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A Conceptual Study of Using an Isothermal Compressor on a Supercritical CO_2 Cycle for Various Nuclear Applications

Jin Young Heo [a], Jeong Ik Lee [a]
[a]*Department of Nuclear and Quantum Engineering, KAIST, Daejeon, South Korea*
Email: jyh9090@gmail.com, jeongiklee@kaist.ac.kr

1. Introduction

The development of recent next-generation nuclear reactors can be broadly classified under two branches: the Gen-IV reactors and the SMR-type reactors. The first type includes sodium fast-cooled reactors (SFRs), molten salt reactors (MSRs), and high temperature gas-cooled reactors (HTGRs), all of which have been under research since the foundation of the Generation IV International Forum (GIF). The other branch includes mainly PWR-type integral reactors such as SMART (System-integrated Modular Advanced Reactor) developed by KAERI (Korea Atomic Energy Institute).

In order to accelerate the deployment of cleaner and safer energy sources, further development of such advanced nuclear power systems is necessary. By aiming to have higher efficiency, lower costs, and reduced system size, next-generation nuclear reactors can have greater advantages which will justify their adoption. Many research efforts focus on these objectives to also propose new concepts and technologies to improve the present state of the art.

To maximize the benefits of advanced reactor designs, the supercritical CO_2 (S-CO_2) power cycle can be adopted to enhance the performance of the power conversion systems. For most of the nuclear reactor systems, the steam Rankine cycle is often used because of its reliability and high efficiency, but occupies a large fraction of the total system size. The potential of replacing the conventional power block with the S-CO_2 power cycle can increase the cycle efficiency and also reduce its overall system size.

The potential of using the S-CO_2 power cycles in advanced nuclear reactors can be further improved by adopting an isothermal compressor to the cycle layout. This paper attempts to improve the cycle layout by replacing the conventional compressor with an isothermal compressor, of which its potential in the S-CO_2 power cycle is conceptually being evaluated. An isothermal compressor minimizes compression work and further reduces the system size by having smaller heat exchanger requirements. The study includes cycle optimization maximizing cycle efficiency with respect to different cycle design parameters.

Previous works have been conducted to evaluate potential advantages of applying the S-CO_2 cycle to several advanced nuclear reactor designs [1-3]. Three nuclear reactor concepts have been selected as reference systems to evaluate the effect of applying an S-CO_2 power cycle with an isothermal compressor in the layout. The selected ones are SMART, SFR, and VHTR, and the reason behind the choices is that each represents a specific maximum temperature. This enables the analysis to cover a temperature range from 300°C to 700°C, and thus evaluate for which conditions the isothermal compressor can bring the greatest performance improvement.

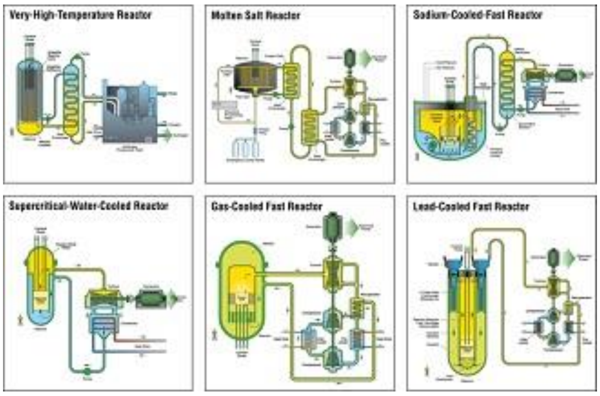

Fig 1.1. Gen-IV Reactor Design Concepts [4]

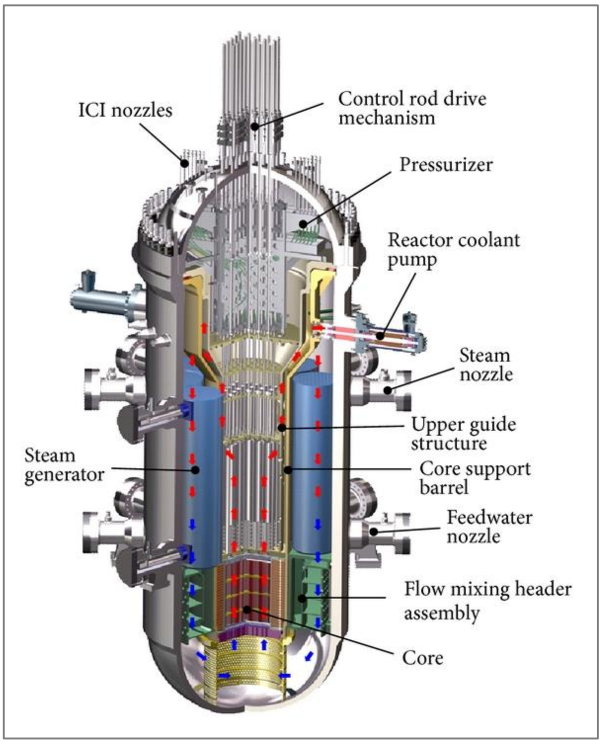

Fig 1.2. SMR-type SMART Reactor by KAERI [5]

