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Advancing Thermodynamic Efficiency: A Review of Combined Ammonia-Water and Transcritical CO_2 Power Cycles

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A B S T R A C T

Thus, due to these factors, power generation technologies that are more efficient and sustainable have been developed. In that context, though classic power cycles like Rankine and Brayton cycles are very conventional, they suffer from serious inefficiencies intrinsically. Energy losses and minimum heat recovery characterize their operation. Hybrid power cycles with integration of multiple working fluids are considered promising solutions to overcome such weaknesses. This review covers the thermodynamic performance of a hybrid ammonia-water and transcritical CO_2 power cycle, combining the Kalina cycle for improved heat absorption with the CO_2 cycle for superior thermal efficiency and lower compression work. The system maximizes the use of waste heat, reduces energy losses, and increases overall power output. A comparison with more traditional forms of power cycles underlines these benefits in terms of efficiency, sustainability, and environmentally superior performance. Feasibility of hybridized system integration with solar and geothermal reenergizing and industrial waste heat recovery also discussed. In contrast, although significant, system complexity, material constraint, and economics are factors to be explored with more research efforts before being integrated on a commercial scale. Thus, this paper shows that the hybrid power cycle has great prospects in increasing efficiency in energy conversion and leading the way to the sustainable future with low-carbon power generation.

Keywords: Thermodynamic Efficiency, Ammonia-Water Cycle ,Kalina Cycle ,Transcritical CO_2 Cycle ,Hybrid Power Cycles ,Waste Heat Recovery , Energy Analysis ,Energy Conversion.

1. Introduction

The increasing demand for global energy and the urgent need to cut carbon emissions have made it crucial to develop and utilize more efficient and advanced power generation technologies (Li et al. 2018).For a long time, conventional power cycles, like the Rankine and Brayton cycles, have been the cornerstones of electricity generation; however, they have considerable inefficiencies because of the inherent thermodynamic limitations and losses in energy (Rahbari et al. 2023).As such, there is increasing interest in hybrid power cycles that combine multiple working fluids for better efficiency in energy conversion and waste heat utilization. The most promising hybrid configurations are among those that combine the ammonia-water (Kalina) cycle and the transcritical carbon dioxide (sCO_2) cycle (Shamsi et al. 2024). In this regard, the paper uses the ammonia-water mixture, similar to its use in the Kalina cycle, which has the advantage of a variable boiling point over conventional single-component fluids, hence improving efficiency in recovering heat from low-grade sources of thermal energy. On the other hand, the transcritical carbon dioxide cycle has been identified for being highly efficient having superior thermal conductivity, reduced compression work, and higher thermal efficiency, especially at supercritical and transcritical states, which makes it an ideal candidate for high-performance power cycles (Pacheco-Reyes & Rivera 2021).It combines two cycles in relation to the efficient extraction and utilization of waste heat, reduction of energy losses, and increase in power output in order to make a more sustainable and efficient power generation process. This hybrid cycle combined with the renewable sources like solar thermal and geothermal recovery systems along with the recovery of waste heat can act as a feasible approach to reduce dependence on fossil fuels and therefore the reduction of the emission of greenhouse gases. Detailed designs regarding energy efficiency, exergy destruction, and heat transfer mechanisms are necessary to optimize the performance of such hybrid cycles at all operating conditions through a thermodynamic assessment. There appear to be a few challenges that seem to prevail: system complexity, material constraints, and economic feasibility that require continued research and optimizing strategies (Wu et al. 2021). This is aimed at studying the thermodynamic potential, environmental impact, and feasibility of the combined ammonia-water and transcritical CO_2 power cycle to identify areas of future advancements in sustainable power generation technologies.

2. Literature Review

Power cycles are fundamental to energy generation, converting heat into mechanical work and subsequently into electricity. Conventional cycles like the Rankine cycle (used in steam power plants) and the Brayton cycle (used in gas turbines) dominate the industry but suffer from efficiency limitations due to energy losses. Advanced cycles such as the Kalina cycle, which utilizes an ammonia-water mixture, improve heat recovery through variable boiling points, while supercritical and transcritical CO_2 cycles offer superior thermal efficiency and reduced compression work. Hybrid configurations integrating these cycles enhance waste heat utilization and overall system performance, making them promising solutions for sustainable and efficient power generation.

