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Thermal and environmental optimization of an intercooled gas turbine toward a sustainable environment

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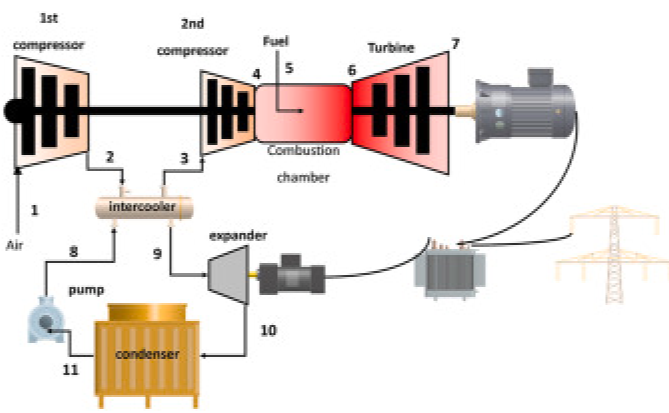
Highlights

- A thermoeconomic study of a gas turbine equipped with intercooling is conducted.
- The intercooler rejected heat is recovered by an Organic Rankine Cycle.
- A parametric study is done and the effects of design variables on performance parameters are investigated.
- A bi-objective optimization is performed and the Pareto front is drawn.

Abstract

In this article, in order to achieve a sustainable environment, the optimization of a GT equipped with intercooling of the compression process is discussed. To limit the exergy destruction in intercooling cooling process and also to reduce the heat dissipation in the environment, an ORC system is applied for heat recovery and more power generation. Decision variables include CPR, first stage CPR, TIT, intercooler effectiveness, HRVG pressure, and superheating degree. During a parametric study, the effect of decision variables on operating factors including exergy efficiency, TCR, and the normalized emission rate of environmental pollutants are investigated. Finally, by performing bi-objective optimization and considering exergy efficiency and TCR as OFs, optimal performance conditions are determined. Finally, it is observed that in optimum conditions, exergy efficiency is 33% and TCR is 0.9 $/s.

Graphical abstract



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Introduction

GTs play a vital role in meeting the world's energy needs. However, environmental concerns have become a significant factor in their development. The combustion of fuel in the gas turbine produces air pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which are known to contribute to the formation of acid rain, smog, and other environmental issues. Gas turbines also produce carbon dioxide (CO2) emissions that contribute to global warming↗. The combustion of fossil fuels in gas turbines produces greenhouse gases such as carbon dioxide and contributes to climate change. As a result, there has been a growing demand for more environmentally friendly and sustainable energy solutions↗. GT manufacturers have been developing new technologies that reduce emissions and increase fuel efficiency to address environmental concerns. Optimization of gas turbines is a crucial process that involves maximizing the performance and efficiency of the system. The primary goal of optimization is to reduce fuel consumption and increase power output while maintaining safe and reliable operation.

There are three categories of techniques that can be used to achieve this:

- Alternative fuels such as hydrogen, biogas, and synthetic fuels produce fewer emissions than traditional fossil fuels and can be produced from renewable sources.

Extensive studies have been conducted on the use of biomass as fuel for gas turbines. As an example, Hai et al. used syngas produced in the gasification process as fuel of a GT. The waste heat of GT exhaust gases is used to produce more electricity by sCO2 cycle and also to produce freshwater by a MED unit (Hai et al., 2023a). Biomass fuel is also used in external combustion GTs. Musharavati et al. used syngas produced from biomass as fuel for an external combustion GT. The waste heat of the system is recovered by a MED unit to produce freshwater (Musharavati et al., 2022). Also, Hai et al. used syngas as a fuel of an external combustion GT, and waste heat recovery is used by a single-pressure steam cycle to generate power (Hai et al., 2023b).

In addition to using syngas produced by biomass gasification in GTs, this renewable fuel can also be used in other energy systems. As an example, DanayiMehr et al. used this fuel as an energy source for a steam cycle (Danayimehr et al., 2023). Yu et al. converted biomass into syngas with the help of gasification process and used it as a source of hydrogen for a SOFC. From the waste heat of this system, with the help of the Sterling engine, the waste heat is recovered and the produced electricity is converted into hydrogen by an electrolyzer (Yu et al., 2023a). Bai et al. presented a multi-generation system based on biomass for electricity, heating and freshwater production (Bai et al., 2023). Also, Duan et al. used the syngas produced by biomass gasification in order to produce the hydrogen required by PEM FC. In order to increase the efficiency of the system, the heat produced by PEM FC is recovered through an absorption chiller to produce cooling. Also, in order to cool the produced syngas, TEG is used and the generated electricity is applied to produce hydrogen (Yu et al., 2023b).

Also, the use of hydrogen fuel as a solution to achieve a sustainable environment has been the focus of researchers. The blending of hydrogen fuel with hydrocarbon fuels reduces the emission of these fuels. As an example, Ozturk et al. blended hydrogen with different ratios of natural gas and in addition to examining the combustion performance, they examined the emissions of these blended fuels (Ozturk et al., 2023). Karaca and Dincer propose a new photoelectrochemical system for clean hydrogen production. They conducted a life cycle assessment on a photoelectrochemical hydrogen production process by a novel photoelectrochemical reactor (Karaca and Dincer, 2023).

