# Potential Improvements of Supercritical Recompression $CO_2$ Brayton Cycle Coupled with KALIMER-600 by Modifying Critical Point of $CO_2$

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## 1. Introduction

Most of the existing designs of a Sodium cooled Fast Reactor (SFR) have a Rankine cycle as an electric power generation cycle. This has the risk of a sodium-water reaction. To prevent any hazards from a sodium-water reaction, an indirect Brayton cycle using Supercritical Carbon dioxide (S-$CO_2$) as the working fluids for a SFR is an alternative approach to improve the current SFR design [1].

The supercritical Brayton cycle is defined as a cycle with operating conditions above the critical point and the main compressor inlet condition located slightly above the critical point of working fluid [2]. This is because the main advantage of the cycle comes from significantly decreased compressor work just above the critical point due to high density near boundary between supercritical state and subcritical state.

For this reason, the minimum temperature and pressure of cycle are just above the $CO_2$ critical point. In other words, the critical point acts as a limitation of the lowest operating condition of the cycle. In general, lowering the minimum temperature of a thermodynamic cycle can increase the efficiency and the minimum temperature can be decreased by shifting the critical point of $CO_2$ as mixed with other gases. In this paper, potential enhancement of S-$CO_2$ cycle coupled with KALIMER-600, which has been developed at KAERI, was investigated using a developed cycle code with a gas mixture property program.

## 2. Development of supercritical Brayton cycle code

Existing commercial codes show unreliable estimates near the critical point of coolant and have no ability to analyze the cycle using a gas mixture as a coolant. As a result, a supercritical Brayton cycle analysis code was developed in MATLAB. Among various cycle layouts, recompression layout has been adopted due to its simplicity and high efficiency [2, 3]. The recompression Brayton cycle consists of a heat source (herein, Intermediate Heat Exchanger, IHX), a turbine, a main compressor, a recompressing compressor, a low temperature recuperator, a high temperature recuperator, and a heat sink (herein, precooler). The configuration of the cycle is shown in Fig. 1.

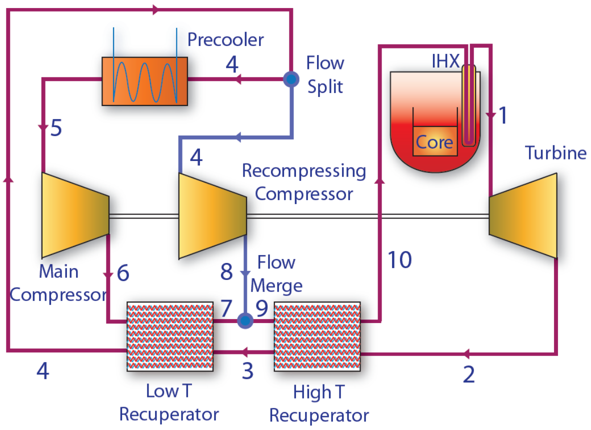

Fig 1. Recompression Brayton cycle layout diagram

To construct the cycle code, three types of subroutines were combined: turbomachinery, recuperator, and precooler. Each subroutine calculates an outlet condition for specified inlet conditions. All thermo-physical properties of fluids have been referenced to the REFPROP program of NIST, which have the most accurate mixture models [4]. A Printed Circuit Heat Exchanger (PCHE) model is adopted to minimize the size of heat exchangers. Pressure loss and temperature variation are computed by using the latest friction factor and Nusselt number correlations, proposed by Ngo [5]. In the case of turbomachinery, an isentropic efficiency was used to estimate outlet conditions.

For verification of the cycle code, the performances of calculated value from the cycle code were compared to Dostal's work [1, 3] and it was successful. As a reference case of this analysis, the input parameters were selected from the work of KALIMER-600 coupled with S-$CO_2$ cycle [6]. The cycle maximum temperature is at 781.15 K, maximum pressure is at 20 MPa, turbine pressure ratio is 2.6, 304.4 K for compressor inlet temperature, 1528.9 MW thermal for reactor power, 0.29 for recompressed mass flow ratio, isentropic efficiencies of turbine, main compressor and recompressing compressor are 93.4 %, 89.1 % and 87.5 %, respectively.

