Investigating the Impact of Refrigerant Mixing on Supercritical CO_2 Power Systems

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1. Introduction

In the 21st century, nuclear power technology is opening new horizons by developing the Generation IV nuclear reactors to respond to the demand for the sustainable energy. These Generation IV reactors embody the quintessence of nuclear energy technology development, anchoring on the high levels of safety, economic feasibility, and non-proliferation excellence. Notable, innovative reactors such as High-Temperature Gas-cooled Reactors (HTGRs), Liquid Fluoride Thorium Reactors (LFTRs), and Supercritical Water-cooled Reactors (SCWRs) promise markedly improved efficiency and stability compared to existing energy systems.

Among these, the advent of the Supercritical CO_2 (S-CO_2) cycle heralds a revolutionary transformation in conventional power conversion systems. Capable of achieving exceptional thermal efficiency even in high-temperature operating environments, the S-CO_2 cycle has garnered global attention for its compact design, operational economy, and environmental benefits [1]. When compared with traditional steam cycles, the S-CO_2 cycle offers superior thermodynamic efficiency, leading to lower operating costs, simplified system architecture, and a positive impact on the environment.

In this research, the authors explore the potential to transcend the limitations of pure CO_2 cycles by blending CO_2 with other refrigerants, thereby improving cycle efficiency and specific work. This is to maximize the performance of the S-CO_2 cycle, thereby enhancing the efficiency and reliability of power conversion systems for Generation IV nuclear reactors [2].

2. Methods and Results

2.1 Cycle Configuration and Boundary Conditions

This study utilizes the simple recuperated Brayton cycle configuration as the reference layout of the S-CO_2 cycle. The cycle is comprised of a precooler, compressor, recuperator, heater, and turbine. Table I summarizes the boundary conditions for cycle design. The objective of this research is to evaluate and optimize the cycle's performance under these conditions. The cycle design has been performed with an in-house cycle optimization code, namely KAIST-ESCA (Evaluator for S-CO_2 cycle based on Adjoint method). KAIST-ESCA utilizes the adjoint method for quick and efficient sensitivity analysis and optimization of S-CO_2 cycle parameters [3].

Table I: Boundary conditions

Component	Value
Heat Input	30MW
Precooler Pressure Drop	150kPa
Heater Pressure Drop	150kPa
Recuperator Pressure Drop	150kPa
Compressor Efficiency	0.84
Recuperator Effectiveness	0.95
Turbine Efficiency	0.93
Maximum Pressure	20MPa
Maximum Temperature	550°C
Minimum Temperature	35°C

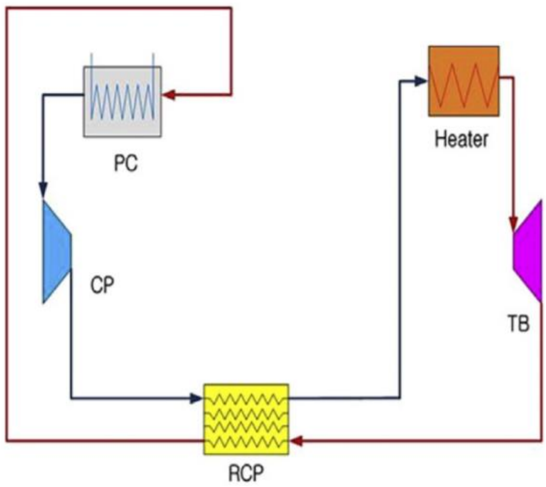

Fig. 1. Simple recuperated cycle layout.

2.2 Candidates for Additive Substance

Previous research was conducted on evaluating the performance of the Brayton cycle by mixing CO_2 with certain R series refrigerants [4].

In this study, the authors identified the entire range of R series refrigerants included in the REFPROP library that can maintain a supercritical state across the entire cycle area under basic operating conditions. R series refrigerants which are capable of maintaining a supercritical state throughout the entire cycle were selected as the subjects of this research. The impact of mixing these refrigerants with CO_2 is systematically analyzed by varying the mass fraction of additive substance from 0.0 to 0.2. Through this process, the authors explored the possibility of performance optimization with specific refrigerant mixtures, aiming to propose more efficient cycle design strategies based on our findings. The thermohydraulic properties and environmental properties of all the refrigerants listed below, including CO_2, are presented in Appendix A.

