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Dependence of Thermal Efficiency on Receiver Temperature of Solar Thermal Power Systems Combined with Supercritical CO_2 Gas Turbine Cycle and Brayton CO_2 Gas Turbine Cycle

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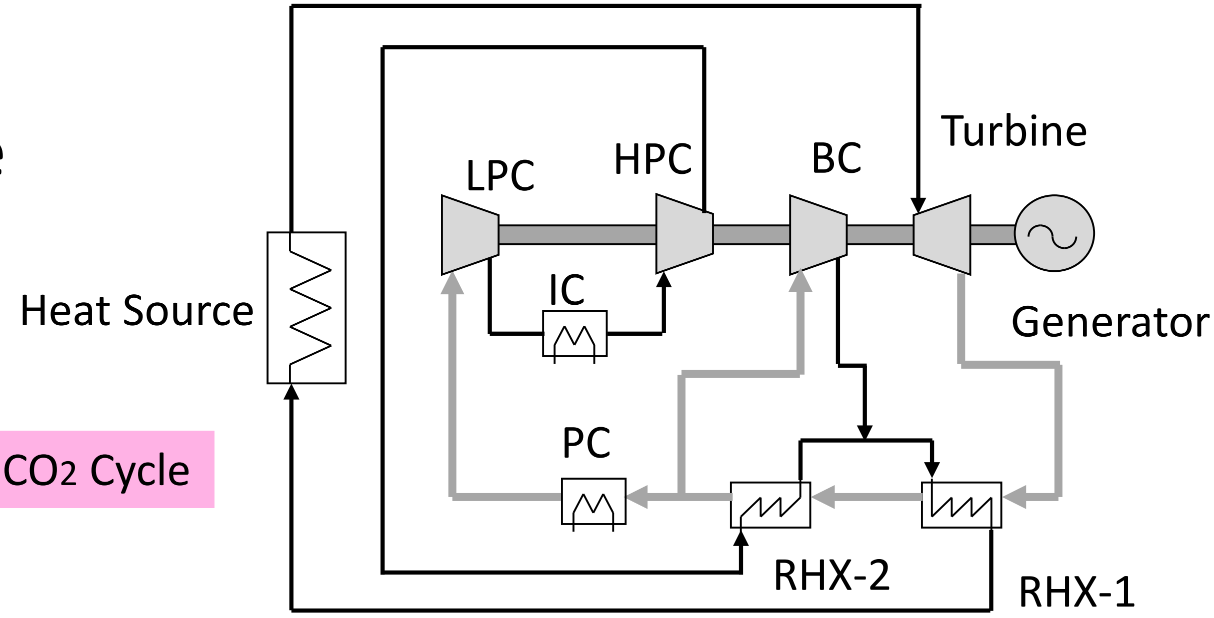
Contents

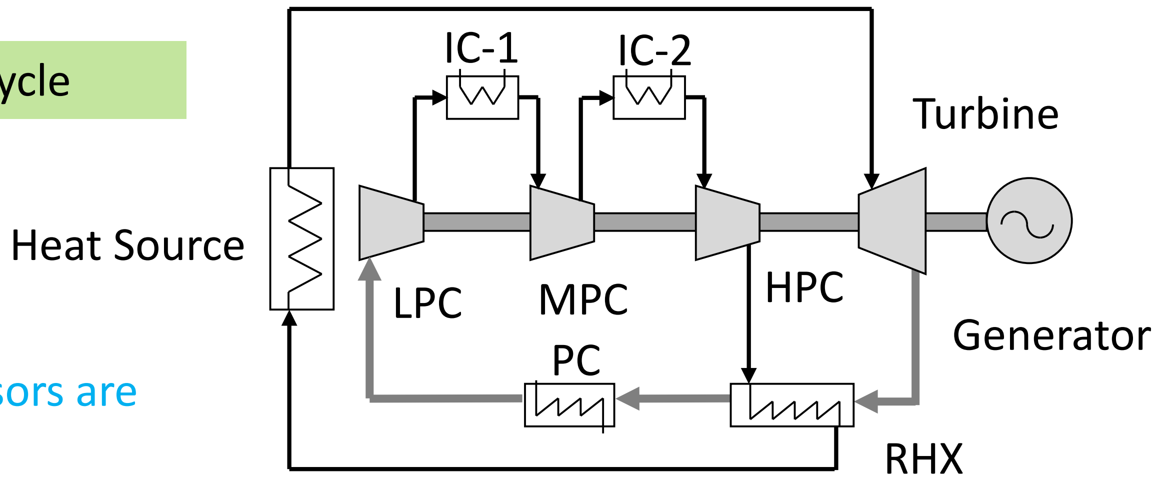
- The supercritical CO_2 Gas turbines are applied to the new solar thermal power generation system provided with a Na cooled tower receiver and an Al heat storage heat exchanger.
- Two supercritical CO_2 cycle schemes called “supercritical CO_2 cycle and “Brayton CO_2 cycle” are examined, in particular, effects of the receiver inlet temperature on the thermal efficiency.
- The receiver efficiency, the Na-Al-CO_2 heat exchanger characteristics, the cycle thermal efficiency and the thermal efficiency of the total system were examined.
- Recuperator size was examined.

