Design and Optimization of He-Xe Brayton cycles system for MW-level space nuclear reactor application

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Abstract

Space reactors hold promising prospects for marine, terrestrial, aerial, and space applications due to their compact size, versatility, and high efficiency. The integration of high-temperature gas-cooled reactors with Brayton cycles is particularly well-suited for megawatt-level exploration missions. A space gas-cooled reactor with a thermal power of 3 MW is selected as the research subject, and its design and optimization are performed using EBSILON simulation software. Efficiency comparisons between direct and indirect Brayton cycles are conducted under various conditions, revealing that the direct Brayton cycle achieves 1.4%-2.8% higher efficiency than the indirect cycle while occupying less space. The efficiencies of four Brayton cycle configurations are compared. At a compressor inlet temperature of 400 K, the recompression cycle exhibits lower efficiency, whereas both the intercooled cycle and the simple reheat cycle achieve efficiencies exceeding 30% when the turbine inlet temperature reaches 1400 K. At a compressor inlet temperature of 350 K, the simple reheat cycle can attain 29.6% efficiency at a turbine inlet temperature of 1200 K. At a compressor inlet temperature of 300 K, all four cycle configurations exhibit efficiencies above 20%. Furthermore, when the turbine inlet temperature exceeds 1150 K, all four configurations achieve efficiencies above 30%. The optimal pressure ratios vary among configurations: 2.2 for the simple reheat cycle and 3.5 for the intercooled cycle. Additionally, the optimal pressure ratio for the recompression cycle depends on its split ratio; the recompression cycle efficiencies are 0.417 and 0.141 at split ratios of 0 and 0.4, respectively. In practical operation, system pressure losses are inevitable. It is found that the efficiency penalty caused by high-pressure relative losses is 1.7% greater than that caused by low-pressure relative losses. Exergy analysis is also employed to verify that the recompression cycle efficiency is lower than that of the simple reheat cycle. Losses in both cycles are concentrated in the cooler and reactor, with the combined cooler and reactor losses of the recompression cycle accounting for 79.6% of the total losses. Finally, the simple reheat cycle is selected as the optimal configuration, and a space reactor system with a thermal power of 3 MW and an electrical power of 1 MW is successfully designed.

Full Text

Preamble

Design and Optimization of He-Xe Brayton Cycle Systems for MW-Level Space Nuclear Reactor Applications

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Space nuclear reactor power systems hold promising prospects for maritime, terrestrial, aerial, and space applications due to their compact size, versatility, and high efficiency. The combination of high-temperature gas-cooled reactors (HTGR) with Brayton cycles is particularly suitable for megawatt-level exploration missions. This study investigates a space gas-cooled reactor with 3 MW thermal power using EBSILON simulation software for design and optimization. Efficiency comparisons between direct and indirect Brayton cycles reveal that the direct cycle achieves 1.4%-2.8% higher efficiency while occupying less space. Four Brayton cycle configurations are evaluated: at a compressor inlet temperature of 400 K, the recompression cycle shows lower efficiency, whereas both the interstage-cooled cycle and simple reheat cycle exceed 30% efficiency when turbine inlet temperature reaches 1400 K. At 350 K compressor inlet temperature, the simple reheat cycle achieves 29.6% efficiency at 1200 K turbine inlet temperature. At 300 K compressor inlet temperature, all four configurations exceed 20% efficiency, and above 1150 K turbine inlet temperature, all exceed 30% efficiency. Optimal pressure ratios differ by configuration: 2.2 for simple reheat and 3.5 for interstage-cooled cycles. For recompression cycles, the optimal pressure ratio depends on the split ratio, with efficiencies of 0.417 and 0.141 at split ratios of 0 and 0.4, respectively. System pressure losses are unavoidable in practice, with high-pressure relative losses reducing efficiency by 1.7% more than low-pressure losses. Recuperator effectiveness and turbomachinery efficiency also significantly impact cycle performance. Exergy analysis confirms that recompression cycle efficiency is lower than simple reheat cycle efficiency, with losses concentrated in the cooler and reactor—accounting for 79.6% of total losses in the recompression cycle. Finally, the simple reheat cycle is selected as the optimal configuration, successfully designing a space reactor system with 3 MW thermal power and 1 MW electrical power.

