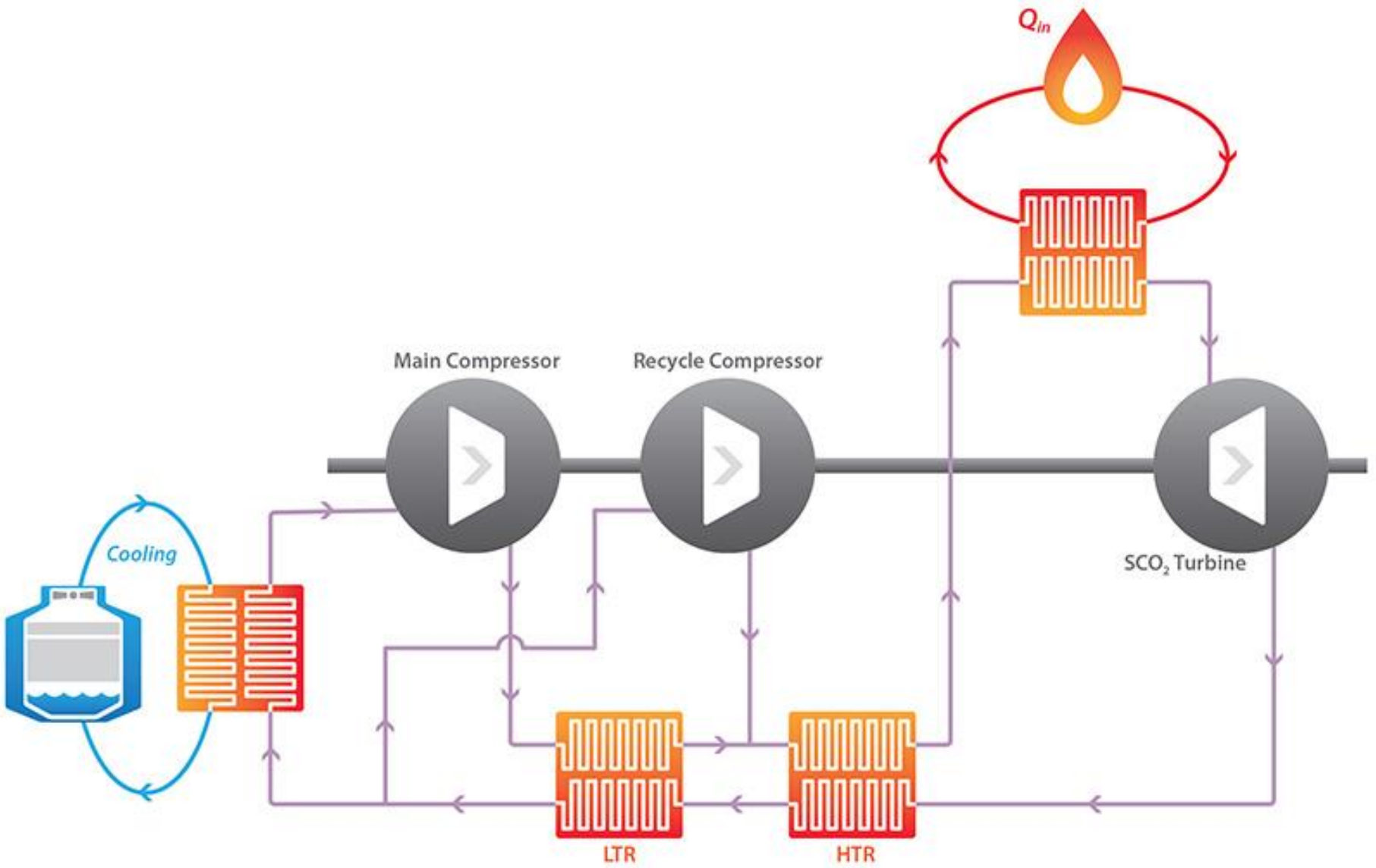
Super-criticial CO2 (S-CO2) Power Cycles

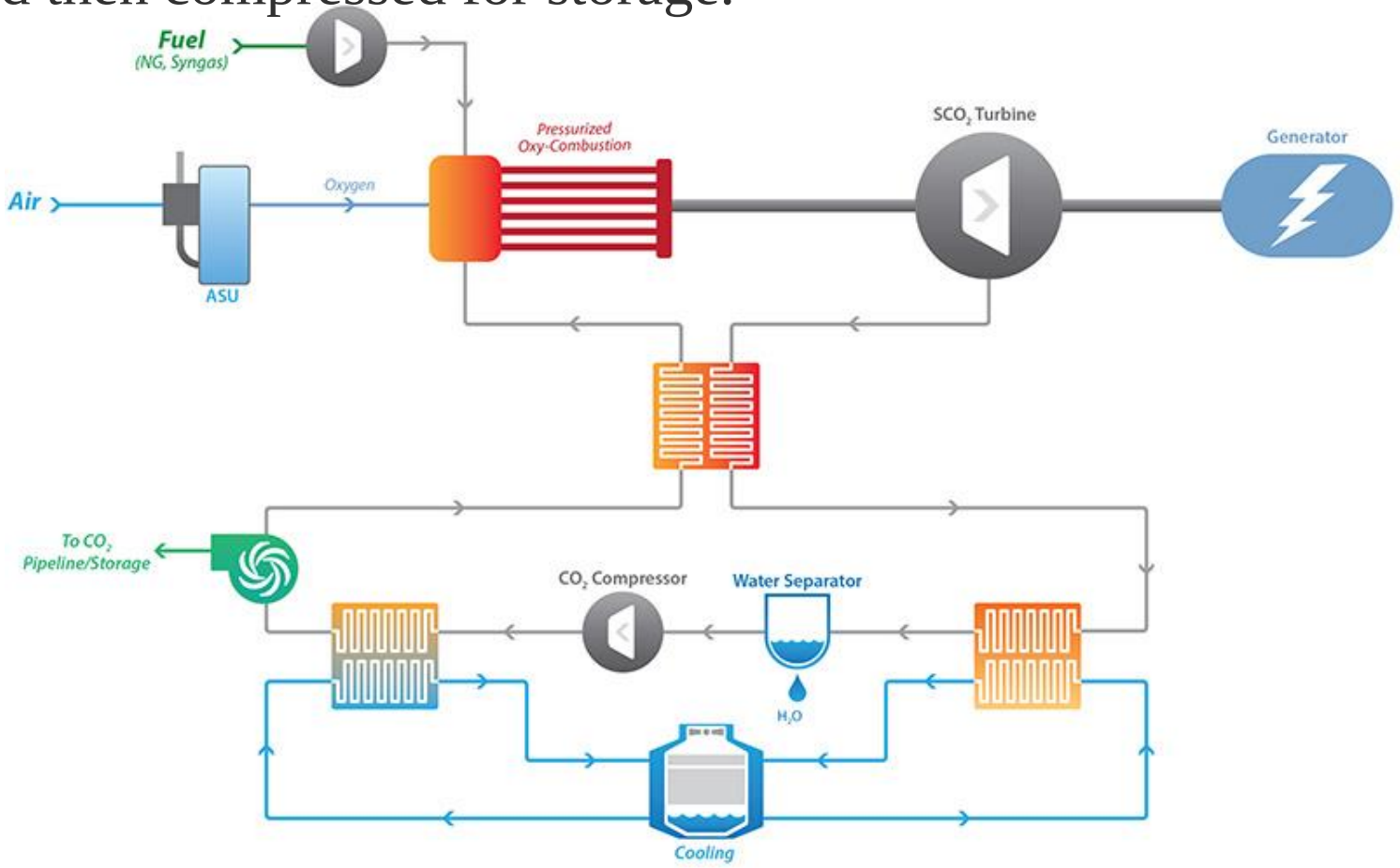
- The supercritical carbon dioxide power cycle operates in a manner similar to other turbine cycles, but it uses CO_2 as the working fluid in the turbomachinery.
- The cycle is operated above the critical point of CO_2 so that it does not change phases (from liquid to gas), but rather undergoes drastic density changes over small ranges of temperature and pressure.
- This allows a large amount of energy to be extracted at high temperature from equipment that is relatively small in size. SCO2 turbines will have a nominal gas path diameter an order of magnitude smaller than utility scale combustion turbines or steam turbines.
- The cycle envisioned for the first fossil-based indirectly heated application is a non-condensing closed-loop Brayton cycle with heat addition and rejection on either side of the expander
- In this cycle, the CO_2 is heated indirectly from a heat source through a heat exchanger, not unlike the way steam would be heated in a conventional boiler.
- Energy is extracted from the CO_2 as it is expanded in the turbine. Remaining heat is extracted in one or more highly efficient heat recuperators to preheat the CO_2 going back to the main heat source. These recuperators help increase the overall efficiency of the cycle by limiting heat rejection from the cycle.

Closed Loop SCO2 Recompression Brayton Cycle Flow Diagram



-Directly fired SCO2 cycles combust fossil fuels with oxygen and the resulting steam/CO_2 mixture is used to drive the turbine.
-Figure below illustrates a potential configuration of this cycle.

-In this particular cycle, the remaining heat in the steam/CO_2 mixture is recuperated to preheat the cooled and compressed CO_2 that is used as the combustion diluent. The mixture is further cooled to condense the water out and then compressed for storage.



OVERVIEW

- The advantages of the S-CO2 cycle are high efficiency in the mild turbine inlet temperature region and a small physical footprint with a simple layout, compact turbomachinery, and heat exchangers.

- Several heat sources including nuclear, fossil fuel, waste heat, and renewable heat sources such as solar thermal or fuel cells are potential application areas of the S-CO2 cycle.

