Performance Evaluation of a Hybrid Ammonia-Water and Transcritical CO_2 Combined Power Cycle for Enhanced Energy Efficiency

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Abstract - The rising global energy demand and the need to cut carbon emissions call for more efficient and sustainable power generation technologies. Traditional thermal cycles like the Rankine cycle face energy losses, necessitating innovative configurations. This study examines a hybrid ammonia-water and transcritical CO_2 power cycle that leverages the strengths of both working fluids for better efficiency. The ammonia-water (Kalina) cycle enhances heat recovery with its variable boiling point, while the sCO_2 cycle offers superior thermal properties and lower compression work. By integrating these cycles, the system optimally utilizes waste heat, reduces energy losses, and boosts power output. A thermodynamic analysis assesses thermal efficiency, exergy destruction, and environmental benefits, with a focus on potential integration with solar and geothermal energy for enhanced sustainability. The results highlight the hybrid cycle's capability to improve energy conversion and minimize environmental impact.

Key Words: Power Cycle, Combined Power Cycle , Thermodynamic Analysis , Energy Efficiency , Exergy Analysis , Waste Heat Utilization , Advanced Power Generation.

1.INTRODUCTION

The global energy sector is increasingly being challenged by rising power demands and the urgent need to reduce carbon emissions [1]. Conventional thermal power cycles, such as the Rankine cycle, suffer from inherent inefficiencies and significant energy losses, necessitating the exploration of alternative and more efficient cycle configurations. In this scenario, combined power cycles that combine multiple working fluids and thermodynamic principles are seen as a potential solution to enhancing energy conversion efficiency and optimizing waste heat utilization [2]. Among such advanced configurations, hybrid ammonia-water and transcritical carbon dioxide (sCO_2) cycle has become the most feasible way to improve power generation performance [3]. Ammonia-water mixture cycle is also popularly known as Kalina cycle that is appreciated with variable boiling points, hence its heat recovery with efficiency [4]. The transcritical CO_2 cycle benefits from better thermal conductivity and less compression work for CO_2, leading to a higher level of thermal efficiency and improved characteristics of heat transfer [5]. These two cycles can be combined in order to design a hybrid system which uses waste heat produced in the sCO_2 cycle to power the ammonia-water cycle. Overall, it is likely to obtain greater efficiency with this system while cutting down energy losses. This also leads to an increase in power output and is accompanied by less fuel consumption and environmental impact [6].

This study seeks to investigate the thermodynamic performance of this hybrid power cycle through a holistic energy and exergy analysis [7]. The emphasis on this research is placed on the investigation of performance metrics concerning thermal efficiency, exergy destruction, and environmental benefits of the suggested cycle in comparison with conventional methods of power generation. This includes the study into the possibility of combining the hybrid cycle with alternative sources of energy, including geothermal and solar power, as a means to further enhance its sustainability [8]. In understanding the technical as well as economic issues involved with this cycle, the research developed here will prove to be the foundation for innovative energy-efficient systems in the power sector.

The increasing demand for sustainable and efficient power generation has led to the exploration of advanced thermodynamic cycles that integrate multiple working fluids to maximize energy efficiency. A promising solution is presented by the hybrid ammonia-water and transcritical CO_2 combined power cycle, leveraging the complementary thermophysical properties of ammonia-water mixtures and supercritical CO_2. This hybrid approach gives improved heat recovery, cycle efficiency, and suitability for low-to-medium-grade applications such as recovering waste heat as well as harvesting renewable energy system [9]. Optimizing interactions between these fluid working fluids this cycle aims towards better energy effectiveness, reduced losses in exergies, along with environmental improvements in sustainability due to the cyclic operation compared with traditional power cycle operations. This paper evaluates the performance of the hybrid cycle through detailed thermodynamic modeling and analysis, providing insights into its potential for practical implementation in next-generation energy systems [10].