Keywords: Brayton cycle; Space nuclear reactor; Exergy analysis; Design and

optimization

Introduction

Energy is indispensable to industry, military applications, and civilian life. As scientific and technological capabilities advance, humanity is expanding its exploration of maritime, terrestrial, aerial, and space domains. However, solar energy lacks autonomy, chemical energy systems have short mission durations, and radioisotope power sources offer low power levels—making them unsuitable for high-power missions [1]. New mobile reactor systems, independent of sunlight and featuring high energy density, have been extensively studied and applied across sea, land, air, and space domains [2]. Space reactor power systems must address three key technical aspects: safety and economics, performance (maximizing power-to-mass ratio), and applicability.

Building on decades of research into portable reactor systems, numerous studies on space nuclear power have emerged. In 2003, NASA established the "Prometheus" program to develop high-power space nuclear reactor systems [3]. Russia initiated development of MWe-class nuclear propulsion spacecraft in 2009, featuring an ultra-high-temperature gas-cooled reactor coupled with a Brayton cycle system that has guided subsequent space reactor designs [4]. The European Space Agency (ESA) has also pursued space nuclear power technology through the DiPoP (Disruptive Technologies for Power and Propulsion) [5] and MEGAHIT [6] programs, completing technical selections for nuclear electric propulsion systems.

Building upon this foundational research, numerous studies on space reactors have appeared. Ju et al. [7] proposed a conceptual design for a helium-xenon gas-cooled fast reactor with hexagonal prismatic fuel elements and investigated its thermal-hydraulic characteristics. Yang et al. [8] conducted neutronics analysis of a prismatic space gas-cooled reactor. Jiang et al. [9] developed a shielding mass estimation model for the Jupiter Icy Moon Orbiter (JIMO) reactor. Yue et al. [10] studied OMEGA (Open-grid Megawatt Gas-cooled spAce nuclear reactor) and developed TASS (Transient Analysis code of scheduled Shutdown and emergency Shutdown), concluding that fuel cladding surface coatings significantly enhance radiative heat transfer. Qin et al. [11] optimized energy conversion efficiency and radiator mass for air-cooled space nuclear reactors, comparing heat pipe radiators (HPR) and liquid droplet radiators (LDR). Meng et al. [12] performed numerical simulations of a 1/12 full-core air-cooled space nuclear reactor under zero-gravity conditions using STAR-CCM+. Li et al. [13] proposed a conceptual design for a 200 kWe integrated space air-cooled reactor using TRISO fuel, concluding that helium-xenon mixture is the optimal working fluid. Alfonso Biondi et al. [14] modeled a closed Brayton cycle driven by a solar parabolic collector, achieving 7.4% efficiency improvement, 21% weight reduction, and a specific mass of 30 kg/kW. Guilherme B. Ribeiro et al. [15] developed a closed regenerative Brayton cycle model for heat exchanger sizing and mass optimization. Wu et al. [16] examined transient safety of gas-cooled reactors and investigated coupled Brayton cycle system performance. Ma et al. [17] studied characteristics of space nuclear power systems with dual Brayton loops after load loss events.

Helium-xenon gas mixtures are commonly used in terrestrial, maritime, aerial, and space reactors. Supported by chemistry and gas dynamics research, numerous studies have examined nuclear aspects of He-Xe mixtures. Wang et al. [18] optimized property calculation models for He-Xe mixtures for natural circulation analysis. Adil Malik et al. [19] analyzed advantages of helium-xenon over pure helium in HTGR turbocompressors. Ma et al. [20] linked thermodynamic performance to system mass for megawatt-scale space reactors, concluding helium-xenon is optimal. Wang et al. [21] numerically investigated thermal-hydraulic properties of He-Xe in a 2$×$2 helically-wrapped rod bundle.

The combination of high-temperature gas-cooled reactors and Brayton cycles represents an important research direction for space nuclear power [22, 23]. Current research primarily focuses on core design and component optimization within Brayton cycles, with fewer studies addressing structural selection of the Brayton cycle itself. For common working fluids like air and supercritical CO_2, different Brayton cycle configurations significantly impact efficiency. This paper investigates optimal Brayton cycle structures and parameters for helium-xenon mixtures, which have large adiabatic indices.

