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Conceptual Design of S-CO_2 Brayton Cycle Radial Turbomachinery for KAIST Micro Modular Reactor

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1. Introduction

S-CO_2 Brayton cycle has high efficiency and compact heat exchangers and turbomachinery. These characteristics are highly suitable for Small Modular Reactor (SMR) application. Nevertheless, certain technical difficulties still exist regarding the S-CO_2 power cycle technology. KAIST proposed a new SMR design, which utilizes S-CO_2 as the working fluid. It was named as KAIST MMR. Compared with existing SMR concepts, KAIST MMR has advantages of achieving smaller volume of power conversion unit (PCU) and containing the core and PCU in one vessel for the complete modularization.

Authors noticed that the compressor and turbine assumed performances of KAIST MMR were conservatively selected previously. Thus, this paper tries to address the best estimate values of each turbomachinery in 10MWe class KAIST MMR.

2. Methods and Results

2.1 Reference Conditions

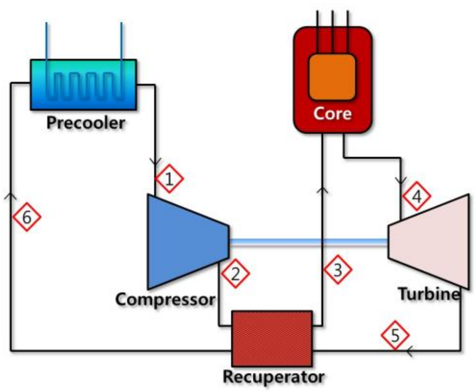

Fig.1. Reference S-CO_2 Recuperated Brayton cycle

The previous study presented that the optimum layout of KAIST MMR is S-CO_2 Recuperated Brayton cycle. Table I is the reference design conditions.

Table I: Reference Design Conditions (15MWe Reactor)

Compressor inlet Temperature	45 ℃
Compressor inlet Pressure	7.5 MPa
Turbine Pressure Ratio	2.621
Turbine inlet Temperature	550 ℃
Mass flow rate	261.55 kg/s
Compressor Efficiency	70 %
Turbine Efficiency	85%
Rotating speed	16000 rpm

2.2 Optimization of Components Condition

One of the most helpful methods for compressor and turbine sizing is to use Balje's n_s-d_s diagram .

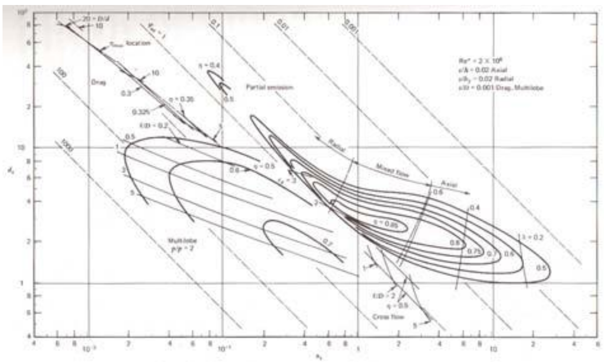

Fig.2. ns-ds diagram for single stage compressor

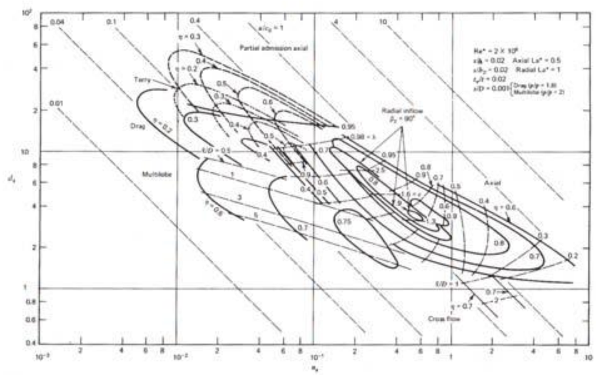

Fig.3. ns-ds diagram for single stage turbine

The contour line in Fig.2 and Fig.3 is a iso-efficiency line of compressor and turbine. The horizontal axis and vertical axis represent specific speed (n_s) and specific diameter (d_s), respectively. Values can be calculated by Eq. (1).

$$n_s = \frac{\omega\sqrt{V_1}}{(gH_{ad})^{\frac{3}{4}}} \; , \; d_s = \frac{D(gH_{ad})^{\frac{1}{4}}}{\sqrt{V_1}} \qquad (1)$$

Each parameter is defined as angular velocity(ω), gravitational acceleration(g), impeller diameter(D), inlet volumetric flow rate(V_1) and adiabatic head(H_{ad}).