- Several techniques can be used to optimize GT design for improved performance and efficiency. These include upgrading the combustion system, improving the compressor and turbine blades, enhancing the cooling system, and optimizing the control system. Aerodynamics is one of the most important factors that can be optimized to increase efficiency and reduce emissions. Advanced materials and coatings can also be used to increase the efficiency of the turbine by withstanding higher temperatures and pressures. Control systems are also critical for optimizing GT design. Advanced control systems can monitor and adjust the operation of the turbine in real-time, optimizing performance and reducing emissions.

- Techniques such as intercooling, regeneration, steam injection, and wet compression can be used to improve the configuration of the GT.

Regeneration is a technique that involves using the waste heat from the turbine exhaust to preheat the compressed air before it enters the combustion chamber. This reduces the amount of fuel required to achieve the desired temperature and pressure, which leads to improved efficiency. Regeneration can be achieved through various methods, such as using a heat exchanger or a regenerator (Nishida et al., 2005; McDonald and Wilson, 1996; Kim and Perez-Blanco, 2007; Zheng et al., 2003; Carapellucci and Giordano, 2021). Intercooling is a technique that involves cooling the compressed air between stages of the turbine to reduce its temperature and increase its density. This allows for more air to be compressed and combusted, which leads to increased power output and efficiency. Intercooling can be achieved through various methods, such as using a heat exchanger or a cooling tower, or using heat recovery techniques such as applying ORC (Canière et al., 2006; Konovalov et al., 2022; Yi et al., 2004; Yu et al., 2022; Alsayegh and Ali, 2020; Dabwan et al., 2023; Zhang et al., 2009).

By implementing these techniques, engineers can significantly improve GT performance. This leads to increased efficiency, reduced emissions, and lower operating costs, all of which contribute to a more sustainable and environmentally-friendly energy source.

Intercooling is a technique used in gas turbines to cool a gas after compression. It is one of the methods to improve the efficiency of the gas turbine which increases the net output work by reducing the work required to drive the compressor by carrying out the compression air in two stages1. In your paragraph, it is mentioned that intercooling process increases the power and efficiency of the GT by decreasing the required power of the compression process.

In practice, the intercooling technique divides the compression process into two or more stages, and by applying cooling heat exchangers between each of two compression processes, cooling of the compressed air is performed. In this study, it is proposed to recover the rejected heat of the cooler heat exchanger by an Organic Rankine cycle (ORC). The Organic Rankine Cycle (ORC) is a type of thermodynamic cycle that is a variation of the Rankine cycle named for its use of an organic, high-molecular-mass fluid whose vaporization temperature is lower than that of water.

The main goals of the present study are presented herein below:

- The aim is to develop an innovative energy system that utilizes waste to increase efficiency and reduce environmental emissions.
- The study will include a thermos-economic analysis to investigate the impact of design variables on performance factors such as exergy efficiency, total cost rate, and pollution emissions.
- A multi-objective optimization will be conducted to determine the optimal operating conditions↗.

Section snippets

System description

Fig. 1 shows the schematic of the studied system. The proposed system includes a CCPP based on GT. Ambient air enters the compressor. Since the increase in pressure is accompanied by an increase in temperature, and on the other hand, an increase in temperature leads to an increase in the required work of the compressor, an intercooling stage is applied. So that after compression in the first compressor, the compressed air enters the intercooling heat exchanger and after reducing the temperature …

Thermodynamic modeling

The required power of the first stage of the compressor is calculated by (Saravanamuttoo et al., 2001): $\dot{W}_{1^{st}AC} = \dot{m}_{air} C_{p,air} \left(T_2 - T_1\right)$

In Eq. (1), the specific heat of the air is calculated according to air mixture and by thermodynamic data bank of EES software.

The temperature at the compressor discharge is given by (Gülen, 2019):

$$\frac{T_2}{T_1} = 1 + \frac{1}{\eta_{s.\ AC}} \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right]$$

In equation (2), k is the ratio of constant pressure to constant volume of specific heat of the air and is calculated by thermodynamic data bank…

Economic modeling

The economic analysis is performed by considering investment, and O&M, fuel, and environmental impacts costs as follows: $\dot{C}_{total} = \sum \dot{Z}_{\mathrm{k}} + \dot{C}_{\mathrm{fuel}} + \dot{C}_{\mathrm{env}}$

The method of levelized cost is applied in this study (Liddament, 1996). The annual levelized cost ($\dot{Z}$), which is in $/year can be written as below:

$$\dot{Z} = 1.06 \left(Z - 0.1 (i+1)^n \right) \frac{i}{1-(1+i)^{-n}}$$

In equation (15), the coefficient of 1.06 is related to the O&M cost of each component. The PEC of each component of the system is presented in Table 3.

The fuel cost is…

Parametric study

In this article, the intercooling of the compression process in a GT is investigated. An ORC system is used to recover the heat rejected by the intercooler. In addition to increasing power production, the heat emitted to the environment is also reduced. Also, this method has a good potential in reducing environmental pollutants in terms of power production. In order to investigate the proposed system, first a parametric study is conducted and the effect of the design variables on the OFs is…

Conclusion

In this study, a power generation system based on GT is investigated. In order to improve performance indicators such as increasing exergy efficiency and reducing the emission of environmental pollutants, an intercooler is used in the GT compression process and its effect on performance and economic indicators is measured. Intercooling cooling leads to the improvement of GT performance by reducing the required work of the compressor. In this study, assuming that the goal of designing a GT is to …

Author contribution statement

Oriza Candra: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; **Amjad Ali**: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Project administration; Software; Validation; Visualization; Writing – review & editing., **Shavan Askar**: Conceptualization; Data curation; Formal analysis; Funding acquisition;…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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