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Preliminary Study on Working Fluids for Power Conversion in Space Heat Pipe Reactors

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1. Introduction

The rapid expansion of private-led space exploration has renewed interest in space nuclear power system, which can provide a stable, and economical energy supply independent of solar irradiance [1]. In particular, nuclear power is widely regarded as the only viable long -term energy source in environments where solar power generation is severely constrained such as the shadowed regions of the Moon or high-latitude and dust-laden areas of Mars. Achieving sustained robotic exploration in such environments requires not only advanced capabilities in base construction, mobility operations, and resource extraction, but also the development of reliable, long-duration power supply systems.

Among the various concepts under consideration, the Heat Pipe Reactor (HPR) offers significant advantages for space applications. Heat pipes serves as passive, high-conductivity thermal devices to transfer nuclear fission heat, eliminating the need for pumps, valves, or active coolant loop [2][3]. This design simplifies reactor architecture, enhances safety, while supporting compact manufacturing and transportable deployment [4].

The Closed Brayton Cycle (CBC) is considered one of the most promising power conversion system, capable of delivering hundreds of kilowatts of electrical power over long operational lifetimes. Helium (He) has been widely investigated as a working fluid due to its high specific heat and chemical inertness. However, its low molecular weight increases susceptibility to leakage and makes large turbomachinery size due to high turbomachinery loading [5]. Therefore, a helium-xenon (He-Xe) mixture has been proposed to improve compressibility while remaining favorable thermal properties, though helium remains prone to leakage [6].

Because working fluid replenishment is infeasible in space environments, alternative working fluids with low leakage can be considered. Nitrogen (N_2) exhibits low chemical reactivity and reduced leakage potential. However, thermal performance is comparatively modest. Supercritical CO_2 (sCO_2) is another promising choice. It offers high thermal efficiency and compact volume of turbomachinery.

This preliminary study compares the performance of He, He-Xe mixture, N2 and sCO2 to explore potential working fluids for space missions.

2. Methods and Results

In this section, the thermodynamic modeling process is described, followed by a performance analysis of each Brayton cycle. The modeling involves thermodynamic calculation for individual components under specified operating conditions, enabling the determination of key performance indicators.

2.1. Thermodynamic modeling

A simple recuperated cycle was adopted to achieve system simplification and miniaturization. The layout of the cycle is shown in Fig. 1, consisting of an intermediate heat exchanger, turbine, compressor, recuperator, pre-cooler, and radiator.

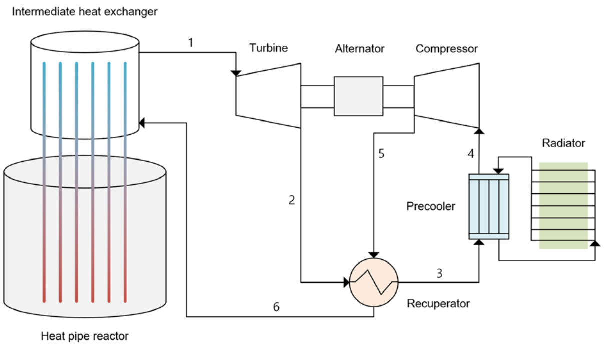

Fig. 1. Configuration of simple recuperated cycle

Thermodynamic properties of the working fluids were obtained from the NIST REFPROP database, except for He-Xe mixture, whose properties were evaluated using semi-empirical correlations presented in Table 1. First, the cycle pressure was determined from the input data. Next, the outlet conditions of the turbomachinery were calculated considering non-isentropic processes. The outlet condition of the recuperator was calculated using the effectiveness method. Finally, the mass flow rate was determined based on the heat power requirements.

<u>Turbine</u>

$$h_{out} = h_{in} - \eta\left(h_{in} - h_{out,i}\right)$$

$$T_{out} = T_{in}\left[1 - \eta\left(1 - \left(\frac{P_{in}}{P_{out}}\right)^{-\frac{\gamma-1}{\gamma}}\right)\right]$$

Compressor

$$h_{out} = h_{in} - \frac{h_{in} - h_{out,i}}{\eta}$$

$$T_{out} = T_{in}\left[1 + \frac{\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta}\right]$$

Recuperator

$$\varepsilon = \frac{Q_h}{\min(Q_{h,max}, Q_{c,max})} = \frac{Q_c}{\min(Q_{h,max}, Q_{c,max})}$$

$$Q_{h,max} = \dot{m}\left(h_{in} - h_{out,i}\right) = \dot{m}c_{p,h}(T_{h,in} - T_{c,in})$$

$$Q_{c,max} = \dot{m}\left(h_{out,i} - h_{in}\right) = \dot{m}c_{p,c}(T_{h,in} - T_{c,in})$$