S-CO2 power cycle

The characteristics and benefits of the S-CO2 cycle

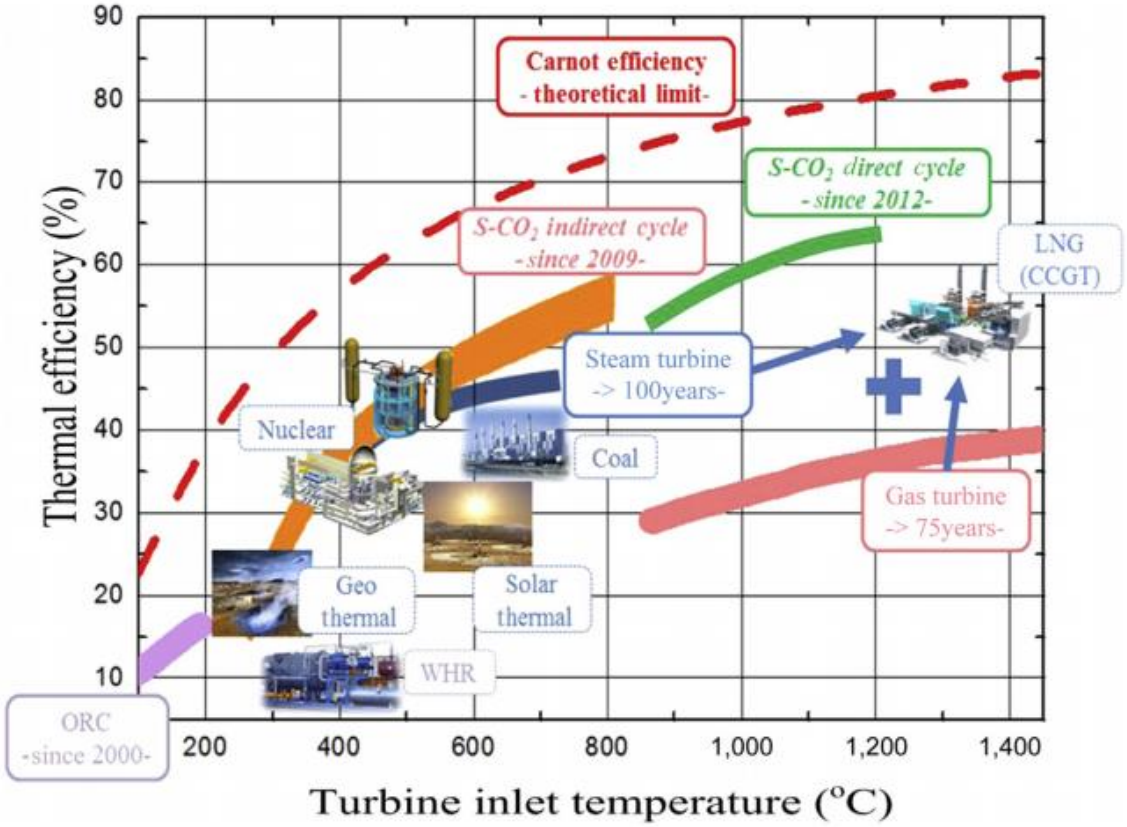


Fig. 1 – Thermal efficiencies of power conversion systems and applications. CCGT, combined cy

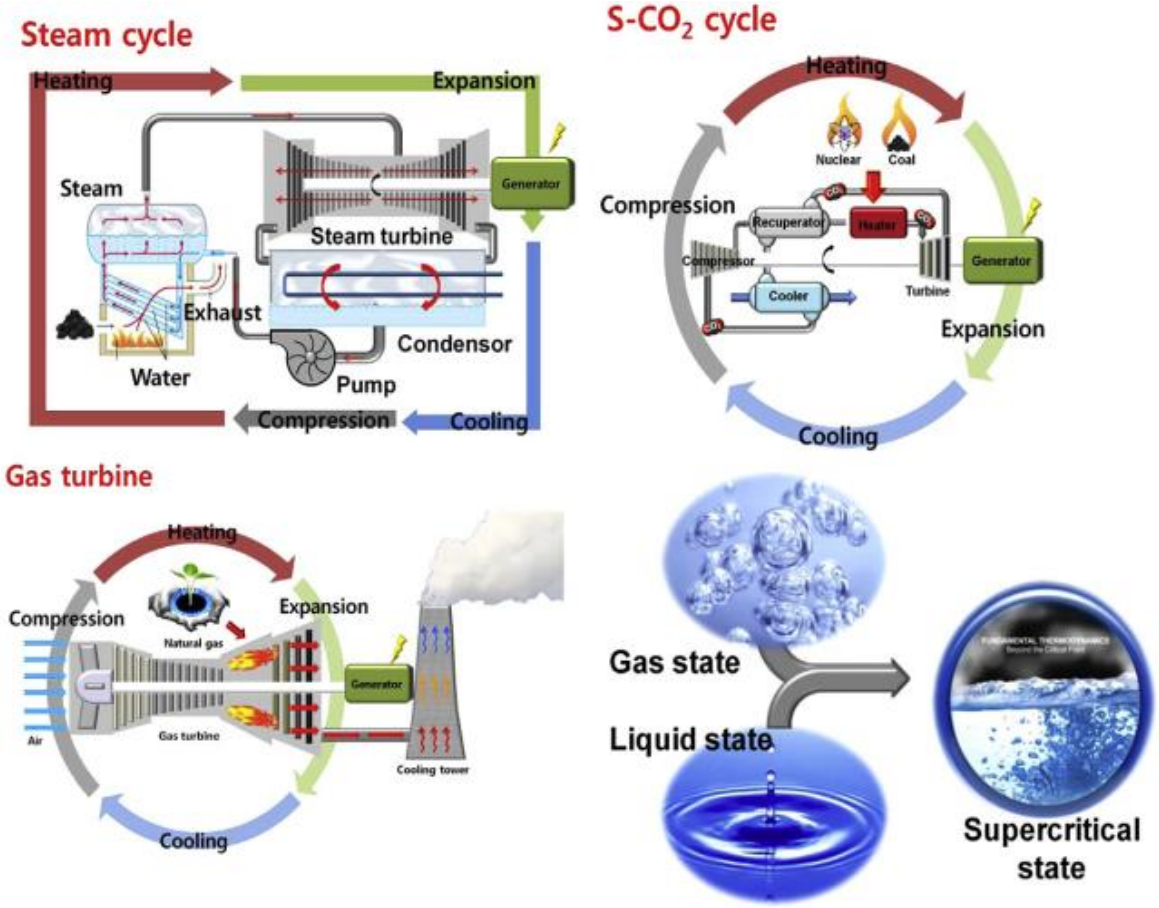


Fig. 2 – Principles of power conversion system. S-CO_2, supercritical CO_2.

- As shown in Fig. 2, the steam Rankine cycle can achieve high efficiency under low turbine inlet temperature conditions because the working fluid is compressed at a liquid state. (liquid water is incompressible and requires less work for compression).
- In contrast, the gas turbine utilizes air, compressible fluid, and a large amount of work is consumed for the compression process. Therefore, the thermal efficiency of gas turbines is not significantly higher than that of a steam Rankine cycle although the turbine inlet temperature is much higher because the compressor requires a large amount of work.
- As schematically shown in Fig. 2, the S-CO2 Brayton cycle is the power conversion system which combines the advantages of both steam Rankine cycle and gas turbine system. In other words, the fluid is compressed in the incompressible region and the higher turbine inlet temperature can be utilized with less material issues compared with the steam Rankine cycle.
- The CO2 critical condition is 30.98 C and 7.38 MPa; the fluid becomes more incompressible near the critical point.

$$Z = \frac{P \cdot M}{\rho \cdot R \cdot T}$$

- The compressibility factor, ***Z***, is defined as the molecular volumetric ratio of a fluid compared with ideal gas. It describes how much the fluid behaves like ideal gas.
- The fluid behaves very close to an ideal gas when this factor is unity and is considered to be an incompressible fluid when it is zero.
- For CO2 near the critical point, the compressibility factor decreases to 0.2-0.5 as shown in Fig. 3, and the compression work can be substantially decreased.

In addition, as S-CO2 is less corrosive compared with steam at the same temperature, the S-CO2 cycle can potentially increase the turbine inlet temperature [1,2].

https://www.youtube.com/watch?v=-gCTKteN5Y4

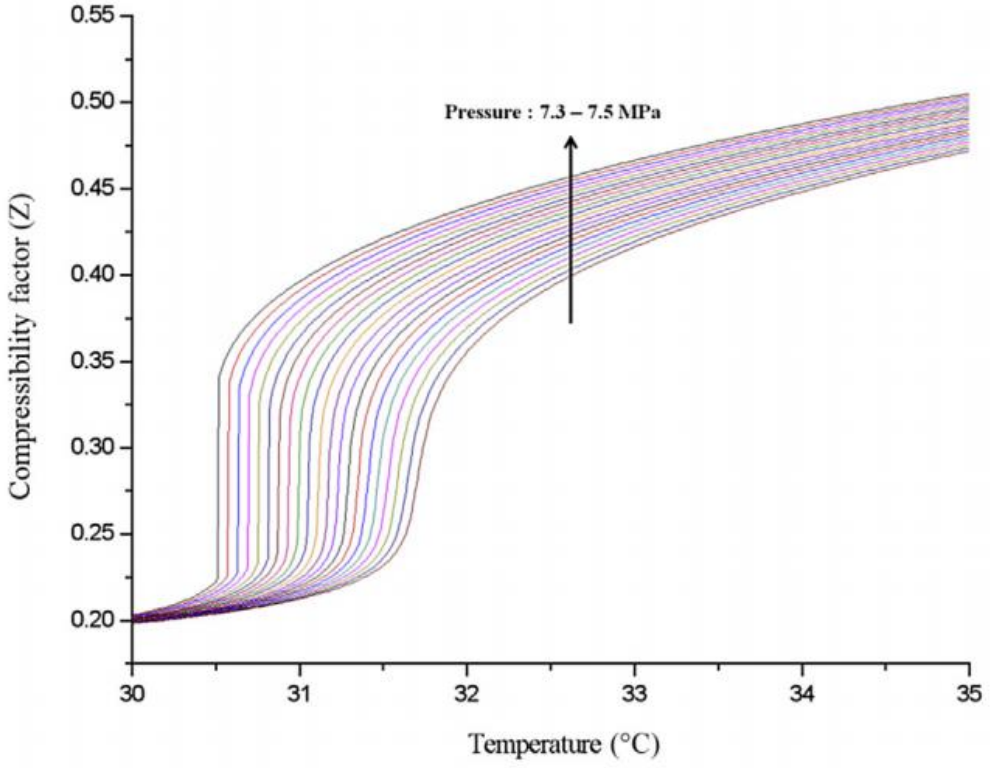


Fig. 3 – CO_2 compressibility factor near the critical point (30.98°C, 7.38 MPa).