System and Model

A. High-Temperature Gas-Cooled Reactor (HTGR) Model

The high-temperature gas-cooled reactor modeled in this study is an open-grid design [24], consisting of upper and lower grids, 654 fuel elements, and 13 control rods. The grids provide axial positioning for fuel elements, which are cylindrical and arranged in a triangular lattice with 14.2 mm spacing. Control rods contain B_4C absorber blocks with 1 mm thick shells and metal rubber gaps to accommodate radial deformation from fission gases. A schematic of the reactor coupled with a Brayton cycle is shown in [Figure 1: see original paper].

Fuel elements comprise uranium dioxide pellets, hot-end and cold-end reflectors, casing, and liner. The fuel is sintered UO_2 discs with central holes; cladding is Mo-Nb-Zr alloy. The central hole vents gaseous fission products to the fuel element' s gas plenum via a dedicated venting device. Design parameters for the open-grid HTGR are listed in .

B. Brayton Cycle Model

The Brayton cycle is a reliable thermodynamic cycle widely used across many fields due to its efficiency and applicability [25]. A simple Brayton cycle consists of four processes: adiabatic compression, isobaric heating, adiabatic expansion, and isobaric heat rejection. The cycle' s core component is the turbomachinery assembly (TAC), integrating turbine, compressor, and generator on a common shaft. Turbine work is distributed to the compressor and generator via the shaft, enabling cycle operation. Additional components include coolers and recuperators.

The temperature-entropy diagram for a simple reheat Brayton cycle is shown in [Figure 2: see original paper]. High-temperature He-Xe mixture from the reactor outlet enters the turbine (1-2), then flows through the recuperator (2-3) before entering the external cooler where NaK cools it on the tube side (3-4). The cooled fluid enters the compressor (4-5), with excess work generating electricity. The fluid then passes through the recuperator (5-6) and returns to the core for reheating (6-1).

To maximize heat utilization, the recompression cycle adds a recompressor and splits the recuperator into two sections. Its temperature-entropy diagram is shown in [Figure 3: see original paper]. Unlike the simple reheat cycle, fluid from the low-temperature recuperator splits through a divider, flowing to both main and recompressors (4-5-6 and 4-7). Recompressor outlet fluid merges with fluid heated by the high-temperature recuperator (7-8) before final heating in the low-temperature recuperator and core. This configuration increases core inlet enthalpy, thereby improving cycle efficiency.

The compressor is the primary power-consuming component. Reducing its power consumption improves system efficiency, which is related to compressor inlet temperature. The interstage-cooled cycle divides compression into two stages with an intercooler, reducing the second compressor’ s inlet temperature and total power consumption. The interstage-cooled cycle diagram is shown in [Figure 4: see original paper].

C. Turbomachinery Model

1) Power Balance

TAC shaft power equals turbine power minus compressor and generator power consumption. This model couples rotor shaft power with rotational speed: positive shaft power increases speed, while negative power decreases it. The mathematical expression is:

$$dN_{Shaft} = \frac{P_{Shaft}}{I \cdot N_{Shaft} \cdot 4\pi^2}$$

Power balance equation on the rotating shaft:

$$P_{Shaft} = P_{Tur} - P_{Com} - P_{Alt}$$

Turbine power generation:

$$P_{Tur} = W_{Tur} \cdot C_{p,g}(T_{cin} - T_{cout})$$

Compressor power consumption:

$$P_{Com} = W_{Com} \cdot C_{p,g}(T_{cin} - T_{cout})$$

Where: N_{Shaft} is TAC rotating shaft speed (s^{-1}); P_{Shaft} is rotor shaft power (W); I is TAC rotor shaft moment of inertia ($kg \cdot s^2$); P_{Tur} is turbine power (W); P_{Com} is compressor power (W); P_{Alt} is AC generator power (W); T_{tin} is turbine inlet temperature (K); T_{tout} is turbine outlet temperature (K); T_{cin} is compressor inlet temperature (K); T_{cout} is compressor outlet temperature (K).