Two CO_2 Gas Turbine Cycles

Supercritical CO_2 Cycle



Brayton CO_2 Cycle



Three compressors are provided.

New Solar Thermal Power Generation with a CO_2 Gas Turbine

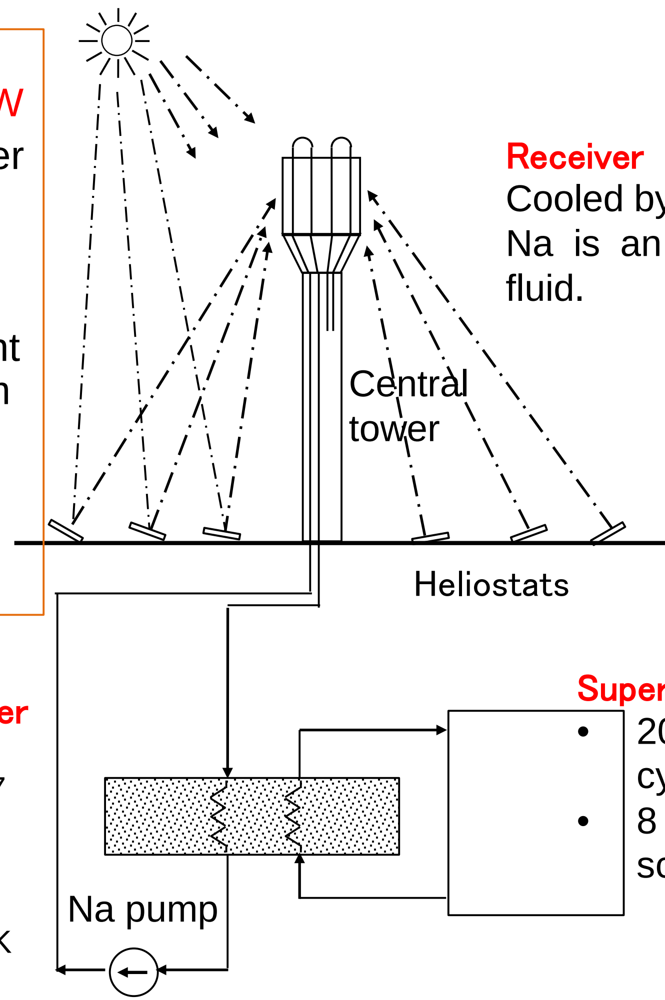
Incident Sunbeam
Thermal Energy = 125 MW

- Heliostat field diameter 800m
- Number of heliostats (φ3.4m) 42,519
- Central receiver height from the ground 100m

Due to the reference (Hasuike)

Receiver
Cooled by Na
Na is an excellent heat transfer fluid.

- Thermal conductivity 70 W/m/K
- Thermal conductivity of molten salt 0.6 W/m/K
- Specific heat 1.3 kJ/kg.K



Na–Al–CO2 Heat Exchanger
Aluminum

- Thermal conductivity 237 W/m/K
- Melting point 660℃
- Heat of fusion 397 kJ/kg
- Specific heat 0.897 kJ/kg.K