Table 1. Thermodynamic properties of noble gases [7]

Density

Pure noble gases

$$P = R_g T[\hat{\rho} + B\hat{\rho}^2 + C\hat{\rho}^3]$$

$$B_r = \frac{B}{V^*} = \Psi_B(\theta) = \left[-102.6 + \left(102.732 - 0.001 \times \theta - \frac{0.44}{\theta^{1.22}}\right) \times \tanh\left(4.5\sqrt{\theta}\right)\right]$$

$$B_{He} = 8.4 - 0.0018 \times T + \frac{115}{\sqrt{T}} - \frac{835}{T}$$

$$C_r = \frac{C}{V^*} = 0.0757 + \left(-0.0862 - 3.6 \times 10^{-5} \times \theta + \frac{0.0237}{\theta^{0.059}}\right) \times \tanh(0.84 \times \theta)$$

$$\theta = \frac{T}{T_{cr}} \qquad V^* = R_g\left(\frac{T_{cr}}{P_{cr}}\right)$$

Mixtures

$$\bar{B} = x_1^2 B_{11} + 2x_1x_2B_{12} + x_2^2 B_{22}$$

$$B_{ii} = V_{ii}^* \times \Psi_B(\theta_i) \qquad B_{ij} = V_{ij}^* \times \Psi_B\left(T/T_{ij}^*\right)$$

$$\bar{C} = x_1^3 C_{111} + 3x_1^2x_2C_{112} + 3x_1x_2^2C_{122} + x_2^3C_{222}$$

$$C_{112} = (C_1^2C_2)^{1/3} \qquad C_{122} = (C_1C_2^2)^{1/3}$$

Specific heat capacity

$$\hat{C}_p = \hat{C}_p^0 + \hat{\rho}R_g\left[\left(B - \frac{TdB}{dT} - T^2\frac{d^2B}{dT^2}\right) + \hat{\rho}\left(C - \frac{T^2}{2}\frac{d^2C}{dT^2}\right)\right] + R_gT\left[\left(B - T\frac{dB}{dT}\right) + \hat{\rho}\left(2C - T\frac{dC}{dT}\right)\right] \times \left[\frac{\partial\hat{\rho}}{\partial T}\right]_p$$

$$\hat{C}_p^0 = \frac{5}{2}R_g \qquad \left[\frac{\partial\hat{\rho}}{\partial T}\right]_p = -\frac{\frac{\hat{\rho} + B\hat{\rho}^2 + C\hat{\rho}^3}{T} + \frac{dB}{dT}\hat{\rho}^2 + \frac{dC}{dT}\hat{\rho}^3}{1 + 2B\hat{\rho} + 3C\hat{\rho}^2}$$

$$\hat{C}_v = \hat{C}_v^0 - \hat{\rho}R_gT\left[\left(2\frac{dB}{dT} + T\frac{d^2B}{dT^2}\right) + \hat{\rho}\left(\frac{dC}{dT} + \frac{T}{2}\frac{d^2C}{dT^2}\right)\right]$$

$$\hat{C}_v^0 = \frac{3}{2}R_g$$

Since the pressure is set to match the reference value through the input data, the temperature was selected as the validation parameter of the code in this study. Table 2 shows the validation results of the simple recuperated code, confirming that the code is properly implemented for various working fluids.

Table 2. Simple recuperated cycle code validation

T (K)	sCO_2		He-Xe	
Position	Ref. [8]	Code	Ref. [9]	Code
1	880.75	880.75	1145.00	1145.00
2	715.85	715.98	923.00	923.63
3	467.35	467.46	581.00	580.87
4	328.15	328.15	400.00	400.00
5	454.25	454.28	555.00	555.47
6	671.45	671.58	904.00	905.22

2.2 Cycle optimization

Table 3 presents the input data used for the cycle performance analysis. The input data were determined with several previous studies. Since the thermophysical properties and performance of the He–Xe mixture vary with composition, a molecular weight of 40 g/mol was adopted in this study [10]. In general, the HPR core has a hexagonal configuration [15][16], and since this study targets a 100-kW class HPR, the thermal power was set to 96 kW for convenience. Based on the given input data, the objective is to adjust the compressor pressure ratio to obtain the optimal cycle efficiency.

