A Conceptual Study of Using an Isothermal Compressor on S-CO_2 Cooled KAIST Micro Modular Reactor (KAIST-MMR)

2016 Korean Nuclear Society Spring Meeting

Jin Young Heo

NPNP

CONTENTS

NPNP Nuclear Power & Propulsion Laboratory

CONTENTS

NPNP Nuclear Power & Propulsion Laboratory

Background – KAIST MMR

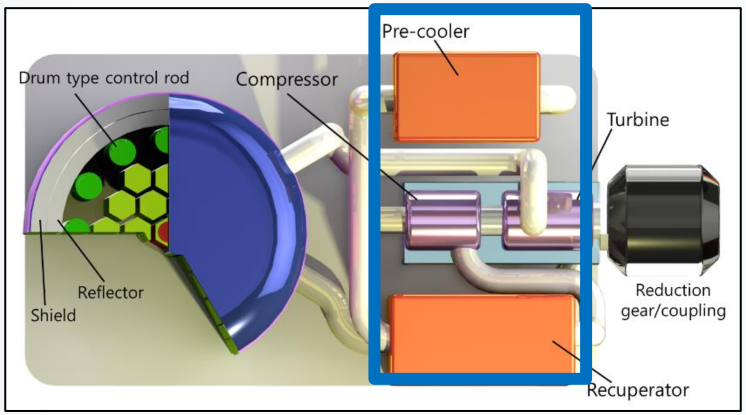


Fig. 1 – Component schematic of KAIST MMR [1]

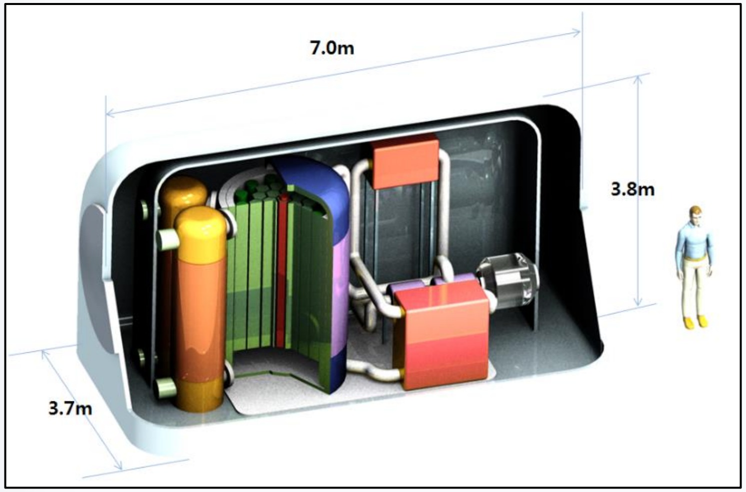


Fig. 2 – Overview schematic of KAIST MMR [1]

Descriptions:

- Small Modular Reactor (SMR) concept
- 12MWe produced from 36MWt nuclear core
- Reactor cooled by supercritical carbon dioxide (S-CO_2)
- Adopts the S-CO_2 Brayton cycle as power conversion system

[1] S. Kim, S. Baik, J. Moon, H. Yu, Y. Jeong, Y. Kim, J. Lee, Conceptual System Design of a Supercritical CO_2 cooled Micro Modular Reactor, Proceedings of ICAPP 2015, May 3-6, Nice, France.

Background – S-CO_2 cycle

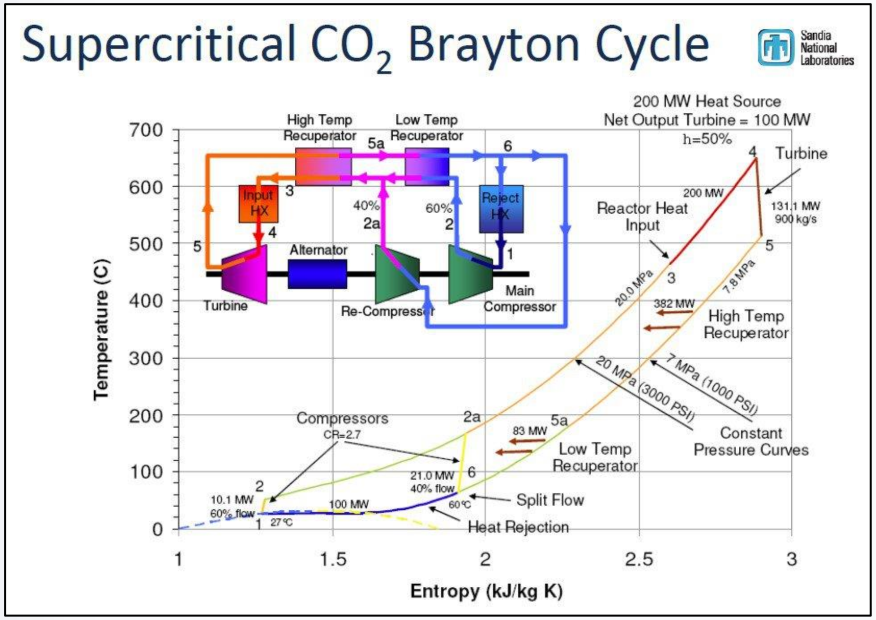


Fig. 3 – Supercritical CO_2 cycle T-s diagram [2]

