

Thermodynamic Analysis of a Solar-Assisted Helium Brayton Cycle-Based Power Generation System

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Abstract - The growing need for sustainable and green energy systems has accelerated the study of high-efficiency renewable power generation technologies. Solar energy has emerged as a particularly promising option among renewable energy supplies due to its abundance, cleanliness and widespread availability. The present thesis develops a thermodynamic analysis of a solar aided helium Brayton cycle coupled with an organic Rankine cycle for efficient and carbon neutral power generation. The helium Brayton cycle plays a big role in total power generation with a net power output of 13,051kW while the ORC is a good waste heat recovery system with an additional generation of 3,002kW. Comparative validation with previous studies showed that the present arrangement delivers higher thermodynamic performance with fewer system components, lower complexity and higher waste heat recovery efficiency. The exergy analysis showed that high irreversibility's are observed in the solar receiver and heat exchanger components due to large temperature changes in heat transfer activities

Keywords: Solar-Assisted Helium Brayton Cycle, Organic Rankine Cycle, Waste Heat Recovery, Energy and Exergy Analysis, Concentrated Solar Thermal Power.

1. INTRODUCTION

Increasing worldwide demand for clean, reliable and sustainable energy has driven research efforts to develop novel power-generation technologies with improved thermal efficiencies and reduced environmental footprints. Traditional fossil fuel power plants are still the main energy industry power source; however, their high dependence on non-renewable resources and greenhouse gas emissions have raised great environmental concerns [1]. Climate change, depletion of fossil fuel resources and growing energy demand have motivated scientists and governments to explore renewable energy alternatives that would enable future sustainable development. One of the most promising renewable energy sources is solar energy, because it is abundant, widely available and eco-friendly [2]. Figure 1.1 depicts CO₂ emission from 1990-2024 as per International Energy Agency (IEA) [3]. The Brayton cycle is an important thermodynamic cycle used in power generation and propulsion applications. It works by compressing a working fluid, adding heat at constant pressure, and then expanding

the fluid via a turbine to get useful work out of it. Air has been traditionally used as the working fluid in Brayton cycle systems, but other gases, such helium, have been of great interest due to their improved thermophysical properties. Helium is an inert gas with good thermal conductivity, low molecular weight, good heat transfer ability and steady performance at high temperature. These properties make helium highly attractive for advanced high temperature power generation systems, especially in the case of nuclear reactors and solar thermal energy systems [5].

2. MATHEMATICAL MODELLING

Engineering Equation Solver (EES) is a powerful computational software often used to solve engineering and thermodynamic problems involving complex algebraic and differential equations. EES is mainly designed for thermal engineering applications and provides an efficient platform for energy, exergy, heat transfer, fluid flow and thermodynamic analysis. It is used in academic research, industrial design and simulation studies because to its user friendly interface and powerful numerical solving features, Rankine cycles, refrigeration systems, heat exchangers, and solar thermal systems. The software can solve large sets of nonlinear equations with high accuracy and fast convergence simultaneously. It also provides tools for parametric analysis, optimization, sensitivity analysis, and graphical plotting which are quite useful in performance assessment and improvement of the system. EES can be used for thermodynamic studies to investigate the effect of different operating parameters on system performance, work, heat transport, and exergy destruction. The software allows both steady-state and transient research, and is a versatile tool for complicated engineering applications. Furthermore, EES enables easy integration of mathematical equations with engineering principles which reduces the computing complexity and enhances the simulation performance. Due to its flexibility, accuracy, and ease of use, EES is one of the most widely used software tools in energy engineering research for thermodynamic modeling and simulation.

Fig. 2 shows the distribution of exergy destruction rate and second law efficiency of numerous components inside the helium Brayton cycle (HBC). Figure 4.1(a) displays the components that contribute the most to the exergy degradation in the system. Thermodynamic irreversibilities leading to exergy destruction are heat transmission across finite temperature differences, friction, pressure drop and mixing of fluids. The results demonstrate that the highest exergy destruction is observed in the solar receiver or heat exchanger section due to large temperature differences during heat transfer. The exergy losses in the mechanical system and the fluid friction cause large exergy losses in the turbines and compressors components. The recuperator has very small exergy destruction because it recovers the waste heat from the turbine exhaust effectively and preheats the compressed helium before it enters the heating section. This heat recovery technique reduces the fuel or solar heat input and increases the overall system efficiency. Figure 1(b) shows the second law efficiency of different HBC components. Higher second-law efficiency components operate closer to optimal thermodynamic conditions and thereby minimize irreversibility. The turbine has a good conversion of thermal energy to mechanical energy and hence a high second law efficiency. On the other hand, the efficiency of compressors and heat exchangers is somewhat reduced due to pressure losses and limitations in heat transmission.

