Study of supercritical gas mixture power cycle application to the nuclear system

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1. Introduction

A development of safe and highly efficient 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 cycle has been suggested as a technical solution for rising energy demand and global warming issues. [1] The SFR with S-CO_2 power cycle can reduce the accident consequence compared to the steam Rankine cycle because of the mild sodium-CO_2 interaction.

The S-CO_2 power conversion cycle can achieve high 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 be designed in a compact size 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. For the purpose of these applications, air-cooled waste heat dissipation is necessary. However, the S-CO_2 power cycle has intrinsic limitation on the minimum temperature which is at the critical temperature (31℃) of CO_2. Because of the small difference with ambient temperature, a large amount of cooling air flow rate and massive heat exchanger is required to reach the target temperature.

In this paper, to improve the system efficiency and ease the air-cooled waste heat removal problem, the mixture of other fluids has been studied.

2. Methods and Results

2.1 Critical point of various fluids

Critical points of various fluids were investigated. As shown in figure 1, the high molecular weight fluids such as propane, SF6, organic refrigerants have higher critical point. In this study, SF6 and R-123 are chosen to increase the critical temperature through mixing with carbon dioxide. Propane was excluded due to the explosion possibility and R-123 was selected as the lowest GWP (global warming potential) among the various organic refrigerants [2-4]. SF6 is also a non-flammable gas and is a stable gas mainly used in high voltage electric circuit breakers. [5]

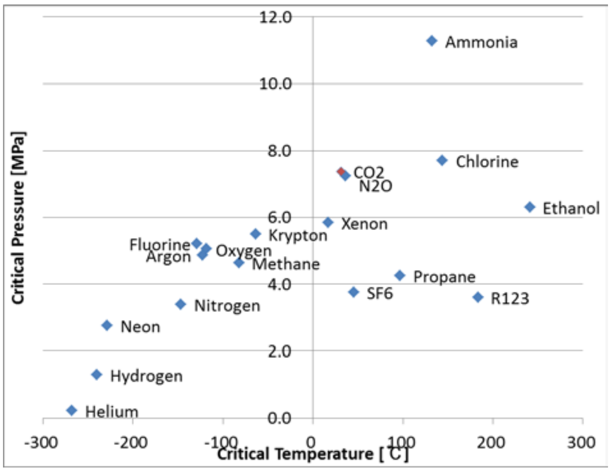

Fig. 1. Critical point of various fluids

2.2 Critical point of a mixed fluid

The critical point is the condition at which the properties of different coexisting states become identical. The critical point of material can be changed by adding other components.

The simplest method for predicting the critical point of a mixed fluid is W.B. Kay's equilibrium critical point model. [6] It is a mole fraction based linear interpolation method as following equations.

$$(P_c)_{\text{mix}} = \sum_i y_i P_{ci} \tag{1}$$

$$(T_c)_{\text{mix}} = \sum_i y_i T_{ci} \tag{2}$$

Where, y_i is mole fraction of the i^{th} component

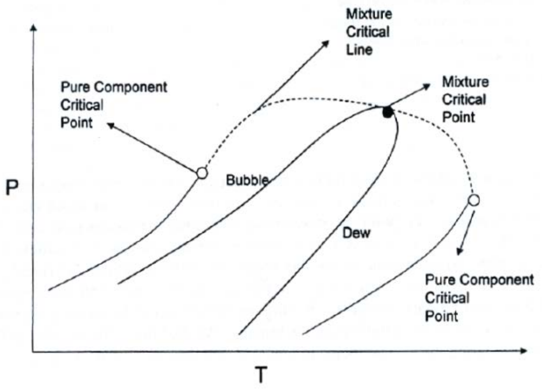

Fig. 2. A certain type of critical locus of binary gas mixture

However, the real gas equilibrium critical point locus shows curved locus rather than linear interpolation results. [7]

In most thermal fluid system engineering, the NIST database provides the most reliable results as an international standard. [8]

According to the NIST mixture data the critical point of actual gas mixture showed all different behavior with their different compositions. This is the most reliable data to date, but the authors will conduct further experimental verifications of the obtained results from the NIST package.

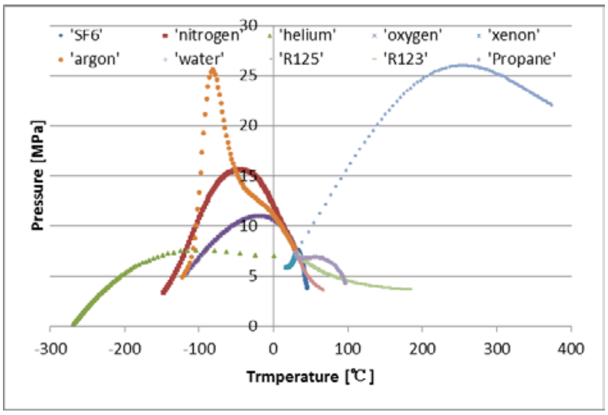

Fig. 3. Critical point of mixture

2.3 System analysis

To design and analyze the S-CO_2 power cycle, KAIST research team developed an in-house code; namely KAIST_CCD. The developed code has been validated and verified by other studies [9-10]. For this study, the developed code is modified to analyze the mixed-fluid supercritical power generation system. In order to consider the only effects of the cycle minimum temperature and the critical point of the fluid, a simple Brayton cycle is analyzed. The pressure losses of the components or additional losses are neglected for this study and assumed efficiency of the components are tabulated in Table I.