<u>Supercritical CO_2 (state beyond the critical point)</u>

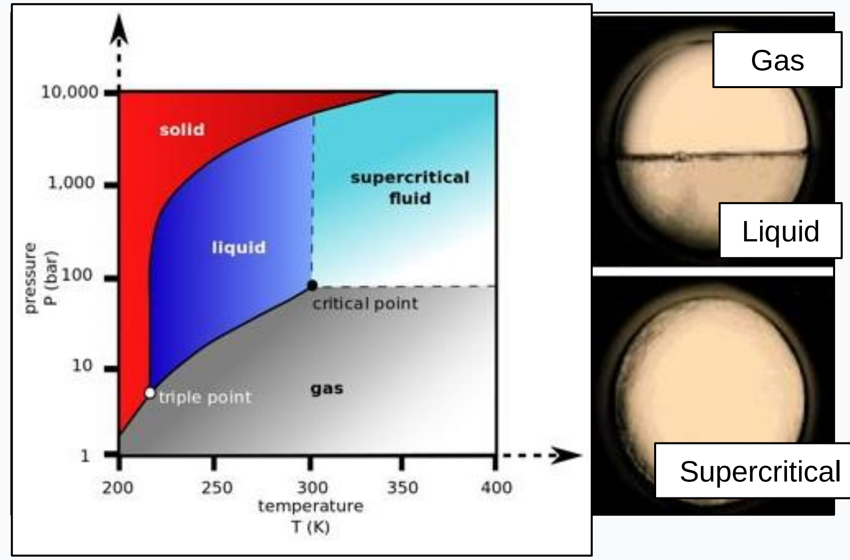


Fig. 4 – Supercritical CO_2 phase diagram [2]

Supercritical CO_2 Cycle:

- New technology to replace conventional steam Rankine cycle
- Working fluid: S-CO_2 (single phase)
- Liquid-like low compressibility factor near critical point

[2] DODGE, EDWARD. "Supercritical Carbon Dioxide Power Cycles Starting to Hit the Market." Breaking Energy. Breaking Energy. Web. 09 May 2016.

NPNP

Background – S-CO_2 cycle

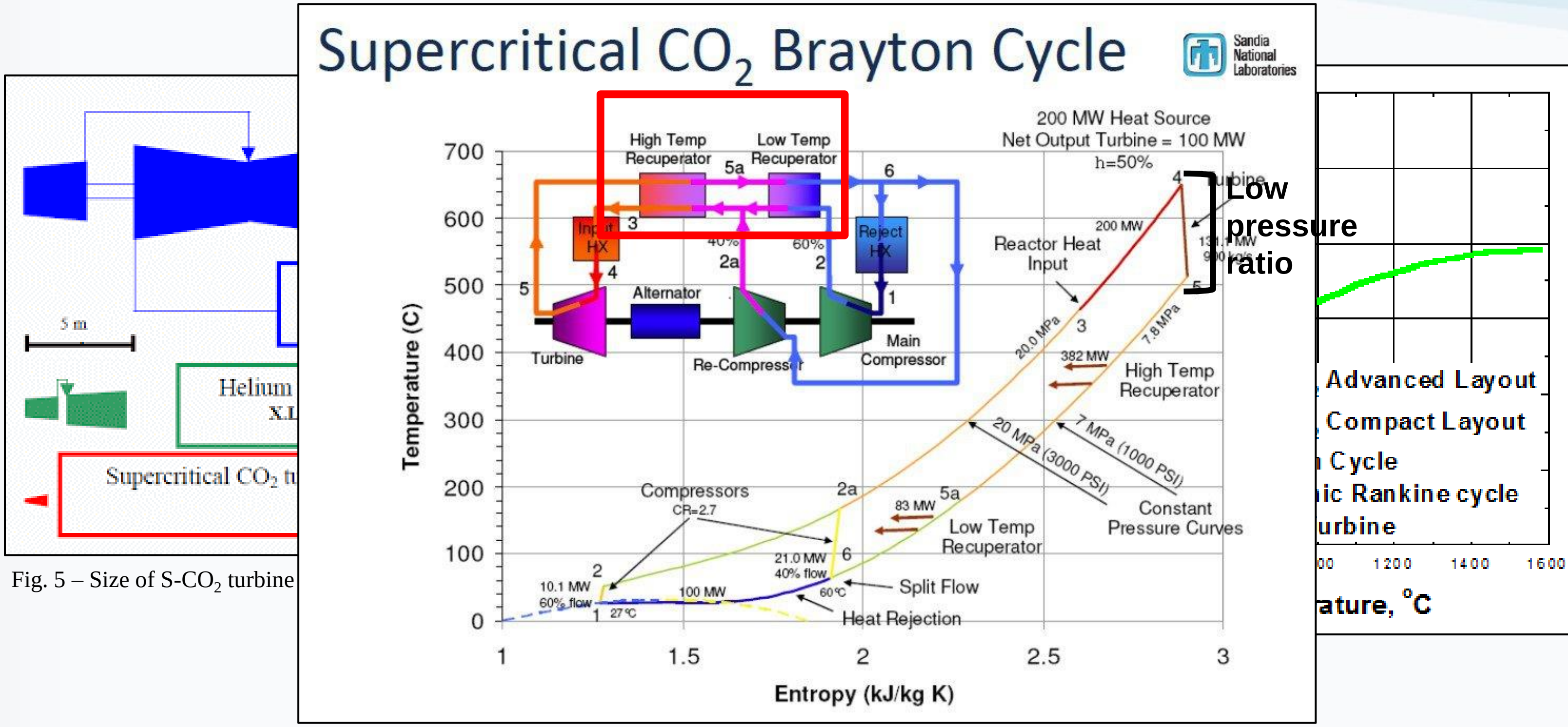


Fig. 5 – Size of S-CO_2 turbine

Advantages	Limitations
-Smaller size turbomachines -Single-phase system -Better efficiency	-Low pressure ratio (higher mass flow rate → pressure losses ↑) -Recuperator with large surface area (larger HX)

[3] V. Dostal, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, Ph. D. Thesis, Massachusetts Institute of Technology, 2004.