2) Flow Characteristic Curve

Turbine and compressor work depends on mass flow rate and inlet/outlet temperatures, obtained from characteristic curves [26]. These curves express temperature and pressure ratios as functions of inlet temperature, inlet pressure, mass flow rate, and shaft speed, enabling calculation under specified boundary conditions.

Compressor pressure ratio curve:

$$P_{cout} = f_{PrC}(T_{cin}, P_{cin}, W_{Com}, N_{Shaft})$$

Compressor temperature ratio curve:

$$T_{cout} = f_{TrC}(T_{cin}, P_{cin}, W_{Com}, N_{Shaft})$$

Turbine pressure ratio curve:

$$P_{tout} = f_{PrT}(T_{tin}, P_{tin}, W_{Com}, N_{Shaft})$$

Turbine temperature ratio curve:

$$T_{tout} = f_{TrT}(T_{tin}, P_{tin}, W_{Com}, N_{Shaft})$$

D. Heat Transfer Model

Every space reactor Brayton cycle includes at least one gas cooler (external heat sink) to cool the working fluid. This is a shell-and-tube counterflow heat exchanger with fins, where high-temperature He-Xe flows on the shell side and water or liquid NaK flows on the tube side as coolant. Heat absorbed on the tube side is radiated to space, enabling continuous waste heat rejection. The cooler contains 400 tubes (6.35 mm outer diameter, 2 m length, 1.058 mm wall thickness), providing 47 m^2 effective gas-side heat transfer area including fins.

The cooler model includes fluid flow heat transfer models for both sides and a heat conduction model for the tubes. The two-side flow model calculates fluid pressure and enthalpy, while the wall conduction model calculates tube temperature, neglecting axial conduction and assuming radial heat transfer only. The control volume division is shown in [Figure 5: see original paper]. High- and low-temperature sides and heat exchanger tubes are divided into N axial control volumes, with tubes further divided radially. For counterflow configuration, high- and low-temperature side numbering orders are reversed.

Energy conservation equation for the ith control volume of high-temperature side gas:

$$GC1_{ci}p, GC1 = \frac{W_{GC1in}(h_{i-1}^{GC1} - h_i^{GC1})}{N_{pipe} \cdot l_i A_{GC1}} - \frac{H_i^{GC1}(T_{M+2,i}^{wall} - T_i^{GC1}) + l_i}{l_i A_{GC1}}$$

Energy conservation equation for the ith control volume of low-temperature side cooled fluid:

$$GC2_{ci}p, GC2 = \frac{W_{GC2in}(h_{i-1}^{GC1} - h_i^{GC2})}{N_{pipe} \cdot l_i A_{GC2}} - \frac{H_i^{GC2}(T_{1,N-i+3}^{GC2} - T_i^{GC1}) + N_{pipe} l_i C_{tubeI} H_i}{N_{pipe} l_i C_{tubeI}}$$

Thermal conductivity equation for the (j,i)th control volume of intermediate heat exchanger wall:

$$N_{pipe} \cdot \rho_{j,i} w c_{j,i} \frac{dT_{j,i}}{dt} + \lambda_{j,i} \frac{\lambda_{j-1,i} - T_{j,i}}{T_{j-1,i} w - r_{j-1}} - \frac{\lambda_{j,i} - T_{j,i}}{T_{j+1,i} w - r_m} = \Phi_{j,i}$$

Boundary conditions on inner surface of heat exchanger tube:

$$w + \lambda_{2,i} \frac{w - T_{1,i}}{T_{2,i} w - r_1} = H_i^{GC2}(T_{1,i} w - T_{N-i+3})$$

Boundary conditions on outer surface of heat exchanger:

$$\lambda_{M+2,i} = H_i^{GC1}(T_i^{GC1} - T_{M+2,i}) \frac{T_{M+2,i}}{r_{M+2}} + \lambda_{M+1,i} - \frac{T_{M+1,i} - r_{M+1}}{}$$

Where: Φ is channel heating perimeter (m); H is convective heat transfer coefficient ($\mathrm{W \cdot m^{-2} \cdot K^{-1}}$); T_w is heat exchanger tube wall temperature (K); W_{in} is inlet mass flow rate ($\mathrm{kg \cdot s^{-1}}$); N_{pipe} is number of heat exchanger tubes; C_{tubeI} is inner circumference (m); W_{wallI} is inner control volume circumference (m); W_{wallO} is outer control volume circumference (m); superscript i is axial control volume number; superscript j is radial control volume number; subscript $GC1$

is high-temperature side; subscript $GC2$ is low-temperature side; subscript w is heat exchanger tube wall.