- One of the main advantages of the S-CO2 Brayton cycle is its compact turbo machinery.
- As the system operates beyond the critical point, the minimum pressure is higher (~7,400 kPa) than any existing steam Rankine cycle (a few kPa) or gas Brayton cycle (~100 kPa), and thus the fluid remains dense throughout the entire power system.
- Therefore, the volumetric flow rate decreases as the fluid density is higher, resulting in 10 times smaller turbomachinery compared with the turbomachinery of a steam Rankine cycle.
- However, the cycle pressure ratio of the S-CO2 Brayton cycle is much smaller compared with the steam Rankine cycle and the turbine outlet temperature is relatively high.
- Therefore, a large amount of heat must be recuperated to increase the thermal efficiency. In other words, the recuperation process in the S-CO2 Brayton cycle greatly influences the thermal efficiency

- One of the S-CO2 Brayton cycle characteristics is that the specific heat of the cold side flow is two to three times higher than that of the hot side flow in recuperators.

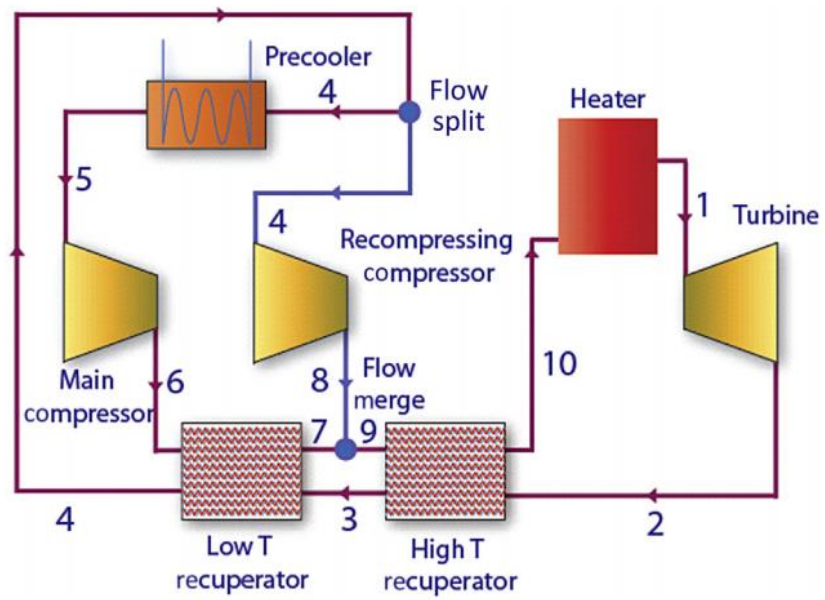


Fig. 4 – S-CO_2 recompressing cycle layout. S-CO_2, supercritical CO_2.

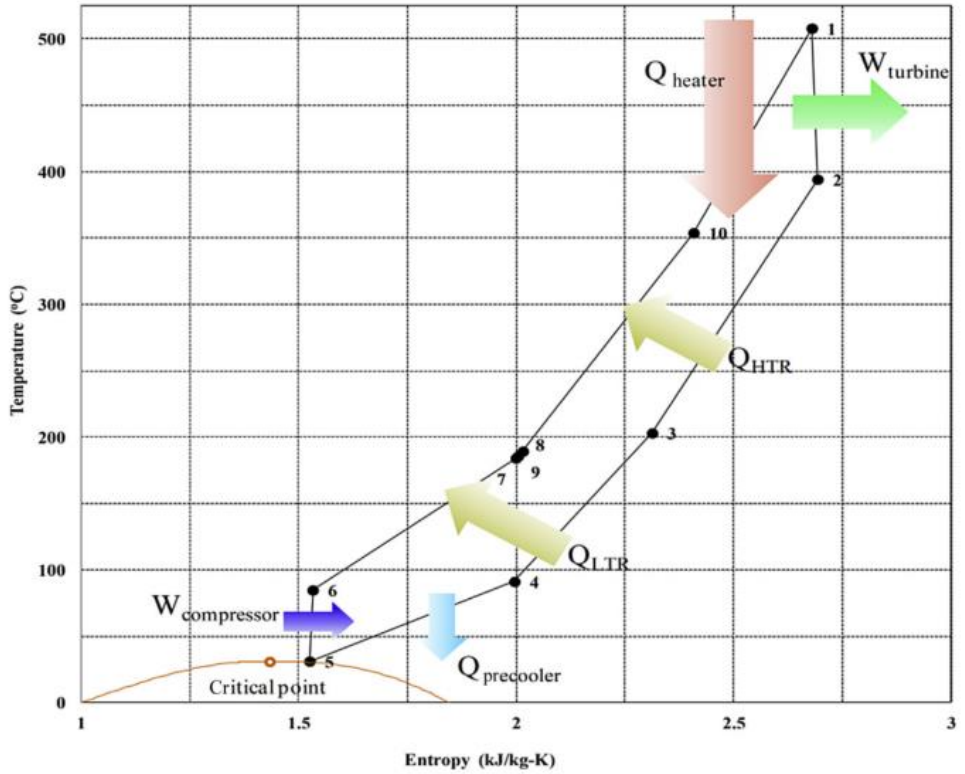
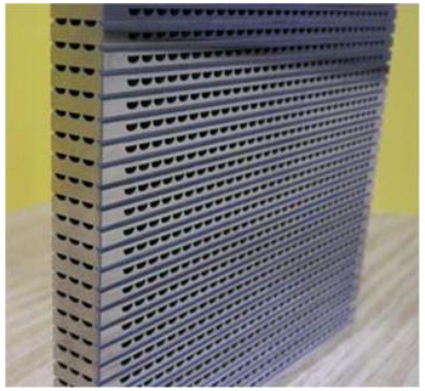


Fig. 5 – T-s diagram of S-CO_2 recompressing cycle. T, temperature; s, entropy; S-CO_2, supercritical CO_2.

It is especially important for the S-CO2 cycle layout design and also explains why the recompressing layout can have high efficiency as shown in Figs. 4 and 5.
The CO2 flow is split to compensate for the specific heat difference in the low temperature recuperator and to maximize the heat recuperation in the recompressing layout. Therefore, the waste heat is reduced and thermal efficiency can be improved.

- The operating condition is important in the S-CO2 heat exchangers. As a large amount of heat is recovered in ***recuperators*** to increase the thermal efficiency, high effectiveness is required and therefore the capital cost increases when conventional Shell and Tube Heat Exchangers (STHE) are utilized.
  - However, various compact heat exchangers with high compactness (up to 10 times compared with STHE), such as a Printed Circuit Heat Exchanger (PCHE), can be applied to the S-CO2 cycle directly.



The benefits of the S-CO2 cycle

(1) The thermal efficiency can be increased up to 5% point compared with the steam Rankine cycle.

(2) The turbomachinery can be much smaller and the overall system size can be reduced up to four times compared with the conventional steam Rankine cycle.

(3) Reduction of water consumption and competitive performance.

(4) Minimum pressure is higher than the CO2 critical pressure (7.38 MPa), the purification system requirements are lower than those of the steam Rankine cycle to prevent air ingress. Thus, the power conversion system can be much simpler.

(5) Among various fluids, CO2 is relatively cheaper and less harmful when an appropriate ventilation system is installed to prepare for a sudden large release of CO2 from the power conversion system.

- **S-CO2 power cycle application**

Many potential advantages exist for the S-CO2 power cycle and it can be applied to various heat sources. For instance, since the S-CO2 cycle can be considered as an alternative to the steam Rankine cycle, it can be applied to nuclear energy reactors.

Other than nuclear energy applications, the S-CO2 power cycle can be utilized as a topping cycle for **fossil fuel powered plants** and a bottoming cycle of **gas combined cycle plants.** There are also promising heat sources soon to be developed, which include several renewable energy sources such as **high temperature fuel cells, concentrated solar power, and geothermal power**.