2. Methods and Results

In order to evaluate the advantages of using the isothermal compressor in an S-CO_2 cycle layout, a framework must be established for defining the performance of the turbomachine.

2.1 Defining the performance of an isothermal compressor

Isothermal compression process allows the working fluid to become compressed at constant temperature, and can theoretically minimize the compression work required. Because the real work needs to be defined in order to calculate the efficiency of the isothermal compressor, the 'infinitesimal approach' is suggested. This framework divides an isothermal compression process into a series of isentropic compression and constant pressure cooling processes, as shown in Fig. 2.1. An additional parameter of compression process number

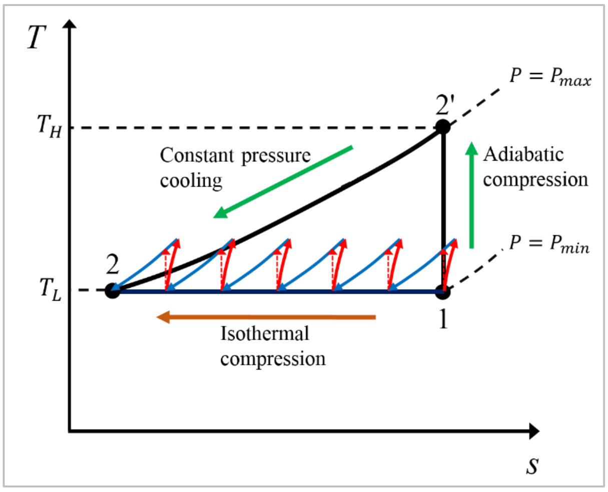

Fig 2.1. T-s diagram of Brayton cycle with isothermal compression in the infinitesimal approach (red – isentropic compression, blue –cooling at constant pressure)

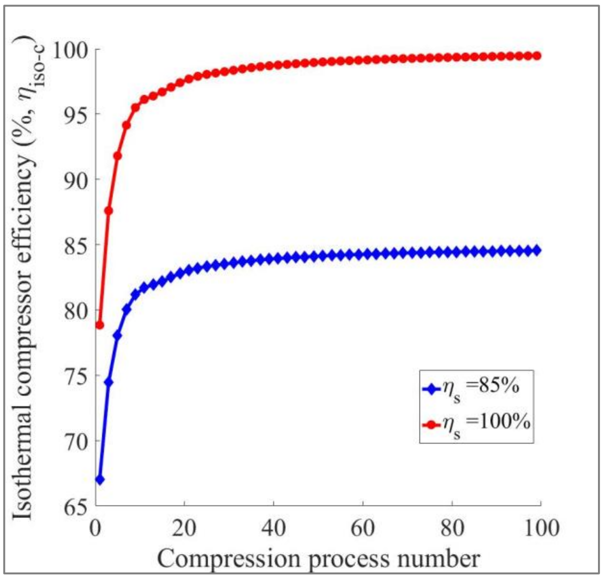

Fig. 2.2. Graph of verifying isothermal compressor efficiency

represents how the isothermal process can be modelled similarly to a multistage compression with intercooling process. The actual compression work is thus calculated by summing the compression work of all the infinitesimal stages.

To verify that this framework is mathematically valid, the compression process number is increased to a large number to check what the corresponding efficiency values are. It can be observed that Fig 2.2 shows graphs converging to the isentropic efficiency of each infinitesimal stage. This confirms that the actual work calculated does not go below the ideal work of the isothermal compressor, and that the increase of compression process number results in becoming closer to the ideal isothermal compression process.

2.2 Cycle operating conditions

Design parameters for performance analysis are obtained from [1-3], and they are selected to formulate the reference values for comparison. Table I specifies various parameters required for analysis. Here, the flow split ratio is defined as the ratio between the mass flow to the main compressor and the total mass flow. Also, the efficiency for the isothermal compressor requires the value of the isentropic efficiency of infinitesimal compression processes, which is named as isothermal stage efficiency here. This value is equal to the given compressor efficiency value in Table I.