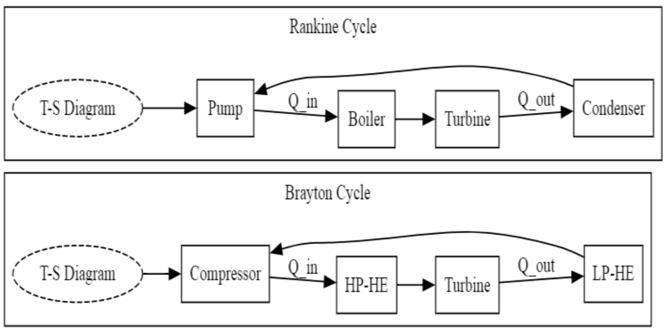

Fig-1: Brayton and Rankine cycles

The Rankine Cycle (steam power cycle) and Brayton Cycle (gas turbine cycle) are shown along with their T-S diagrams. In the Rankine Cycle, a pump pressurizes liquid, a boiler adds heat (Qin) to convert it into steam, a turbine extracts work, and a condenser removes heat (Qout) to return the fluid to liquid form. This cycle is widely used in steam power plants. In the Brayton Cycle, a compressor pressurizes air, a high-pressure heat exchanger (HP-HE) adds heat (Qin), a turbine extracts work, and a low-pressure heat exchanger (LP-HE) removes heat (Qout). It is commonly used in gas turbines and jet engines. The key difference is that the Rankine Cycle involves phase change (liquid to steam), while the Brayton Cycle operates with gases throughout.

2. LITERATURE REVIEW

The ammonia-water power cycle is recognized as a promising approach for utilizing emission-free heat sources in distributed energy systems. However, many existing studies assume a constant turbine efficiency, which simplifies analysis but does not fully capture its impact on system performance. To improve accuracy, an advanced model incorporating one-dimensional turbine optimization has been proposed, enhancing energy, exergy, economic, and environmental (4E) assessments. When applied to the Kalina cycle, this model reveals up to a 26% deviation from conventional methods, emphasizing the importance of precise turbine efficiency estimations. Additionally, new environmental indicators have been introduced to provide a more comprehensive evaluation of power cycles with different configurations and heat sources[11]. A hybrid ammonia-water refrigeration (HAWR) system combines compressor-based and absorption refrigeration methods to enhance energy storage efficiency. Its performance is analyzed using key thermodynamic metrics, with a solar-powered ammonia absorption unit studied through simulations and experiments. Aspen Plus software is used to model and optimize the system. Findings show that adjusting the compressor's output improves refrigeration control, with an optimal pressure of 600 kPa. Under ideal conditions, solar energy contributes 44.3% to cooling, while reliance on electricity rises to 79.5% in less favorable conditions. The system remains stable, achieving a COP of 0.738 for solar radiation levels above 800 W/m²[12]. A comprehensive review of power cycles used in steam-dominated electricity generation examines Rankine and transcritical CO_2 (T-CO_2) cycles, along with nuclear, natural gas, solar-assisted, and binary fuel cell systems. Performance is assessed based on power output, energy efficiency, thermal efficiency, and exergy efficiency. Geothermal plants produce between 199.1 kW and 19,448 kW, with thermal efficiencies ranging from 6.5% to 16.63%. Solar power plants generate between 550.9 kW and 4,500 kW, while NH_3+H_2O fuel-cell systems achieve power outputs between 1,015 kW and 20,125 kW, with thermal efficiency between 25.4% and 70.3%. The Kalina cycle is recognized for its potential to enhance system efficiency, offering valuable insights into sustainable power generation[13]. A redesigned ammonia-water power cycle has been developed to function at two pressure levels, integrating two separators and a heater to improve efficiency. Optimizing temperature alignment during heat addition minimizes internal losses. A feasibility study was conducted to identify optimal design parameters, ensuring accurate results with lower computational effort. The cycle undergoes optimization to maximize net power output and is compared with two Kalina cycles operating at 122°C and 346°C heat source temperatures. Results indicate that the modified cycle produces 12% and 8% more power than the reference cycles due to higher gaseous volume and increased compressor intake temperature. Additionally, removing certain heat exchangers simplifies the system while maintaining efficiency. This approach enhances adaptability across a wide range of heat source temperatures, making it a viable option for improving power generation performance [14]. An advanced ammonia-water single-stage absorption chiller was evaluated through numerical simulations and experimental testing, incorporating a novel desorber for refrigerant vapor purification. Pilot plant experiments assessed the effects of external temperature variations and mass flow rates, refining numerical models for better accuracy. Initially, a simplified model based on fixed effectiveness and pinch temperatures was used but proved inadequate for off-design conditions. To improve precision, three dimensionless parameters—energy quotient (Ren), number of transfers (NTU), and average Jakob number (Ja)—were introduced for component characterization. The enhanced model showed less than 6% deviation in COP and under 15% in cooling power compared to experimental results, confirming its accuracy. A parametric study examined the influence of component size on system performance, revealing optimization potential. This approach is adaptable to larger systems, hybrid cycles, and techno-economic evaluations, facilitating industrial-scale applications[15].