Supercritical CO_2 Gas Turbine

- 20 MPa supercritical CO_2 cycle scheme
- 8 MPa Brayton CO_2 cycle scheme

Receiver

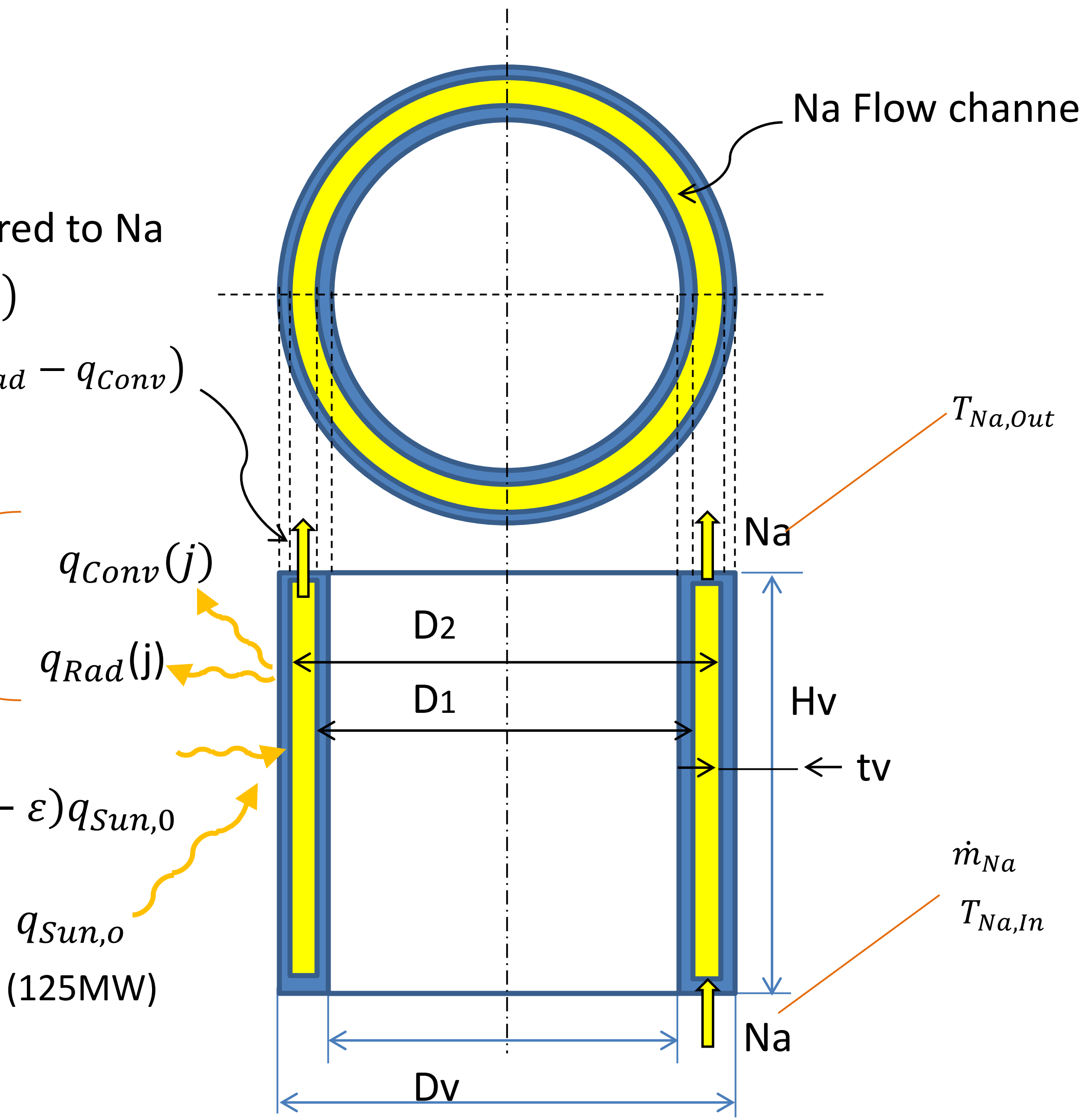
Thermal Energy transferred to Na

$$\dot{m}C_P\left(T_{Na,Out} - T_{Na,In}\right)$$
$$= \pi D_2 H_V\left(q_{Sun,In} - q_{Rad} - q_{Conv}\right)$$