Table 3. Input data of simple recuperated cycle [9]-[14]

Parameter	Unit	Value
Heat power	kW	96.00
Turbine		
Inlet temperature	K	1023.15
Isentropic efficiency	%	87.50
Pressure ratio		Determined
Compressor		
Inlet temperature	K	400.00
Inlet pressure (except sCO_2)	MPa	1.00
Outlet pressure (for sCO_2)	MPa	20.00
Isentropic efficiency	%	82.50
Pressure ratio		Variable
Recuperator		
Effectiveness	%	95.00
Hot side pressure drop	%	1.50
Cold side pressure drop	%	0.60
Pressure drop		
Intermediate heat exchanger	%	2.70
Precooler	%	1.00
Efficiency		
Mechanical	%	86.50
Alternator	%	92.50
Cycle efficiency	%	Optimized

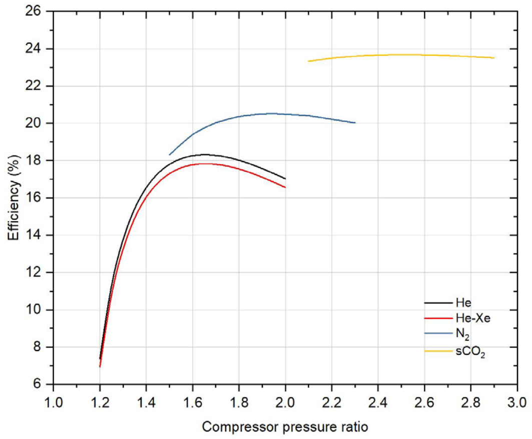

Fig. 2. Cycle efficiency optimization

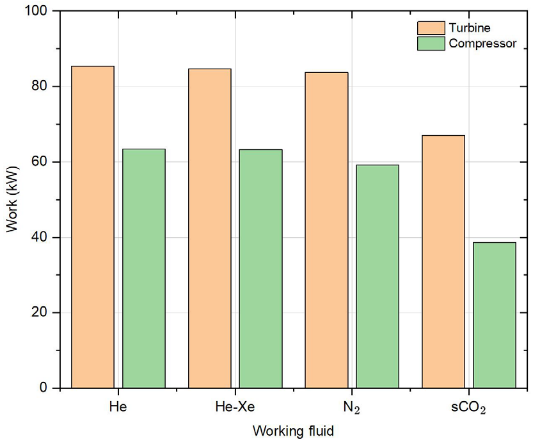

Fig. 3. Turbomachinery work

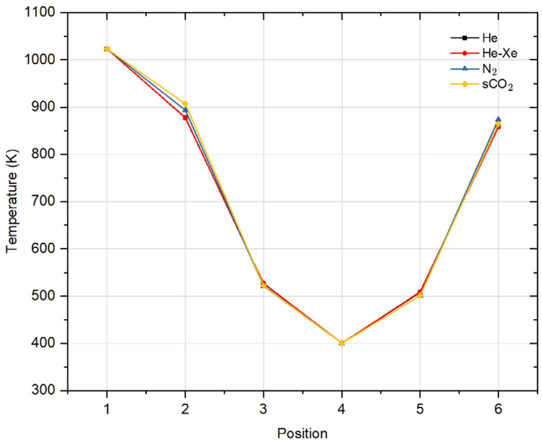

Fig. 4. Optimized cycle temperature distribution

Fig. 2 shows the cycle efficiency optimization results for different working fluids. The optimal efficiency of the He-Xe mixture is nearly identical to that of He, while showing differences of approximately 2.7 % compared to N_2 and 5.8 % compared to sCO_2. As shown in Fig. 3, the efficiency of N_2 is higher because the turbine work remains nearly the same but the compressor work is reduced. In the case of sCO_2, although the turbine work is significantly reduced, the compressor work decreases even further, resulting in a higher efficiency. Fig. 4 illustrates the temperature distribution at each cycle position under optimal efficiency conditions, which shows generally similar trends despite minor differences. However, as depicted in Fig. 5, there is a significant difference in isobaric specific heat among the working fluids. Therefore, although the temperature distributions are similar, considerable differences in mass flow rate are observed, ultimately resulting in the distinct differences in specific work that appear clearly in Fig. 6.

