understanding on the benefits of different types of gas turbine cycle topologies. The research measures the degree of improvement attributed to each of the adjustments, thus, informing the further design measures aimed at control of maximum efficiency and fuel consumption. It reiterates the importance of careful consideration of trade-offs because some innovations can uplift one aspect of performance and negatively impact another.

A thorough study conducted by Igoma et al., (2016) on the effect of ambient temperature on the performance of gas turbines was done using the Trans-Amadi power station Phase II as a study case. Their study involved the development of a thermodynamic model of gas turbine unit, based on actual operation data obtained in a period of 13 months of constant operation. This has been a substantial data on the relationship between the environmental temperature and the output of the turbines which has allowed researchers to come up with important insights on performance patterns when subjected to various thermal conditions.

The findings of the study revealed that there is a qualitative and measurable impact of ambient temperature on key performance indicators. Every one degree Celsius increase in ambient temperature led to a 0.12% loss in power production and power differential in the turbine. Moreover, thermal nature efficiency was declined by 1.17 per cent and the heat rate which is a measure of energy consumption required per unit output fell substantially by 27.18. The specific fuel consumption rose by 3.57, which is an indication that high

temperatures lead to reduced fuel efficiency. These results highlight how gas turbine systems are vulnerable to the environment and why temperature-sensitive processes should be used.

The determination found out that the optimal ambient temperature that would reduce the level of fuel consumption in the Trans-Amadi station was 30degC. This temperature gave the best performance to the turbine and this implies that there was a thermal sweet spot that can be used in future operational strategies. The researchers recommended the introduction of inlet air cooling sources, i.e. either misting systems or heat exchangers, to maintain or to reach this ideal state. Such systems can modify the temperature of incoming air, thus, balancing the combustion processes and improving the efficiency of the whole system. Ambient temperature is an important parameter that dictates the performance of gas turbines and needs to be a main factor in the system design and in the operation of the gas turbine. Their results endorse the integration of temperature regulation mechanisms into the elaborate plans to exploit the maximum power, reduce the costs of fuel, and enhance the reliability of turbine operations. The study has valuable contributions to the engineering of thermal power, as it focused on the importance of the environmental variables in the functionality of an energy system.

Ogbonnaya (2011) enhanced the utility of a gas turbine power plant through a computer based model of the engine, which was used to optimize performance of a gas turbine. Various data on operation were used to model the system and eventually simulated. The result shows that the total system efficiency has improved by 39.2 to 46.25 after the main maintenance. It was established that compressor fouling has a negative impact on the system, resulting in the reduction of the efficiency. To obtain the best performance of gas turbine, it is recommended that the operators combine the manual cleaning of the compressor with the offline and online washing. The air filtration system design is a very important aspect of the gas turbine that determines its performance based on the quality of air intake.

Aderibigbe et al. (2019) conducted a wide-scale performance evaluation of a 270MW gas power plant, which included nine units, each with a rating of 30MW. In their study they have focused on two main thermodynamic indicators which are exergy and heat rate to establish the performance of the plant. They attempted to quantify the degree of irreversibility in the system in different load conditions by looking at the amount of entropy generated in the various components. Such an approach provided a deeper understanding of the processes that have contributed to energy losses and how they affect the overall performance of the plant. The authors highlighted Exergy efficiency as a diagnostic tool used in the determination of important thermodynamic losses. Unlike the traditional energy assessments, exergy analysis takes into account the quality of energy and its ability to perform valuable work. Based on this view, the inquiry found factors in the plant, which made the greatest contribution in terms of inefficiencies. This made it possible to make accurate suggestions on how the system can be improved to make it more effective.

It was found that the major exergy destruction in every unit is in the combustion chamber. The result is consistent with the nature of the combustion processes, which inherently are highly irreversible due to the rapid chemical reactions and heat transfer. It was highlighted in the analysis that these losses needed to be reduced either by improved combustion methods or by design modification to increase thermodynamic efficiency of the plant. In addition to Exergy analysis, the paper highlighted the necessity of the understanding of the heat rate, that is, the amount of fuel energy consumed to produce one unit of electrical energy, of the plant. The researchers used the data of heat rate to correlate with exergy losses to obtain important information about the performances of individual components. This two-volume approach strategy provided a detailed view of the plant performance and generated practical recommendations regarding optimization of their operations.

Further, the research showed that evaluation of the performance in a variety of load conditions is important in studying the dynamic performance of the system. Load-dependent study showed how the different constituents reacted to the change in operational demand and this is necessary in the design of flexible and resilient power systems. The findings suggest that continuous evaluation and adaptive control procedures

could be necessary to maintain the optimum performance in different operating environments. The study presents huge information on the analysis of power plant performance. Their analysis offers a detailed approach to the definition of inefficiencies and the control of gas turbine system improvements by combining Exergy and heat rate data. The study will contribute to our understanding of thermodynamic behavior in large-scale power plants and provide some practical implications to engineers and operators who would like to maximize the conversion efficiency of energy.