Background – MMR Layout

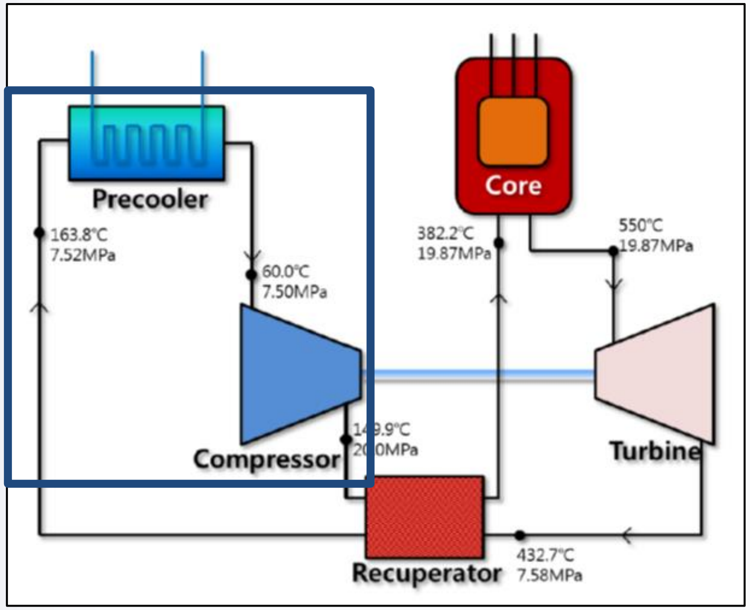


Fig. 6 – Schematic figure of simple recuperated S-CO_2 Brayton cycle [1]

Descriptions

- Reference cycle: simple recuperated Brayton cycle
- Turbine inlet T: 550℃, Compressor inlet T: 60℃
- Net cycle efficiency η_{net}=32.5%
- New layout suggested to reduce hardware sizing, and improve cycle efficiency

Research objectives:

1. Further increase cycle net efficiency through design modifications
2. Reduce the total sizing of the power cycle system

Background – isothermal compression

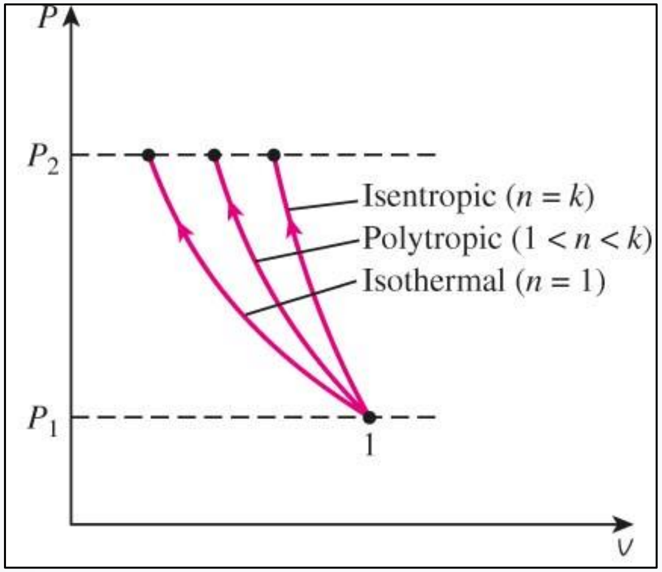


Fig. 7 – Types of compression processes on P-v diagram [4]

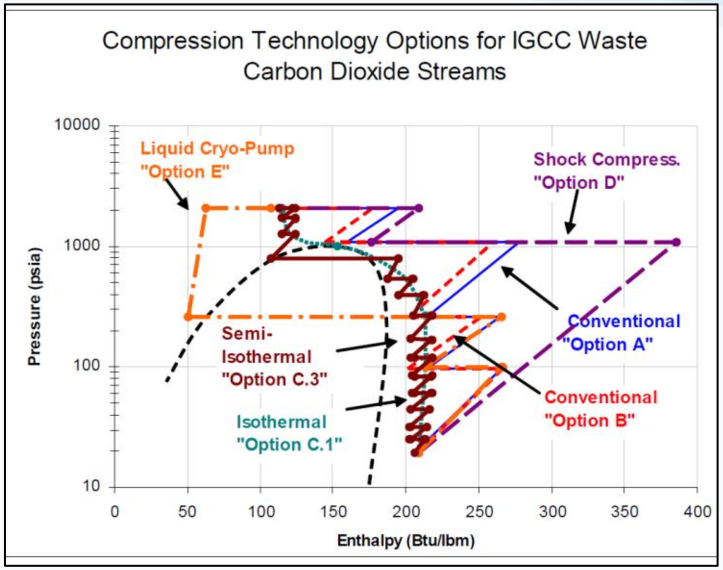


Fig. 8 - Compressor technology options on P-h diagram [5]

Descriptions:

- Minimum compression work
- In reality, perfect isothermal compression is impossible
- Various ways to realize **"near" isothermal compression process**, by removing heat of compression during compression process

[5] Moore, J. Jeffrey, Ph.D, Marybeth G. Nored, Ryan S. Gernentz, and Klaus Brun, Ph.D. "Novel Concepts for the Compression of Large Volumes of Carbon Dioxide." (2007). Web. 29 Jan. 2016.