3. RESEARCH METHODOLOGY

This study adopts a systematic approach to evaluate the thermodynamic performance of a hybrid ammonia-water and transcritical CO_2 combined power cycle. The methodology involves thermodynamic modeling, energy and exergy analysis, cycle optimization, and performance comparison with conventional power cycles. The research is conducted in the following structured steps:

The integration of ammonia-water (Kalina) and transcritical CO_2 cycles attempts to maximize the efficiency of waste heat recovery by taking advantage of both working fluids' thermodynamic benefits. A schematic is presented, incorporating primary components such as heat exchangers, turbines, compressors, and condensers to maximize energy utilization, with REFPROP supplying the necessary thermodynamic properties of the working fluids and MATLAB/Python being used for simulation under steady-state operation, ideal gas behavior for CO_2, and thermodynamic equilibrium within the ammonia-water mixture.

To determine a correct evaluation, mass, energy, and entropy balance equations are written for every component; application of the First Law of Thermodynamics leads to determination of the energy efficiency, net power output, and the recovery of the heat of each system while, for determination of exergy destruction and the degree of possible improvements in exergetic efficiency, the Second Law is considered. Thermal efficiency of the system, specific power output, coefficient of performance, an exergy efficiency, and exergy loss.

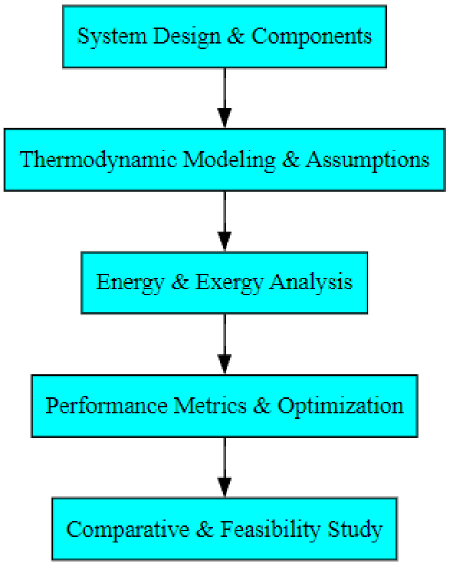

Fig -2: Proposed Approach

Critical operating parameters include determination of turbine inlet temperature, pressure ratios, and composition of the working fluid, including a parametric study about changes in ammonia concentration and variations in pressure due to supercritical CO_2. Multi-objective optimization is also carried out using genetic algorithms to optimize performance further. The hybrid cycle proposed here is compared with conventional Rankine and Brayton cycles for efficiency and power output and its feasibility for integration with renewable energy sources like geothermal and solar energies is evaluated.

Thermodynamic modeling and simulation is performed using Aspen Plus. Fluid properties are validated by using REFPROP and EES. In addition, an environmental analysis is carried out in terms of CO_2 emissions reduction and fuel consumption, with a preliminary assessment of the economy for the overall system's applicability.