Omar et al. (2017) conducted an in-depth investigation of how regeneration affects the work of gas turbines with a focus on the thermal efficiency of turbines and the generation of power. Their study used the operating data of the Al-Zawias power plant in constructing a thermodynamic model of the turbine system. The model was simulated in two conditions, with a regenerator and without a regenerator, to determine the effects of regeneration on overall cycle performance. Other extrinsic factors that were investigated include ambient temperature, regeneration efficiency and compression ratio that greatly affect the efficiency of the turbine cycle.

The results of the simulation showed that application of a regenerator into the gas turbine system had a great effect on the thermal efficiency and output power. This was enhanced by a reduction of exhaust gas temperature which indicated an increase in the efficiency of energy retrieval and utilization in the cycle. The effectiveness of the regenerator and ambient temperature were used to establish the magnitude of these benefits. The best performance improvements were observed using an exceptionally effective regenerator with optimal temperature settings, which indicated that optimization, is required in the system. Even though these advantages are present, the paper has also highlighted the possible drawbacks associated with regeneration. Of great concern is the fact that the heat recovery process increases the turbine inlet temperature. When improperly controlled, this high temperature may subject the turbine blades to thermal stress and may cause erosion of the materials and reduced service life of the components. This finding underscores the need to provide careful thermal considerations during the adoption of regeneration within the gas turbine systems.

Another risk that was noted in the study is the rise in the emissions of nitrogen oxide (NO_x) with high combustion temperatures. Temperature plays an important role in the production of NO_x, thus, the use of a regenerator can positively affect efficiency but has an unwanted effect on increasing the index of the severity of the NO_x of a system. The performance of the turbine against environmental impact trade off shows that controlling emission should be a major concern in the design and operation of the turbines. Omar et al. implore the introduction of emission indices as critical performance indicators, which ensure that improvement in efficiency does not translate to increased environmental harm.

The study provides a fair perspective on the importance of regeneration in the functioning of the gas turbines. The technology has very clear benefits as far as energy efficiency and power output are concerned, yet there are also problems related to thermal stress and pollutant emission. They have found the necessity of the holistic approach to turbines optimization considering both the technical aspect and environmental sustainability. The research holds much value in the mind of the engineers and decision-makers who are interested in ensuring that the efficiency of power generation systems is enhanced without compromising the integrity of operations and being environmentally responsible.

Hanna et al. (2016) carried out a large-scale study to evaluate the performance of a solar chimney power plant turbine by comparing experimental results to numerical models. The researchers put up a physical testing device right at the power plant to certify the reliability of their research results. This set up allowed them to test the performance of the turbine and its power generating characteristics under identical ambient conditions as those of the main facility. The experimental evaluation focused on such key performance indicators as turbine rotational speed (rpm), electrical power production and the efficiency of the turbines.

At the same time as the physical experiments, the team performed a numerical experiment with the help of ANSYS CFX 16.1, a commercial workflow on computational fluid dynamics (CFD). In this simulation, the

airflow in the turbine was simulated to reflect the overall performance of the system. The authors aimed to estimate the validity of the theoretical model by trying to simulate internal flow dynamics on the basis of their predictive power concerning life behavior. The experimental-numerical methodology allowed making a full comparison and provided better insight into the working nature of the turbine.

The results of the two methods showed a consistent power production of 1.2W to 4.4W. Trend in pressure drop was observed to increase simultaneously with turbine acceleration though the study had slight variation before the rotating speed exceeded 1800 rpm. This behavior signaled that there was stability at high speeds. The turbine achieved an average performance of 57 percent, which was acceptable to the system under considerations. The results confirmed that the theoretical model used in the CFD simulation was mainly true and could be reliably applied to predict the performance of the turbine.

Moreover, the high level of correlation between the experimental data and the calculations results highlighted the effectiveness of CFD in the modeling of renewable energy sources like solar chimney turbines. The study has pointed out that these simulations may also be used as a powerful design and optimization tool, which reduces the need to perform significant physical testing. The results obtained by Hanna et al. established that a combination of both experimental validation and numerical modeling can provide a solid framework of evaluating and improving the effectiveness of sustainable energy systems.