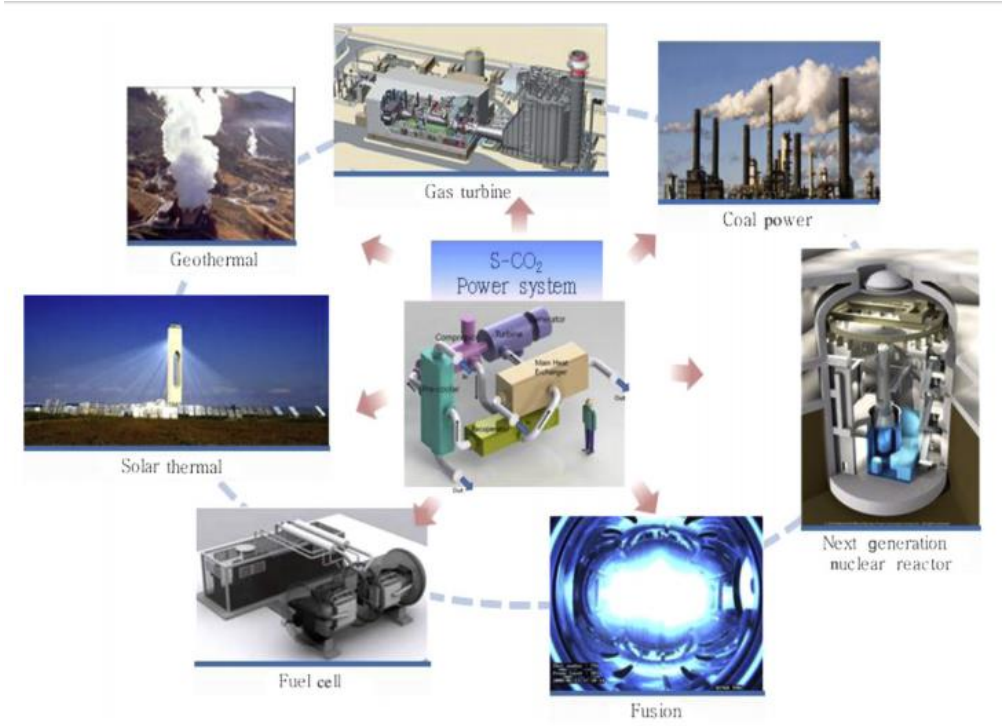


Fig. 7 – The potential application of S-CO_2 cycle. S-CO_2, supercritical CO_2.

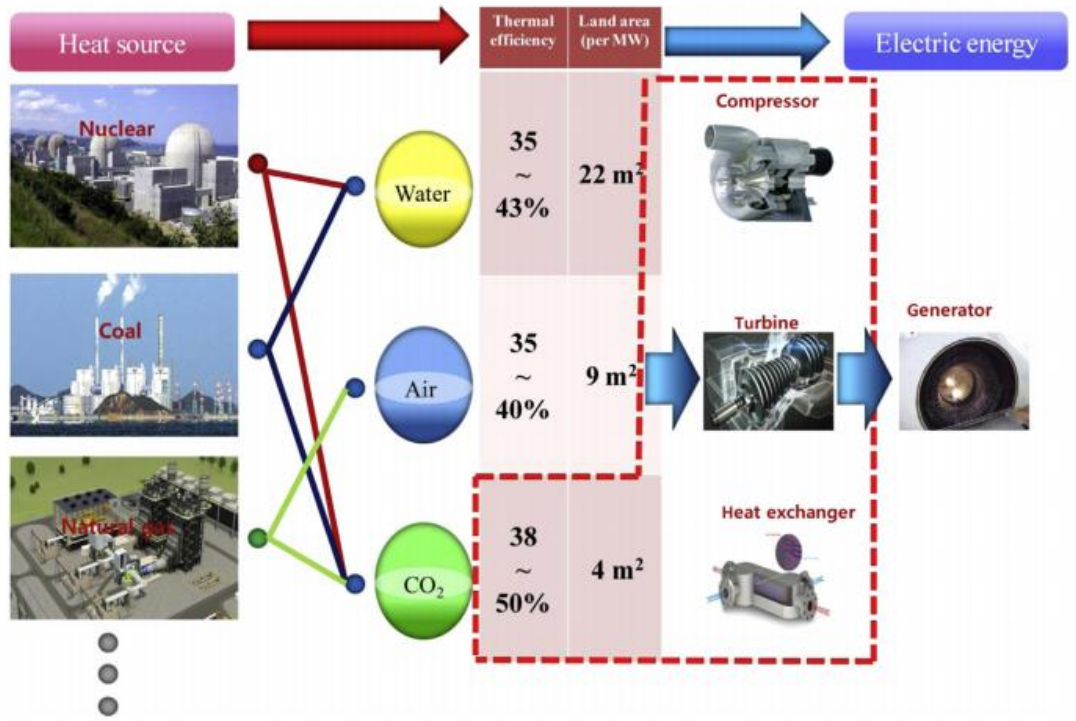


Fig. 6 – The comparison of steam, air, S-CO_2 power conversion systems [11,12]. S-CO_2, supercritical CO_2.

The CO2 flow can be separated depending on the application. Therefore, the cycle can be categorized depending on whether the flow is split or not.

Single (non-split) flow layouts are composed of *intercooling*, *reheating*, *precompression*, *interrecuperation*, *and split expansion* cycles as shown in Fig. 8.

The intercooling and reheating layouts are adopted to minimize or maximize the compression or expansion work, respectively.

One of the major characteristics of the S-CO2 cycle is its low pressure ratio because the limit of minimum pressure in the system is influenced by the critical pressure (7.38 MPa), which is relatively high compared with the steam Rankine cycle (~0.07 MPa) or air Brayton cycle (~0.1 MPa).

As the exhaust CO2 temperature in the turbine is still high due to the low cycle pressure ratio, the heat can be recuperated in several ways.

In the single flow layouts, the interrecuperation, precompression, and split expansion layouts are suggested depending on the position where the recuperation process occurs.

- **S-CO2 cycle layout classification**

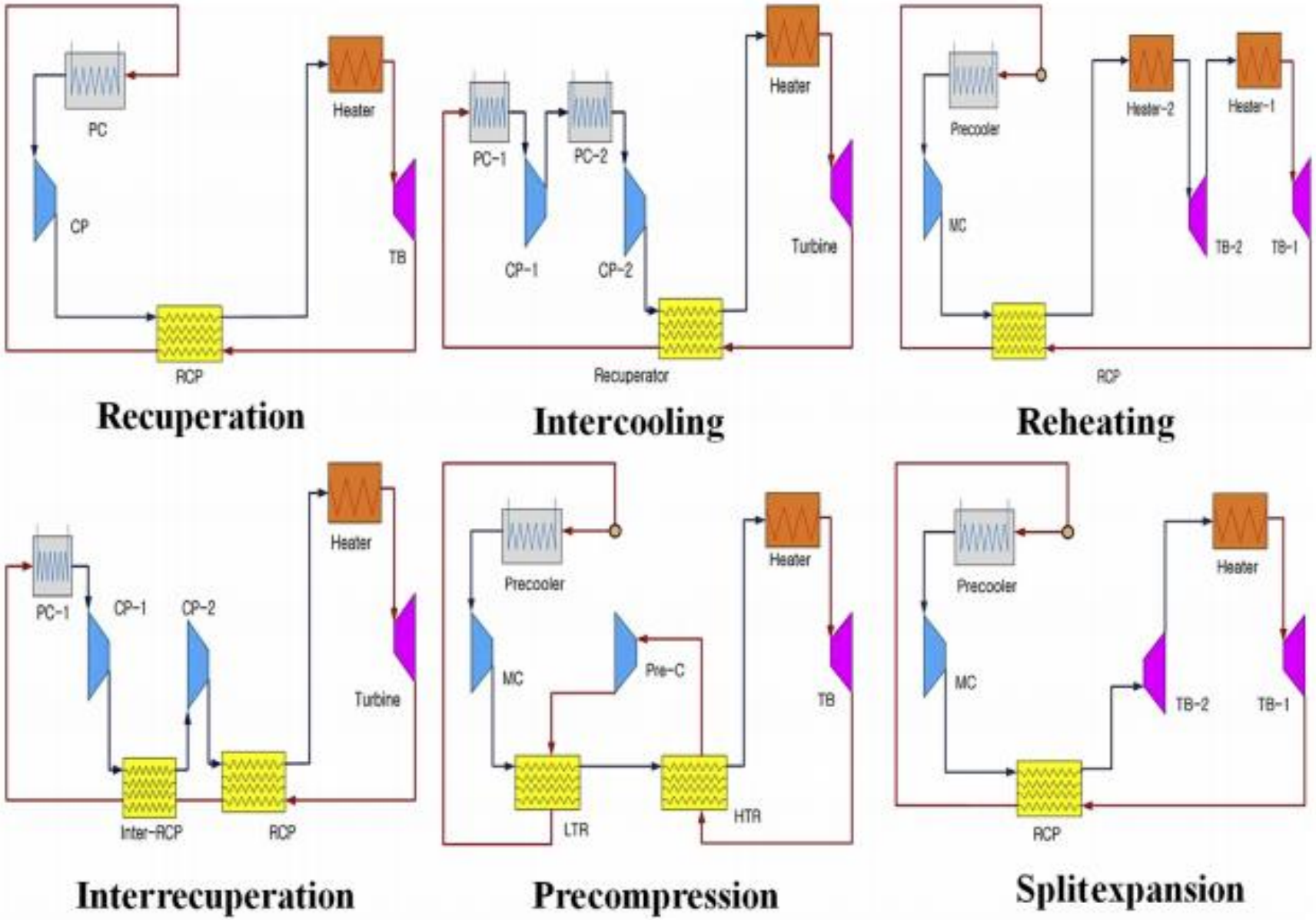


Fig. 8 — S-CO_2 cycle single flow layouts. S-CO_2, supercritical CO_2.

The split flow layouts are composed of recompression, modified recompression, preheating, and turbine split flow 1, 2, and 3 as shown in Fig. 9.

The difference between the recompression layout and the others is the recuperation process.