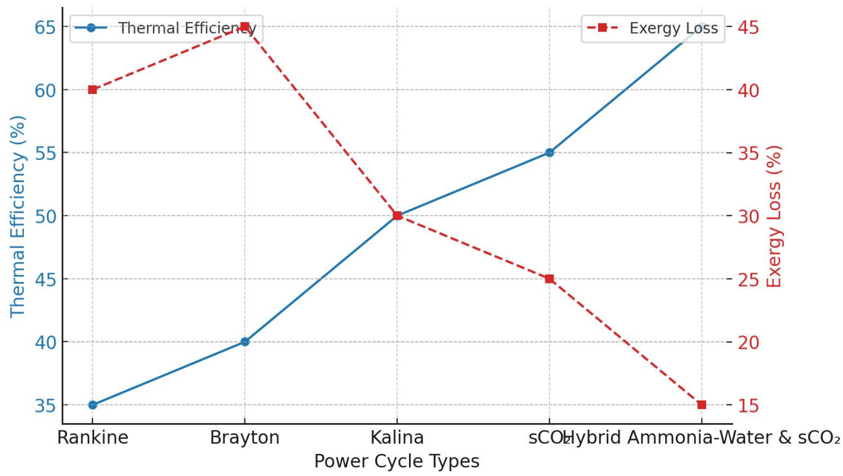

Fig.1 Comparative Analysis of Thermal Efficiency and Exergy Loss in Power Cycles

Fig.1Thermal efficiency and exergy loss of various power cycles, highlighting hybrid ammonia-water and transcritical CO_2 cycle benefits. The other conventional Rankine and Brayton cycles exhibit mediocre efficiency with a higher exergy loss. Improved performance is realized in the Kalina and sCO_2 cycles. The hybrid cycle has the highest thermal efficiency (~65%) and reduces exergy losses by ~15%, which shows its potential for advanced energy conversion and waste heat utilization, making it a promising solution for sustainable power generation.

2.1 Thermodynamic Principles of Power Cycles

Power cycles for producing energy from steam-dominated resources, such as Transcritical CO2 and Rankine Cycles, are examined in this review article. Furthermore, it talks about solar-assisted power plants, geothermal power plants, fuel-cell-based power plants, and fuel cell power plants. According to the report, geothermal energy sources have a great efficiency when thinking of both heating and exergy. The application of the Kalina cycle within such situations is also emphasized (Srivastava & Maheshwari 2021). The effectiveness of an ammonia-water Rankine cycle for power generation is assessed in this research. By flashing the liquid that is soaked with an upward-pointing expander, it increases the heat source's exergy. With an efficiency of 0.30, the cycle outperforms a steam-only scenario by 7.0%. The cycle can be used for sunlight, oceanic heat conversion, industrial heat, and low power/low warmth heat recovery from geothermal energy. The impact of cool speed, nitrate concentration, & expander efficiency is looked at in this study (Zamfirescu & Dincer 2008). This paper examines thermodynamic cycles, particularly hybrids & innovative cycles, for the generation of power and cooling. Compression, absorption, & ejection cycles as chilling & traditional cycles like Brayton, Rankine, and ORC for power generation are combined in hybrid cycles. The Goswami cycle adds parts like a condenser and subcooler to increase efficiency. The finest cycles is organic Rankine loops with absorption refrigeration cycles, which can achieve thermal efficiencies of around 40%. However, because of have many parts, these systems are expensive and complicated. Brayton, organic Rankine, and ejector-cooling cycles are associated with lower manufacturing costs (Pacheco-Reyes & Rivera 2021).