To improve heat utilization and thermal efficiency, each Brayton cycle loop includes at least one plate-fin recuperator. High-temperature fluid from the turbine outlet preheats compressor outlet fluid, increasing working fluid enthalpy and reducing core heat absorption, thereby significantly improving cycle thermal efficiency. The recuperator model is fundamentally similar to the gas cooler model, differing only in working fluid temperature levels.

E. Auxiliary Model

Helium-xenon gas mixtures are crucial in space reactor research, and their combination with HTGR Brayton cycles is well-suited for MW-level space missions. Accurate gas modeling is essential, as pressure losses and thermophysical properties significantly impact cycle efficiency.

Transport properties of pure He and Xe can be calculated using Chapman-Enskog theory [27] and mixed via Hirschfelder' s method [28]. Given molecular weights (M_w), mole fractions (x), and adiabatic indices (γ), the mixture' s average molecular weight (M_{w0}) and adiabatic index (γ_0) are:

$$M_{w0} = x_{Xe} + (1 - x_{Xe})M_{He}$$

$$\gamma_0 = x_{Xe}\gamma_{Xe} + (1 - x_{Xe})\gamma_{He}$$

The gas mixture constant is:

$$R_0 = \frac{R_g}{M_{w0}}$$

Where $R_0 = 8.3145$ J/(mol · K) is the ideal gas constant.

Density (ρ), speed of sound (c), and specific heat at constant pressure (c_p) are:

$$\rho(T, p) = \frac{p}{R_0 T}$$

$$c(T) = (\gamma R_0 T)^{1/2}$$

$$c_p(\gamma, M_w) = \frac{R_0}{M_{w0}}(1 - 1/\gamma)$$

Kinetic viscosity (μ) and thermal conductivity (λ) use Lennard-Jones potential theory in Hirschfelder' s method. Lennard-Jones coefficients for He and Xe are:

$$\epsilon_{He} = 10.2\text{K}, \sigma_{He} = 2.576$$

$$\epsilon_{Xe} = 229\text{K}, \sigma_{Xe} = 4.055$$

Combined with the transport theory prediction curve $\Omega(T)$, the equations for monatomic gas properties are:

$$\Omega(T) = 0.92495 + 2.07368 \times 10^{-?} T + 0.719288 T^{-1.151049} - 5.46452 \times 10^{-?}$$

$$\mu(M_w, \epsilon, \sigma, T) = \frac{(M_w T)^{1/2}}{\sigma^2 \Omega(T/\epsilon)} \times 2.6693 \times 10^{-6}$$

$$\lambda(M_w, \epsilon, \sigma, T) = 8.322 \times 10^{-2} \frac{\text{W}}{\text{m}} \cdot \frac{(T/M_w)^{1/2}}{\sigma^2 \Omega(T/\epsilon)}$$

Gas mixture transport properties are determined by:

$$\Phi_{HX}(T) = \left[1 + \left(\frac{\mu_{He}(T)}{\mu_{Xe}(T)}\right)^{0.5} \left(\frac{M_{w,Xe}}{M_{w,He}}\right)^{0.25}\right]^2 \left[8\left(1 + \frac{M_{w,He}}{M_{w,Xe}}\right)\right]^{-0.5}$$

$$\Phi_{XH}(T) = \left[1 + \left(\frac{\mu_{Xe}(T)}{\mu_{He}(T)}\right)^{0.5} \left(\frac{M_{w,He}}{M_{w,Xe}}\right)^{0.25}\right]^2 \left[8\left(1 + \frac{M_{w,Xe}}{M_{w,He}}\right)\right]^{-0.5}$$

$$\lambda_{mix}(T) = \frac{x_{He}\lambda_{He}(T)}{x_{He} + x_{Xe}\Phi_{HX}(T)} + \frac{x_{Xe}\lambda_{Xe}(T)}{x_{Xe} + x_{He}\Phi_{XH}(T)}$$

$$\mu_{mix}(T) = \frac{x_{He}\mu_{He}(T)}{x_{He} + x_{Xe}\Phi_{HX}(T)} + \frac{x_{Xe}\mu_{Xe}(T)}{x_{Xe} + x_{He}\Phi_{XH}(T)}$$

F. Model Verification

EBSILON is a power plant visualization and thermodynamic modeling software for heat balance calculations. S4 reactor modeling and thermal-hydraulic analysis using EBSILON are well-established [29]. The reactor is modeled in EBSILON to verify its reliability for space reactor simulation, with parameters referenced from literature [30]. Simulation results are shown in .