The use of solar thermal power generation in this study significantly contributes to the field since it offers a valid means of assessing the work of turbines. It reiterates the importance of the use of ambient-condition-matched experiments in ensuring realistic and practical results. The findings of the research suggest the greater use of CFD models in the investigations of renewable energy, specifically in systems when the environmental variables considerably influence the operational efficiency. There is limited integration of hydrodynamic optimization and firefighting performance, particularly regarding monitor recoil forces, stability, and station-keeping requirements (Chuku & Dilosi, 2026).

Zahid (2022) conducted a comprehensive research aimed at assessing how water injection affects the emission of nitrogen oxide (NO_x) in the aviation engines by a combination of numerical tools using the pyCycle performance tool. The computational fluid dynamics (CFD) software made it possible to carry out a thermodynamic investigation optimizing engine cycles based on a variety of water injection plans to be used in aircraft missions with different range capabilities. The study was founded on the assumption that the formation of NO_x emissions is majorly generated when there is high-temperature burning in the airplane engines significantly affecting the worsening of air quality. The aim is to determine the water injection which is used to reduce the emissions by simulating different conditions and ensure that there is no interference with the engine.

The findings showed that water injection particularly in turbofan engines could potentially reduce NO_x emissions by a maximum of 80 and still maintaining the fuel efficiency of the aircraft. This large reduction is attributed to the cooling effect of water which, in turn, lowers the combustion temperatures, and therefore, prevents the formation of NO_x. The locating of the water injection in the engine cycle is vital in determining the overall effectiveness of the water injection. The injecting of water before the compressor was beneficial as it would reduce the power used in the compressor, therefore enhancing the performance. On the other hand, adding water to the downstream of the compressor led to lowered fuel efficiency, and therefore a trade-off that needs ample care during the design and operation of the engine.

Later research established that the water injection effectiveness in reducing emission of NO_x is far more pronounced in engines that use rich front-end combustors compared to engines that use lean burn designs. It means that the combustion strategy used by the engine has a significant impact on the outcome of water injection interventions. In the case of short range missions, typically at less than 3000 kilometers, the extra weight of extra water is compensated by the performance improvement gains achieved through upstream injection. The balance is influenced by factors such as the amount of injected water and the particular design

of the combustor design of the engine highlighting the need to have custom solutions based on the mission profiles and engine design.

Conversely, over long range flights (more than 3000 kilometers) the weight disadvantage of water injection is often counterbalanced by the disadvantage of performance and water injection is a less efficient method of power addition. The trade-offs are more pronounced, in such cases, and the gains of the reduction of NO_x might not justify the costs of operation. The paper emphasizes the importance of a strategic implementation of water injection, as it depends on the duration of the missions, engine set up, and the location of injection to improve the environmental and performance outcomes.

The authors of the study carried out by Agbadede and Allision (2020) had a thorough numerical study, aiming to investigate the effects of water injection on nitrogen oxide (NO_x) emissions in a twin-shaft aero-derivative gas turbine combustor. Their analysis was based on a gas turbine which was the design after the GE LM2500 Class Engine which is a leading and a highly regarded type of gas turbine in the aviation and industrial industry. They made use of the GasTurb14 simulation software to model the performance of the engine in various conditions of operation, and thus, the behaviour of both the design point and the off-design point was modelled. Such approach has enabled the researchers to test how the engine will respond to water injection in different operating conditions that creates a comprehensive framework on how to test the effectiveness of the emission control measures.

The study focused on the direct water injection into the combustor and evaluating its effects at different levels of water fuel ratios. The researchers could change this ratio to see the changes in NO_x production under incremental changes in water content during combustion. The principle of this method relies on the thermodynamic principle according to which, before being introduced to the combustion chamber, water absorbs heat and decreases the temperature of the flame. Since the rate of NO_x formation is highly affected by temperature, it is possible to reduce NO_x emissions by lowering the maximum combustion temperature. Simulation results revealed a clear and consistent pattern: the higher the water to fuel ratio, the higher the corresponding reduction in the emissions of NO_x. This finding shows the effectiveness of water injection as a viable process of reducing adverse emissions in gas turbine engines. The reduction in NO_x was attributed to the cooling effect of water that does not only reduce the temperature of combustion but also change the chemical kinetics of the combustion reaction thus limiting the processes through which NO_x is produced.

More so, the paper has discussed the importance of maximizing the water- to- fuel ratio to achieve the maximum emissions reduction without compromising engine performance. The trade-offs between efficiency and pollution management were not thoroughly investigated in the study but provided the basis of the further studies on how to balance the benefits of the environment with operational needs. The given paper is very informative on the topic of sustainable engine design as it introduces a legitimate approach to reducing the amount of NO_x emissions in the aero-derivative gas turbines through the use of selective water injection.