Figure 2 illustrates the importance of limiting exergy degradation in critical components to boost the system's performance. The results indicate that the overall thermodynamic performance of the helium Brayton cycle can be improved greatly by improving the heat transfer devices and reducing the pressure losses.

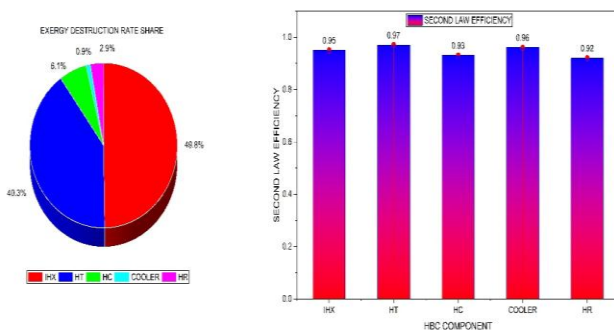


Fig. 2 (a) Exergy destruction rate share, (b) Second law efficiency of HBC component

Fig. 3 shows the distribution of exergy destruction and the second law efficiency of organic Rankine cycle (ORC) components in the combined power generation system. Figure 3(a) shows the % distribution of exergy destruction among the main ORC components, evaporator, condenser, turbine pump and recuperator. The evaporator usually experiences the most exergy degradation due to large temperature differences between the heat source and the

working fluid in the heat transfer. This irreversibility reduces the available useful energy in the system. The main component that causes exergy destruction is the condenser, because it rejects heat to the environment, which is a waste of useful energy. In contrast, the ORC turbine has lower exergy destruction due to its high efficiency in converting thermal energy into mechanical power. Likewise the pump has low exergy losses due to the lower power consumption requirements. The recuperator improves the cycle efficiency by recovering the leftover heat from the turbine exhaust and transferring it to the working fluid before it enters the evaporator. Figure 3 (b) presents the second law efficiency of the components of Organic Rankine Cycle. The turbine usually has a better second law efficiency due to the effective expansion operations. In general, Figure 3 indicates that the integration of ORC is effective in utilizing the waste heat of the helium Brayton cycle and significantly improves the overall energy and exergy efficiency of the combined system.

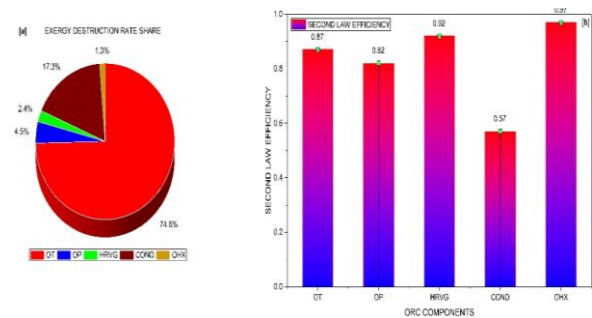


Fig. 3 (a) Exergy destruction rate share, (b) Second law efficiency of ORC component

PARAMETRIC ANALYSIS

Effect Of HBC Compressor Pressure Ratio on System Performance

Figure 4 shows the variation of work production with compressor pressure ratio for the helium Brayton cycle. The compressor pressure ratio is one of the most important operating characteristics with a high influence on the cycle performance. Higher pressure ratios increase the temperature rise during heat addition and increase the available enthalpy drop across the turbine. The consequence is better power output and better thermal efficiency. But above some pressure ratio, the increase in compressor work exceeds the increase in turbine effort. This causes the network output to start decreasing or remaining constant. Excessively high pressure ratios also result in increased irreversibility due to fluid friction and pressure losses. There is an optimum pressure ratio at which the maximum net work output is obtained. The figure illustrates the importance of selecting the right compressor pressure ratio in the design of a system. Good optimization will lead to minimum energy losses and compressor power consumption and will result in optimum power production. The trends observed agree with the thermodynamic features of Brayton

cycle systems and highlight the importance of the appropriate operating conditions for higher efficiency of the combined cycle.