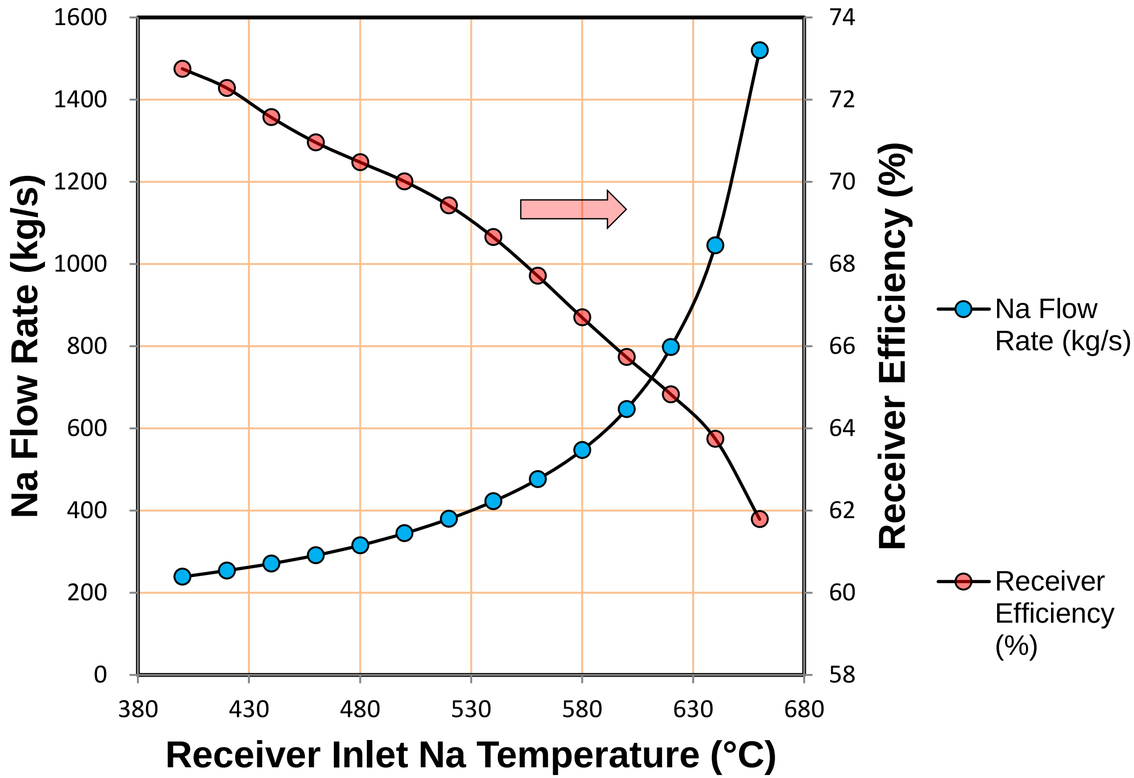
Thermal Energy Loss

Dependent on not only the outlet temperature but also the inlet temperature

$$q_{Sun,In} = (1-\varepsilon)q_{Sun,0}$$



Receiver Characteristics

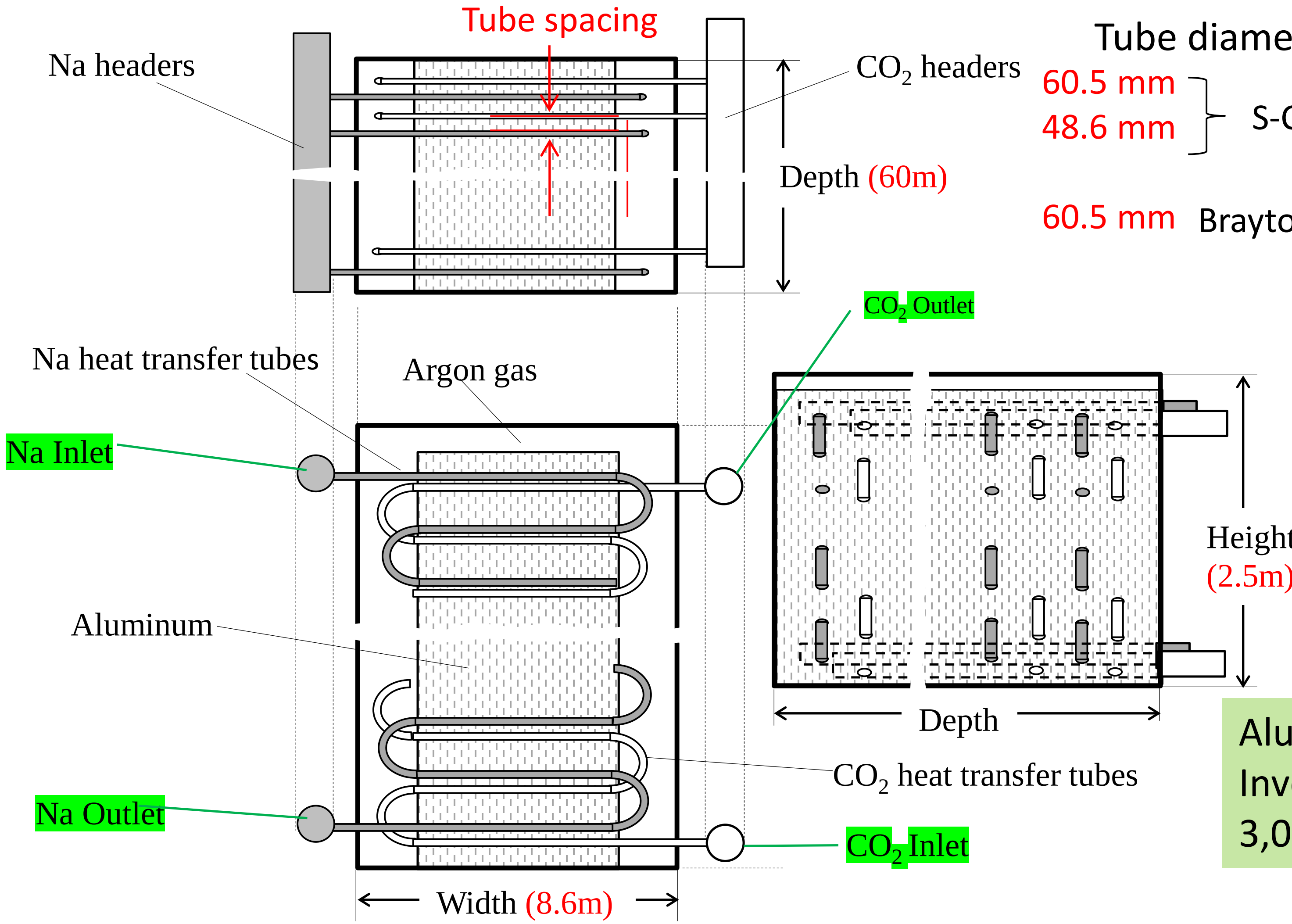


<u>Assumptions</u>

- Na outlet temperature = 700℃
- Maximum shell temperature = 780℃
- Shell design temperature = 800℃
- Material = Alloy 800H (σa = 14.9 MPa)
- Na inlet pressure = 0.13 MPa
- Na pressure drop = Less than 0.02 MPa

250℃ increase of Na inlet temperature results in the receiver efficiency reduction of 10%.