Sharafoddini et al. (2021) conducted a detailed experiment of the effects of water vapor injection on the fuel consumption in a gas turbine combustion chamber. Using FLUENT computational fluid dynamics (CFD) software, they modeled a triadic geometry of the combustion chamber: the first part was air input nozzles and fuel injectors, the second part was the main body of the chamber and the third part was the exhaust outlet. The systematic modeling approach allowed performing a large-scale modeling of combustion dynamics in a variety of settings. The authors sprayed water vapor into the chamber using different types of fuels and varied the angle of air entering the chamber in order to investigate how these parameters influenced the combustion behavior and the efficiency.

The simulation assumed the simultaneous injecting of fuel and water vapor whereby the researchers could test their simultaneous effects on the thermal profile and the overall performance of the combustor. One of the main conclusions was the fact that the temperature distribution across the combustion chamber considerably decreased as a result of water vapor injection. At such a ratio as 8 water vapor to fuel, the overall

thermal efficiency of the system grew to 95 percent. This has been enhanced by the cooling effect of the water vapor which lowers the highest combined temperatures and creates more stable flame properties. This is critical in controlling temperature to ensure that the engine is more fuel-efficient and that it does not subject the engine parts to unnecessary thermal stress.

Later research showed that the carbon content of the fuel had a significant influence on the pattern of combustion and characteristics of the flame. Indicatively, butane which has a lower carbon concentration than hexane produced a flame which extended towards the chamber body indicating an extended flame spread. On the other hand, the octane, which has more carbon than hexane, had a shorter flame with a high-temperature core. These variances have been linked to the molecular structure of the fuels whereby the more the carbon atoms the stronger the combustion zones. The increased core of the flame has a direct effect on the formation of nitrogen oxides (NO_x) since higher temperatures will increase the formation of nitrogen oxides through thermal reactions.

The study further examined the localization of NO_x production in the combustor in mapping along the axis of symmetry. The results showed that the NO_x level peaked in the position of maximum temperature and gradually dropped in the exhaust as the temperature dropped. This trend highlights the climatic sensitive nature of NO_x formation and shows how one can inject water vapor as a remediation strategy. Gas turbines become more efficient and reduce the environmental impact through water vapor which lowers the combustion temperatures and reduce the number of dangerous emissions. The work provides important details on optimization of the design and operation of combustion chamber with regards to enhanced performance and sustainability.

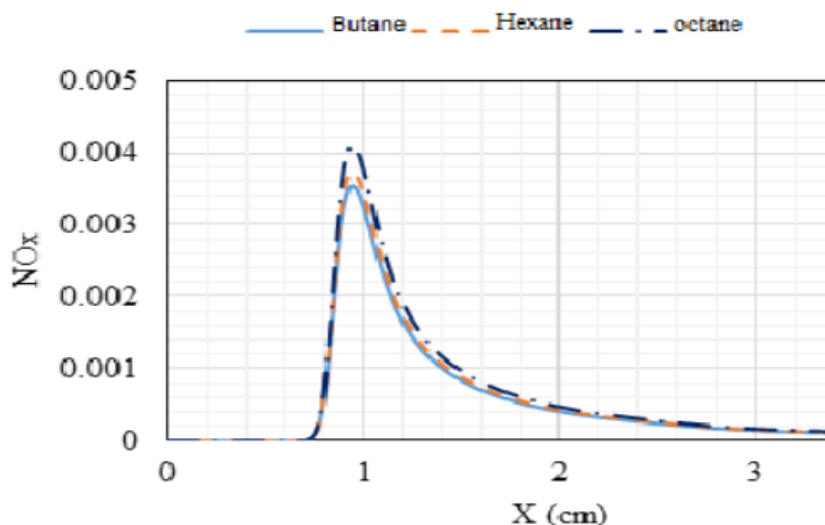


Figure 1: Plot of NO_x Formation Distribution against the Combustor Axis of Symmetry.

(Sharafoddini, et al., 2021)

Concept and Theoretical Framework of Gas Turbine

Gas turbines operate according to Brayton cycle. It is a thermodynamic model which simplifies complex real-life processes to a series of idealized reversible phases, providing a theoretical basis of gas turbine operation. Their effectiveness is best determined and contrasted with the help of a closed, perfect Brayton Cycle to become more efficient and create a corresponding benchmark (Cengel and Boles, 2015).

The theoretical Brayton system has four individual processes and each of them is internally reversible, which means that they occur and no energy is lost due to friction and other inefficiencies. These are normally described in terms of two kinds of thermodynamic diagrams, which include: Pressure v Specific Volume (P-

v) diagram and Temperature v Specific Entropy (T-s) diagram, as is illustrated in figure 2 below. T-s diagram comes in handy when it comes to assessing thermal efficiency.