In the recompression layout, the flow is split and high specific heat in the cold side flow is matched with the hot side large flow with lower specific heat in the low temperature recuperator (LTR) to maximize the cycle efficiency. In the

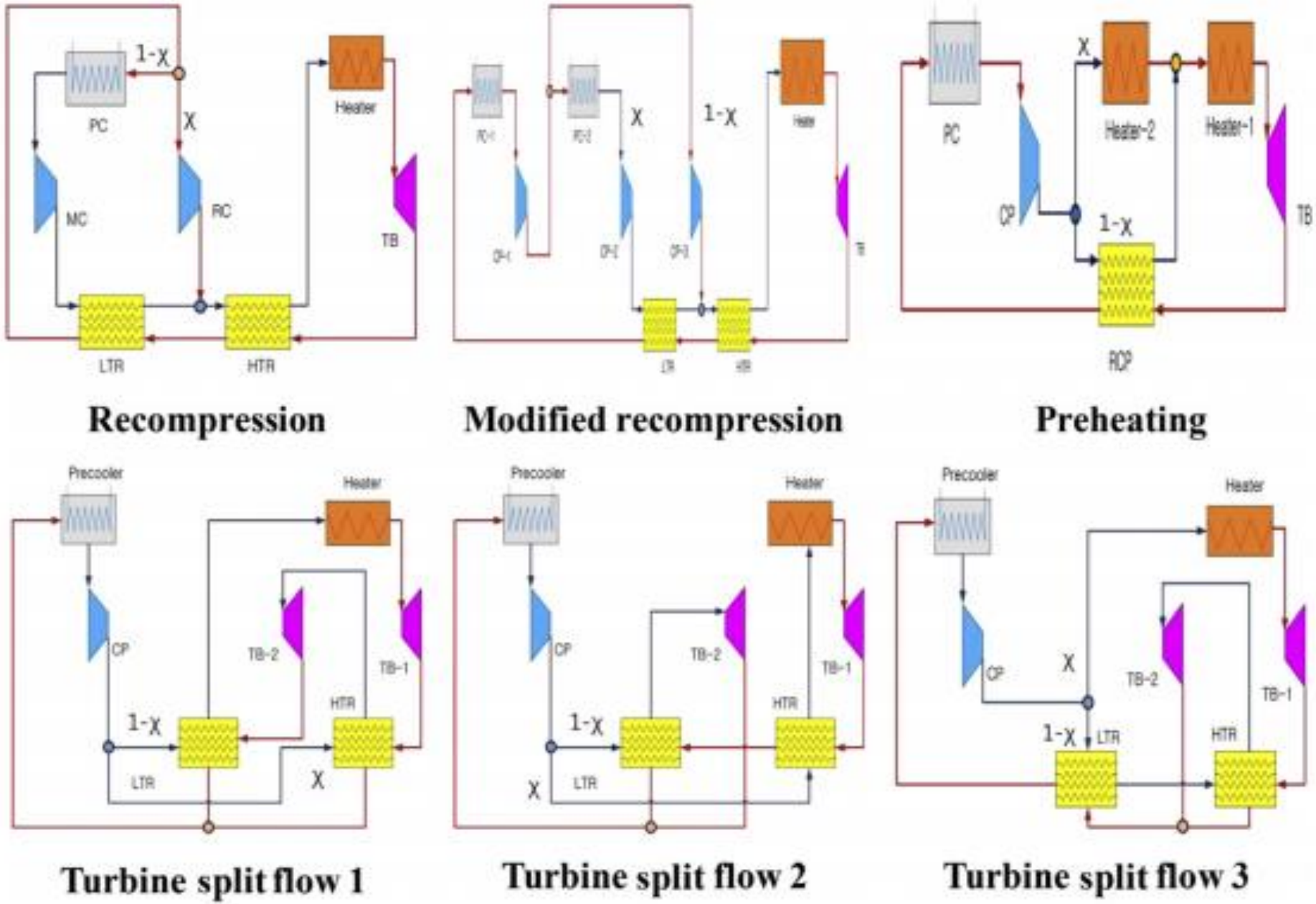


Fig. 9 – S-CO_2 cycle split flow layouts. S-CO_2, supercritical CO_2.

Table 2 – S-CO_2 single flow layout design conditions.

Layout	Recuperation	Intercooling	Reheating	Interrecuperation	Precompression	Split-expansion
Turbine inlet temperature (°C)	500					
IHX inlet temperature (°C)	275.9	249.7	334.5	314.6	281.1	270.0
CO_2 mass flow rate (kg/sec)	354.4	315.5	339.0	430.7	363.1	364.2
Compressor inlet temperature (°C)	32					
Compressor inlet & outlet pressure (MPa)	7.5/25				6.16/7.5 7.5/25	7.5/25
Turbine & compressor isentropic efficiency (%)	92/88					
HT/LT recuperator effectiveness (%)	95/95					

HT, high temperature; LT, low temperature; IHX, intermediate heat exchanger; S-CO_2, supercritical CO_2.

Table 3 – S-CO_2 split flow layout design conditions.

Layout	Recompression	Modified recompression	Preheating	Turbine split flow 1	Turbine split flow 2	Turbine split flow 3
Turbine inlet temperature (°C)		500				
IHX inlet temperature (°C)	335.5	283.3	98.7	150.4	275.9	98.7
CO_2 mass flow rate (kg/sec)	486.1	367.1	262.6	377.1	708.9	383.0
Compressor inlet temperature (°C)	32					
Compressor inlet & outlet pressure (MPa)	7.5/25	5.0/7.5 7.5/25	7.5/25			
Turbine & compressor isentropic efficiency (%)	92/88					
HT/LT recuperator effectiveness (%)	95/95					
Flow split ratio (m_H/m_T)	0.31	0.4	0.5	0.43	0.5	0.46

HT, high temperature; LT, low temperature; IHX, intermediate heat exchanger; S-CO_2, supercritical CO_2.

Performance comparison of S-CO2 cycle layouts

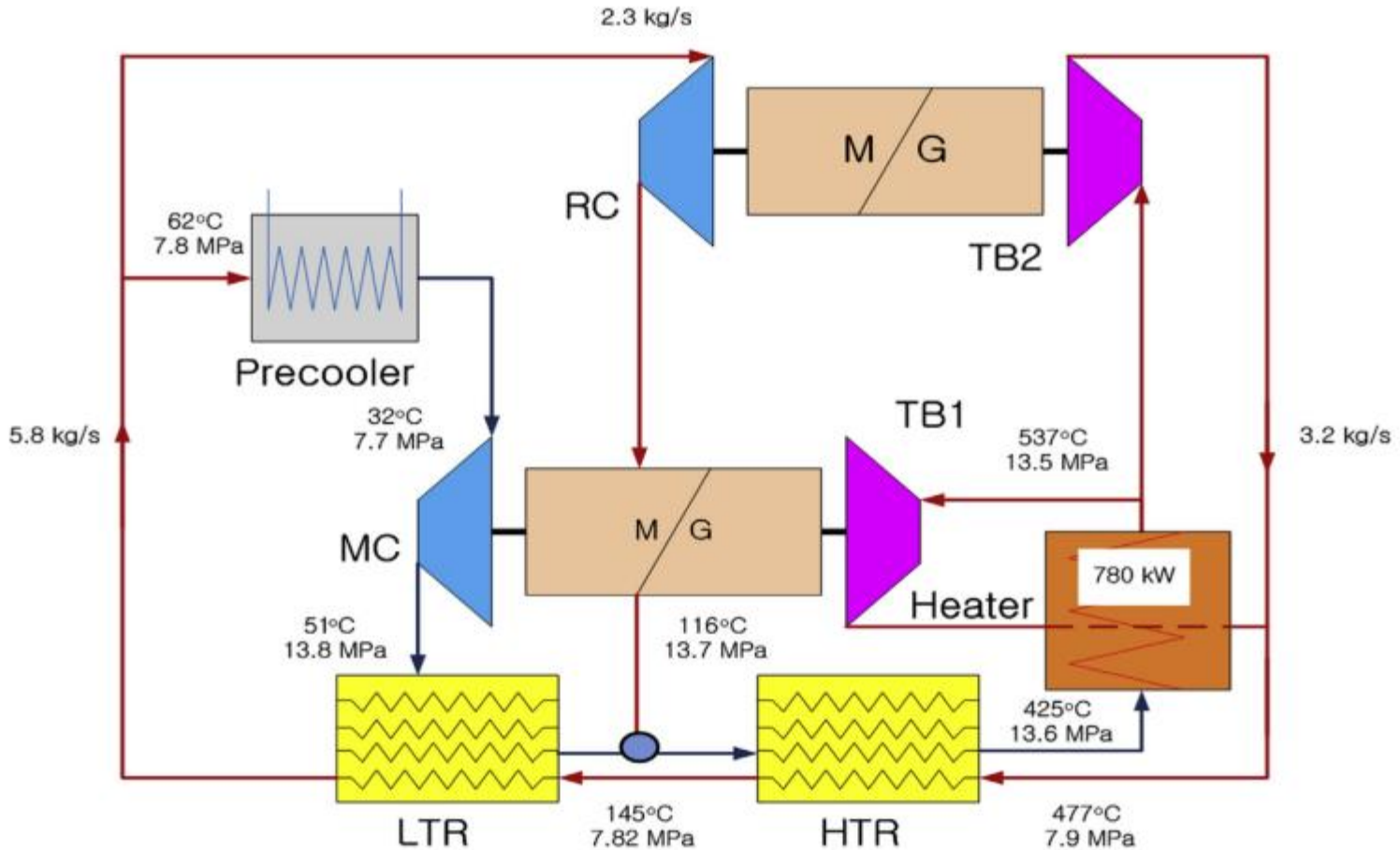


Fig. 12 – The layout of SNL experiment loop. HTR, high temperature recuperator; LTR, low temperature recuperator; M/G, motor generator alternator; MC, main compressor; RC, recompression compressor; SNL, Sandia National Laboratory; TB,