Table III: Results of the state properties for KAIST MMR

	1	2	3	4	5	6
Pressure (MPa)	7.50	20.00	19.97	19.87	7.58	7.52
Temperature (℃)	45.00	126.91	371.85	550.00	434.35	141.66
Enthalpy (kJ/kg)	433.90	493.15	828.00	1035.20	916.25	581.40
Entropy (kJ/kg-K)	1.76	1.81	2.46	2.74	2.77	2.17

After design target efficiency is selected, specific speed and specific diameter are determined from each diagram. Compressor rotation speed and impeller diameter can be calculated with obtained specific speed and specific diameter since volumetric flow rate, adiabatic head and gravitational acceleration are given values from the cycle calculation. During the calculation, REFPROP was utilized to obtain thermodynamic properties of S-CO_2.

The pressure ratio was determined from the Reference value, 2.621. The best design conditions are shown in Table II. The compressor and turbine are all single stage machine. The rotating speed is 20,100 RPM which is faster than 16,000 to obtain higher efficiency.

For the same type of turbomachinery, usually higher efficiency results in increased specific speeds. It can be observed from Eq. (1) that angular velocity increases for higher specific speed. Thus, increase of component efficiency will lead to higher rotating speed.

Table II: Design Conditions of the Compressor and Turbine

	Compressor	Turbine
Specific velocity	0.643	0.492
Specific diameter	4.068	3.653
Rotating speed	20100 rpm	20100 rpm
Efficiency	84.94 %	90.94 %
Diameter	0.253 m	0.320 m

2.3 Cycle design results

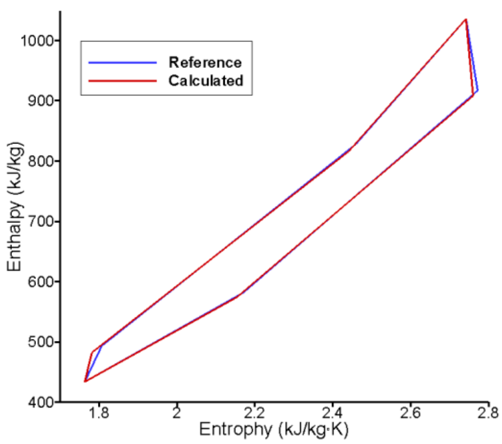

Fig.4. h-s Diagram of Reference and Calculated

The performance is now more favorable, since the reference data showed thermal efficiency of 28.82% at 2.621 of pressure ratio.

By using in-house codes developed by KAIST research team, the new electric power from KAIST MMR was estimated for given pressure ratio and components efficiencies. The proposed 10MWe class operating conditions were modified.

In Fig. 4, higher efficiency of each component results in decrease of compressor work and increase of turbine work, respectively. Table III shows the state properties of applying the best design conditions. The number of Station was marked on the basis of Fig. 1. Table IV implies that the net work output is increased by improving efficiency of each component.

Table IV: Results of Optimum Conditions and Reference for KAIST MMR

	Reference	Calculated
Compressor efficiency	70 %	84.94 %
Turbine efficiency	85 %	90.94 %
Rotating speed	16000 rpm	20100 rpm
Pressure ratio	2.621	2.621
Mass flow rate	174.35	165.20
Thermal efficiency	28.82 %	35.81 %
Net electric output	10.02 MWe	12.45 MWe

3. Conclusions

The turbomachinery size of the S-CO_2 cycle is smaller than helium Brayton cycle and steam Rankine cycle. The suggested SMR concept adopts passive cooling system by using air. This method can cool reactor without external electricity supply. Small size and more flexible installation in the inland area will be necessary characteristics for the future nuclear application in the water limited region. KAIST MMR meets all these requirements by utilizing S-CO_2 as a working fluid.

This paper presents the work for further increasing the system performance by estimating the component efficiency more realistically. The cycle layout adopted for the application is S-CO_2 recuperated Brayton cycle. The best efficiency of compressor and turbine was evaluated to be 84.94% and 90.94%, respectively. By using KAIST in-house code, thermal efficiency and net output were increased to 35.81% and 12.45MWe, respectively, for the same core thermal power. More refined cycle layout and suitable turbomachinery design will be performed in the near future.

ACKNOWLEDGEMENT

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