Na-Al-CO2 Heat Exchanger



Tube diameter:

60.5 mm, 48.6 mm — S-CO2 Cycle

60.5 mm — Brayton CO2 Cycle

Aluminum Inventory 3,000 ton

The values of tube spacing at the design point are 209 mm, 254 mm and 326 mm for the S-CO2 cycle (60.5 mm), S-CO2 cycle (48.6 mm) and the Brayton cycle, respectively.

Assumptions in the HX Analyses

- Steady state
- One dimensional heat transfer
- The flow of Na and CO_2 is counter flow
- Al melting behavior is not considered explicitly. Instead, the energy storage is considered by separating the energy of ratio (β) from the energy transferred from Na to CO_2.
- The value of β is 30%, which coincides with the power demand at night. This determines Al inventory and then the HX dimensions.
- Temperatures of the CO_2 cycles are determined so as to achieve the maximum cycle thermal efficiency.
- The values of tube spacing between Na tubes and CO_2 tubes are adjusted to the heat load.

β = 30% and Aluminum Inventory

- Total solar thermal energy
- =125MW × about 65% × 12hr = 3.5 × 10^6 MJ
- Demand

Daytime	6:00-18:00	100% × 12hr	= 12hr
Night	18:00-20:00	100% × 2hr = 2hr	
	20:00-24:00	60% × 4hr = 2.4hr	= 5hr
	24:00 - 6:00	10% × 6hr = 0.6hr	

- Heat storage needed

5/17 = 30%

3.51 × 10^6 MJ × 0.3 = 1.053 × 10^6 MJ

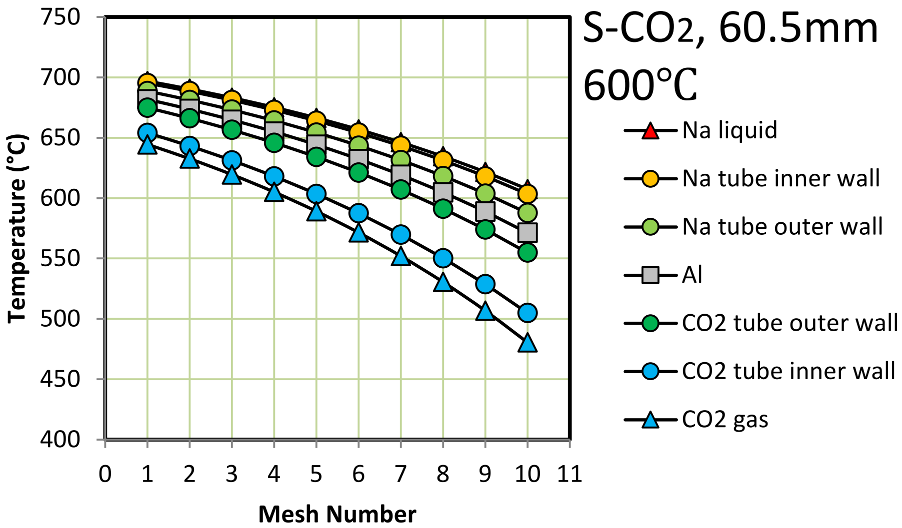
- Heat storage capacity

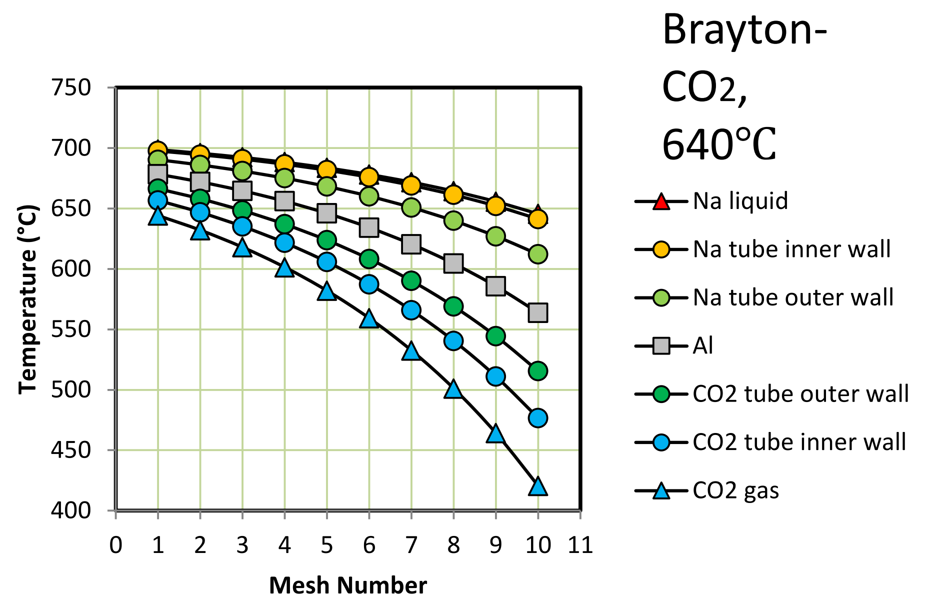
Latent heat	0.397 MJ/kg × 30% = 0.119MJ/kg
Sensible heat	0.897 × 10^{-3} MJ/K × 250K = 0.224 MJ/kg
Total	0.119 MJ/kg + 0.224 MJ/kg = 0.343 MJ/kg

