Enhancement of Gas Turbine Efficiency by Using Recuperator and Intercooler Systems /Original Article

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تعزيز كفاءة التوربينات الغازية باستخدام أنظمة الاسترجاع الحراري والتبريد البيني

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Abstract

High power density and operational flexibility make gas turbines an indispensable part of contemporary energy conversion systems. However, in the simple cycle configuration, the thermal efficiency is generally low because the exhaust heat loss is large and the compression work is high. The current investigation is focused on enhancing the thermal efficiency of a gas turbine by the introduction of two augmentation schemes, namely a recuperator and an intercooler.

A numerical and thermal simulation study was carried out to model the gas turbine cycle based on the first and second laws of thermodynamics. Simplicity and Modified cycles Performance of simple and modified cycle are investigated. The results showed that the recuperator raised the thermal efficiency of the overall system by about 6–10%, and the compressor work was alleviated by the intercooling system by about 12%. A maximum improvement of about 15% for the overall efficiency was obtained from the application of both schemes simultaneously when compared to the simple cycle.

The results verify that the parallel use of a recuperator and intercooler is a feasible and attractive alternative for increasing the energy output of a gas turbine. The integration process will be very valuable for application in Iraqi gas power plants to enhance fuel economy and sustainable energy generation.

Keywords: Gas turbine, thermal efficiency, recuperator, intercooler, numerical analysis, thermal simulation

المستلخص

تُعدّ التوربينات الغازية من أهم منظومات تحويل الطاقة في التطبيقات الصناعية ومحطات توليد القدرة الكهربائية، وذلك لما تتميز به من كثافة قدرة عالية ومرونة تشغيلية كبيرة. إلا أن كفاءتها الحرارية في دورة التشغيل البسيطة تبقى محدودة نسبيًا، نتيجة الفواقد الحرارية الكبيرة المصاحبة لغازات العادم، إضافة إلى الارتفاع الكبير في الشغل المستهلك من قبل الضاغط. يهدف هذا البحث إلى تحسين الكفاءة الحرارية للتوربين الغازي من خلال دمج نظامين لتحسين الأداء، هما نظام الاسترجاع الحراري (Recuperator) ونظام التبريد البيني (Intercooler).

أُجريت دراسة تحليلية عددية ومحاكاة حرارية لدورة التوربين الغازي اعتمادًا على القانونين الأول والثاني للديناميكا الحرارية، حيث تم نمذجة وتحليل أداء أربع حالات تشغيلية مختلفة تشمل: الدورة البسيطة، دورة مزودة بمسترجع حراري، دورة مزودة بنظام تبريد بيني، والدورة المركبة التي تجمع بين النظامين معًا. أظهرت نتائج المحاكاة أن استخدام المسترجع الحراري أدى إلى رفع الكفاءة الحرارية للنظام بنسبة تراوحت بين (6–10%) نتيجة الاستفادة من حرارة غازات العادم في تسخين الهواء الداخل إلى غرفة الاحتراق. كما بيّنت النتائج أن نظام التبريد البيني أسهم في تقليل شغل الضاغط بنسبة تقارب (12%)، مما انعكس إيجابًا على القدرة الصافية المنتجة.

وقد تحقق أعلى تحسن في الأداء عند دمج النظامين معًا، حيث بلغت الزيادة الكلية في الكفاءة الحرارية حوالي (15%) مقارنة بالدورة البسيطة، إلى جانب انخفاض ملحوظ في درجة حرارة غازات العادم وتحسن القدرة الصافية للنظام. تؤكد نتائج الدراسة أن الاستخدام المتزامن للمسترجع الحراري والتبريد البيني يُعد خيارًا هندسيًا فعالًا وقابلًا للتطبيق العملي لرفع كفاءة التوربينات الغازية وتحسين استغلال الطاقة. كما تُعد هذه المنظومة مناسبة بشكل خاص للتطبيق في محطات توليد الطاقة الغازية في العراق، لما لها من دور مهم في تحسين اقتصاد الوقود وتقليل الفواقد الحرارية وتعزيز استدامة منظومة الطاقة.