Table II: All cases analyzed in this study

CASE 1	CO_2	CASE 13	CO_2 + R-125
CASE 2	CO_2 + R-11	CASE 14	CO_2 + R-134a
CASE 3	CO_2 + R-12	CASE 15	CO_2 + R-141b
CASE 4	CO_2 + R-14	CASE 16	CO_2 + R-142b
CASE 5	CO_2 + R-21	CASE 17	CO_2 + R-152a
CASE 6	CO_2 + R-22	CASE 18	CO_2 + R-227ea
CASE 7	CO_2 + R-23	CASE 19	CO_2 + R-236ea
CASE 8	CO_2 + R-113	CASE 20	CO_2 + R-236fa
CASE 9	CO_2 + R-115	CASE 21	CO_2 + R-245ca
CASE 10	CO_2 + R-116	CASE 22	CO_2 + R-245fa
CASE 11	CO_2 + R-123	CASE 23	CO_2 + R-365mfc
CASE 12	CO_2 + R-124	CASE 24	CO_2 + RC-318

2.3 Results of Cycle Efficiency and Specific Work

This study focuses on selecting the optimal mixed fluid to maximize the performance and applicability of the S-CO_2 cycle. Fig. 2 illustrates the cycle efficiency when mixing CO_2 with various refrigerants, increasing the mass fraction from 0.0 to 0.2. The research findings indicate a trend of decreasing efficiency as the mass fraction increases when CO_2 is mixed with all refrigerants except for R-12, compared to the use of pure CO_2. However, the decrease in efficiency, except when mixed with R-12, does not imply that other refrigerants cannot be good options to maximize the cycle's performance and applicability.

One of the greatest advantages of the S-CO_2 cycle is its relatively small size compared to other power generation systems, offering potential applications in special environments such as marine propulsion, as well as in various other fields. Given that the S-CO_2 cycle is currently in the development stage, this research emphasizes selecting mixed fluids that can further reduce the size of total system to suit various application areas.

When generating the same amount of net work, a decrease in mass flow rate can lead to a reduction in the system's size. Therefore, by comparing the specific work, which is the net work divided by the mass flow rate, the authors sought to explore the potential of mixed fluids that could enable the cycle to be applicable in various fields.

Fig. 3 presents the specific work when mixing CO_2 with different refrigerants, increasing the mass fraction from 0.0 to 0.2. In the case of specific work, it was observed that for all refrigerants mixed with CO_2, except for R-123, RC-318, and R-113, there is a trend of increasing specific work as the mass fraction increases, compared to the use of CO_2 alone.

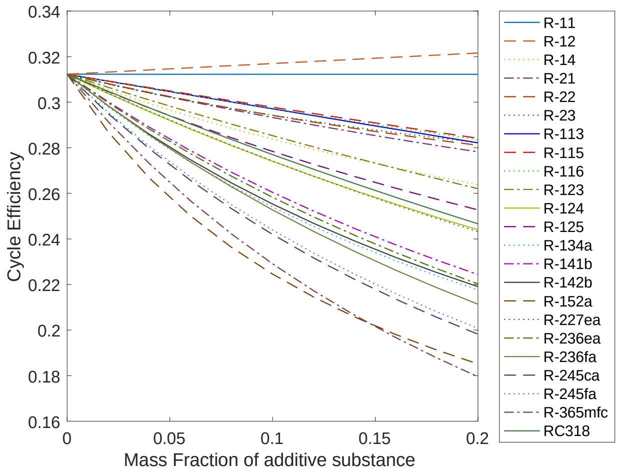

Fig. 2. Cycle Efficiency According to Types of Refrigerants and Mass Fraction

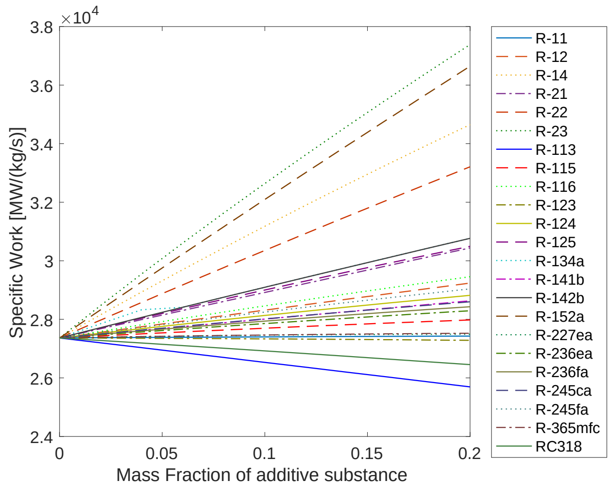

Fig. 3. Cycle Specific Work According to Types of Refrigerants and Mass Fraction

2.4 Selection of Optimal Additive Substance

Therefore, this study classified refrigerants that increase the specific work by more than 20% when mixed with CO_2 at a mass fraction of 0.2 as optimal mixed fluids for maximizing the applicability of the S-CO_2 cycle. The refrigerants that meet this criterion are R-23, R-152a, R-14, and R-22. This research excluded the remaining refrigerants and presented the Cycle Efficiency and Specific Work for these selected refrigerants at various mass fractions in Fig. 4 and Fig. 5, respectively.