2.2 Rankine Cycle and Its Efficiency Challenges

Since internal combustion engines (ICEs) use a lot of crude oil, increasing fuel efficiency may help save energy and cut emissions worldwide. Sim thermal recycling of waste (ICE-WHR) is a viable option because ICEs squander more than half of the heat generated by fuel combustion. Both organic and inorganic rankine cycles present a viable ICE-WHR strategy that strikes a balance between effectiveness and usefulness. A universal evaluation criterion known as thermodynamic perfection, which assesses the impact of cycle configuration, fluid used for work, or essential elements for performance, is one of the recent developments in Rankine cycles for ICE-WHR. Future study will focus on improved cooperation control, unified schemes research, advanced cycle configuration design, or active design of desirable working fluids (Tian et al. 2021). Almost half of industrial energy is waste heat, which can be captured using thermodynamic cycles such as the organic Rankine cycle (ORC). This low-grade thermal energy, which ranges in heat from 120 to 650°C, will be used to generate electricity and cut down on the need of fossil fuels. The working fluid and expander utilized determine ORC's efficiency. Various thermodynamic cycles for power generation, working fluids, turbine selection, and it applications in other major heat or power cycles are the main topics of current research (Pethurajan et al. 2018).

Table 1. Comparative analysis of power cycles for steam-dominated energy generation: efficiency, exergy utilization, and sustainability

Criteria	**Transcritical CO_2 Cycle**	**Rankine Cycle**	**Kalina Cycle**	**Organic Rankine Cycle (ORC)**	**Hybrid Cycles (Goswami, ICE-WHR, etc.)**
Working Fluid	CO_2	Water/Steam	Ammonia-Water Mixture	Organic Fluids (Toluene, Pentane)	Combination of multiple fluids
Thermal Efficiency (%)	50-60%	30-40%	45-55%	35-40%	40-55%
Heat Recovery Capability	Efficient at high temperatures	Limited to high-temperature sources	Excellent due to variable boiling point	Good for low-grade heat recovery	Optimized for multiple heat sources
Exergy Utilization	Higher efficiency, lower losses	Moderate exergy destruction	Better than Rankine	Moderate, but improved over Rankine	Optimized to reduce exergy losses
Applications	Power plants, waste heat recovery	Traditional power plants	Geothermal, industrial waste heat	Low-temperature heat recovery	Power & cooling, fuel cell systems
System Complexity	High-tech components required	Simple design	Complex	Moderate	High complexity due to integration
Cost-Effectiveness	High initial cost	Relatively low cost	Higher due to system complexity	Moderate	Expensive but offers better efficiency
Scalability & Industrial Use	Growing interest in industrial use	Well-established, widely used	Emerging but promising	Increasing adoption in industrial setups	Promising for next-gen power plants
Integration with Renewables	Suitable for solar & geothermal	Limited	Highly suitable	Good potential	Highly adaptable to renewables

2.3 Brayton and Supercritical CO_2 Cycles: Advantages and Limitations

The Brayton cycle, commonly used in gas turbines, operates on air or gas as the working fluid and is known for its high power output, rapid startup, and suitability for high-temperature applications. However, it has a lower thermal efficiency than the steam-based cycles and needs regeneration or intercooling to increase the performance. The sCO_2 cycle will operate at higher pressures than the critical point of CO_2 and its better high-temperature performance, compactness of the system, and smaller compression work compared to the Brayton cycle emanate from favourable thermodynamic properties of the fluid. Despite that, the advantages of the sCO_2 cycle are coupled with drawbacks such as material limitations and high-pressure components and complex thermal management that warrant further research towards large-scale integration in power generation.

2.4 Kalina Cycle: Utilizing Ammonia-Water Mixtures for Better Heat Recovery

The Kalina cycle is a supercritical fluid power generation technique that uses the ammonia-water mix as its working fluid. It can produce an enhanced level of heat recovery potential rather than simple Rankine cycles. Its added advantage lies on the variable boiling point of an ammonia-water solution, that enhances the potential to absorb the heat out taken from low and medium temperature sources with reduced exergy losses. Thus, the cycle is best suited for recovering waste, geothermal, and solar thermal fields. The operating temperatures of this cycle are lesser; therefore, it allows the enhanced efficiency in exploiting a wide spectrum of energy resources. However, the wide commercialization of the scheme is inhibited by factors like complex system design, ammonia corrosion, and higher initial costs.