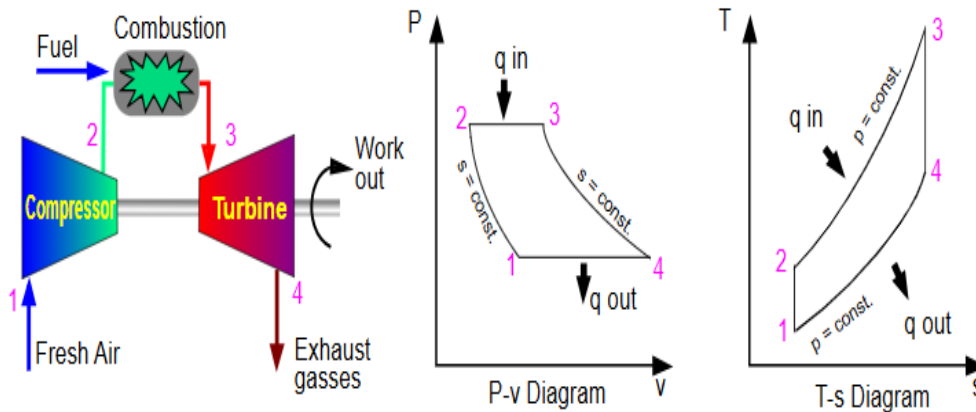


Figure 2: Shows Working Cycle in a Gas Turbine

Figure 2 below depicts Isentropic Compression (Process 1-2) of the working fluid to produce a high-pressure and high-temperature fluid where a loss due to friction and turbulence is assumed to be zero. The temperature of the fluid is greatly raised due to the work done in it (W_c). The metric that is significant in this scenario is the pressure ratio (r_p), and this has a significant impact on efficiency of the cycle. In the isobaric or constant pressure addition of heat (Process 2-3), hot pressure air goes into the combustor where it burns its fuel injecting heat energy but without changing pressure. The outcome of this process is a significant rise of temperature and volume of the gas, and the pressure remains unchanged. The reaction is isobaric, which means that the pressure does not change but instead the energy of combustion plays a significant role in enhancing thermal and physical properties of the air flow. The top cycle temperature, T_3 , is an important parameter which is limited by the metallurgical constraints of the turbine blades and other inner parts of the turbine. Isentropic Expansion (Process 3-4): The gas exiting the combustor is of high-energy, which mixes and passes through a turbine. The gas causes a work on the turbine blades (W_t), and it causes the turbine rotor to rotate. This production is considered to be a drop in the pressure and temperature.

In the final stage of the cycle also known as the isobaric or constant-pressure heat rejection (Process 4-1), the system releases heat to the outer world. This process is essential in the process of restoring the working fluid to state, so that the cycle could resume again. Even though the temperature and energy content is decreasing, the pressure is independent of this process and allows a smooth and continuous change and continuity in the thermodynamic cycle under constant pressure (Q_{out}). In the open-cycle engine, this can be said to be the exhaust stage where the spent gases are released to the atmosphere and replaced by fresh air intake (Saravanamuttoo, et al., 2001).

Concept of Thermal Efficiency Pressure Ratio of the Ideal Brayton Cycle

Thermal efficiency (η_{th}) is a factor showing how effectively a heat engine makes use of the fuel energy to produce useful work. It is one way of determining the efficiency of the engine in using the thermal energy produced by the combustion of fuel. The rate at which the engine works will be compared to the overall heat input in the fuel in order to determine efficiency. The higher the ratio the higher is the efficiency of the engine in terms of utilizing the fuel energy into mechanical power.

$$\text{Thermal Efficiency}(\eta_{th}) = \frac{W_t - W_c}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \quad (1)$$

For the ideal Brayton cycle, after algebraic manipulation using the constant specific heat assumption and the isentropic relationships for an ideal gas, this simplifies to:

$$\text{Thermal Efficiency}(\eta_{th}) = 1 - \left(\frac{1}{r_p}\right)^{\frac{(\gamma-1)}{\gamma}} \quad (2)$$

Where:

r_p = pressure ratio (P_2/P_1)

γ = ratio of specific heats (C_p/C_v) for air at room temperature.

The formula is of the critical importance. Two main factors which depend on the pressure ratio and the working fluid properties determine the efficiency of the ideal Brayton cycle in transferring heat to useful work. The engine performance is enhanced with the difference between high and low pressure of the cycle and the optimum choice of the fluid used in the transfer of energy in the system. These indirectly affect the amount of energy which can be obtained out of the fuel and turned into mechanical power. It has a monotonically rising pattern with the pressure ratio as shown in Figure 2. The main motivation behind the ongoing pursuit of high compressor pressure ratios during the gas turbine design is that it directly affects the potential future improvement in efficiency (Cengel and Boles, 2015).