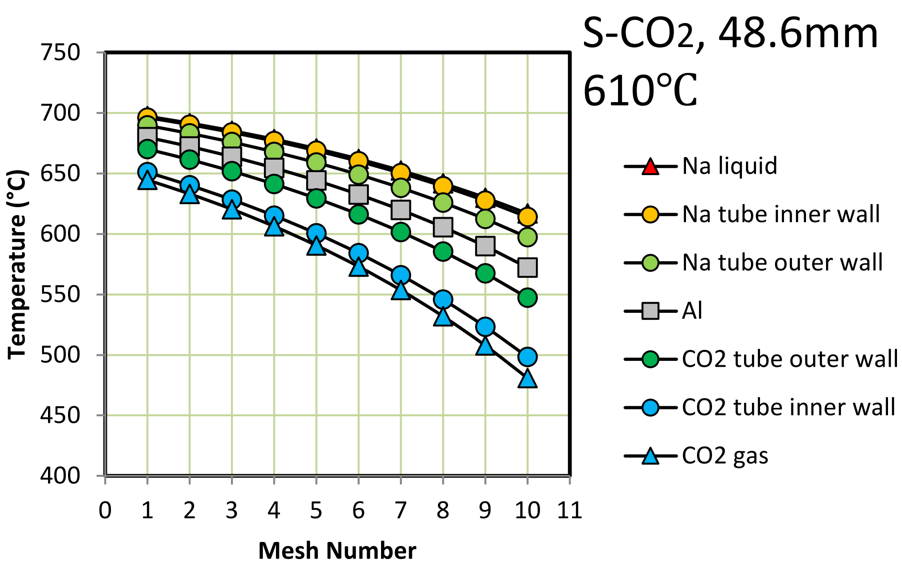
- Aluminum inventory needed

(1.053 × 10^6 MJ)/ (0.343 MJ/kg) = 3.07 × 10^3 ton

Temperature Distributions in HX

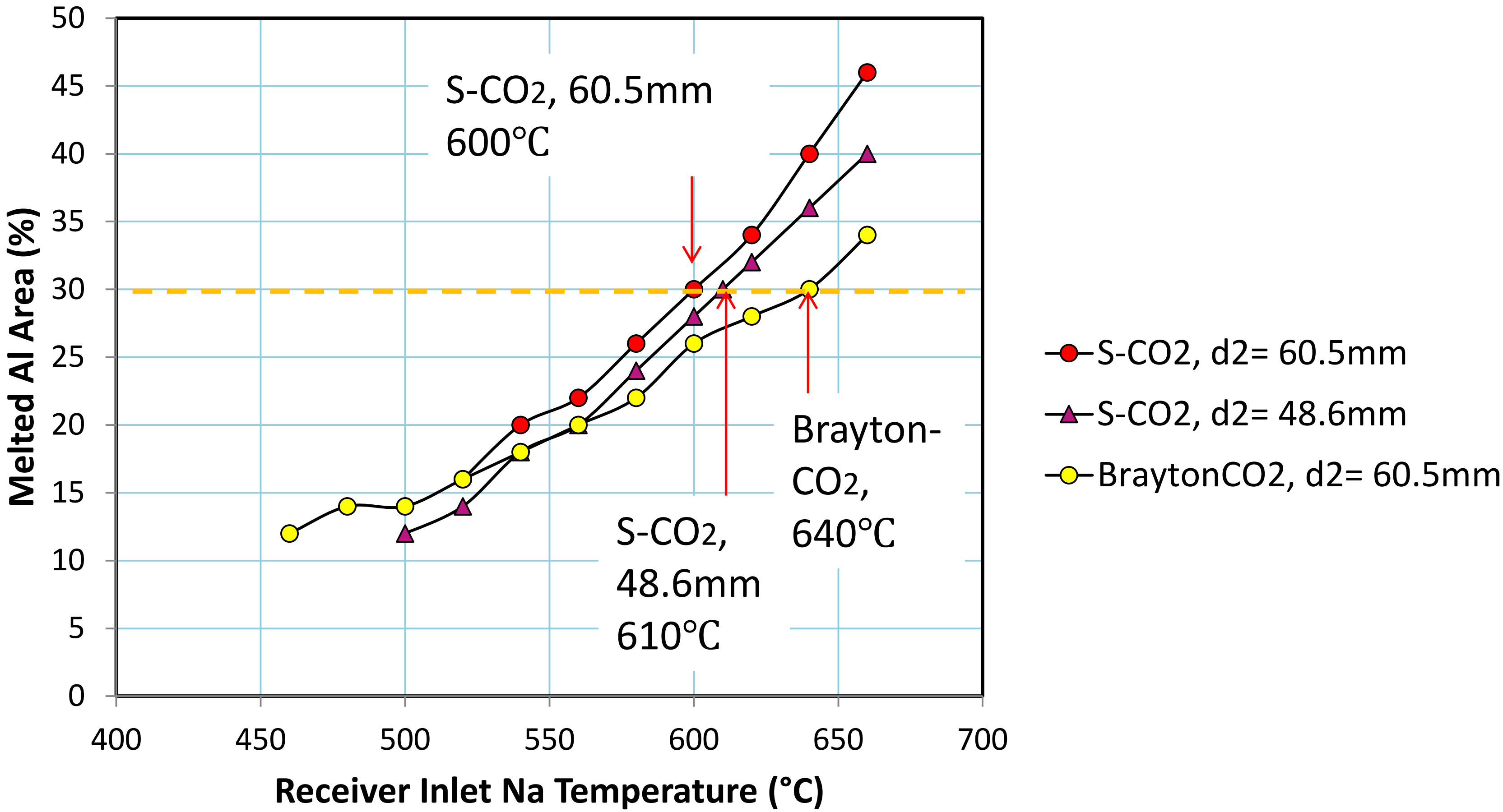




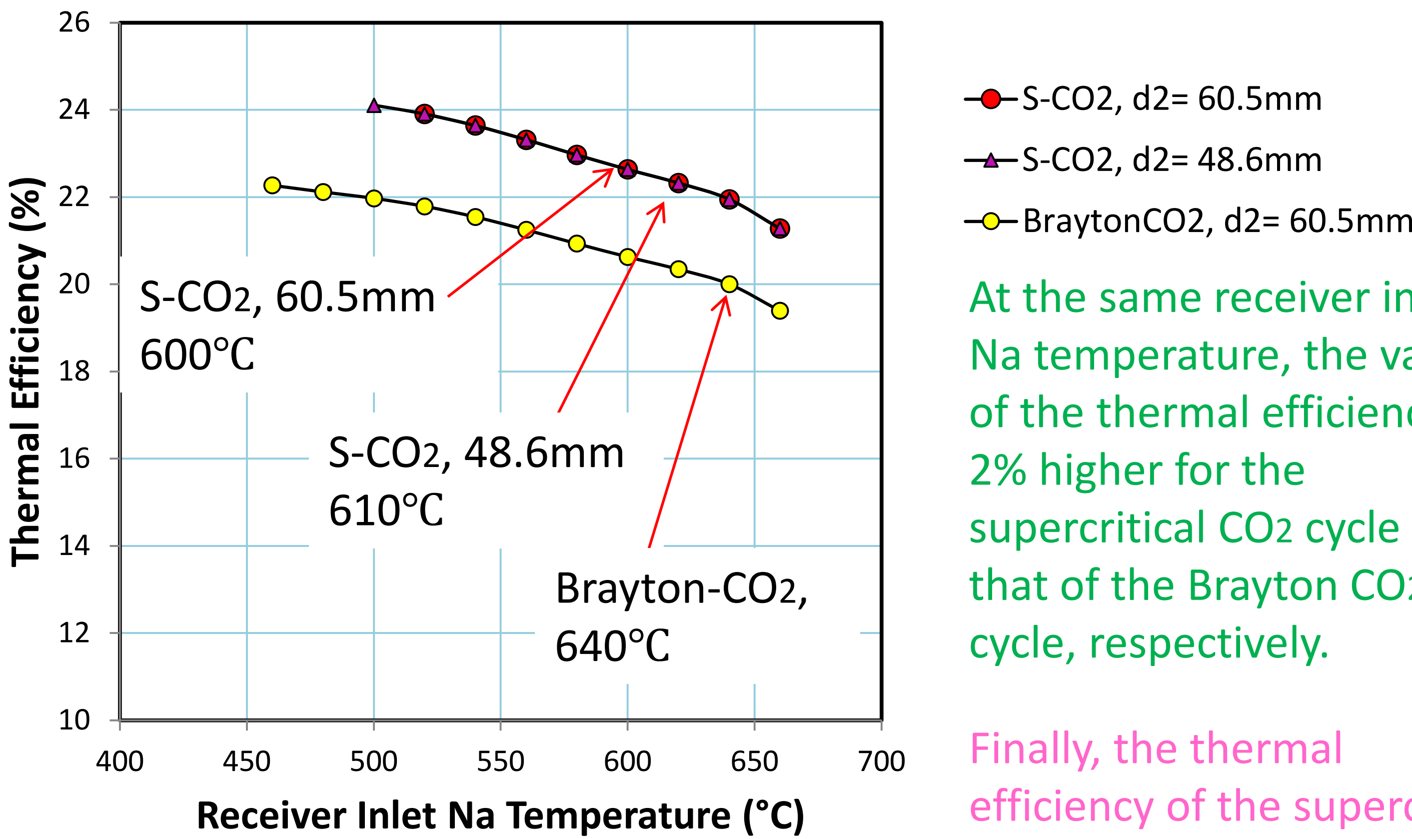


- Since the CO_2 inlet temperature is low: 397℃ in the Brayton CO_2 cycle, the inlet temperature vary widely at the CO_2 inlet.
- The main heat resistance occurs at the wall.
- No large difference is observed between the tube sizes of 60.5mm and 48.6mm.