Background – isothermal compressor

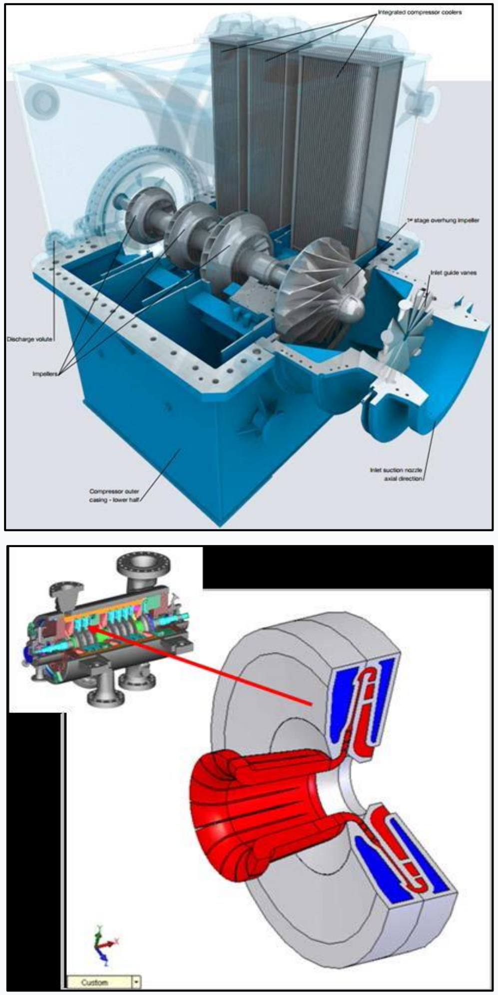


Fig. 9,10 – Concepts of isothermal compressor for compressing CO_2 [5]

<u>Isothermal compressor technology:</u>

- Previous researches mainly done for carbon capture applications
- MAN Turbo, SwRI are pursuing further development
- But, has not been applied to S-CO_2 cycles

→ In this study, the potential of using isothermal compressor technology to S-CO_2 power cycle is studied

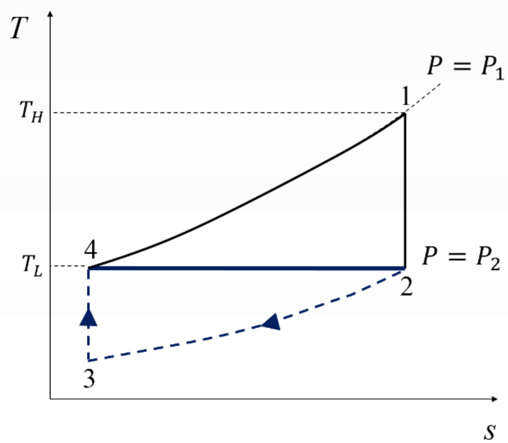
CONTENTS

NPNP Nuclear Power & Propulsion Laboratory

CONTENTS

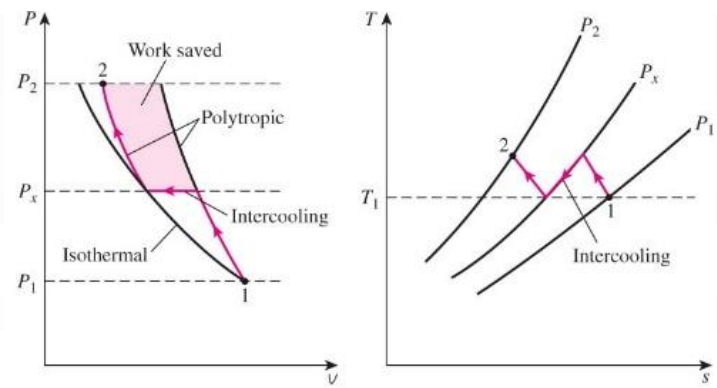
Definition – isothermal compressor

2-Staged Approach



- Simplifies the problem as two-stage, cooling and adiabatic compression
- Conventional frame of compressor efficiency
- Inflexible to changes in layout and operating conditions

Infinitesimal Approach



- Requires hardware design parameters including the number of intercooling stages and polytropic coefficients
- Mathematically complex for calculation
- Flexible under various conditions

Definition – isothermal compressor

Infinitesimal Approach

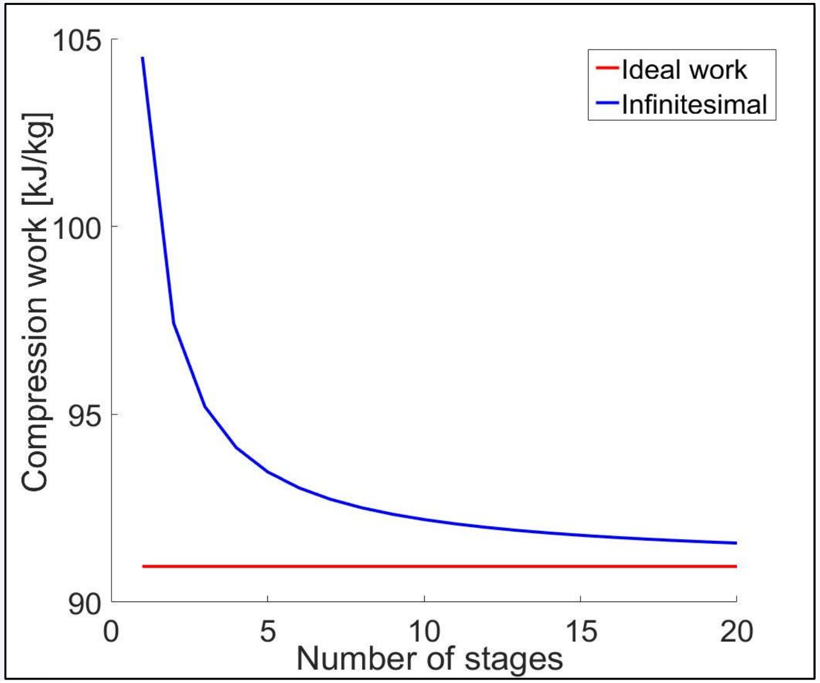


Fig. 12 –Calculation of isothermal compression work under ideal gas asssumptions

Descriptions:

- Isentropic compression (red) + cooling (blue)
- Total real work = $\sum_m w_{x,i}$
  (m: number of intermediate stages, $w_{x,i}$: work of isentropic compressions)
- Under ideal gas assumptions, infinitesimal approach converges to ideal isothermal compression

Optimal pressure ratio of multistage compression + cooling process:

$$P_{ratio} = \frac{P_{out}}{P_{in}} = \frac{P_{x1}}{P_{in}}\frac{P_{x2}}{P_{x1}}\cdots\frac{P_{x,m}}{P_{x,m-1}} \quad , \qquad P_{ratio,inf} = (P_{ratio})^{\frac{1}{m}}$$

Isentropic efficiency of isothermal compression (infinitesimal approach)

$$\eta_{iso-c} = \frac{ideal\ work}{actual\ work} = \frac{isentropic\ multistage\ compression\ work}{actual\ multistage\ compression\ work}$$

CONTENTS

NPNP

CONTENTS

Analysis – Conditions

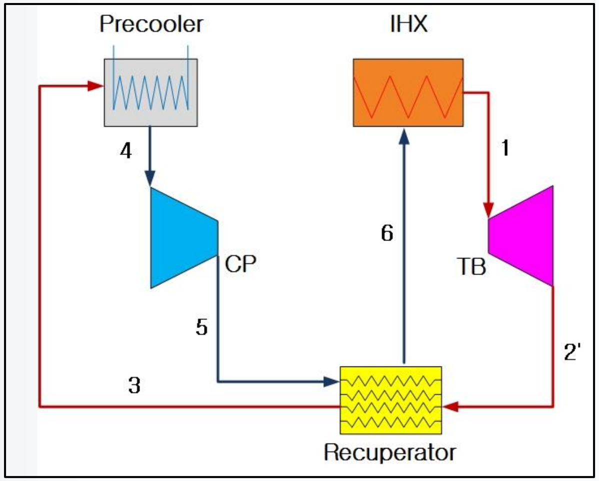


Fig. 13 – Schematic figure of simple recuperated S-CO_2 Brayton cycle

Design Parameters	Values
Q (MWth)	36.2
Turbine inlet temperature (°C)	550
Compressor outlet pressure (MPa)	20
Compressor inlet temperature (°C)	60
Pressure ratio	2.59
Turbine efficiency (%)	92.3
Compressor efficiency (%) (Isentropic compression stage efficiency)	**85.0**
Recuperator effectiveness (%)	94.6