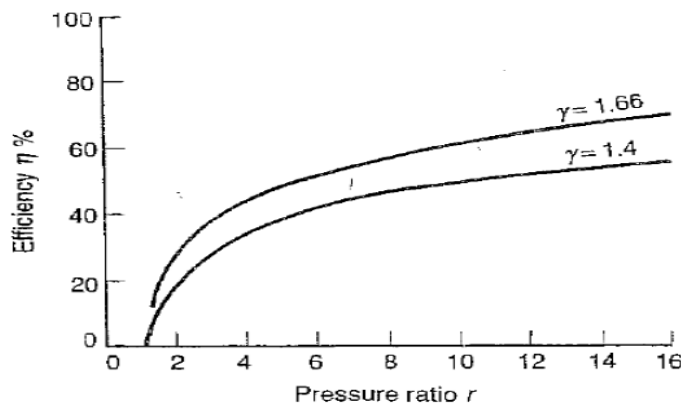


Figure 3: Relationship between Thermal Efficiency(η_{th}) and Pressure Ratio (r_p)

(Cohen et al.,1996).

Concept of Net Work Output and Optimum Pressure Ratio

The use of the fluid moving out of the turbine is the sum of all the beneficial work (expressed in the fluid pressure head) and this is denoted as the GT network. Efficiency always increases with the pressure ratio but the same cannot be said of the network output. At a given input gas turbine temperature (T_3), there is a specific ratio of pressure which gives maximum net power output. This is a vital consideration to engines designed with maximum power as opposed to maximum efficiency. The network output curve peaked at the high compressor work at high pressure ratios that greatly reduced the output of the turbine thereby creating insignificant network availability (Cohen et al., 1996).

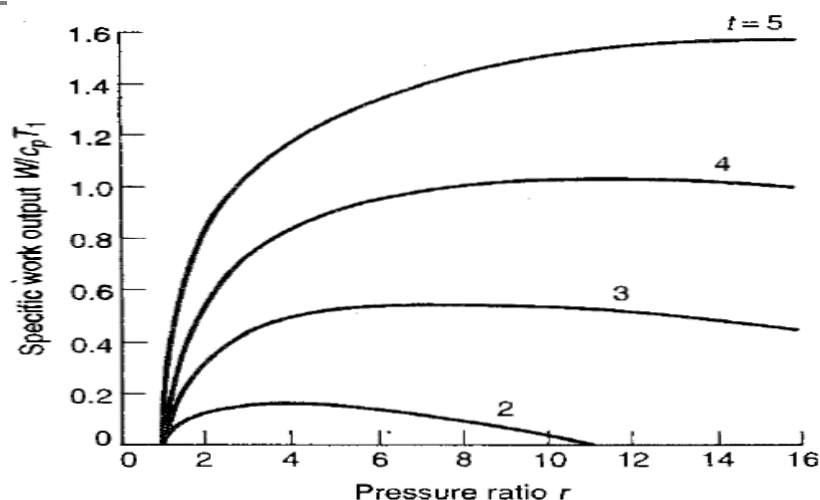


Figure 4: Relationship between Specific Work Output(W) and Pressure Ratio (r_p)

(Cohen et al., 1996)

Components of Gas Turbine

The realisation of the Brayton cycle requires sophisticated parts that are designed to handle high pressure, temperature and centrifugal force. The gas turbines are made up of three major components which work together to create power: The compressor which forces the incoming air to high pressure; the combustion chamber (or combustor) where the fuel is ignited to create thermal energy, and the turbine which uses the energy available in the hot gases to perform useful work. These parts are the key principles of operation of gas turbines.

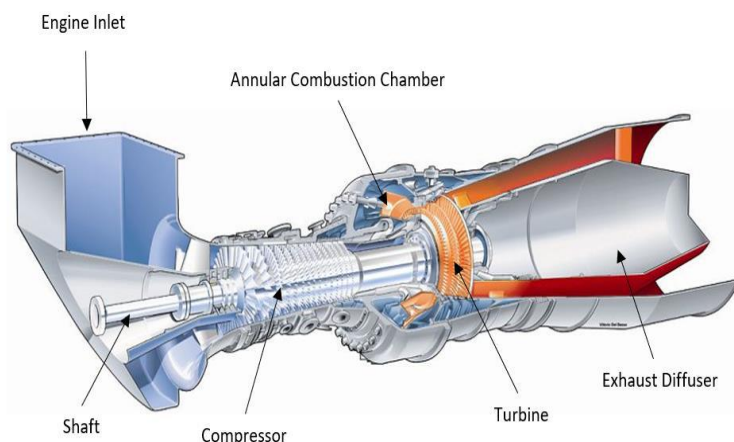


Figure 5: Schematics of a Gas Turbine Showing Essential Components (Cohen et al., 1996).