Aluminum Melting Area



Thermal Efficiency of the Total System



At the same receiver inlet Na temperature, the value of the thermal efficiency is 2% higher for the supercritical CO_2 cycle than that of the Brayton CO_2 cycle, respectively.

Finally, the thermal efficiency of the supercritical CO_2 cycle is 2.6% higher than the Brayton cycle.

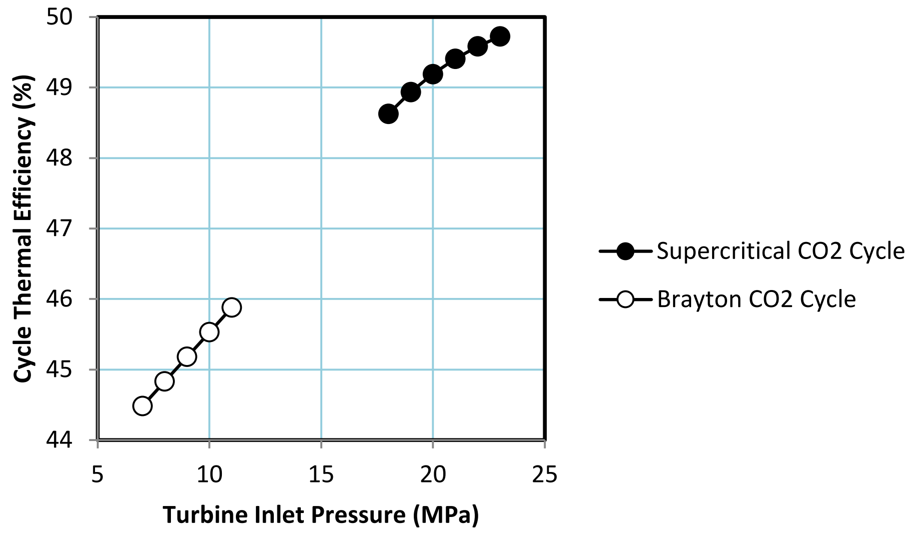
$$Thermal\ efficiency = \frac{Power\ output}{Solar\ energy\ input\ (125\ MW)}$$