الكلمات االمفتاحية: التوربين الغازي، الكفاءة الحرارية، المسترجع الحراري، التبريد البيني، التحليل العددي، المحاكاة الحرارية

1. Introduction

Gas turbines play a key role in thermal system applications to directly convert chemical energy of fuel into mechanical energy at the rotating shaft, which is then connected to a generator to produce electricity, or to a compressor or to other types of loads (e.g., for aircraft or ship propulsion). They exhibit a very high-power density over a wide range of loads and can be started quickly and maintained easier than steam turbines [1]. With the development of energy generation technologies in recent decades, worldwide attention has progressively been directed at enhancing the thermal efficiency of the gas turbine based on the ever-growing fossil fuel prices and the need to minimize the emission of gases harmful to the environment [2]. Although gas turbines are extensively applied in power plants around the world, their thermal efficiency is still limited when operating in simple cycle mode, which is about 30% –35%. This is mainly caused by the loss of a large amount of thermal energy carried away by exhaust gases at high temperatures over 500°C [3]. This large heat loss has been invited the researchers to proposed auxiliary systems to recover a fraction of the wasted heat to increase the overall efficiency of the thermal cycle without significant end modifications of the basic turbine components.

Among the most now a day s widely used engineering measures to realize this objective is the use of recuperators, which are heat exchangers that recover the heat of the hot exhaust gas to the compressed air going toward the combustion chamber. The air temperature is increased prior to combustion and so less fuel is needed to attain the same operating temperature [4]. It has been experimentally proven that thermal efficiency would increase by about 5 to 10% depending on heat exchanger effectiveness and the temperature of operation [1].

There is also the intercooling mechanism, an additional critical technological strategy that further increases the gas turbine effectiveness. The general rule is that the system is considered in multi -stage compressors, cooling the air between stages upon leaving the first stage and entering into the second one. Decreasing the work of compression by cooling the air compressing [5,6]. Thermal modeling results have suggested that due to the reduction in mechanical power needed by the compressor, intercooling may increase the overall performance of the plant as well as the economic feasibility [3].

The recuperator and intercooler concept is a high-level engineering design solution to realize high efficiency and low emission gas turbine cycles. The recuperator serves to recover waste heat in the exhaust gases, while the intercooling minimizes the power required by the compressor, leading to an increase in the net output of the cycle as a whole [2]. Thermal design investigations show the coupling of the two processes can raise the overall cycle efficiency by up to 15% compared to the simple cycle without major influences on the fabrication or maintenance cost [4].

The practical implication of the current study is derived from the fact that Iraq is at present trying to enhance and improve the working efficiency of its power generation system in order to keep up with the soaring demand of electricity with minimum fuel consumption loss. Most Afghan gas plants have already been fitted with simple cycle; thus, the thermal losses are high and the output power is low. Consequently, the introduction of recuperator and intercooling systems constitutes a step in the right direction for enhancing the energy conversion efficiency and the sustainability of the power sector [7]. Hence, this study is focused on the analysis of the integrated effect of recuperator and intercooling configurations on gas turbine efficiency through the develop- ment of a mathematical model based on the first law of thermodynamics along with thermal simulations and numerical calculations by utilizing com- mercial engineering software. The goal is to predict the increase in efficiency and network output due to the application of such systems for a wide range of operating conditions.

The results of this study are anticipated to contribute to the design of a new generation gas turbine in Iraq and give realistic advice to the energy sector authorities to how and if such systems can be implemented in national power stations.

1.1 Problem of the research

As result of high operating temperature and speed of response to energy load, gas turbine has become one of the key building blocks in power generation systems. However, an important limitation to its application is the fact that its thermal efficiency is much lower than that of other energy conversion systems, such as steam turbines or combined-cycle systems [8]. Decrease in efficiency is ascribable to the loss of considerable heat with exhaust gases and to the high work consumed by the air compressor which causes a decrease in the net power output and increase in the rate of fuel consumption [9].