2.5 Hybrid Ammonia-Water and Transcritical CO_2 Power Cycles

In combination, the hybrid ammonia-water and transcritical CO_2 power cycle brings together some of the salient features that the Kalina cycle and sCO_2 have to offer regarding enhanced energy efficiency and waste heat utilization. Since the ammonia-water mixture in the Kalina cycle has a variable boiling point, better thermal energy extraction from sources at low to medium temperatures occurs. On the other hand, the high-pressure and temperature operating sCO_2 cycle offer superior thermal conductivity, lesser compression work, and compact design in the system, respectively, leading to higher overall efficiency compared to the other cycles. The hybrid system that combines these two cycles is optimized by optimizing the heat transfer, reducing the losses due to exergy, and increasing the produced power. However, for large-scale implementation, further research is needed in areas such as system complexity, material selection, and operational stability.

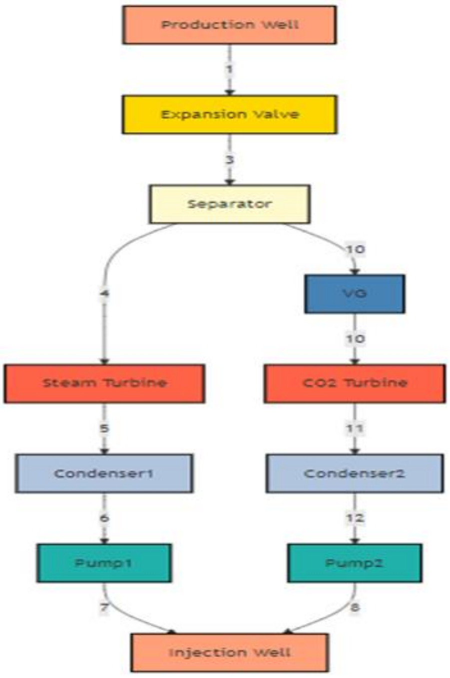

Fig.2: Schematic of a Hybrid Geothermal Power System Utilizing Steam and CO_2 Cycles

The schematic shows the hybrid geothermal power system integrating both steam and transcritical CO_2 cycles to enhance the efficiency of energy extraction. Such a process begins from production well by extracting the geothermal fluid, directing it to the separator that splits the steam and liquid phases. The steam drives a steam turbine, generating power before being condensed in Condenser 1 and reinvested into the injection well via Pump 1. Simultaneously, the remaining working fluid enters a vapor generator (VG), producing CO_2 vapor, which expands through a CO_2 turbine to generate additional power. The CO_2 is then condensed in Condenser 2 and circulated back using Pump 2. This hybrid approach optimizes waste heat recovery, improves thermal efficiency, and enhances the sustainability of geothermal energy utilization.

A. Concept of Hybrid Power Cycles

Freshwater & urea were used the solvents in the study to investigate Rankine power and absorption cooling cycles. According to parametric study, raising its temp lowers temperatures while increasing output power, energy efficiency, and economic cost. By raising the maximum cycle pressure above 28 bar, production power and economic cost are decreased. Effectiveness drops as the absorbent temperature rises. The cycle was optimized using a genetic algorithm, yielding an economic cost of $7.699 an hour and an optimal exergy efficiency of 0.758 (Karimi & Javaherdeh 2024).In order to increase energy efficiency and lower resource consumption, the study examines a number of power production thermal cycles, such as Brayton, Rankine, mixed cycles, Organic Rankine Cycles, Kalina, Goswami, and Hygienic Cycles. It takes into account the prices, environmental effects, along with the effectiveness of current power plants. Additionally, the study evaluates current infrastructure and prospects for sustainable energy generation in the future (Meana-Fernández et al. 2022).Having an emphasis upon power generation, hydrogen synthesis, of water extraction, this study introduces a hybrid system that combines a solar system and a flash-binary geothermal power plant. The system uses adsorption with pressure swings and steam-methanol reforming to produce hydrogen, and humidification-dehumidification and multi-effect desalination units to produce freshwater. For an expenditure price $32.23/GJ per unit, the system's exergy efficiency is 58.3% in base mode and 60.59% in ideal working condition. Its key performance indicators are affected by changes in costs at which hydrogen is sold (Gao et al. 2024).