Compared to reference values, EBSILON simulation errors are within acceptable deviation ranges, demonstrating the software' s reliability for subsequent space reactor power system analyses.

Results and Discussion

A. Comparison of Direct and Indirect Brayton Cycle Efficiencies

Direct and indirect Brayton cycles each have advantages and disadvantages. Direct cycles are compact and cost-effective but allow radioactivity throughout the loop. Indirect cycles physically separate primary and secondary loops, isolating radioactivity but requiring more space and incurring additional power consumption. Both cycles using 40 g/mol helium-xenon mixture are simulated in EBSILON at 3 MW thermal power. The indirect cycle' s primary loop pump is replaced with a compressor, and a numerical transmitter ensures equal flow rates in both loops. Simulation results are shown in [Figure 6: see original paper].

Three parameters—turbine inlet temperature, pressure ratio, and compressor inlet temperature—are varied to observe efficiency changes, with results shown in [Figure 7: see original paper]. Both cycles follow similar trends, but direct cycles are 1.4%-2.8% more efficient due to fewer components (reducing pressure losses) and absence of an additional pump in the primary loop. For high-power missions like deep space exploration, direct cycles are more suitable, offering higher efficiency in a more compact structure [31]. While indirect cycles isolate radioactivity, this advantage is less significant than the efficiency penalty.

B. Comparison of Four Brayton Cycle Structure Efficiencies

To improve Brayton cycle efficiency, researchers modify structures with interstage cooling and recompression. While recompression cycles are common for air and supercritical CO_2 [32–34], helium-xenon mixtures with high adiabatic indices may respond differently.

Four Brayton cycle structures are modeled in EBSILON, as shown in [Figure 8: see original paper]. Both compressor and turbine inlet temperatures can serve as boundary conditions for complete circuit design. The effect of turbine inlet temperature on efficiency is investigated at compressor inlet temperatures of 300 K, 350 K, and 400 K, with turbine inlet temperature varying from 950 K to 1500 K. Results are shown in [Figure 9: see original paper].

At 400 K compressor inlet temperature, efficiency ranks as: $\eta_{interstage-cooled} > \eta_{simple-reheat} > \eta_{interstage-cooled-recompression} > \eta_{recompression}$. At 1000 K turbine inlet temperature, recompression cycle efficiency is only 9.1%, and below 1200 K, it remains under 20%. This is attributed to the helium-xenon mixture' s large adiabatic index (stable around 1.67 at high temperatures), which magnifies compressor power consumption effects. Above 1400 K turbine inlet temperature, both interstage-cooled and simple reheat cycles exceed 30% efficiency, with less than 2% difference between them. Considering structural compactness, the simple reheat cycle is preferable.

At 350 K compressor inlet temperature, simple reheat cycle achieves 29.6% and 35.2% efficiency at 1200 K and 1500 K turbine inlet temperatures, respectively.

Below 1350 K turbine inlet temperature, $\eta_{interstage-cooled-recompression} > \eta_{recompression}$; above 1350 K, the relationship reverses.

At 300 K compressor inlet temperature, all four cycles exceed 20% efficiency, and above 1150 K turbine inlet temperature, all exceed 30%. At 1500 K turbine inlet temperature, both recompression and simple reheat cycles reach 38.2% efficiency, as low compressor inlet temperature minimizes recompressor power consumption, making its negative effect comparable to the positive effect of increased reactor inlet enthalpy.

Considering material properties, component characteristics, and costs, further increasing turbine inlet temperature or reducing compressor inlet temperature is challenging. Summarizing these results, the simple reheat cycle maintains significant advantages across all compressor and turbine inlet temperature variations.