For a long time, from the engineering point of view, the problem has been whether the thermal and dynamic design of the gas turbine could be improved by introducing auxiliary systems, such as the recuperator and the intercooler, which enable to regain a portion of the lost heat and also to lessen the compression work [6]. However, majority of these works address general theoretical and/or experimental models based on ideal working conditions and no elaborate numerical analysis or thermal simulation which are specifically designed for the actual operating conditions of Iraqi gas power plants, subjected to severe environmental conditions with ambient temperature surpassing 45•c in summer season have been reported [10].

The problem of this research is clearly the poor performance of gas turbines in Iraq because they work on simple cycles without thermal efficiencies or working systems. This imperfection causes large energy losses and degradation in the economic and environmental performances of the power generation station. Hence the fundamental question of research is: What are the limits of predictive power of theory if it is based on physical reality?

To what extent can systems of recuperator and intercooling improve, in terms of usability, thermal efficiency and plant performance of gas turbines by a real numerical model and thermal simulation?

1.2 From this main question stem a number of other questions are born

1. What is the gain in thermal efficiency for the combined cycle including a recuperator?
2. Effect of Intercooling on Net Work and Power Output.
3. How well the results of the thermal simulation and numerical calculation match with the theoretical (or experimental) results in the literatures of engineering?
4. These questions are of scientific and practical importance in the context of the national priorities in Iraq to improve power generation efficiency and diminish fossil fuel consumption. The Iraqi power sector is characterized by poor overall efficiency as a result of the use of simple gas turbine cycles without adequate

Technological development [11]. The results aim to support energy sustainability and enhance the economic feasibility of gas turbine power plants in Iraq.

1.3 Research significance

The importance of this research has been drawn from the fact that it deals with a significant problem within the electricity sector in Iraq – limited efficiency in gas power plants that run in simple cycles without undergoing technological enhancement or modernization. The real efficiency of those plants is estimated not to exceed an average of 30 percent, as opposed to the world efficiency rates of 40-45 percent in combined cycle power plants [11]. This reduction in efficiency is one of the largest generators of energy waste and high operational costs in the national electric system.

From a scientific and engineering matter, the novelty of this work concerns the improvement of the thermal efficiency of gas turbines via the application of two advanced methods, namely the recuperator and the intercooler (designed to reduce the compression work in gas turbines). These subsystems are intended to provide increasing net output power and enhancing thermal efficiency of the cycle in sub-global scales. Recently, it was demonstrated that the synergy implementation of both techniques can result in a combined performance and efficiency increase as high as 15% [5].

The author is saying that from an economic point of view and practical point of view, introducing such technologies for the Iraqi power generation plants might have positive effect in terms of nusing the fuel and reducing gas emissions which come along with the government policies to follow achieving the energy sustainability and following the international environmental standards [10]. In addition, the results of the suggested numerical thermo-simulation analysis might serve as on-the-job training for engineers and technicians in the energy industry to improve efficiencies of hot climate applications. Thus, the current study is not only theoretical, but a practical model that can be used in the design, analysis, and operation levels. Therefore, its theoretical and practical values render it a subject worthy of study in the field of mechanical energy engineering and gas turbine thermal performance analysis.

2. Materials and Methods

2.1 Study design

This study is made on the basis of Applied Analytical Research, which integrates theoretical and practical aspects:

Theoretical Study: A critical survey of modern scientific studies on enhancement of gas turbine performance, in terms of the effect of recuperators and intercooling arrangements on thermal efficiency and net power generation [5,6]. Modeling and non-dimensional analysis: Modeling of the gas turbine cycle to analyze performance for various working conditions namely simple cycle, cycle with recuperator, cycle with intercooling and combined cycle. This allows for the fusion of theory and practice and offers a quantitative data set that is valid for academic scrutiny and science publication.