Table I: Design specifications of the S-CO_2 cycle under the selected

Design Parameters	**SMART**	**SFR**	**VHTR**
Thermal power (MWth)	330	250	600
Turbine inlet temperature (°C)	310	472	850
Compressor outlet pressure (MPa)	15	20	20
Compressor inlet temperature (°C)	32	32	32
Turbine pressure ratio	Optimized	Optimized	Optimized
Turbine efficiency (%)	90	90	90
Compressor efficiency (%)	89	89	89
Recompressing compressor efficiency (%)	89	89	89
Isothermal stage efficiency (%)	89	89	89
Recuperator effectiveness (%)	95	95	95
Heat exchanger pressure drop (kPa)	100	100	100
Generator efficiency (%)	98	98	98
Flow split ratio (%)	Optimized	Optimized	Optimized

2.3 Cycle analysis method for layout options

The analysis has been conducted using the KAIST-Closed Cycle Design (KAIST-CCD) in-house code for cycle analysis. Two cycle layouts are selected as reference layouts: the simple recuperated Brayton cycle and the recompressing Brayton cycle. Here, the cycle layout is modified so that the conventional adiabatic compressor is replaced with the isothermal compressor, and the layouts for which the isothermal compressor is applied are named "*iso-Brayton*" cycles.

Each of the three reference conditions is applied to the two given cycle layouts, and the two iso-Brayton cycle layouts are placed in comparison to evaluate changes in cycle performance. The simple recuperated Brayton cycle and the recompressing Brayton cycle are shown in Figs. 2.3 and 2.4, respectively. For the recompressing iso-Brayton cycle, MC and RC correspondingly refer to the modified layout that replaces the conventional main compressor and the recompressing compressor with isothermal compressors. Due to the difficulties arising from the pinch-point problem in the recuperators, the recompression iso-Brayton RC cycle layout has been omitted from the analysis.

Main two parameters left open for optimization are the pressure ratio and the flow split ratio. Pressure ratio is increased up to the value at which the minimum pressure

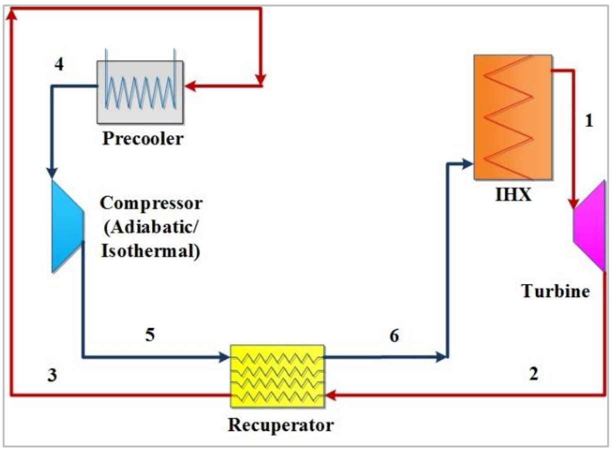

Fig. 2.3. Simple recuperated Brayton cycle layout

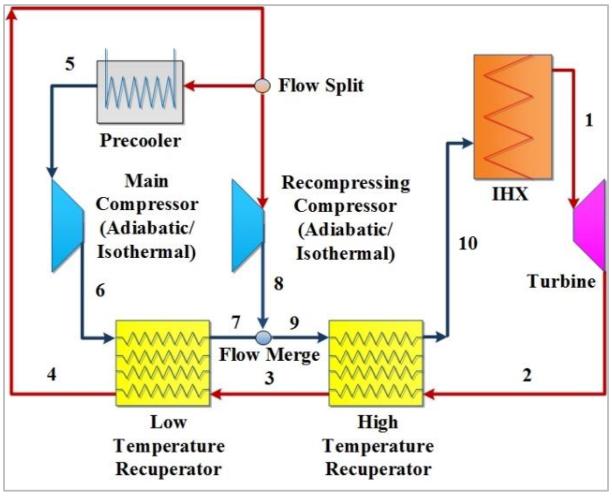

Fig. 2.4. Recompression Brayton cycle layout with an isothermal compressor

is above the critical pressure of CO_2. The cycle design conditions are optimized and selected at maximum cycle net efficiency.

At the point of maximum efficiency, the sum of the UA for the recuperator, precooler, and the isothermal compressor is calculated for comparison among different proposed layouts. The UA is calculated using the LMTD method, with the coolant assumed to be water at 25°C. The estimated UA of the system provides an approximation of the size required by heat exchanger components in the cycle layout. For the isothermal compressor, each UA value is obtained by using the Because the isothermal compressor for S-CO_2 cycles has not been conceptually designed yet, estimation of the UA value is suitable for comparison.