Upon analyzing the cycle efficiency results, it was observed that the efficiency of mixtures containing R-23, R-14, and R-22 decreased by no more than 20% across the entire range of mass fractions compared to using CO_2 alone. In contrast, the efficiency of mixtures containing R-152a decreased by up to 40% across the entire range of mass fractions compared to using CO_2 alone. Consequently, considering both the increase in specific work and the decrease in cycle efficiency, R-23, R-14, and R-22 were concluded to be suitable as mixed fluids.

Additionally, while the specific work of R-12 only improved by approximately 6.8% at a mass fraction of 0.2 compared to using pure CO_2, it uniquely demonstrated an increase in efficiency with CO_2 at any mass fraction among all the refrigerants tested. This indicates that although R-12 may not significantly reduce the overall system size compared to the current system using pure CO_2, it possesses the potential to achieve a smaller size and higher efficiency. Consequently, R-12 can be considered a viable mixed fluid for maximizing the performance and applicability of the S-CO_2 cycle. The cycle efficiency and specific work with respect to the mixing mass fraction of R-12 are also presented in Fig. 4 and Fig. 5, respectively.

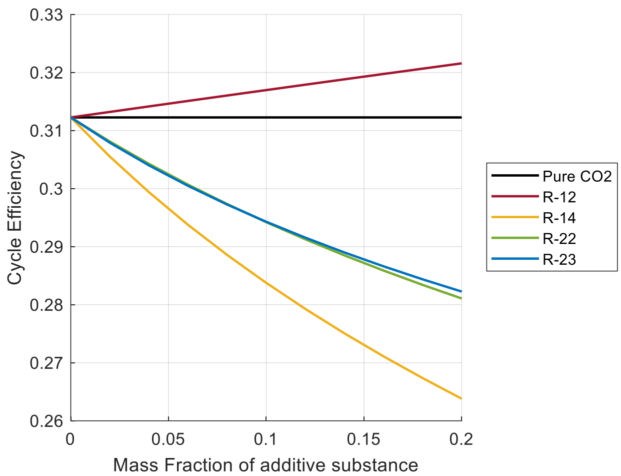

Fig. 4. Cycle Efficiency of R-12, R-14, R-22, and R-23 according to mass fraction

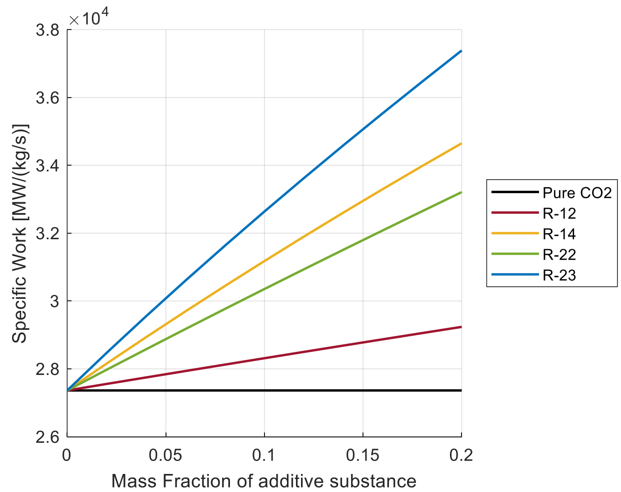

Fig. 5. Specific Work of R-12, R-14, R-22, and R-23 according to mass fraction

The efficiencies of R-12, R-14, R-22, and R-23 mixture cycles are elaborated in the following sections by presenting the compressor work, turbine work, and the net work, respectively. Additionally, the specific work of each mixture cycle is detailed below, in relation to their mass flow rates.