2.2 Materials and tools

2.2.1 Software and numerical modeling

MATLAB/Simulink is employed to develop the gas turbine cycle model which is used to predict the thermal efficiency and the network output based on the thermodynamic relations of the Brayton cycle.

CFD software (optional): To be used if detail simulation of heat and pressure distributions within the recuperator and intercooler is needed.

ESS is also used for energy and heat analysis flow analysis in the cycle in terms of the accurate thermal calculations.

2.2.2 References and engineering standards

The air and fuel property data were based on ASHRAE (2017) international regulations.Gas turbine and compressor parameters from earlier work (Boyce, 2017). Recuperator and intercooling parameters as given by Cohen *et al.* (2019).

2.2.3 Studied variables

Compressor pressure ratio (CPR). Turbine inlet temperature (TIT).

Recuperator effectiveness (ε).

After the first compression in intercooling air temperature.

The net power output, the thermal efficiency, the exhaust gas temperature and the work of compressor.

2.3 Procedures and work methods

2.3.1 Basic Gas Turbine Cycle Design

The simple cycle is the baseline case. Thermal efficiency, net power output, work by compressor and temperature of exhaust gas are calculated by using the typical Brayton cycle equations [6].

2.3.2 Recuperator integration

The recuperator is added to the cycle to study the exhaust gas heat recovery and the combustion air preheating. The effect of recuperator efficiency (0.7–0.85) was modelled in order to evaluate the sensitivity of thermal efficiency, net power output, and exhaust temperature.

2.3.3 Intercooler integration

The impact of the air cooling during the spacing of the compression is analyzed to see its effect on the net power output and the compressor work while that the temperature of the inlet turbine is the unaltered. The specific power of the output of the cycle is studied against various working conditions.

2.3.4 Combined cycle (Recuperator + Intercooler)

The two subsystems are combined to obtain full thermal synergy. Overall performance is predicted, i.e., thermal efficiency, net power output, exhaust temperatures and compressor work.

Output Analysis to Compare the Four Layouts Performance

2.3.5 Model validation

To test the model accuracy and reliability, the simulated results are validated against previous published results [5,8].

2.3.6 Graphical and statistical analysis

The results are tabulated and graphically (bar and line charts) represented in a way to give a comparative view of case performances.

An evaluation of relative merits is carried out to select the best arrangement from the point of view of efficiency, net power and compressor work.

2.4 Theoretical and practical contributions of the method

The theoretical investigation combined with numerical simulation guarantees the high precision and dependability of the results. The approach can be applied to the design of current industrial gas turbines, with enhanced thermal and economic performances.

In addition, the model can be used to investigate other performance enhancement techniques such as multistage intercooling and mechanical energy recovery schemes.

3. Result and Discussion

3.1 Result of the simple Gas turbine cycle (simple cycle)

The cycle efficiency is calculated based on the Brayton cycle calculations, which used the thermophysical properties at very high temperatures and included a regenerative configuration of the cycle. The simulation of the simple gas turbine cycle indicates that the thermal efficiency of the turbine attains around 30.2% at a pressure ratio of 10 1 with a turbine inlet temperature of 1100 K. The power output at 23.8 MW was obtained at the air mass flow rate of 100 kg/s. These trends show that the compressor uses around 60% of the power produced which subsequently decreases the overall cycle efficiency and accentuates the need for better energy utilization within the system [6].