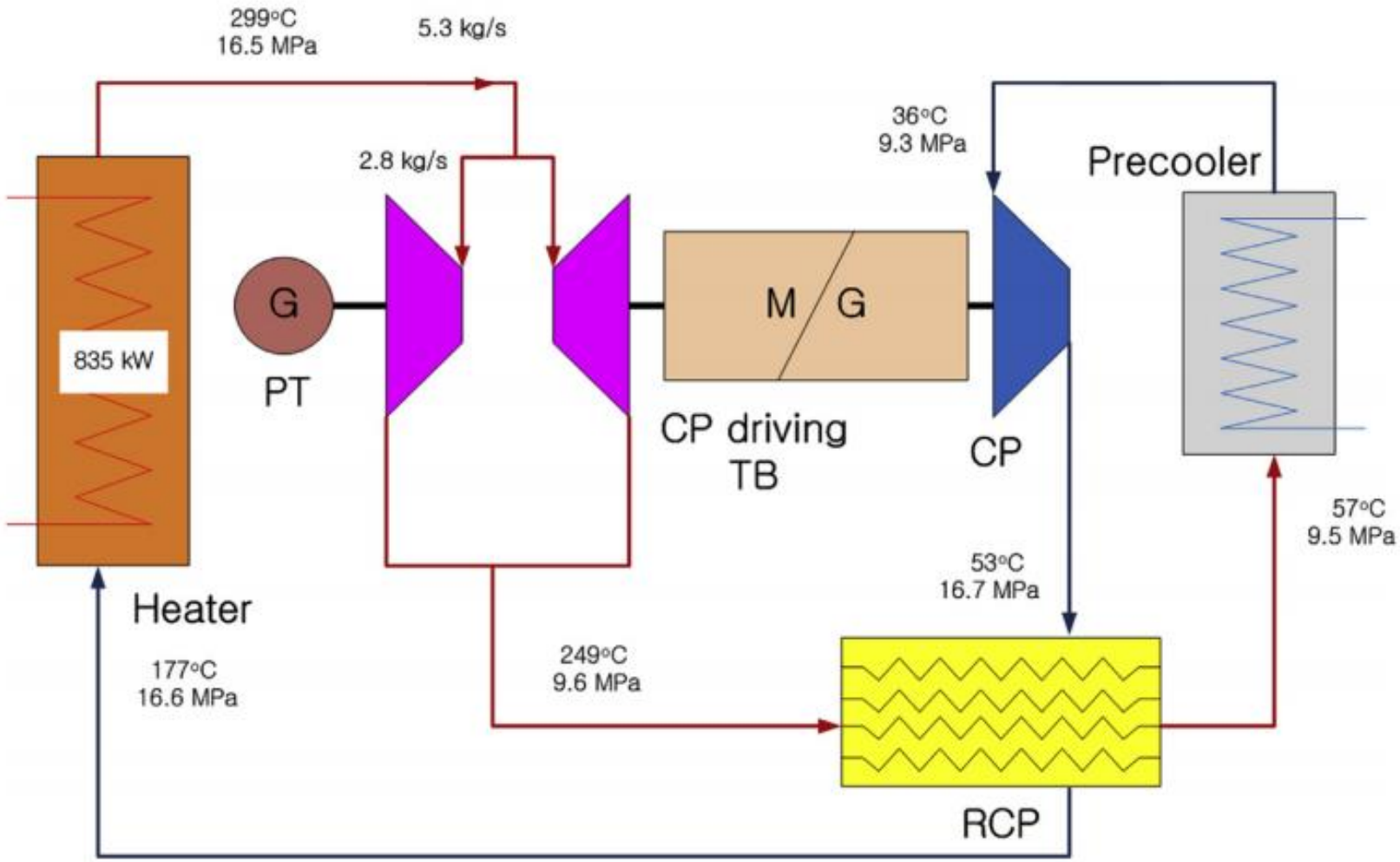


Fig. 13 – The layout of KAPL experiment loop. CP, compressor; G, generator; KAPL, Knolls Atomic Power Laboratory; M/G, motor generator alternator; RCP, recuperator; TB, turbine [41].

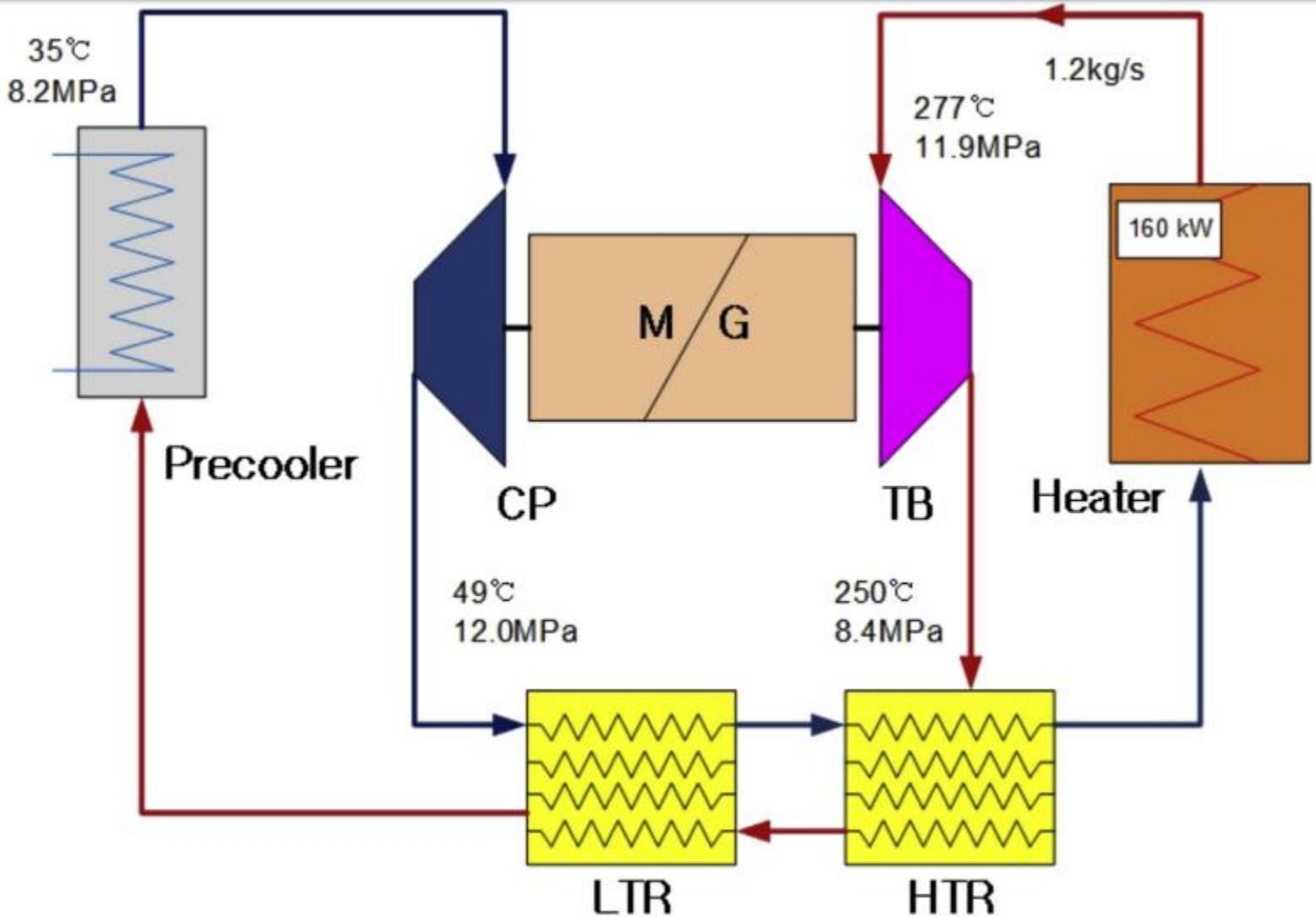


Fig. 14 – The layout of IAE experiment loop. CP, compressor; HTR, high temperature recuperator; IAE, Institute of Applied Energy; LTR, low temperature recuperator; M/G, motor generator alternator; TB, turbine [42].

Table 4 – The design comparison of existing S-CO_2 integral system loops.

	Sandia National Lab (US)	Knolls Atomic Power Lab (US)	Institute of Applied Energy (Japan)
Turbomachinery type	2-TAC	1-TAC, 1-turbine	1-TAC (2-recuperaters)
Cycle layout	Recompressing	Simple recuperated	Simple recuperated
Heat (kW)	780	834.9	160
Efficiency (%)	31.5	14.7	7
Mass flow rate (kg/sec)	3.5 (target) 2.7 (achieved)	5.35 (target) 3.54 (achieved)	1.4 (achieved)
T.I.T (°C)	537 (target) 342 (achieved)	300 (target)	277 (achieved)
Pressure ratio	1.8 (target) 1.65 (achieved)	1.8 (target) 1.44 (achieved)	1.4 (achieved)
Rotating speed (×1,000 rpm)	75 (target) 52 (achieved)	75 (target) 55-60 (achieved)	69 (achieved)
Turbine efficiency (%)	86 (turbine 1) 87 (turbine 2)	79.8 (power turbine) 79.7 (compressor driving turbine)	65

S-CO_2, supercritical CO_2.