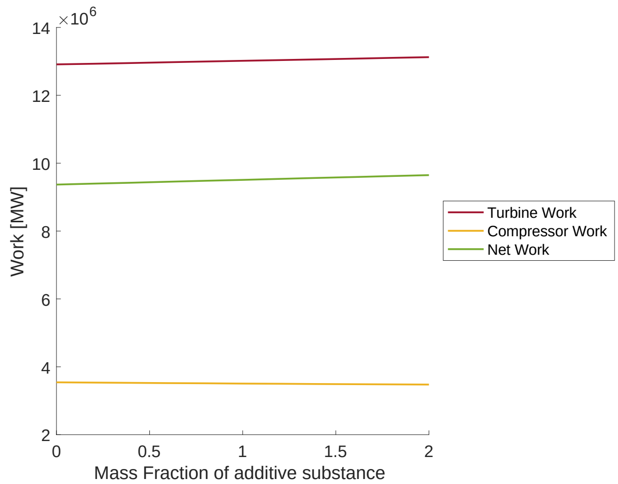

Fig. 6. Net Work, Turbine Work, and Compressor Work of R-12

As observed in Fig. 4, when the mixed fluid is R-12, an increase in cycle efficiency is observed. To understand the reason behind this phenomenon, the data presented in Fig. 6 was analyzed. It shows that the increase in turbine work is greater than the decrease in compressor work, resulting in a net increase in net work. The cycle efficiency is calculated by dividing the net work by the heat input (Q_{in}). In this study, with Q_{in} fixed at 30MW, this leads to an increase in the cycle efficiency of R-12 mixture.

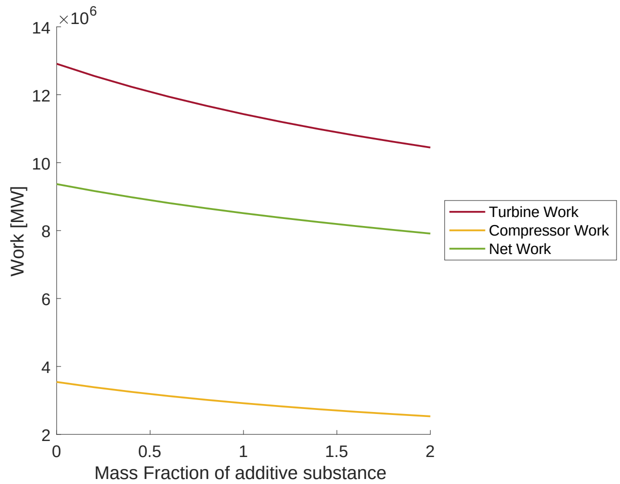

Fig. 7. Net Work, Turbine Work, and Compressor Work of R-14

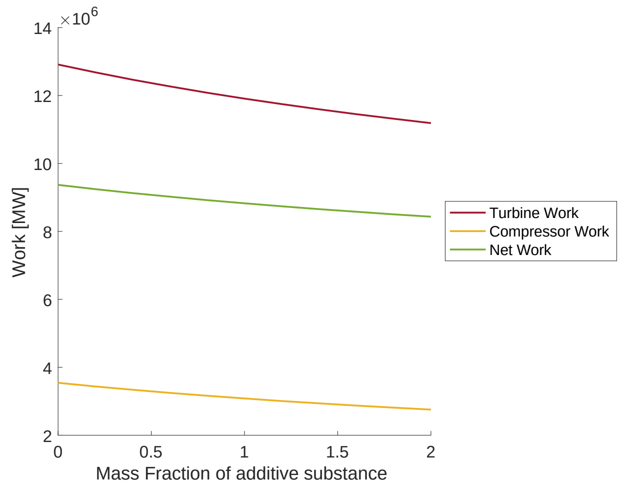

Fig. 8. Net Work, Turbine Work, and Compressor Work of R-22

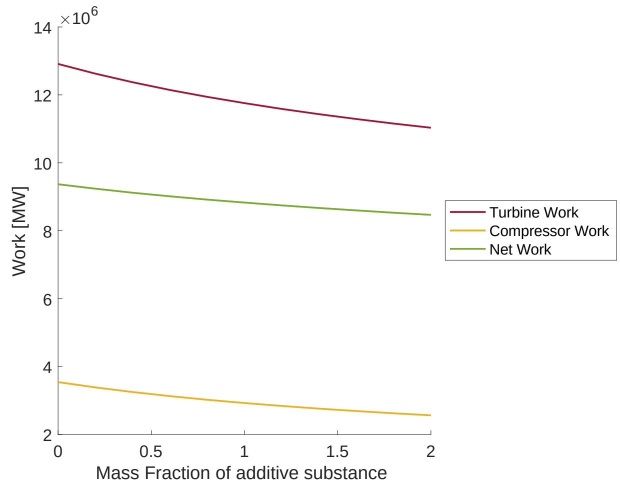

Fig. 9. Net Work, Turbine Work, and Compressor Work of R-23

As observed in Fig. 4, when the mixed fluids are R-14, R-22, and R-23, a decrease in cycle efficiency is observed. To understand the reason behind this phenomenon, the data presented in Fig. 7, Fig. 8, and Fig. 9 was analyzed. It shows that the decrease in compressor work is greater than the decrease in turbine work, resulting in a net decrease in net work. The cycle efficiency is calculated by dividing the net work by the heat input (Q_{in}). In this study, with Q_{in} fixed at 30MW, a decrease in the efficiency of R-14, R-22, and R-23 mixture cycle is observed.