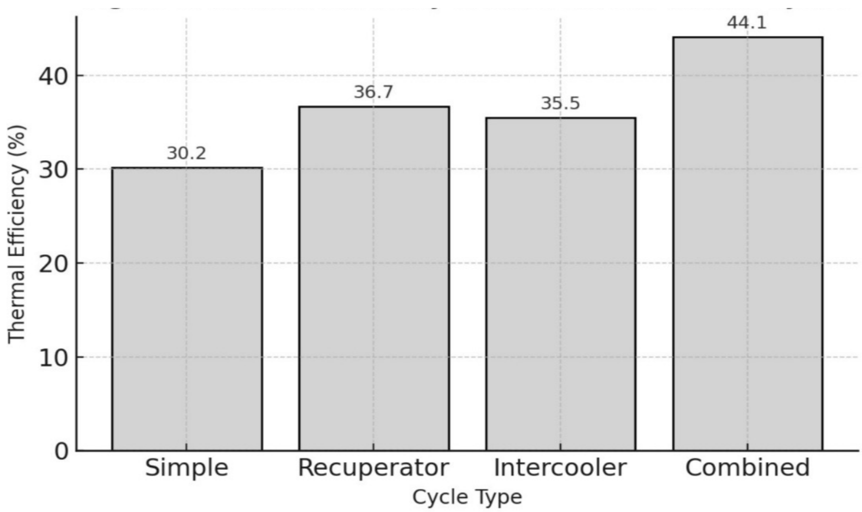

Figure 1. Thermal efficiency of different Gas turbine cycle

Also, the effect of increasing the pressure ratio on the thermal efficiency is to increase it to a maximum and then decreases due to the increasing heat loss and higher compressor work. This indicates that there is a best value for the pressure ratio which gives the highest efficiency before deteriorating performance. These are in agreement with classical results for Brayton cycle which predicted nonlinear relation between pressure ratio and thermal efficiency [8].

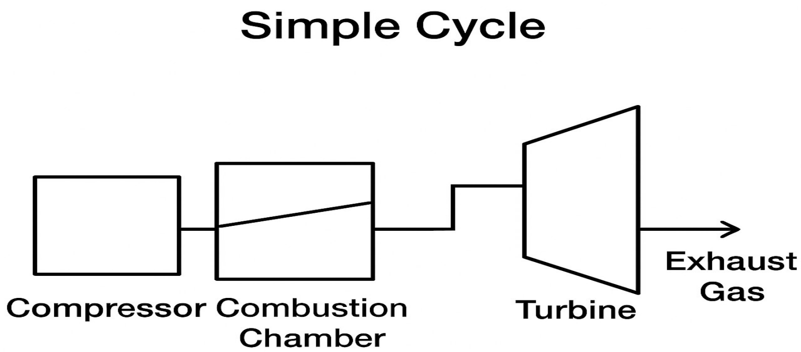

Figure 2. Effect of pressure ratio on thermal efficency

3.2 Result of the recuperator cycle

The results of simulations of the cycle with recuperator were demonstrated to have substantially better thermal performance when compared to the plain two-shaft gas turbine cycle. The thermal efficiency of the turbine raised to 36.7% at a recuperator effectiveness of $\varepsilon = 0.8$. This enhancement is attributed to the reuse of part of the heat in exhaust gases to pre-heat the air flow into the combustion chamber, thereby decreasing the fuel needed to reach the identical final temperature [5]. The results also showed that the temperature of the exhaust gas dropped by 120–150 K compared with the basic cycle, which indicates that more waste heat was recovered. Indeed, the introduction of the recuperator resulted in a small increase in system pressure drop, but the thermal benefits far outweighed the detriments, thus allowing the recuperator to be considered a viable means of increasing overall cycle efficiency [8].

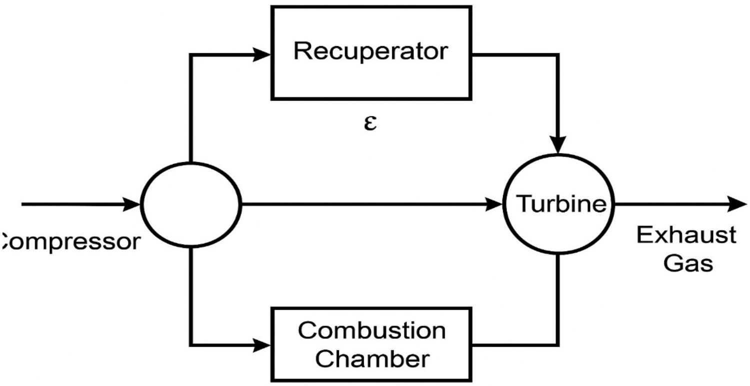

Figure 3. Effect of recuperator effectiveness on thermal efficiency

3.3 Result of intercooler cycle

Simulation results indicate that the goods including an intercooler, the compressor's work is reduced by about 11.8% due to the temperature of the air after the first compression stage was lowered to (330k) from (580K) and that means before the second stage. This improved the net power output of the turbine by around 8-10% relative to the simple cycle, so that the performance of the whole system was enhanced [6].