Table 1 – Representative design parameters for KAIST-MMR cycle analysis

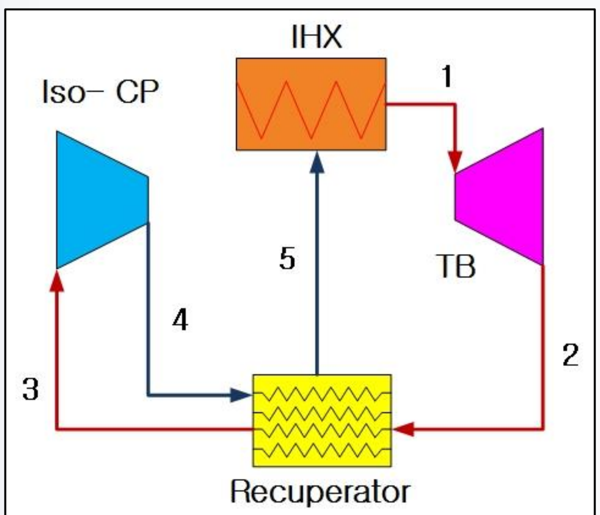


Fig. 14 – Schematic figure of S-CO_2 iso-Brayton cycle

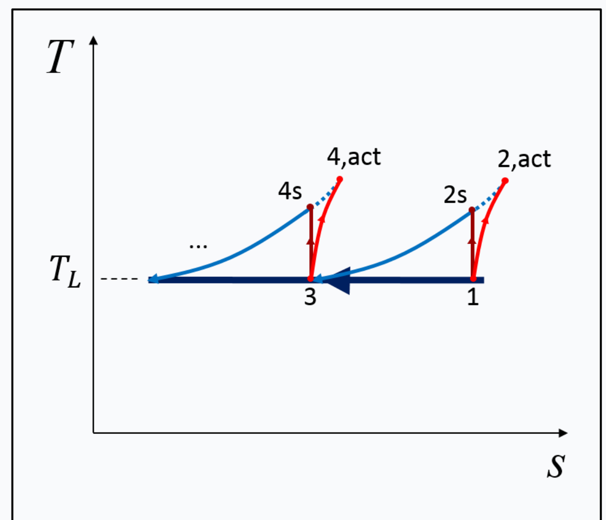


Fig. 14b – Diagram of isentropic compression stage efficiency

Analysis – Simple Recuperated

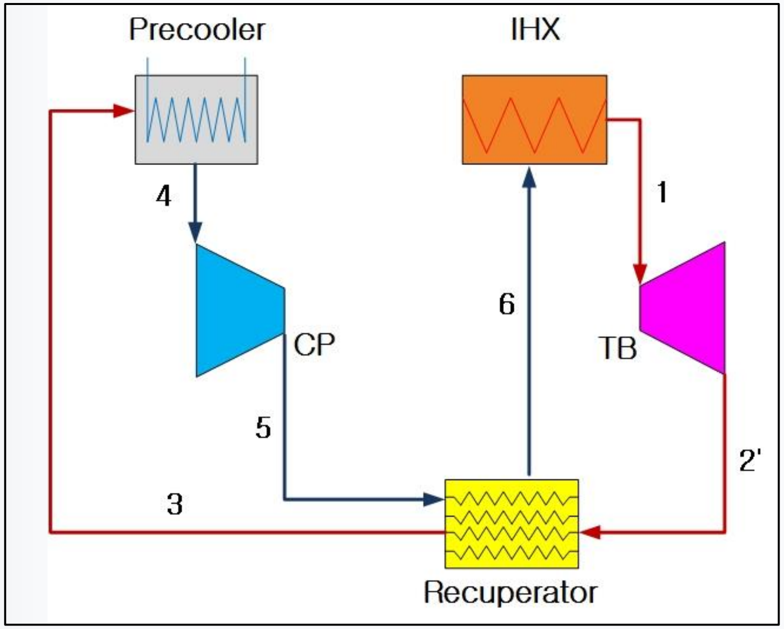


Fig. 15 – Schematic figure of simple recuperated S-CO_2 Brayton cycle

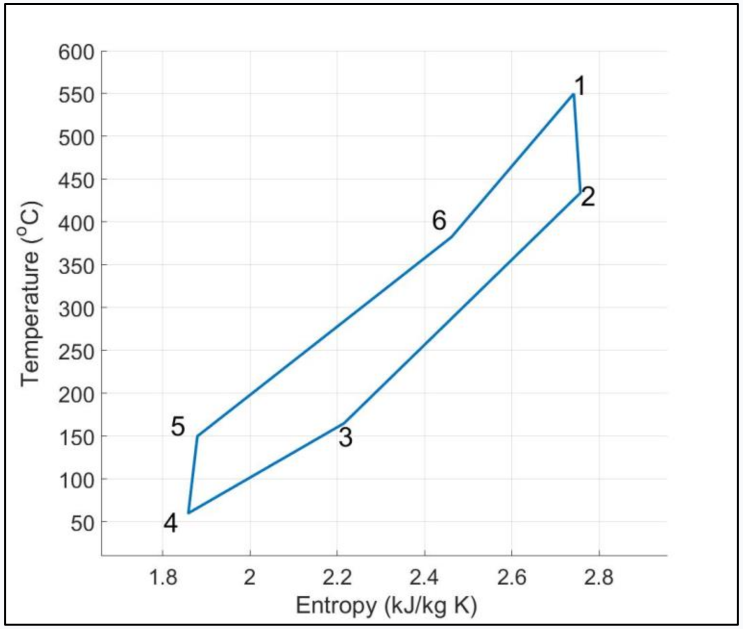


Fig. 16 – T-s diagram of simple recuperated S-CO_2 Brayton cycle under KAIST-MMR conditions

Cycle Performance Parameters	Values
Cycle Net Efficiency (%)	32.5
Compressor Work (MW)	10.2
Cycle Net Work (MW)	11.8
CO_2 mass flow (kg/s)	175.69

Table 2 – Cycle performance results of simple recuperated S-CO_2 Brayton cycle under KAIST-MMR conditions