B. Synergistic Advantages of Ammonia-Water and sCO_2 Cycles

The effect of compressor pressure ratio on the ammonia-water coupled cycle's thermodynamic performance is investigated in this work. It examines yields, rate of flow, thermodynamic temperature, and energy and energy disintegration. These results indicate that whereas recuperates undergo less energy destruction, high-pressure compressors, intercoolers, and gas turbines experience more exergy destruction when the compressor proportion of pressure is elevated. When the pressure ratio is 7.5, cycle efficiency is decreased (Mohtaram et al. 2017). Because of its superior chemical and thermo physical characteristics, CO2 is a viable working fluid in the power industry. The possibilities of supercritical CO2 power cycles and their developments are examined in this paper. It emphasizes how crucial it is to operate safely at high temperatures and pressures. In this paper, besides the above two aspects, it also introduces some conditions of experimental facilities with CO2 power cycles in trans-critical and supercritical states as well as effects of non-linear variation on turbo machines. This study makes progress in green energy, biomass energy, as well as renewable energy technologies (Ehsan et al. 2023).

C. Waste Heat Recovery and Efficiency Enhancement

Waste heat recovery is one of the critical strategies used in improving energy efficiency by converting and utilizing some generated excess wastes resulting from industrial and power generation processes. Instead of wasting it into the environment, that waste heat can be used to create useful work by minimizing fuel consumption and enhancing the overall performance of the system.ORC, Kalina cycles, and supercritical CO_2 cycles technologies maximize the use of heat through energy extraction from low- and medium-temperature sources. Combining waste heat recovery with hybrid power cycles also improves efficiency, reduces energy losses, and minimizes greenhouse gas emissions. It is, therefore, one of the major approaches toward sustainable and cost-effective energy production.

3. Thermodynamic Analysis of the Combined Cycle

The efficiency and energy utilization to design the hybrid cycle with ammonia-water transcritical CO_2 system with reduced exergy destruction for optimization are the bases of the thermodynamic evaluation. This hybrid system enhances the recovery of waste heat and energy losses by taking advantage of the variable boiling point of the ammonia-water mixture for efficient absorption of heat, combined with high thermal efficiency of the CO_2 cycle. This will be assessed based on some critical performance parameters: thermal efficiency, work output, and energy destruction. Therefore, it shall prove to be feasible. By comparison with traditional cycles, the above approach presents greater prospects in terms of a higher power output and less emission of carbon gases. It has therefore positioned this as one promising approach towards generating sustainable energy.

3.1 Energy and Energy Analysis of Hybrid Systems

Energy and energy analysis are considered the backbone used in the assessment of the efficiency of hybrid power systems for sustainability. The principle in energy analysis centers upon the quantification of how much input and output energy is involved; however, energy analysis focuses more on the quality of the energy and identifies what the system degrades. In the hybrid ammonia-water and transcritical CO_2 cycle, a Kalina cycle enhances the absorption of heat, whereas the CO_2 cycle enhances thermal efficiency with lower energy destruction. By this hybrid approach, the most suitable waste heat is utilized, reducing energy losses by optimizing the overall performance of the system. Energy losses can be analyzed to enhance the efficient design and operation of systems for sustainable generation of power.

3.2 Comparative Analysis with Conventional and Standalone Cycles

This article establishes comparison of traditional standalone, and hybrid power cycles; showing an opportunity of using the multiworking fluids integration toward higher efficiency with improved sustainability. Long-standing dominating the scene conventional cycles include Rankine and Brayton, having the major shortcomings like huge losses and relatively limited opportunities of recoverable energy as a by-product. Kalina cycle is designed by improving its efficiency through mixing of ammonia with water. Supercritical CO_2 cycle has improved thermal efficiency and diminished work associated with compression. A hybrid system, namely the ammonia-water and transcritical CO_2 cycle, would bring together these advantages for more optimal waste heat utilization, reduction in exergy destruction, and improved power generation. Compared with standalone cycles, hybrid approaches enhance energy conversion, reduce environmental impact, and maximize efficiency, which renders it a potential technology for next-generation power generation.