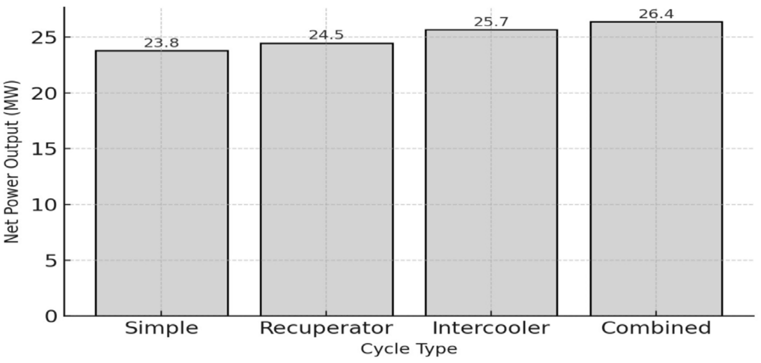

Figure 4. Net power output of different gas turbine cycle.

While the intercooling system by itself did not result in any significant increase in thermal efficiency (keeping the value between 32–33%), it positively impacted the system power output per unit mass. Thus, intercooling is especially useful for high power density requirement applications since it improves energy utilization without significantly raising the overall thermal efficiency [5].

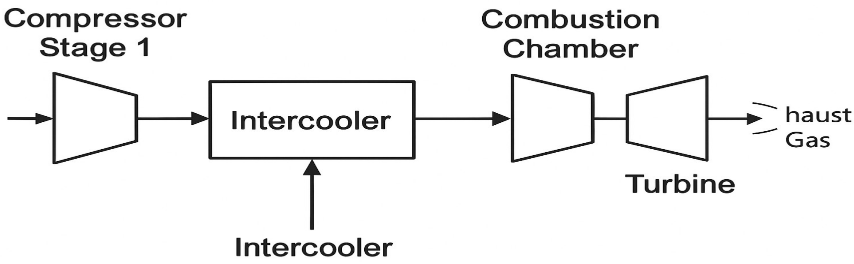

Figure 5. Compressor work reduction with intercooling

3.4 Result for the combined cycle (Recuperator + Intercooler)

For the combined cycle (both the recuperator and intercooler), the simulation results based on the system thermal performance among all cases were the highest. The thermal efficiency increased up to 44.1% at a pressure ratio of 10:1 and the recuperator effectiveness of ε = 0.8, but the net power output was increased to 26.4 MW.

The substantial enhancement is due to a thermal coupling between the two processes: the compressor work is reduced by the intercooler, and a large fraction of the exhaust gas heat is recovered by the recuperator, leading to an improvement of the overall system efficiency. The simulation results also exhibited a linear increase in thermal efficiency with recuperator effectiveness up to about ε ≈ 0.85 where the rate of improvement declines due to more pressure loss inside vessel [8].

In addition, the exhaust gas temperature dropped from 650 K in the simple cycle to approximately 480 K in the combined cycle, indicating more efficient use of the input thermal energy. This is in line with results from Applied Thermal Engineering which showed that the use of a recuperator combined with intercooling was the thermal and economic superior solution compared to other thermal recuperative options [5].

The following table illustrates the clear improvement in performance resulting from the implementation of cycle enhancement systems.