C. Effect of Pressure Ratio on Efficiency

In Brayton cycles, maximum and minimum pressures occur at compressor inlet and outlet, respectively, with their ratio defining the pressure ratio. This study controls compressor outlet pressure at constant values (1.6, 1.8, 2.0, 2.2, 2.4 MPa) to investigate pressure ratio effects. Simple reheat and interstage-cooled cycle results are shown in [Figure 10: see original paper].

For simple reheat cycles, efficiency curves increase then decrease with pressure ratio, peaking at 2.2. At this optimal ratio, efficiency increases from 30.9% to 33.4% as compressor outlet pressure rises from 1.6 to 2.4 MPa. For interstage-cooled cycles, efficiency is more sensitive to pressure ratio changes before peaking, then decreases more slowly. Regardless of compressor outlet pressure, maximum efficiency occurs at a pressure ratio of 3.5, with efficiency increasing from 42.7% to 44.7% as pressure rises from 1.6 to 2.4 MPa.

Additional simulations for recompression cycles at split ratios of 0.2, 0.25, 0.3, 0.35, and 0.4 are shown in [Figure 11: see original paper]. Optimal pressure ratios vary with split ratio, with larger split ratios corresponding to smaller optimal pressure ratios. Maximum efficiency (0.339) occurs at a split ratio of 0.2 and compressor outlet pressure of 2.4 MPa, approximately equal to simple reheat cycle maximum but significantly lower than interstage-cooled cycle maximum.

D. Effect of Split Ratio on Recompression Efficiency

The split ratio significantly affects recompression cycle efficiency. Varying the splitter' s diversion ratio from 0 to 0.4 yields the results shown in [Figure 12: see original paper]. As split ratio increases from 0 to 0.4, recompression cycle efficiency decreases substantially. At a split ratio near 0, the recompressor consumes negligible power, making the cycle approach a simple recuperation cycle with two recuperators. Based on previous results, this configuration can achieve 41.7% efficiency. As split ratio approaches 1, the system tends toward a Brayton cycle without recuperators, drastically reducing efficiency to only 14.1% at a split ratio of 0.4.

E. Influence of Recuperator on Efficiency

Building on previous simulations, [Figure 13: see original paper] shows recuperator effectiveness impact on Brayton cycle efficiency. Increasing recuperator effectiveness consistently improves cycle efficiency across all configurations. Raising effectiveness from 0.6 to 0.9 increases simple reheat cycle efficiency by 21.7%, with efficiency exceeding 30% when effectiveness reaches 0.78. Interstage-cooled cycle efficiency remains approximately 5% higher than simple reheat cycle, but the latter offers greater applicability due to having one fewer cooler than the interstage-cooled configuration.

F. Effect of Pressure Loss on Efficiency

Pressure losses in Brayton cycles are inevitable, occurring in coolers, recuperators, components, and piping. Pipeline losses are divided into high-pressure and low-pressure losses, defined in EBSILON by setting pipes at compressor inlet and outlet to study their respective effects. Results are shown in [Figure 14: see original paper].

Increasing high-pressure relative loss from 0% to 10% reduces simple reheat and recompression cycle efficiencies by 9% and 7%, respectively. Equivalent low-pressure relative loss reduces efficiencies by 7.3% and 5.3%, respectively. High-pressure loss has a slightly greater effect because it more significantly impacts the pressure ratio.

G. Impact of TAC on Efficiency

Turbine, compressor, and generator efficiencies all affect Brayton cycle performance, including isentropic and mechanical efficiencies. The effect of mechanical efficiency is studied at turbine and compressor isentropic efficiencies of 0.80, 0.82, 0.84, 0.86, 0.88, and 0.90, with generator efficiency effects also evaluated. Results are shown in [Figure 15: see original paper].

Increasing any component efficiency consistently improves system cycle efficiency. For turbines, increasing mechanical efficiency at constant isentropic efficiency raises system efficiency by about 6%, while increasing isentropic efficiency at constant mechanical efficiency improves efficiency by about 5%. For compressors, these values are 3.5% and 5%, respectively. Increasing generator efficiency from 0.9 to 0.99 raises system efficiency by 2.9%.