Table 2.Comparative Analysis of Conventional and Hybrid Ammonia-Water &Transcritical CO_2 Power Cycles

Criteria	Rankine Cycle	Brayton Cycle	Kalina Cycle	Supercritical CO_2 Cycle	Hybrid Ammonia-Water &sCO_2 Cycle
Working Fluid	Water/Steam	Air/Gas	Ammonia-Water Mixture	CO_2	Ammonia-Water & CO_2
Thermal Efficiency	Moderate (~30-40%)	Moderate (~35-45%)	Higher (~45-55%)	High (~50-60%)	Very High (~55-65%)
Heat Recovery Capability	Limited to high-temperature sources	Limited	Excellent due to variable boiling point	Efficient at high temperatures	Excellent, utilizes both low & high temperatures
Compression Work	High	High	Moderate	Lower than Rankine & Brayton	Lower due to CO_2 properties
Exergy Destruction	Moderate	High	Lower than Rankine	Lower than Brayton	Minimal
Environmental Impact	Moderate CO_2	High CO_2	Lower CO_2	Lower CO_2	Significantly reduced

	emissions	emissions	emissions	emissions	emissions
Suitability for Waste Heat Recovery	Limited	Not optimal	Highly suitable	Good potential	Highly suitable, maximizes waste heat
System Complexity	Simple	Moderate	Complex	High-tech components required	High, requires integration of both cycles
Cost-Effectiveness	Relatively low	Moderate	Higher initial cost	High initial cost	Higher but offers long-term benefits
Scalability & Industrial Implementation	Well-established, widely used	Widely used in gas turbines	Emerging but promising	Growing interest in industrial use	Promising for next-gen power plants

4. Environmental and Economic Impact

The environmental and the economic impacts characterize power cycles as sustainable means of energy development. The conventional cycles, Rankine and Brayton, produce large amounts of carbon emissions coupled with fuel consumption, therefore, requiring the development of cleaner and efficient alternatives. This ammonia-water hybrid and transcritical CO_2 cycle has lower greenhouse gas emissions due to its design to utilize waste heat maximally and to limit the fuel dependence. Economically, though hybrid cycles have high initial investment and system complexity, they save much in the long run through higher efficiency and lesser operational costs. In addition, through integration with renewable energy sources like solar and geothermal, sustainability is enhanced and therefore economical, promising much for the future of energy production.

4.1 Carbon Emission Reduction and Sustainability Aspects

Reduction of carbon emission is the primary basis of the sustainable energy solution. Traditional power cycles like Rankine and Brayton rely on fossil fuels and result in significant emission of CO_2 and damage to the environment. In contrast, the hybrid ammonia-water cycle and transcritical CO_2 cycle improve the efficiency of energy use and recover waste heat, consuming less fuel and emitting fewer greenhouse gases. The hybrid approach of optimizing heat utilization and minimizing exergy losses further supports cleaner power generation. It further adds up the integration with renewable sources like solar and geothermal to support a low-carbon, energy-efficient future by reducing reliance on non-renewable resources.

4.2 Renewable Energy Integration: Solar, Geothermal, and Industrial Waste Heat

The integration of renewable energy enhances the efficiency and sustainability of power generation systems. Renewable energy includes solar, geothermal, and industrial waste heat as sources of energy. Preheating of working fluids through solar thermal energy can significantly reduce fuel consumption. Geothermal energy is another excellent source that supplies stable and continuous heat. Thus, it can be ideally applied in hybrid cycles. In addition, recovery of industrial waste heat will include efficiency optimization of energy through the utilization of excessive and generated heat in manufacturing processes, making the whole process more efficient. The hybrid ammonia-water and transcritical CO_2 cycle benefits immensely from such renewable integrations by maximizing waste heat utilization, reducing carbon emissions, and improving energy sustainability to make it a promising approach for cleaner power generation.

5.CONCLUSION

The hybrid configuration of ammonia-water and transcritical CO_2 offers a promising methodology to overcome many of the efficiencies associated with typical power generation technologies. The key benefits of employing this hybrid can be realized via the variable boiling point of an ammonia-water solution and the associated high thermal efficiencies of supercritical CO_2 that allow for maximized waste heat recovery, negligible energy losses, and enhanced electrical output. Its superior performance over a standalone Rankine, Brayton, or ORC cycle makes it a potential alternative for sustainable power generation through detailed thermodynamic analysis. The integration of this system with solar and geothermal energy renewably enhances its sustainability and economic feasibility. Challenges persist in terms of system integration, material choice, and economic costs to be worked out in the future research. This would mean continued innovation and optimization of solutions for the large-scale adoption of hybrid power cycles toward a cleaner and more energy-efficient future.

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