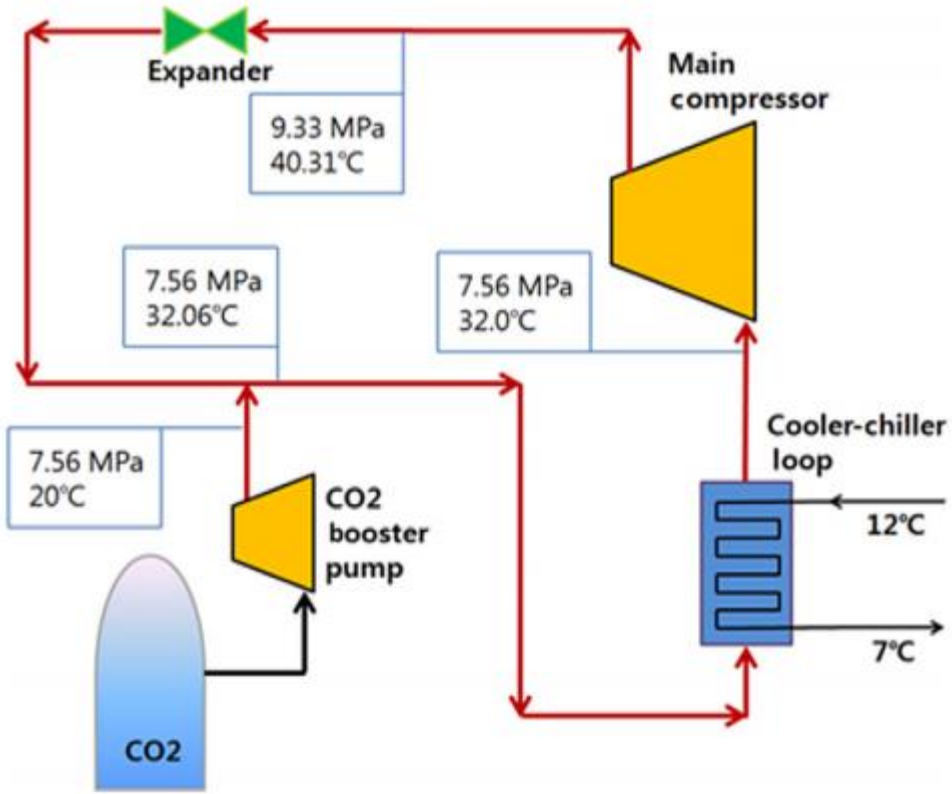
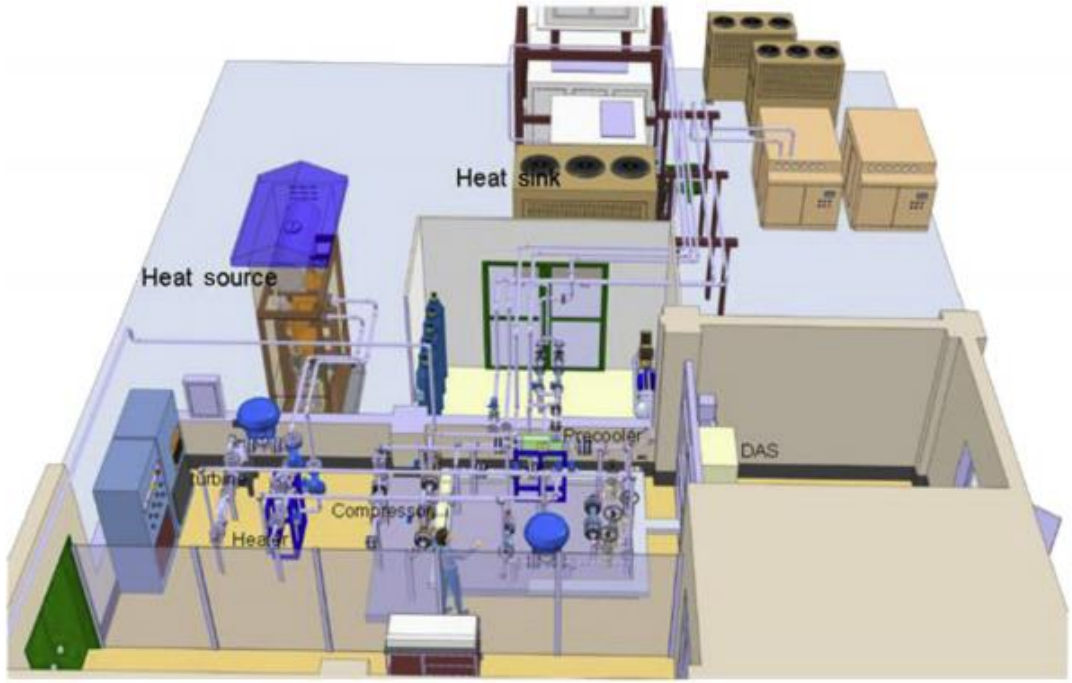


Fig. 15 – The layout of S-CO_2 pressurizing experiment (SCO_2PE). S-CO_2, supercritical CO_2.



Fig. 16 – S-CO_2 pressurizing experiment (SCO_2PE). S-CO_2, supercritical CO_2.



ig. 18 – S-CO_2 integral experiment loop (SCIEL). DAS, data acquisition system; S-CO_2, supercritical CO_2.

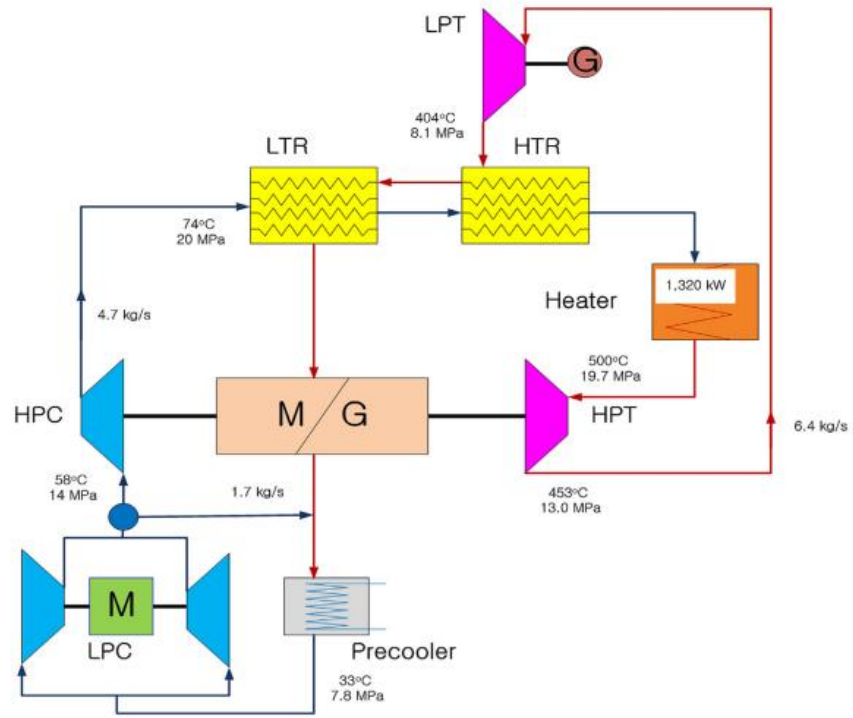


Fig. 17 – The layout of S-CO_2 integral experiment loop (SCIEL). HPC, high pressure compressor; HPT, high pressure turbine; HTR, high temperature recuperator, LPC, low pressure compressor; LPT, low pressure turnine; LTR, low temperature recuperator; M/G, motor generator alternator; S-CO_2, supercritical CO_2.

3. Supercritical CO2 Rankine cycle

A basic supercritical CO2 Rankine cycle consists of gas heater, expansion turbine, condenser and pump (Fig. 5). The P–V and T–S diagrams are shown in Fig. 3. The theoretical research outcomes on basic cycle are presented in this section.

Energy analysis

The aim of energy analysis is assessment of cycle or system performances based on first law of thermodynamic, which may includes heat transfer and fluid flow. The following general assumptions have been made for most the analyses of supercritical CO2 Rankine cycle: (i) each component is considered as a steadyflow system; (ii) the kinetic and potential energies as well as the heat and friction losses ar neglected; (iii) the pump and the turbine isentropic efficiencies are taken constant; and (iv) saturated liquid is supposed at the condenser exit. The pump and turbine work transfer rates are respectively given by

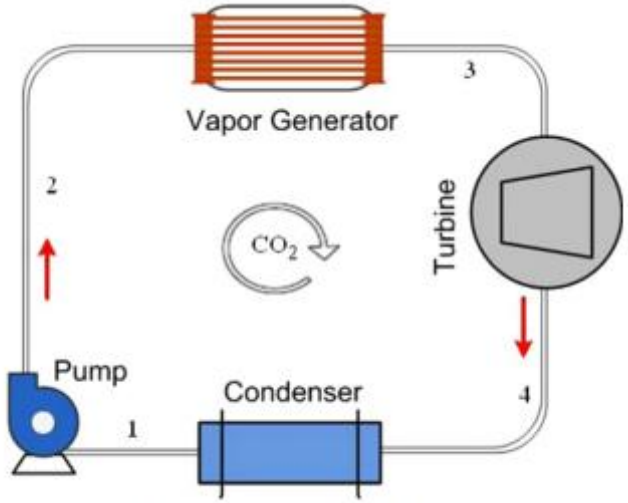


Fig. 5. Layout of supercritical CO_2 Rankine cycle.

$$\dot{W}_p = \dot{m}(h_2 - h_1) \quad (1)$$

$$\dot{W}_t = \dot{m}(h_3 - h_4) \quad (2)$$

The heat input and heat rejection rates are respectively given by

$$\dot{Q}_h = \dot{m}(h_3 - h_2) \quad (3)$$

$$\dot{Q}_c = \dot{m}(h_4 - h_1) \quad (4)$$

According to the first law of thermodynamics, the net power output is given by

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_p = \dot{Q}_h - \dot{Q}_c \quad (5)$$