The Compressor

The compressor also provides the combustor with the amount of high-pressure air that is required, and consumes energy during the compression process. The centrifugal and axial compressors are the two major types of gas turbines due to their ability to offer a continuous and high-velocity supply of air through the system at a relatively high pressure. Gas turbines use either centrifugal compressors or axial compressors, which can be categorized as dynamic compressors also referred to as turbo-compressors. Their design is such that they are capable of controlling large volumes of air and increasing the pressure of the air and making

them invaluable to the super-optimal functioning of turbine engines. because of the fact that they impart a continuous velocity to the air, which is pressurized.

A centrifugal compressor can be made up of one outer casing (stationary) and one rotating impeller (rotating). When the impeller rotates, it is a force that drives an air towards the inside at high speed. The high speed air then follows a series of non-moving, spreading ducts which slow it down. The air slows down in these divergent channels and therefore the more the air is at rest, the higher its weight is, which increases the effectiveness of the compressor to increase the engine-usage air pressure. They are simpler and more resilient but cannot be used in larger engines because of the limiting frontal and mass flow (Dixon, et al., 2014).

An axial flow compressor is a structure that comprises of many stages with two basic components in each stage and these components are a series of rotating blades known as rotors, these blades propel the air forward and a series of stationary blades known as stators that direct and streamline the movement of the air. This alternating mode makes it easy to maintain a constant increase of air pressure as it passes through the compressor making it extremely efficient in high-velocity engines. The stages are symbolized by each row, and the pressure ratios are induced by each step. A modern axial compressor can have over 15 stages in the high-pressure compressor. Axial compressors have high efficiency and can handle very large air mass flows making them suitable to large aviation and power generation turbines (Cumpsty, et al., 2015). Axial compressors are never as efficient as ideal, and they lose aerodynamically through friction, shockwaves and flow separation. High compressor efficiency is very important to the overall performance of gas turbines (Dixon et al., 2014).

The Combustion Chamber (Combustor)

Constant-pressure heat addition occurs at the combustor and this occurs in Figure during process of 2-3. The design poses a complex engineering problem that involves fluid mechanics, heat transfer and combustion chemistry. The basic requirements of the combustion chamber in order to have the ideal performance of the gas turbine are:

a) High combustion efficiency which guarantees full combustion of the injected fuel.

Keeping the pressure difference between the compressor outlet and the turbine inlet at a low pressure when the air flows through the combustion chamber is important in ensuring that the engine is optimized. Under this segment when pressure is kept relatively a constant, then the system will be able to run on a more efficient system that ensures that the turbine is supplied with the necessary volume of air rich in energy to generate the best power without any unnecessary wastage.

Combustion should not become unstable and the flame should be kept in the required operating conditions to prevent knocking.

d) The product coming out of the combustion device into the turbine should maintain a stable temperature distribution to prevent excessive heat concentration in any of the internal components.

The compressed air flowing into the combustor is not only used to burn it rather it is separated into main and secondary streams. The main air was mixed with fuel and directly burnt in the recirculation zone, which was assured of full combustion. The secondary or diluting air cools the products of combustion to the correct degree of the turbine inlet. Can-annular and totally annular combustors are available and mostly the latter type is used in modern engines due to its robust design and uniform casing (Lefebvre, et al., 2010).

The main types of traditional combustors are referred to as a diffusion flame or non-premixed combustors, which combines simultaneously fuels and air during combustion. This results in regions of un-stoichiometric proportions of air-fuel. This will result in high peak flame temperatures that trigger high thermal NO_x

production. Dry-low emissions (DLE) combustors were developed to meet the environmental requirement. The DLE combustors work through a process that is termed lean-premixed combustion. This shows that the fuel is carefully and evenly mixed with air in lean mixture before it is burned in a mixture that contains more air than fuel. Having a consistent mixture of fuel and air is not too rich and improves the combustion process leading to high efficiency and less unwanted emissions like nitrogen oxides. The lean mixture burns in a lower and more uniform temperature, therefore reducing the thermal NO_x formation (Lieuwen, et al., 2013).