Table I: Description of analysis

System type	Simple Brayton
Working Fluid	CO_2 / CO_2+SF6 / CO_2+R-123
Maximum Pressure	20 MPa
Maximum Temperature	500 ℃
Compressor efficiency	80 %
Turbine efficiency	90 %
Pressure losses	0 % - neglected

3. Results and comparisons

As a reference point, the results of the pure S-CO_2 cycle with the lowest temperature change are shown in figure 4. It can be seen that the efficiency of the pure CO_2 cycle deteriorates with the increase of the cycle minmum temperature. It is obvious in thermodynamic point of view, but it is a big degradation compared to a small temperature increase. It is the fact that the compressor operating point is increaingly far from the critical point.

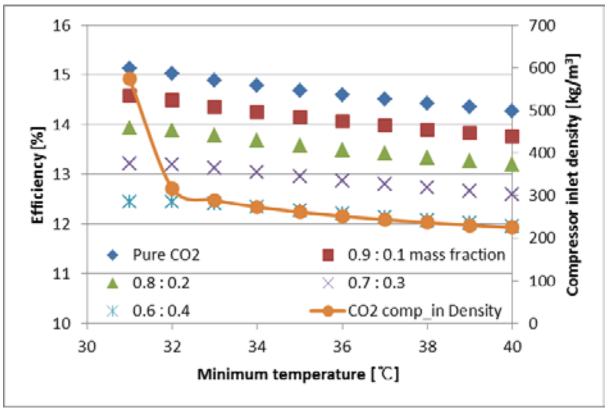

Fig. 4. Comparison of CO_2 and SF6 mixture Brayton cycle efficiency change on with minimum temperature change.

The result of mixing SF6 showed less efficiency rather than pure CO_2 case. This is because the turbine work is more reduced, even though the compression work is reduced as the compressor inlet density increases. The authors confirmed that the mixing of SF6 is not efficient.

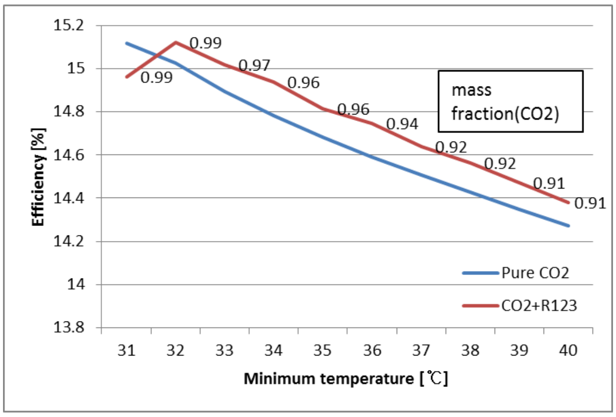

Fig. 5. Comparison of CO_2 and R-123 mixture Brayton cycle efficiency change on with minimum temperature change.

However, the results of R-123 showed an increase in efficiency because a 20 to 30% higher density reduced the compression work by 25 to 40% even at the same condition.

As the temperature increases, the mixing amount of R-123 is adjusted to have highest efficiency. The authors conclude that this method can be used as a way to reduce the efficiency degradation of pure S-CO_2 power cycles in summer season. For the 31 to 40℃

temperature change, the mass fraction of R-123 is 0.01 to 0.1 and it is appeared in figure 5.

4. Conclusions

In order to overcome the minimum temperature limit of the S-CO_2 power generation system, study on mixture of working fluid has been conducted. It has been concluded that by mixing high molecular weight fluids (Propane, SF6, Organic refrigerants…) can increase the critical temperature. According to the results, the authors concluded that the R-123 can reduce the efficiency degradation of pure S-CO_2 power cycles at higher minimum temperature. It is also believed that the S-CO_2 power conversion technology can be applied to tropical environments or even desert climates by mixing other fluids. If the total power system is designed with efficient air-cooled waste heat removal system, the S-CO_2 power cycle can be applied for the distributed power generation.

However, the results of the study are the analysis of the lowest temperature and compression work of the simple Brayton system. Additional analysis will be followed on highly efficient system configurations (recuperation and recompression cycle). Also the experimental verification will be conducted on the critical point of the mixture.

In addition, the technical feasibility of high temperature core application will be confirmed through further studies on the high temperature pyrolysis, corrosion, physical and chemical stability of mixed fluid in supercritical state.

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