In the reference case, the heat exchanger performance was estimated using the log-mean temperature difference (LMTD) method and conventional correlations [7]. However, in this code, the axial node-divided method was used due to the huge fluctuation of properties of working fluids and the outlet condition of heat exchanger was calculated based on the latest correlations. Therefore, the re-optimized value was calculated by slightly changed pressure ratio and flow split ratio for the same layout, which is listed in Table 1.

Table 1. Performance of recompression S-$CO_2$ cycle

| | Reference value | Calculated value |
|---|---|---|
| Turbine P ratio | 2.60 | 2.61 |
| Cycle P ratio | 2.70 | 2.69 |
| Turbine work | 986.2 MW | 916.1 MW |
| Main compressor work | 167.0 MW | 115.0 MW |
| Recompressing compressor work | 165.5 MW | 139.6 MW |
| High T recuperator heat load | 1747.3 MW | 1752.9 MW |
| Low T recuperator heat load | 1070.7 MW | 1073.6 MW |
| Precooler heat load | 876.2 MW | 867.3 MW |
| Flow split ratio | 29 % | 30.28 % |
| Thermal cycle efficiency | 42.8 % | 43.27 % |
| Working fluid mass flow rate | 8076.6 kg/s | 7465.9 kg/s |

## 3. Supercritical Brayton cycle using binary gas mixture as a working fluid

As previously mentioned, extended cycle operating range by lowering the minimum cycle temperature has a potential to increase cycle efficiency. The lowest cycle operation condition strongly depends on the critical point of working fluids. In this analysis, the critical point of $CO_2$ was decreased by adding a small amount of other gases. Among available gases, several gases were chosen as candidates for the gas mixture. Most toxic and flammable gases were excluded due to safety issues. Selected gas mixtures were $CO_2$ mixed with $N_2$, $O_2$, He and Ar.

To evaluate the effects of binary gas mixture as working fluid in the supercritical Brayton cycle, the cycle efficiencies were calculated for several different critical temperatures from 304 K to 292 K. The compressor inlet temperature was maintained at 0.27 K above the critical temperature of the coolant. Other parameters were fixed to reference case of the S-$CO_2$ Brayton cycle except cooling water inlet temperature.

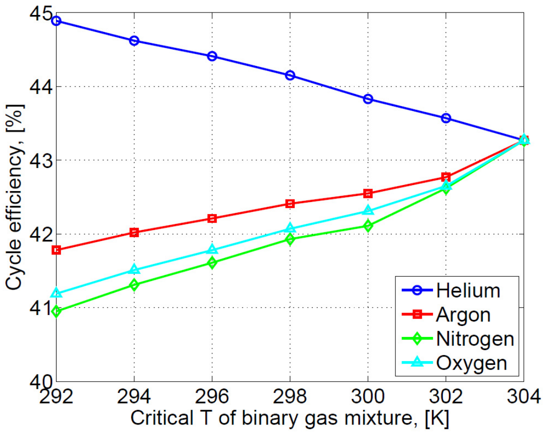

Fig 2. Cycle efficiency change vs critical temperature of different binary gas mixture

Figure 2 shows the variation of cycle efficiency with the change of critical temperature of gas mixture. The tendency of the cycle efficiency variation is clearly divided into two categories. The efficiency of $CO_2$-He binary mixture increases by 1.62 %. Unlike the $CO_2$-He binary mixture, the cycle efficiencies of $CO_2$-Ar, $CO_2$-$N_2$, and $CO_2$-$O_2$ binary mixtures decreased compared to the pure S-$CO_2$ cycle: - 1.49 %, - 2.32 %, and - 2.08 %, respectively.

## 3. Conclusions

In order to design a safe and more efficient BOP system for a SFR, various gas mixtures have been evaluated as working fluids in the supercritical Brayton cycle. The critical temperatures of all gas mixture candidates were decreased, but the critical pressure variation differed between various mixtures. In particular, the decrease in critical pressure leads to an increase in the optimum cycle pressure ratio, and this enhances the total cycle efficiency. In conclusion, lowering the critical temperature and critical pressure of the coolant has a positive effect on the total cycle efficiency.

## 4. Acknowledgement

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