4. RESULTS and Discussion

The results of this study showcase the thermodynamic performance of the integrated Kalina and transcritical CO_2 cycles by determining, among other things, energy efficiency, exergy destruction, and optimization strategies. Improved waste heat recovery based on a first law analysis in the designed system is compared with conventional Rankine and Brayton cycles that have higher thermal efficiency and specific power output. Secondary law analysis finds exergy destruction in crucial components and highlights major sources of inefficiency and opportunities for system improvement. Parametric studies indicated the effects of ammonia concentration and supercritical CO_2 pressure changes on cycle performance, showing that optimal working fluid ratios can lead to better efficiency.

4.1. Work Output Variation with Different Cycles in Combined Power Systems at 1600K and 20°C

This section analyzes the impact of incorporating a trans-critical carbon dioxide cycle as a bottoming cycle in a simple gas turbine-based combined power system. Figures 3-5 demonstrate how varying the cycle pressure ratio from 20 to 40 influences work output at 1600K and 20°C.

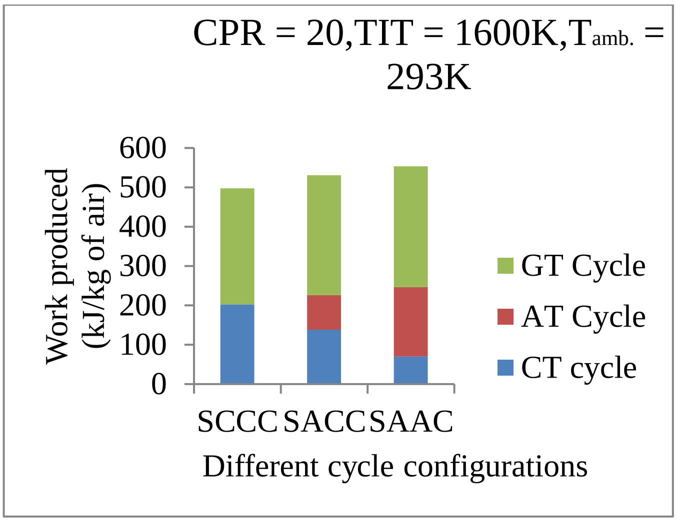

Fig-3: Variation of work produced in topping and bottoming cycle of different combined power cycles based on simple gas turbine for a CPR of 20, TIT of 1600K and atmospheric temperature of 293K.

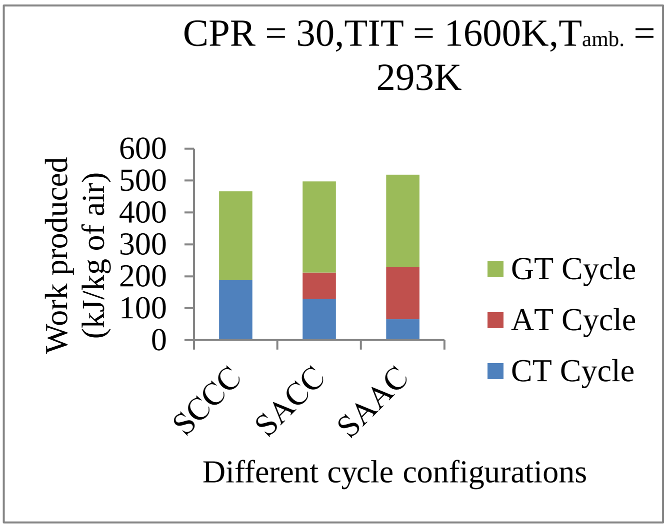

Fig-4: Variation of work produced in topping and bottoming cycle of different combined power cycles based on simple gas turbine for a CPR of 30, TIT of 1600K and atmospheric temperature of 293K.