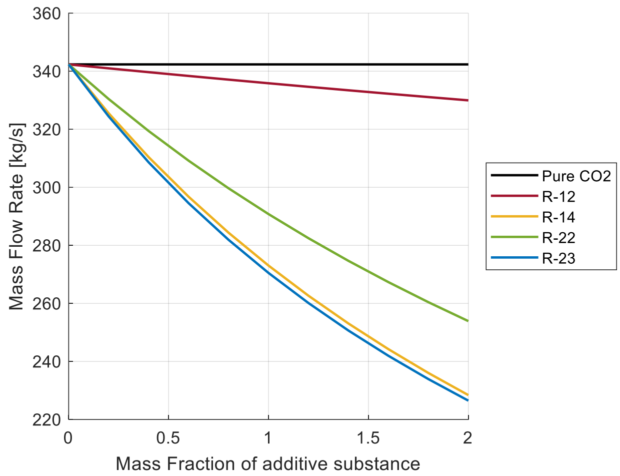

Fig. 10. Mass Flow Rate of R-12, R-14, R-22, and R-23

As observed in Fig. 5, when the mixed fluid is R-12, R-14, R-22, and R-23, an increase in specific work is observed. To understand the reason behind this phenomenon, the data presented in Fig. 10 was analyzed. It shows that the decrease in mass flow rate resulted in the increase in specific work. In this study, with Q_{in} fixed at 30MW, this leads to an increase in the specific work of R-12, R-14, R-22, and R-23.

The decrease in mass flow rate for R-12 was found to be relatively smaller compared to the decrease in mass flow rate for R-14, R-22, and R-23. Consequently, the specific work for R-14, R-22, and R-23 was measured to be significantly higher than that of R-12.

3. Conclusions

In this study, it has been demonstrated that R-12, R-14, R-22, and R-23 possess the potential to enhance the performance and applicability of the S-CO_2 cycle. Should further research be conducted across various mass fraction ranges, operating conditions, and layouts for these mixed fluids, it is anticipated that a better mixture of CO_2 with other fluids can be found. This could lead to a substantial reduction in the overall system size, and enable the system to become more adaptable to diverse application areas.

4. ACKNOWLEDGEMENT

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Appendix A

Table A-1: Thermohydraulic properties of refrigerants

Refrigerant	T_c [°C]	P_c [MPa]	Boiling Point [°C]
CO_2 (R-744)	31.1	7.38	-78.5
R-11	198	4.38	23.8
R-12	112	4.10	-29.8
R-14	-45.6	3.74	-128.0
R-21	178.5	5.23	8.9
R-22	96.2	4.98	-40.8
R-23	-82.1	4.81	-82.1
R-113	214	3.47	47.6
R-115	178	3.18	-38.0
R-116	128.85	4.006	-78.2
R-123	183	3.64	27.8
R-124	194.5	4.06	-11.3
R-125	66.1	3.62	-48.5
R-134a	101.1	4.06	-26.1
R-141b	204.4	4.32	32.0
R-152a	113.5	4.52	-24.7
R-227ea	101.7	2.90	-16.4
R-236ea	146.1	3.26	1.4
R-236fa	124.9	3.21	-1.4
R-245ca	174.5	3.65	15.1
R-245fa	154.1	3.63	15.3
R-365mfc	178	3.33	40.2
RC-318	28.85	4.07	-29.2

Table A-2: Environmental properties of refrigerants

Refrigerant	GWP	Atmospheric lifetime [yr]
CO_2 (R-744)	1	-
R-11	4750	50
R-12	10900	100
R-14	7390	50000
R-21	176	1.9
R-22	1810	12
R-23	14800	270
R-113	6130	85
R-115	8830	500
R-116	12200	3200
R-123	77	1.4
R-124	609	5.8
R-125	3500	29
R-134a	1430	14
R-141b	725	9.3
R-152a	124	1.4
R-227ea	3220	36.5
R-236ea	1370	8.9
R-236fa	9810	209
R-245ca	693	6.6
R-245fa	1030	7.7
R-365mfc	794	8.6
RC-318	8830	3200