2.4 Optimized cycle results

Five cycle layouts are compared under three different nuclear reactor conditions. Fig. 2.5 – 2.7 show the optimized cycle net efficiencies and the corresponding total UA value. On the x-axis, the acronyms referring from the nomenclature section represent each cycle layout optimized to provide the following values on the y-axis. The results of optimization for each layout are net efficiencies on the left side, and the total UA on the right side.

It can be observed that for the SMART case, the efficiency can achieve up to 42% using the recuperated iso-Brayton cycle layout. This shows that the advantage of using an isothermal compressor in a simple recuperated cycle layout, and displays potential for a large gap of investment.

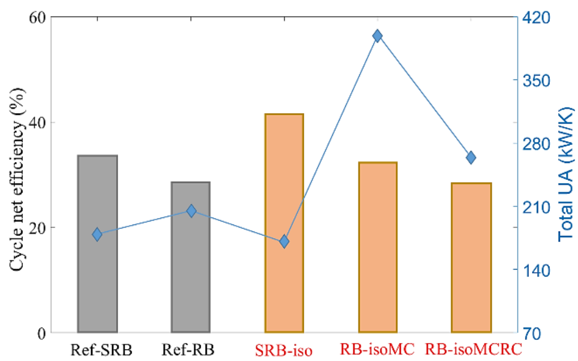

Fig. 2.5. Cycle net efficiencies and total UA for comparison under SMART conditions

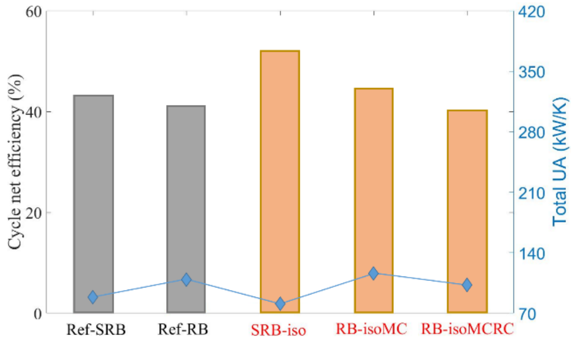

Fig. 2.6. Cycle net efficiencies and total UA for comparison under SFR conditions

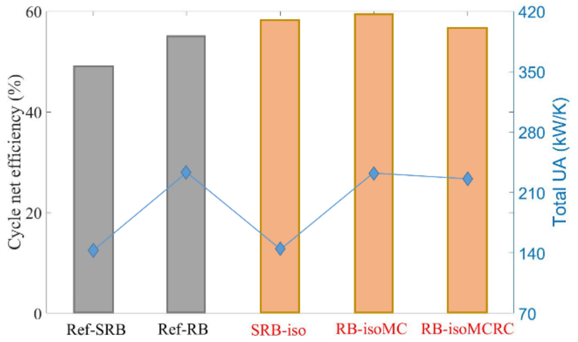

Fig. 2.7. Cycle net efficiencies and total UA for comparison under VHTR conditions

For the SFR case, the highest efficiency is achieved through the recompression iso-Brayton MC cycle layout. Furthermore, the VHTR condition yields the recuperated iso-Brayton cycle, which performs best among other cycle layouts. In all of the cases, using the recuperated iso-Brayton cycle brings the greatest efficiency gain when compared to the reference cycle layout.

The total UA gives a rough understanding of the heat exchanging part in a cycle layout. This includes the estimated UA of the isothermal compressor which contributes to the analysis of heat exchange requirements in the system. It can be seen that the recompression Brayton cycle layouts have higher UA than the simple recuperated Brayton layouts. Furthermore, using the isothermal compressor requires almost the same or smaller UA value compared to the reference cycle layouts.

3. Conclusions

The S-CO_2 iso-Brayton cycle layouts have been effective in improving the cycle efficiencies of the next-generation nuclear reactors. By using the isothermal compressor, the net efficiency can be improved by 8% points for the simple recuperated cycle layout, and 5% points for the recompression cycle layout. It is also noted that the estimated UA values required for the iso-Brayton cycle layouts are almost the same or less compared to those of the reference cycle layouts.

NOMENCLATURE

Ref-SRB	Reference simple recuperated Brayton
Ref-RB	Reference recompression Brayton
SRB-iso	Simple recuperated iso-Brayton
RB-isoMC	Recompression iso-Brayton MC
RB-isoMCRC	Recompression iso-Brayton MCRC

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