The net specific power output (net power output per unit mass flow rate) has been also taken as performance parameter in some studies. In case of solar collector as gas generator, the heat input to the cycle can be found by multiplying solar collector area, solar intensity and collector efficiency, which depends on collector type, material and fluid, design and operating conditions. For other type of heat sources, the heat input can be found by multiplying heat capacity rate and temperature drop of heating fluid. Finally, the thermal efficiency is given by

$$\eta_{th} = \dot{W}_{net} / \dot{Q}_h$$

Turbine volumetric expansion ratio was used to measure of turbine size [74], which is specific volume ratio of turbine outlet to inlet. Recovery efficiency also can be used as performance parameter, which is defined as the ratio of net power output to the available thermal power from the heat source [74].

$$\eta_{rev} = 1 - \frac{2T_l}{T_h + T_l}.$$

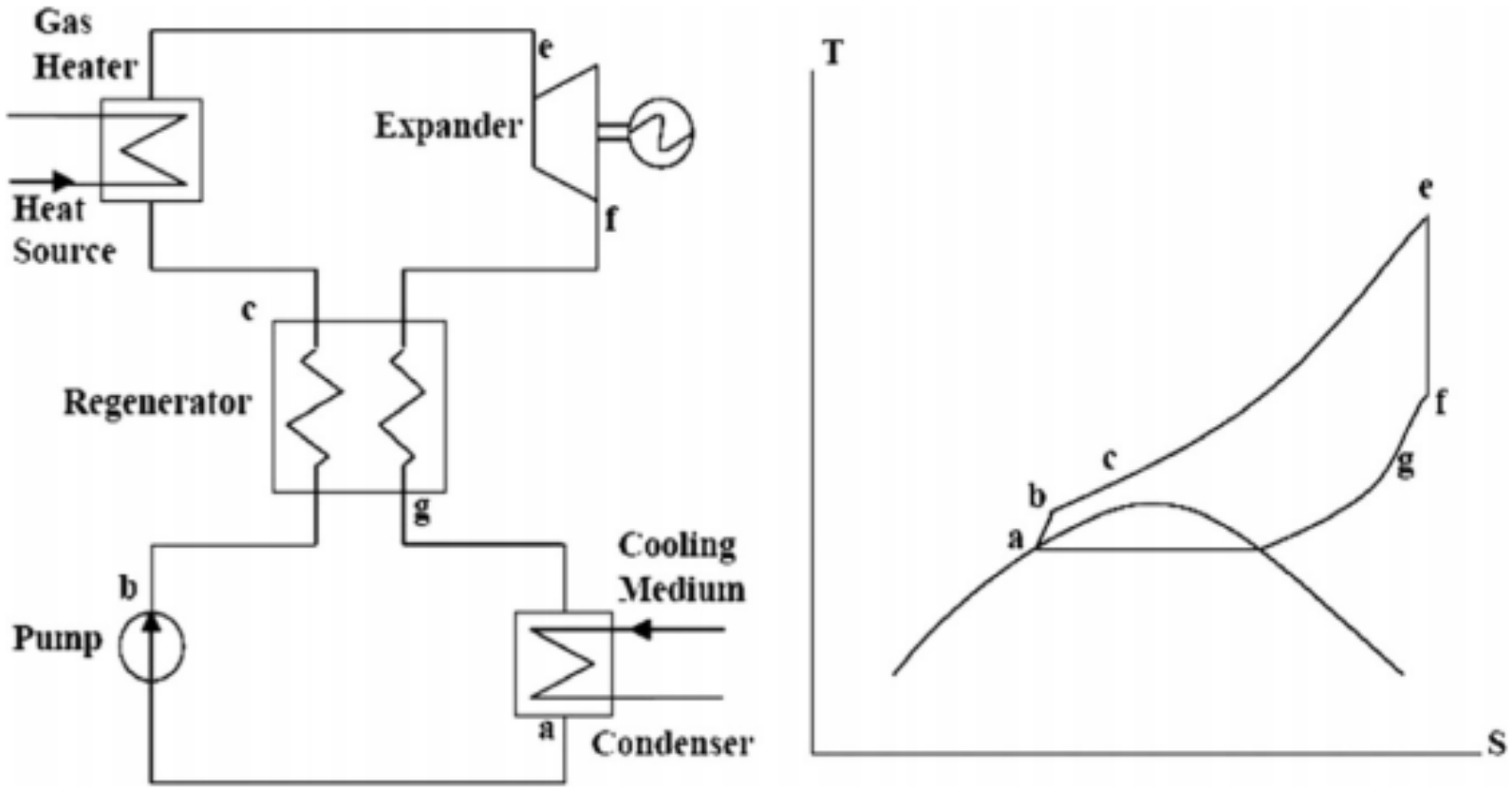


Fig. 7. Supercritical CO_2 Rankine cycle with internal heat exchanger.

CO2 Rankine cycle with cogeneration of heat and power

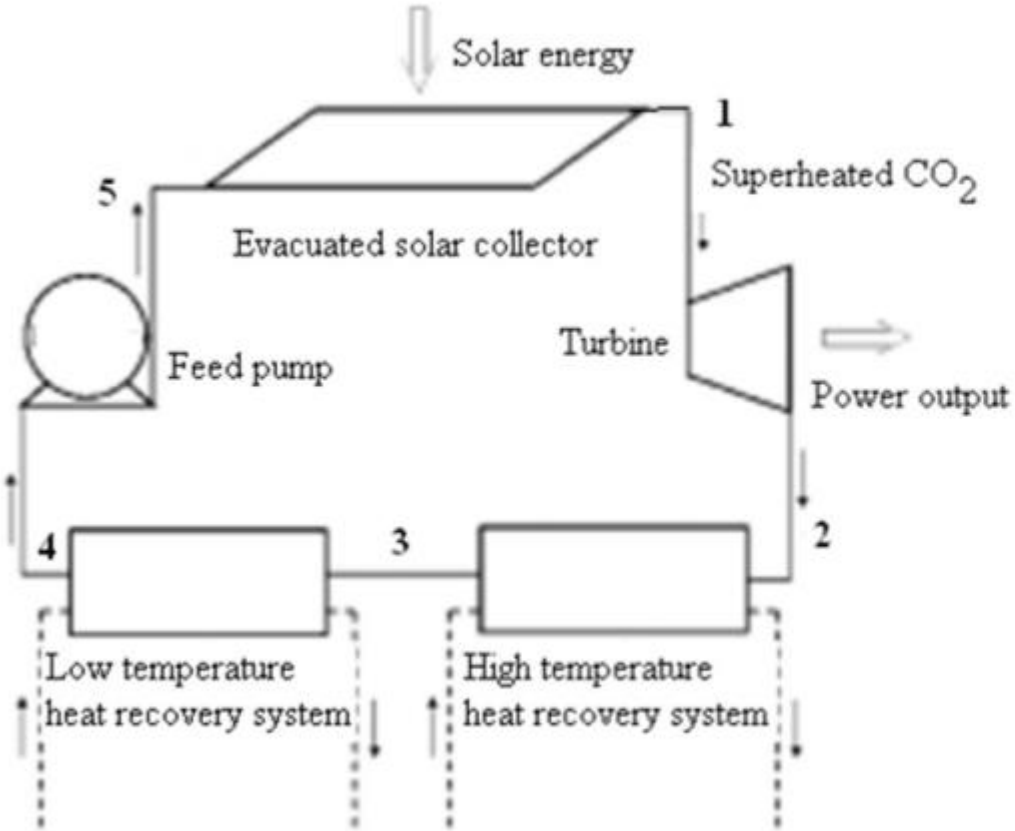


Fig. 8. Supercritical CO_2 Rankine cycle for cogeneration of power and heat.

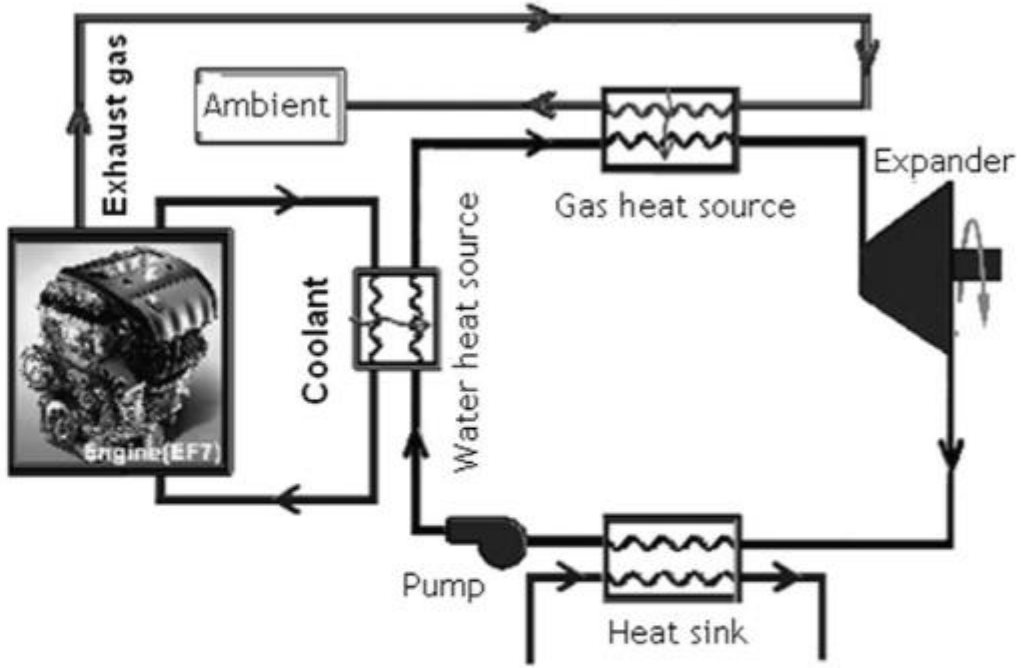


Fig. 9. Supercritical CO_2 Rankine cycle with multiple heat sources.