H. Exergy Analysis

In thermodynamics, exergy is a critical parameter for evaluating cycle performance. Analyzing energy loss magnitude and distribution is essential for assessing economic and thermal efficiency. Based on the first and second laws, exergy analysis elucidates transformations, transfers, utilization, and losses, quantifying system performance [35].

Exergy analysis is applied to simple reheat and recompression cycles. EBSILON obtains energy loss distributions to analyze low-efficiency causes and provide improvement guidance. Simple reheat cycle (1200 K, 2 MPa) exergy calculations are shown in , [Figure 16: see original paper], and [Figure 17: see original paper].

In the simple reheat cycle, reactor and external cooler losses are highest at 44.6% and 30.9% of total losses, respectively. Turbine and compressor losses are smaller at 5.3% and 4.7%. Reactor and cooler exergy efficiencies are low, with cooler efficiency at only 30.371%, representing a major reason for reduced system efficiency.

Recompression cycle (1200 K, 2 MPa) component exergy results are shown in , [Figure 18: see original paper], and [Figure 19: see original paper]. Similar to the simple reheat cycle, losses concentrate in reactor (37.6%) and external cooler (42.0%). Cooler energy efficiency is only 17.194%, directly causing lower recompression cycle efficiency.

Comparative exergy loss analysis confirms recompression cycle efficiency is lower than simple reheat cycle efficiency in most cases. [Figure 20: see original paper] shows the recompression cycle's external cooler loss is 919.594 kJ/kg, far exceeding the simple reheat cycle' s 583.93 kJ/kg. Although recompression increases reactor inlet enthalpy, greater irreversible losses in the external cooler reduce net system work, decreasing overall efficiency.

Conclusion

This paper investigates Brayton cycle efficiency comparison and sensitivity analysis for a 3 MW thermal power gas-cooled reactor, with main conclusions:

1. **Direct vs. Indirect Cycles**: Varying turbine and compressor inlet temperatures and pressure ratios while controlling other boundary conditions shows direct cycles are 1.4%-2.8% more efficient than indirect cycles.

2. **Four Brayton Cycle Configurations**: Comparing efficiencies across turbine inlet temperatures at fixed compressor inlet temperatures reveals that at higher compressor inlet temperatures, recompression cycles negatively affect efficiency, while interstage-cooled and simple reheat cycles achieve highest efficiency. Both exceed 30% efficiency above 1400 K turbine inlet temperature. At moderate compressor inlet temperatures, interstage-cooled and simple reheat cycles maintain high efficiency, with $\eta_{interstage-cooled-recompression} > \eta_{recompression}$ below 1350 K turbine inlet temperature, and the reverse above 1350 K. At lower compressor inlet temperatures, all four cycles exceed 20% efficiency, with both recompression and simple reheat cycles reaching 38.2% efficiency at 1500 K turbine inlet temperature, eliminating the recompressor' s negative effect.

3. **Pressure Ratio Effects**: For simple reheat and interstage-cooled cycles, optimal pressure ratios are 2.2 and 3.5, respectively, independent of maximum system pressure. For recompression cycles, different split ratios correspond to different optimal pressure ratios, with larger split ratios requiring smaller optimal pressure ratios.

4. **Split Ratio Effects**: Split ratio significantly impacts recompression cycle efficiency, which decreases as split ratio increases from 0 to 0.4, dropping efficiency from 0.417 to 0.141. Low split ratios approach simple reheat cycles with two recuperators, while high ratios approach Brayton cycles without recuperators.

5. **Pressure Loss Effects**: Simulating relative pressure losses at compressor inlet and outlet shows high-pressure losses have slightly greater impact. Simple reheat and recompression cycle efficiencies decrease by 9% and 7%, respectively, when high-pressure relative loss increases from 0% to 10%.

6. **TAC Efficiency Effects**: Component efficiencies affect cycle performance and can be maximized in practical engineering applications.

A simple reheat cycle with 3 MW thermal power and 1 MW electrical power is designed using EBSILON. System parameters are shown in . The system meets MW-level space exploration mission requirements while maintaining high loop efficiency with 5% relative pressure loss. The system schematic is shown in [Figure 21: see original paper].

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Note: Figure translations are in progress. See original paper for figures.