The Turbine

The turbine works by taking the energy of the hot and high pressure gases that are released by the combustor. The growth and flow of the gases through multiple rows of blades cause the rotation of the turbine, which is enforced by the principle of response. The main role of a turbine is to utilize energy as a means of driving the compressor, though, at the same time, it also generates useful mechanical work that can be utilized elsewhere in the system. Turbines are similar to compressors, and they may be centrifugal turbines or axial turbines, though the latter are mainly applied on large engines. As per the plant arrangement, some of the gas expansion happens in the high-pressure turbine which has a sole duty of propelling the compressor. The remainder of the expansion is in a separate free turbine that is not connected to the compressor but serves to drive a secondary load, i.e. a generator or propulsion.

The high temperatures in the turbine inlet and the high load in the rotating blades, make use of complex metallic alloys to make the interior parts of the turbine. Such specialty materials are designed to withstand higher temperature levels and mechanical pressures that ensure durability and reliability in tough conditions. All these operational conditions give rise to complicated design challenges and require sophisticated cooling systems as a means of efficient use of cooled air that is taken off the compressor. Some of the compressed air is used to cool the internal passages of the blades and vanes which form protective layers of cool air on the surfaces of the blades and vanes (Dixon, et al., 2014).

Limitation of Reviewed Works

The constraints that were found in the reviewed articles are to injected water composition and injection rate. Also, the difficulty is associated with the accurate model of the complex thermofluid mechanics of the combustion processes. The assumed boundary conditions and other sources of losses that are not calculated cause distortion of accurate predictions of performance indicators. A major weakness of recent studies is that they are sensitive to the short-term changes.

Knowledge Gap

Significant information gaps persist concerning the performance enhancement of gas turbine power plants. There is inadequate comprehension of the performance enhancement of a basic gas turbine functioning at temperatures below the specified turbine inlet temperature, while producing shaft power beyond the rated output and maintaining NO_x emissions below the required threshold. Agbadede and Allison (2023) performed simulations on a twin-shaft aero-derivative gas turbine utilizing GASTURB software. They adjusted the water-to-fuel ratios from 0 to 0.8 and noted decreases in the NO_x severity index. The study did not establish an optimal injection ratio; rather, it provided a spectrum of effects, so reinforcing the assertion that several investigations depend on technical assumptions without identifying optimal values.

Current Research

This study provides critical insights for improving the performance of a 135MW single-shaft gas turbine engine through the direct introduction of water into the combustion chamber. The method emphasizes the utilization of water injections to enhance efficiency and maximize engine performance. The performance criteria include Power Output, NO_x Severity Index, Specific Fuel Consumption, Thermal Efficiency, Heat

Rate, and Turbine Inlet Temperature, which are assessed using numerical simulation with GasTurb15 performance software. The performance metrics were assessed in normal operational mode without water injection, while the water injection mode evaluated a range of water-to-fuel ratios to ascertain the optimal injection ratio. The simulation data were exported to MS Excel for subsequent analysis and display.

OBSERVATIONS AND CONCLUSION

Observations

The reviewed literature consistently identifies water injection as a critical mechanism for controlling combustion temperature and mitigating NOx emissions in gas turbine systems. The dominant mechanism involves thermal dilution, whereby injected water reduces peak flame temperature and suppresses thermal NOx formation. Numerical simulations and experimental studies demonstrate a strong correlation between increasing water-to-fuel ratios and decreasing NOx severity indices. In addition to emission reduction, water injection improves combustion stability by moderating temperature gradients and enhancing flame uniformity. Furthermore, increased mass flow rate associated with water addition contributes to improved turbine expansion characteristics and, in some cases, higher power output. However, these benefits are offset by increased fuel consumption due to reduced combustion temperatures and altered thermodynamic efficiency. This establishes a fundamental trade-off between environmental performance and fuel economy. Overall, water injection emerges as an effective but highly parameter-sensitive technique, requiring careful optimization to balance emissions reduction with thermodynamic performance and operational efficiency.

Conclusion

The literature demonstrates that direct water injection is an effective approach for reducing NOx emissions and improving combustion stability in gas turbine systems. Its impact on thermodynamic performance is complex, offering potential gains in power output while introducing trade-offs in fuel consumption and efficiency. Compared with alternative enhancement techniques such as regeneration and combined cycles, water injection provides a more flexible and cost-effective solution, particularly for retrofitting existing systems. However, its effectiveness is highly dependent on precise control of injection parameters and operating conditions.

A critical gap remains in defining optimal water injection strategies that simultaneously maximize efficiency, minimize emissions, and ensure operational reliability. Existing studies are constrained by reliance on simplified models and limited multi-objective optimization. This study addresses these limitations through a simulation-based evaluation of water injection in a 135 MW single-spool gas turbine using GasTurb. The findings are expected to provide a systematic basis for optimizing performance parameters and advancing sustainable gas turbine operation under modern energy and environmental requirements.

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