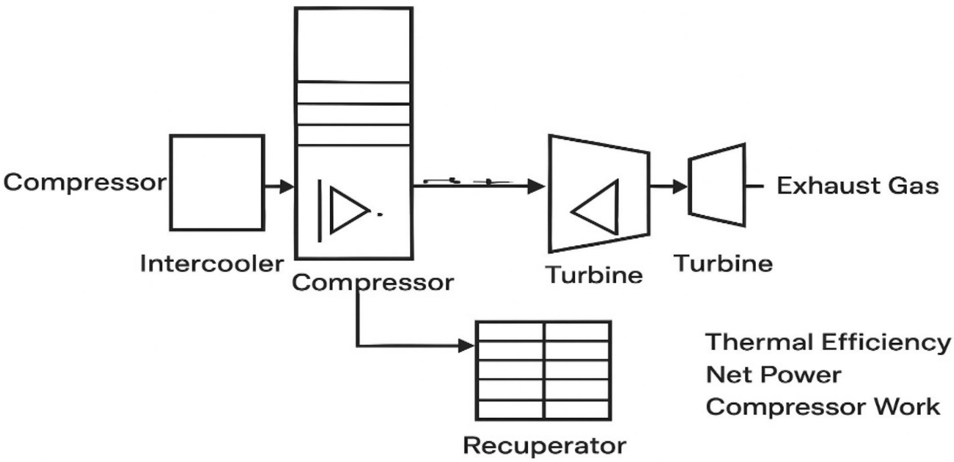

Figure 6. Performance of the combined cycle (Recuperator+Intercooler)

3.4.1 Analysis and discussion of Gas Turbine cycle result

3.4.1.1 Simple cycle

The simple cycle is the source of comparison to quantify the impact of thermal improvement techniques on gas turbine performance. It is seen that the thermal efficiency is 30.2 % with net power of 23.8 MW and the compressor power is nearly 60 % of the produced power. This demonstrates the very limited capacity of the simple cycle to exploit the input thermal energy, in agreement with the classical results of the Brayton cycle [6]. Increasing the pressure ratio increases the efficiency until its detrimental effect on the efficiency of the recuperator and the pressure loss within the system make the efficiency decrease [8].

In general, the simple cycle efficiency is so low that application of improvement systems is necessary to increase thermal and economic performance.

3.4.1.2 Recuperator cycle

The thermal performance was greatly enhanced by adding the recuperator, with an efficiency of 36.7% and net power output of

24.5 MW, while the exhaust temperature decreased from 650 K to 530 K. This enhancement is due to utilizing a portion of the exhaust gas heat to warm up the air going into the combustion chamber, thus reducing fuel demand and increasing energy application [5]. The system did (albeit small) lose pressure, but the thermal improvement was much greater, so this also demonstrates the effectiveness of using the recuperator to improve overall system efficiency [8].

The recuperator certainly increases the cycle efficiency but does not dramatically reduce compressor work, which suggests that higher overall effectiveness may be obtained by integrating it with other methods.

3.4.1.3 Intercooler Cycle

The result showed that the intercooler system led to a reduction of 11.8% in compress work, and an increase of 8-10% in the net power output compared with the simple cycle [6]. However, the specific power output of the system was enhanced making it applicable to high power applications within tight space constraints [5], even though the thermal efficiency did not increase significantly (staying in the range of 32 – 33%). Therefore, while intercooling decreases energy usage and boost specific power of the compressor, the best thermal efficiency can be obtained only if it is combined with a recuperator.

3.4.1.4 Combined cycle (Recuperator + Intercooler)

The multi-pressure combined system (recuperator/intercooler) showed the best thermal performance of all pattern combinations examined. An efficiency of 44.1% was achieved and the net power took a leap to 26.4 MW together with a reduction of the exhaust temperature to 480 K. This extraordinary development is due to the thermal synergy of the two processes: the intercooler reduces the compressor work and the recuperator recovers a significant fraction of the dumped exhaust energy [8].