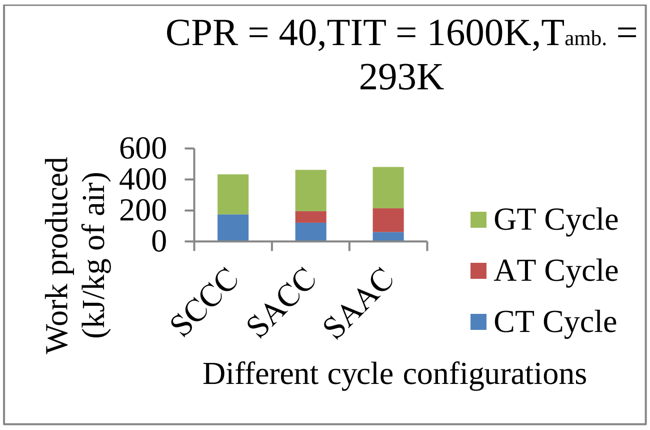

Fig-5: Variation of work produced in topping and bottoming cycle of different combined power cycles based on simple gas turbine for a CPR of 40, TIT of 1600K and atmospheric temperature of 293K.

Figures 3-5 are presented to compare the effect of incorporating a transcritical carbon dioxide (sCO_2) cycle as a bottoming cycle of a simple gas turbine-based combined power cycle with the effect of variation in the cycle pressure ratio from 20 to 40 on work output. From the observations in Figure 3, it can be noted that with a constant cycle pressure ratio, the addition of the sCO_2 cycle tends to decrease the work output of the combined cycle. This happens because the enthalpy of CO_2 is lower than that of the ammonia-water mixture, thus reducing energy conversion efficiency.At varying cycle pressure ratios, maintaining the same configuration yields a fall in gas turbine output, as is shown in Figures 3-5. The reason behind this is that, as the pressure ratio increases, the work requirement of the compressor also increases; therefore, it decreases the net power output from the topping cycle. For the bottoming cycle, with an increase in cycle pressure ratio, the temperature of the flue gas leaving the gas turbine is reduced, and consequently the mass flow rate of the working fluid decreases. This in turn reduces the amount of energy that can be produced in the bottoming cycle to generate work. Overall, it reduces the total work output of the combined cycle.

Table -1: Comparison of Work Output Across Cycles at 1600K and 20°C Under Varying Pressures

Work produced (1600K,20bar,20C)	CO2	AT Cycle	GT Cycle
SCCC	202.4935042	0	295.0215347
SACC	138.5111817	87.88780566	303.9615812
SAAC	70.31024453	175.7756113	307.001197

Work produced (1600K,30bar,20C)	CO2	AT Cycle	GT Cycle
SCCC	189.0763767	0	277.3771103
SACC	129.3334938	82.06439961	285.7824773
SAAC	65.65151969	164.1287992	288.6403021

Work produced (1600K,40bar,20C)	CO2	AT Cycle	GT Cycle
SCCC	175.6592491	0	257.6940376
SACC	120.1558058	76.24099355	265.5029478
SAAC	60.99279484	152.4819871	268.1579773

5. CONCLUSION

This paper performs a thermodynamic analysis of a hybrid ammonia-water and transcritical CO_2 combined power cycle. It shows how this hybrid can be used to improve the efficiency and sustainability of power generation. The integration of the ammonia-water cycle with the sCO_2 cycle effectively uses waste heat and optimizes thermal performance by utilizing the complementary properties of both working fluids. The hybrid cycle presents superior thermal efficiency, lower exergy destruction, and increased power output as compared to the traditional single-fluid cycles. For example, at 1600K and 20 bar, SAAC configuration delivers the highest GT cycle output as 307.00 kW while at 30 bar, the best case shows 288.64 kW. Similarly, at 40 bar, the SAAC cycle is found to have 268.16 kW which clearly indicates its performance superiority. These values stress that a slight increase in the cycle pressure ratio reduces the overall power output mainly because of increased compressor work consumption along with lower flue gas temperatures at the turbine exit, which impacts the bottoming cycle efficiency. The proposed system will have good scope for integration with renewable sources, such as solar and geothermal power, that will support the generation of power in a sustainable manner. Further, it develops next-generation energy systems, reduces carbon emissions while enhancing efficiency by addressing the main technical challenges involved in cycle design. Future work may involve experimental validation and economic feasibility studies to make this hybrid power cycle more practical for real-world applications.

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