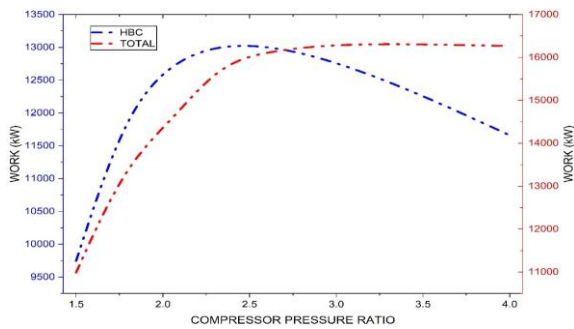


Fig. 4. Effect of compressor pressure ratio on work output

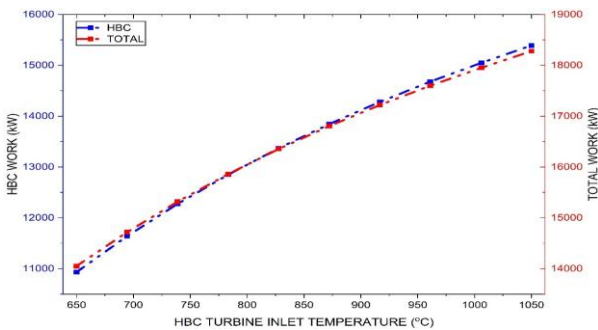


Fig. 5 Effect of HBC Turbine inlet temperature on work output

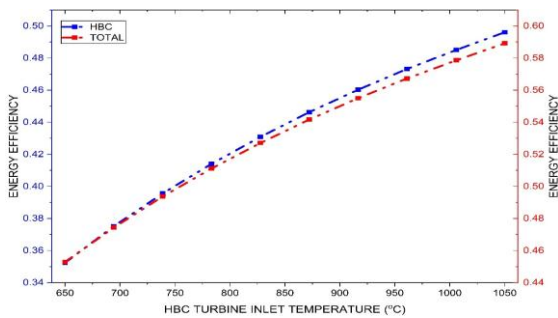


Fig. 6 Effect of HBC Turbine inlet temperature on energy efficiency

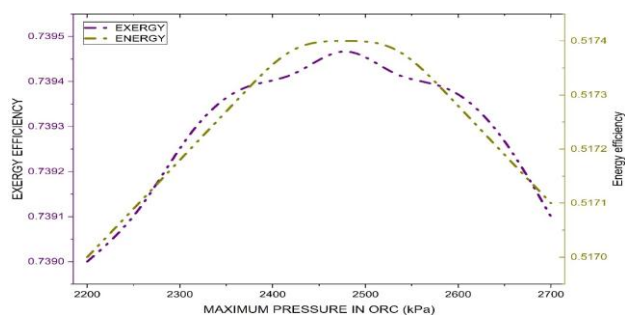


Fig. 7 Effect of ORC maximum pressure on energy efficiency and exergy efficiency

4. CONCLUSIONS:

This was followed by a comparative validation analysis in conjunction with the previous published work by V. Zare et al., which validated the reliability and accuracy of the current thermodynamic model. The proposed arrangement showed an improved thermodynamic performance while using less number of system components thereby reducing the system complexity and improving the operational practicality. The present system achieved a net power output of 16,052 kW which is more than that of the reference system. The total energy efficiency and exergy efficiency were calculated as 51.74% and 73.95%, respectively, which indicates an efficient usage of the provided thermal energy and lower thermodynamic irreversibilities. The exergy analysis revealed large irreversibility's inside the solar receiver, heat exchanger sections, compressor and turbine due to finite temperature differences, pressure drops and fluid friction. The relative exergy destruction was lower for the recuperate because of the effective heat recovery from the turbine exhaust gases. The ORC evaporator and condenser were identified as the major causes of exergy deterioration in the bottoming cycle. The results show that the overall performance of the system might be further improved by designing the heat exchanger optimally and reducing the pressure losses.

The parametric analysis showed that the compressor pressure ratio, turbine inlet temperature and ORC maximum pressure have great influence on the system performance. It was observed that network production, energy efficiency and exergy efficiency are considerably enhanced by increasing the turbine inlet temperature owing to better turbine expansion and optimum heat utilization. The compressor pressure ratio had an optimal working range, beyond which an excess work caused a decrease in system performance. The ORC maximum pressure had excellent values for waste heat recovery and cycle efficiency. The suggested solar-assisted helium Brayton cycle coupled with recuperated ORC showed improved thermodynamic efficiency, efficient waste heat recovery, reduced system complexity, and maximized use of renewable solar energy. The obtained results verify the feasibility of the proposed combined cycle system for future sustainable and high efficiency power production applications.

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BIOGRAPHIES



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