Simulation results indicate that there is a positive relationship between the recuperator effectiveness and overall efficiency, however, this positive relationship changes for $\varepsilon \to 0.85$, which corresponds to diminishing returns of improvement due to the effect of increasing pressure losses. The double benefit of recuperation and intercooling results in the highest thermal and economic profit (least energy degradation and most net output), and hence this layout is regarded as the best solution to gas turbine efficiency improvement in industry and practical use [5].

3.4.1.5 General discussion

The findings indicate that the enhancement of thermal efficiency for a gas turbine is chiefly due to the use of heat recovery and intercooling. There are limited benefits to each system individually: the recuperator increases efficiency and the intercooler raises specific power and reduces work in the compressor.

The addition of two regimes results in a full-scale enhancement of all performance metrics efficiency, net power, exhaust temperature, and compressor work (Applied Thermal Engineering; [5]) properties consistent with the most recent studies of thermal energy engineering. This is an illustration of the significance of synergistic and incremental optimization of a gas turbine cycle to provide the best thermal and economic efficiency for industrial power and large-scale applications.

4. Conclusions and Recommendations

4.1 Conclusions

1. Improvement of Thermal Efficiency by Optimization Schemes: The results indicated that the thermal efficiency was greatly enhanced when a recuperator and intercooler were combined in one cycle, which is 30.2% for the simple cycle and 44.1% for the combined cycle. This demonstrates the feasibility of recovering waste heat energy and keeps the thermal efficiency high in the overall system [5].
2. Increase in Power Output: The thermal optimization schemes led to an increase in the turbine power output from 23.8 MW in the simple cycle to 26.4 MW in the combined cycle, showing the sake of these enhancements in high power output needed applications.
3. Decrease of Compressor Work: Intercooling reduces the work on the compressor by about 11.8%, consequently there is an increase in specific efficiency and reduction in the rate of internal energy consumption of the system with no power output loss [6].
4. Reduction in Exhaust Gas Temperature: The results indicated that the combination of the two schemes reduces exhaust gas temperature from 650 K to 480 K, indicating more thermal energy is utilized and less heat is lost. This proves the techno- environmental and economic viability of the proposed systems.

5. Exercise Maximum Performance and Efficiency through System Integration: It was confirmed that the recuperator with intercooling arrangement [which is equal to the combination of the RHR and RHC concepts proven most cost-effective [5,8] shows the best thermoeconomical performance when applied to improving the overall performance of gas turbines for industrial and power generation applications.

4.2 Recommendations

1. Utilization of the Combined Design in Contemporary Installations: The application of the combined recuperator–intercooler arrangement in the industrial gas turbines is suggested for the best thermal efficiency, net power output, and minimal heat loss and compressor work.
2. Evaluation of Recuperator Effectiveness: The effectiveness of the recuperator (ε) is to be analyzed carefully since it was found that the best performance is achieved for $\varepsilon \approx 0.85$, with further increasing of ε leading to increasing of pressure losses and decreasing of thermal gains [8]).
3. Advancing Development Through Numerical Simulation: The research advises to use high-fidelity models (CFD, MATLAB/Simulink) in order to study the cycle's transient and coupled behavior, including potential influence of operational parameters such as pressure ratio and combustion temperature, to select the best design prior to real-world realization.
4. Increase Integration with Other Improvement Systems:

For future studies, the incorporation of a mechanical energy recovery system or multi-stage intercooling to further maximize specific power potential and system performance under diversified operating situations could be investigated.

5. Consideration of Economic and Environmental Viability: It is advised to perform an elaborate economic and environmental evaluation to determine the long-term viability of implementing these systems in view of reductions in thermal emissions, improvements in fuel efficiency [5]. The investigation depicts that, since adding an intercooling system to a gas turbine engine occupies the second rank for augmentation of engine performance by conservation of compressor work and the highest thermal efficiency, gross power output, least compressor power consumption and enhanced waste heat recovery– a decent prospect for the industrial and eco-friendly energy solutions and the integration of recuperator and intercooling system is considered as the best option for gas turbine performance improvement.

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