Analysis – Infinitesimal iso-Brayton

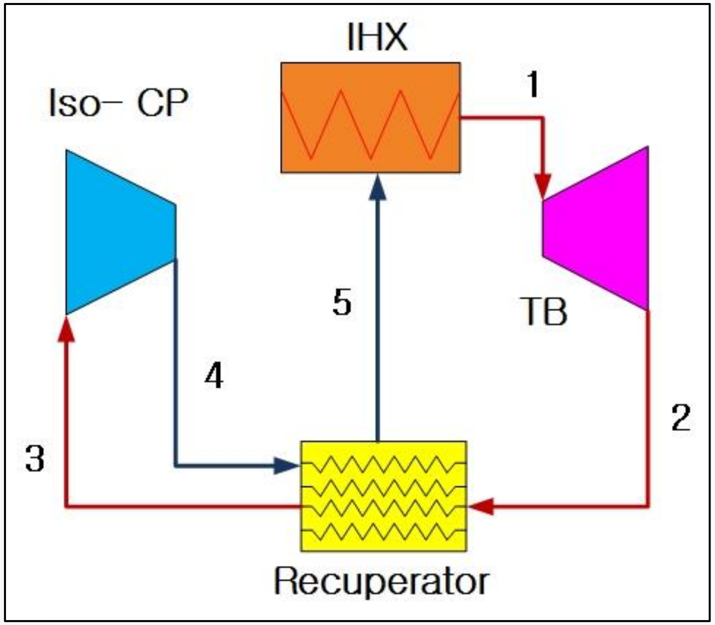


Fig. 17 – Cycle layout of iso-Brayton cycle in infinitesimal approach

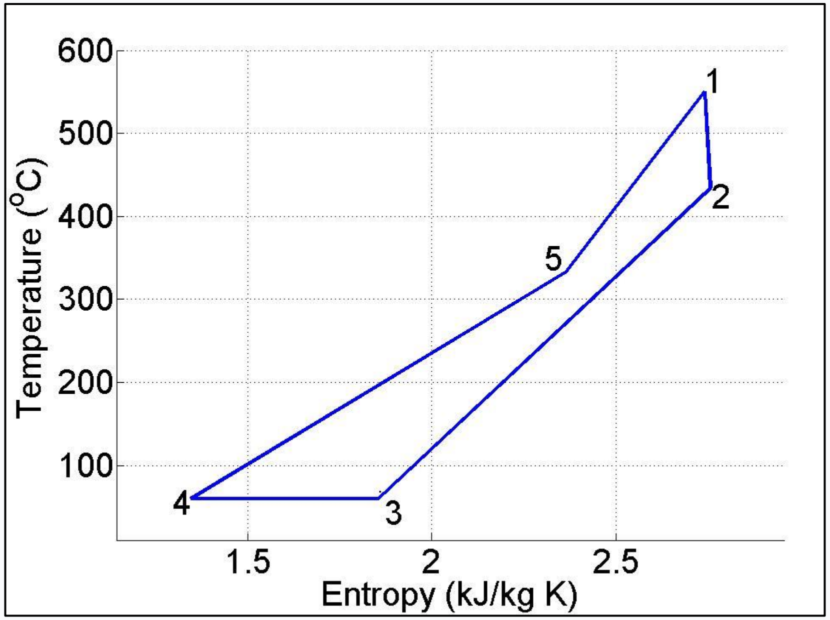


Fig. 18 – T-s diagram of iso-Brayton cycle in infinitesimal approach under KAIST-MMR conditions

Cycle Performance Parameters	**Values**
Cycle Net Efficiency (%)	33.4
Compressor Work (MW)	4.7
Cycle Net Work (MW)	12.1
CO_2 mass flow (kg/s)	135.57

Table 3 – Cycle performance results of S-CO_2 iso-Brayton cycle under KAIST-MMR conditions

Analysis – Comparison

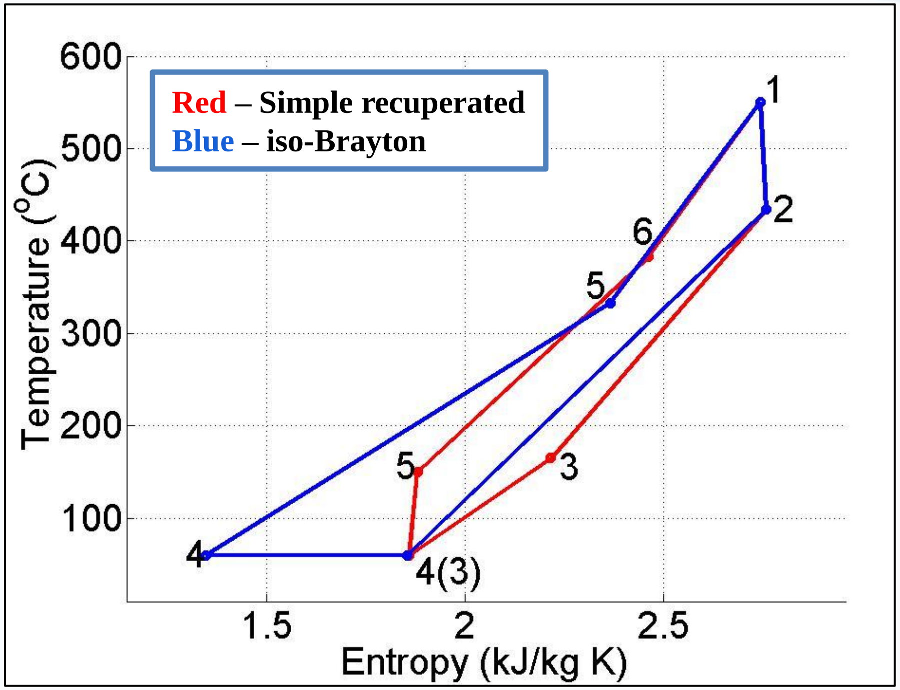


Fig. 21 – T-s diagram of simple recuperated S-CO_2 Brayton cycle and iso-Brayton cycle under KAIST-MMR conditions

Cycle Performance Parameters	Simple Recuperated	Iso-Brayton
Cycle Net Efficiency (%)	32.5	33.4
Compressor Work (MW)	10.2	4.7
CO_2 mass flow (kg/s)	175.69	135.57

CONTENTS

CONTENTS

Conclusions

1. Although the technology is only conceptual, using an isothermal compressor in the KAIST-MMR layout **increases cycle net efficiency**.

2. Combining the pre-cooler and the compressor to one turbomachine has potential to **reduce the total sizing** of the reactor system.

3. Having reduced mass flow rate implies less pump work, less pressure drop in piping.

4. Through the isothermal compressor, total compressor work can be reduced greatly, up to 50%.

Further Works

1. Heat exchanger sizing analysis via KAIST-HXD in-house code

2. Isothermal compressor turbomachinery design via KAIST-TMD code

3. Optimization of cycle layout and parameters (e.g. sensitivity analysis with pressure ratio)

4. Experimental setup and analysis using KAIST SCO_2PE for near isothermal compression experiments

Fig. 23 – KAIST SCO_2PE Experimental Apparatus

References

[1] S. Kim, S. Baik, J. Moon, H. Yu, Y. Jeong, Y. Kim, J. Lee, Conceptual System Design of a Supercritical CO_2 cooled Micro Modular Reactor, Pro ceedings of ICAPP 2015, May 3-6, Nice, France.

[2] DODGE, EDWARD. "Supercritical Carbon Dioxide Power Cycles Starting to Hit the Market." Breaking Energy. Breaking Energy. Web. 09May 2016.