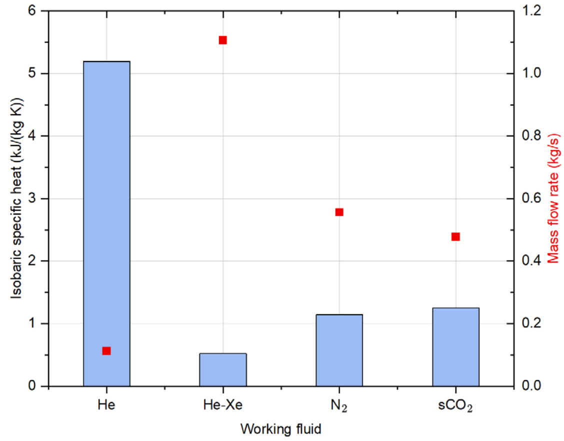

Fig. 5. Isobaric specific heat at turbine inlet and mass flow rate

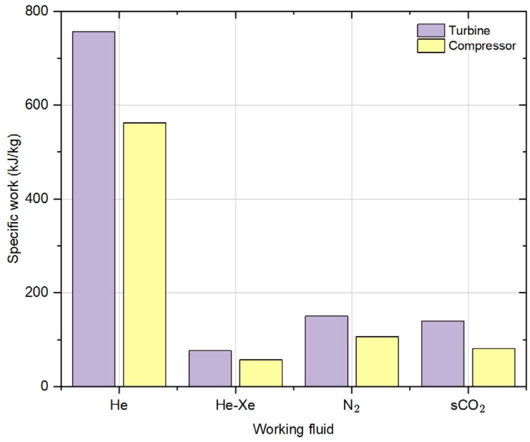

Fig. 6. Specific work

The specific work (enthalpy rise or drop) is a useful indicator of the aerodynamic loading of a single-shaft turbomachinery [10]. The aerodynamic loading of the blades is expressed as below. Thus, the turbomachinery size is determined by the aerodynamic loading. The aerodynamic loading can be reduced to an acceptable value by increasing the rotational speed or enlarging the impeller diameter for a given specific work. However, the impeller diameter increase requires thicker and heavier disks and blades to sustain mechanical stress, which consequently increases the turbomachinery mass. Conversely, at the same rotational speed, a decrease in specific work reduces the blade diameter, thereby lowering both the size and mass of the turbomachinery.

$$\lambda = \frac{\Delta H}{R^2 \omega^2}$$

3. Conclusions and Further works

In this study, a simple recuperated cycle was modeled as the power conversion system of a space heat pipe reactor, and a performance analysis was conducted for different working fluids. The cycle optimization results showed that the efficiency of the He-Xe mixture was nearly identical to that of He, while differences of 2.7 % and 5.8 % were observed compared to N_2 and sCO_2, respectively. Due to the differences in isobaric specific heat among the working fluids, distinct differences in mass flow rate and specific work were observed despite similar temperature distributions, which directly affect the size and the mass of the turbomachinery.

In space reactor systems, component size and mass represent critical limiting factors. The operating pressure of sCO_2 generally ranges from 7.6 to 20.0 MPa, which requires thicker piping to withstand the high pressure, leading to disadvantages in terms of mass. In the case of He-Xe mixture, the leakage of helium can alter the mixture properties, making it difficult to ensure stable system performance. Therefore, based on the results of this study, N_2 emerges as an attractive option, balancing efficiency with turbomachinery size reduction, while also being easier to handle due to low operating pressure and negligible leakage. Further works will calculate the required heat exchanger area and also investigate the feasibility of another options such as neon and argon as working fluids.

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NOMENCLATURE

B, B_{ii}	Second virial coefficient for a pure gas (m^3/mole)
B_{ij}	Second virial interaction coefficient (m^3/mole)
$\bar{B}$	Second virial coefficient of gas mixture (m^3/mole)
C, C_{iii}	Third virial coefficient of pure gas (m^6/mole^2)
C_{ijj}	Third virial interaction coefficient (m^6/mole^2)
$\bar{C}$	Third virial coefficient of gas mixture (m^6/mole^2)
P	Pressure (Pa)
R_g	Perfect gas constant (=8.31441 J/(mol K))
T_{cr}	Critical temperature of pure gas (K)
T_{ij}^*	Interaction temperature (K)
V_{ii}^*	Characteristic molar volume of pure gas (m^3/mole)
V_{ij}^*	Characteristic interaction molar volume (m^3/mole)
λ	Aerodynamic loading
R	Radius of blades (m)
ω	Rotational speed (1/s)
Greek symbols	
θ	Reduced temperature
$\hat{\rho}$	Molar density (mole/ m^3)
γ	Specific heat ratio

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