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Experimental study of CO_2 based gas mixture power cycle application to the nuclear system

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1. Introduction

A development of highly efficient and safe nuclear power conversion system has received worldwide attention. In this point of view, a sodium-cooled fast reactor (SFR) with a supercritical carbon dioxide (S-CO_2) Brayton power generation cycle has been suggested. The suggested power conversion system can be a future technical solution for rising energy demand and global warming issues [1].

The S-CO_2 power conversion cycle can achieve high thermal efficiency by reducing compression work due to the liquid-like fluid characteristic (e.g. High density, low compressibility) of the CO_2 near the critical point (31℃, 7.4MPa). Moreover, the power cycle can have small footprint due to the high density of working fluid. Furthermore, the compact S-CO_2 power cycle technology can enable nuclear energy to be utilized in various applications such as distributed power generation and marine propulsion. However, the S-CO_2 power cycle has intrinsic limitation on the minimum temperature which is at the critical temperature (31℃) of CO_2. In order to improve the S-CO_2 system regarding the minimum temperature limitation, a research on the CO_2 based gas mixture power cycle has been conducted previously [2-5].

As an experimental verification of the suggested idea, the authors conducted the compressor test with CO_2 + refrigerant (R-32) as a working fluid. In this paper, the experimental results are analyzed and compared with CO_2 reference cases to show the technical feasibility of the suggested ideas.

2. Experimental approach

2.1 CO_2 based gas mixture power cycle

The critical point is the condition at which the properties of different coexisting states become identical. The critical point of substance is the intrinsic property and the critical point can be changed by adding other substances. [7] From the previous studies [4-5], possible candidates which can improve the CO_2 power cycle have been investigated. Through these studies the R-32 was selected in this experimental study to confirm the obtained theoretical results and show the further technical feasibilities.

For the basic information, 1st law thermal efficiency comparison result depending on working fluid composition is plotted in Figure 1 and thermodynamic properties of each substance are tabulated in Table I.

$$\text{Thermal efficiency } (\eta_{th}) = \frac{W_{net,out}}{Q_{in}} \quad (1)$$

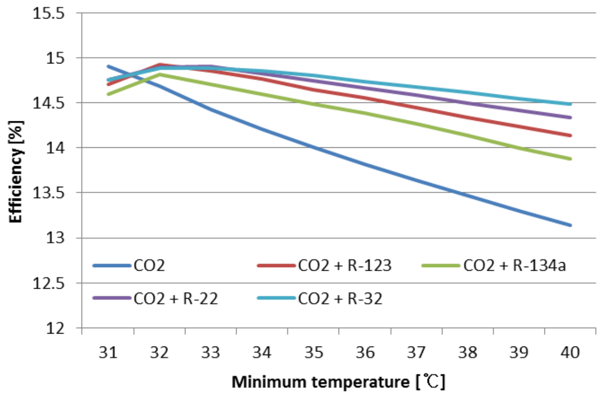

Fig.1. Efficiency comparison of CO_2+refrigerant cases (R-123 / R-134a / R-22 / R-32) with CO_2 reference case [5]

Table I: Information of each substance

Substance	Molar mass [kg/kmol]	T_c [℃]	P_c [MPa]	D_c [kg/m^3]
CO_2	44.01	30.98	7.3773	467.6
SF_6	146.06	45.57	3.7550	742.3
R-123 ($CHCl_2CF_3$)	152.93	183.68	3.6618	550.0
R-134a (CF_3CH_2F)	102.03	101.06	4.0593	511.9
R-22 ($CHClF_2$)	86.47	96.15	4.9900	523.8
R-32 (CH_2F_2)	52.02	78.11	5.7820	424.0

2.2 Experimental facility (S-CO_2PE)

The authors conducted a compressor performance test with CO_2+R-32 (0.88:0.12 mass fractions) mixture by utilizing KAIST-S-CO_2PE facility. The experimental facility, which is shown in Figure 2, is an S-CO_2 power cycle demonstration facility. The KAIST-S-CO_2PE facility was configured with simple Brayton cycle layout [12] and it has been utilized for performance test of S-CO_2 power cycle component such as centrifugal compressor, PCHE (Printed Circuit Heat Exchanger) and STHE (Shell and Tube Heat Exchanger) types of pre-cooler. The 26kW powered compressor was operating at 3600rpm for the test with 234mm diameter impeller (radial, shrouded type).

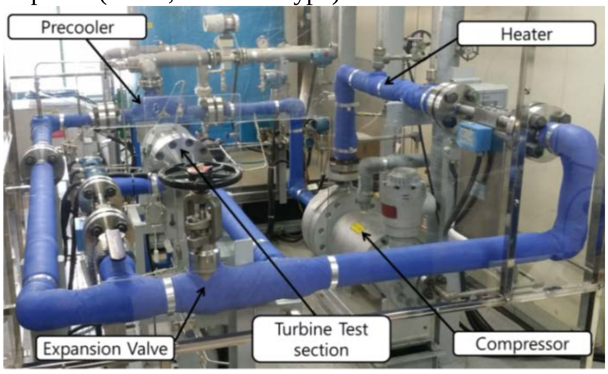

Fig.2. S-CO_2 power cycle demonstration facility (S-CO_2PE facility)

In order to set up the mixing ratio of the working fluid, the high accurate scale (CAS HB-150, Max 150kg, ±10g) was utilized to measure the charged weight of each fluid. With CO_2+R-32 (0.88:0.12 mass fractions), compressor was operated at same temperature, pressure, mass flowrate operating conditions with CO_2 cases. The selected mass fraction is the optimum composition which can achieve highest thermal efficiency at 37℃ cycle minimum temperature.