[3] V. Dostal, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, Ph. D. Thesis, Massachusetts Institute of Technology, 2004.

[4] Çengel, Yunus A., and Michael A. Boles. Thermodynamics: An Engineering Approach. 7th ed. Boston: McGraw-Hill, 2011. 361-362. Print.

[5] Moore, J. Jeffrey, Ph.D, Marybeth G. Nored, Ryan S. Gernentz, and Klaus Brun, Ph.D. "Novel Concepts for the Compression of Large Volumes of Carbon Dioxide." (2007). Web. 29 Jan. 2016.

THANK YOU!

Appendix

Under ideal gas assumptions,

Equation (1):

$$\eta_{iso-c} = \frac{w_{iso-c}}{w_{real,a,c}} = \frac{RT_L \ln\frac{P_1}{P_2}}{h_4 - h_3} = \frac{RT_L \ln\frac{P_1}{P_2}}{h_{4s} - h_3}\eta_{a,c} = \frac{RT_L \ln\frac{P_1}{P_2}}{\frac{kRT_3}{k-1}\left(\left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}} - 1\right)}\eta_{a,c}$$

$$= \frac{\frac{k-1}{k}\left(\frac{T_L}{T_3}\right)\ln\left(\frac{P_1}{P_2}\right)}{\left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}} - 1}\eta_{a,c} = \frac{\frac{k-1}{k}\ln\left(\frac{P_1}{P_2}\right)}{1 - \left(\frac{P_1}{P_2}\right)^{-\frac{k-1}{k}}}\eta_{a,c}$$

$$\left(h_{4s} - h_3 = \int_3^{4s} vdP = \frac{kRT_4}{k-1}\left(\left(\frac{P_{4s}}{P_3}\right)^{\frac{k-1}{k}} - 1\right)\right.$$

$$\left. = \frac{kRT_4}{k-1}\left(\left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}} - 1\right), \left(\frac{T_L}{T_3}\right)_s = \left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}}\right)$$

Equation (2):

$$\eta_{iso-Brayton} = \frac{q_{in} - q_{out}}{q_{in}}$$

$$= \frac{(h_1 - h_4) - \left(RT_L \ln\frac{P_1}{P_2}\cdot\frac{1}{\eta_{iso-c}} - (h_4 - h_2)\right)}{h_1 - h_4}$$

$$= 1 - \frac{(h_4 - h_3) - (h_4 - h_2)}{h_1 - h_4} = 1 - \frac{h_2 - h_3}{h_1 - h_4}$$

$$\left(h_4 = h_3 + \frac{1}{\eta_c}(h_{4s} - h_3), \qquad h_1 = h_2 - \eta_T(h_1 - h_{2s})\right)$$

Further elaborating Equation (2),

$$\eta_{iso-Brayton} = 1 - \frac{h_1 - \eta_T(h_1 - h_{2s}) - h_3}{h_1 - h_3 - \frac{1}{\eta_c}(h_{4s} - h_3)}$$

$$= \frac{\eta_T\left(r^{\frac{k-1}{k}} - 1\right) - \frac{1}{\eta_c}\left(1 - r^{-\frac{k-1}{k}}\right)}{r^{\frac{k-1}{k}} - r^{-\frac{k-1}{k}} - \frac{1}{\eta_c}\left(1 - r^{-\frac{k-1}{k}}\right)} \quad \left(r = \frac{P_1}{P_2}\right)$$

Further elaborating Equations (3) and (4),

$$h_{2'} - h_6 = h_5 - h_{4'}$$
$$h_5 = h_{4'} + \epsilon(h_{2'} - h_{4'})$$
$$h_6 = h_{2'} - \epsilon(h_{2'} - h_{4'})$$

$$\eta_{recup} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{h_6 - h_{3'}}{h_1 - h_5}$$

$$= \frac{\eta_T(T_H - T_{2'}) - \frac{1}{\eta_c}(T_{4'} - T_L)}{T_H - (1-\epsilon)\left(T_L + \frac{1}{\eta_c}(T_{4'} - T_L)\right) - \epsilon(T_H - \eta_T(T_H - T_{2'}))}$$

$$= \frac{\eta_T r^{\frac{k-1}{k}}\left(1 - (r')^{-\frac{k-1}{k}}\right) - \frac{1}{\eta_c}\left((r')^{\frac{k-1}{k}} - 1\right)}{r^{\frac{k-1}{k}} - (1-\epsilon)\left(1 + \frac{1}{\eta_c}\left((r')^{\frac{k-1}{k}} - 1\right)\right) - \epsilon r^{\frac{k-1}{k}}\left(1 - \eta_T\left(1 - (r')^{-\frac{k-1}{k}}\right)\right)}$$

$$= \frac{\eta_T r^{\frac{k-1}{k}}\left(1 - (r')^{-\frac{k-1}{k}}\right) - \frac{1}{\eta_c}\left((r')^{\frac{k-1}{k}} - 1\right)}{r^{\frac{k-1}{k}} - (1-\epsilon)\left(1 + \frac{1}{\eta_c}\left((r')^{\frac{k-1}{k}} - 1\right)\right) - \epsilon r^{\frac{k-1}{k}}\left(1 - \eta_T\left(1 - (r')^{-\frac{k-1}{k}}\right)\right)} \quad \left(r' = \frac{P_1}{P_{2'}}\right)$$

$$\left(h_{4'} = h_3 + \frac{1}{\eta_c}(h_{4s} - h_3), \qquad h_{2'} = h_1 - \eta_T(h_1 - h_{2's})\right)$$

NPNP Nuclear Power & Propulsion Laboratory