3. Results and comparisons

From the accumulated experimental results with S-CO_2 conditions, the author compared thermal-hydraulic performances with CO_2+R-32 mixture working fluid cases. As shown in Table Ⅱ, the CO_2+R-32 case showed 1~2% higher pressure ratio than pure CO_2 cases.

Table Ⅱ: Experimental results of CO_2 and CO_2+R-32 (0.88:0.12) case

#	T [℃]	P [MPa]	CO_2		CO_2 + R-32 (0.88:0.12)		$\frac{PR2}{PR1}$
			Mass flow rate [kg/s]	PR1 Pressure ratio [-]	Mass flow rate [kg/s]	PR2 Pressure ratio [-]	
4-1	31	8.4	3.96	1.11	4.15	1.12	1.007
4-2			2.97	1.12	2.96	1.12	1.007
4-3			2.00	1.11	1.93	1.12	1.005
5-1	29.2	7.8	3.94	1.12	3.91	1.13	1.010
5-2			2.99	1.12	2.99	1.14	1.009
5-3			2.02	1.12	2.02	1.13	1.008
5-4			3.88	1.11	3.82	1.12	1.008
10-1	37	8.4	3.16	1.08	3.09	1.11	1.021
10-2			2.29	1.08	2.27	1.11	1.020
10-3			1.61	1.08	1.57	1.1	1.020
10-4			0.82	1.08	0.80	1.1	1.018
14-1	33	7.4	2.81	1.11	2.81	1.12	1.006
14-2			2.09	1.11	2.02	1.12	1.005
14-3			1.35	1.11	1.35	1.11	1.005
14-4			0.65	1.10	0.64	1.11	1.004

To clarify the increase of the pressure ratio, the pressure ratio and pressure difference of the compressor inlet and outlet are plotted in figures 3 & 4.

The red circles represent the test cases of the mixed fluid (CO_2+R-32, 0.88:0.12 mass fractions), and it can be confirmed that the result has a similar tendency to the result of the same high density case of previous pure CO_2 results. [12]

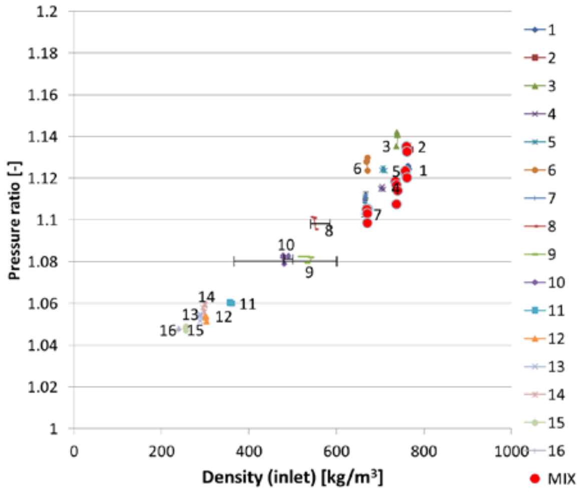

Fig.3. S-CO_2PE compressor performance test result (pressure ratio = P_{out}/P_{in}) in various inlet density condition

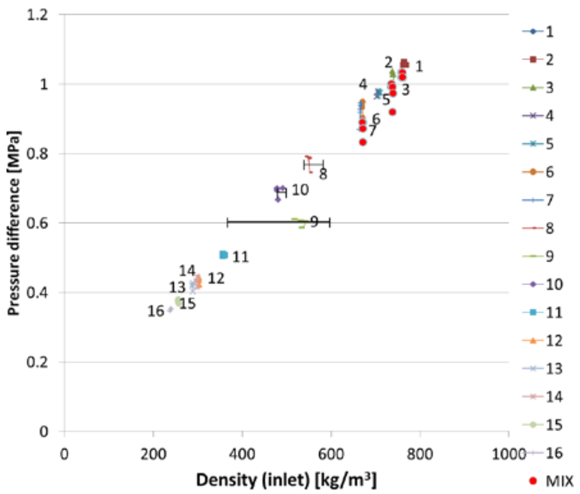

Fig.4. S-CO_2PE compressor performance test result (pressure difference = P_{out}-P_{in}) in various inlet density condition

4. Conclusions

In order to improve the thermodynamic performance of the S-CO_2 power cycle and reduce the limitation of the cycle minimum temperature, a study on the CO_2 based mixture is conducted. To increase the critical temperature and lower the critical pressure, mixing higher molecular weight organic refrigerants (such as R-123, R-134a, R-22, R-32…) are suggested.

In this study, the authors conducted a preliminary experimental study with CO_2+R-32 (0.88:0.12 mass fractions). As expected, the compressor pressure ratio has increased while maintaining the same operating temperature, pressure and mass flowrate condition. The 1~2% increase of pressure ratio was caused by 10~40% increase of compressor inlet density. And it was confirmed that the result has a similar tendency to the result of the same high density case of pure CO_2 results. The amount of the performance increase seemed relatively small due to the limitation of low speed compressor, but the difference can be larger in high performance, high speed compressor. Conversely, less work or less speed may be required to raise the same pressure if the CO_2 power system is designed with the mixture.

The authors conclude that the CO_2+R-32 can potentially reduce the efficiency degradation of pure S-CO_2 power cycles at higher ultimate heat sink temperature environment. It is also believed that the S-CO_2 power conversion technology can be applied to desert climates by mixing other fluids while enjoying the benefit of the S-CO_2 power cycle.

Based on the preliminary results, further study on the CO_2 based gas mixture power cycle will be followed to confirm superior substance and optimal mixing ratio. Furthermore the technical feasibility for the high temperature heat source applications will be confirmed as well in the future.

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