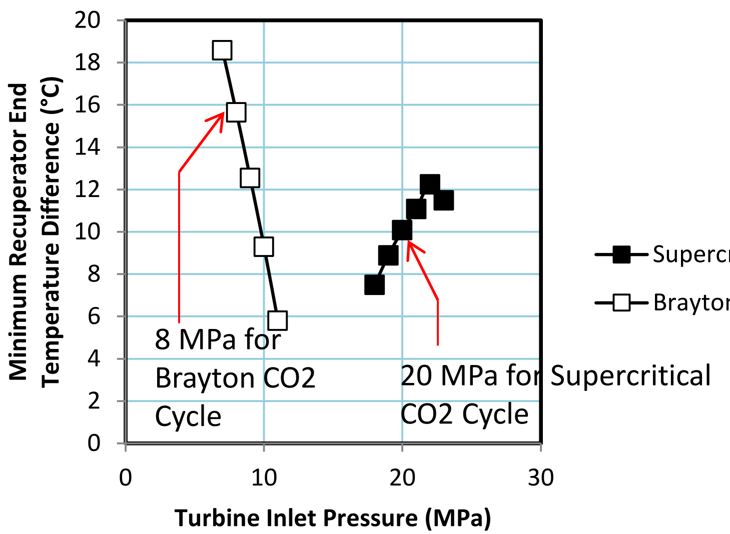
$$= (Receiver\ efficiency) \times (1-\beta) \times (Cycle\ thermel\ efficiency)$$

Cycle Thermal Efficiency of Supercritical CO_2 Cycles

Assumptions

- Turbine inlet temperature = 650℃
- One intercooling for the supercritical CO_2 GT cycle.
- Two intercooling for the Brayton CO_2 GT and He GT cycles.
- Then, 3 compressors
- Recuperator effectiveness = 91% for CO_2 GT cycles
- It = 93% for He GT cycle (Recuperator effectiveness = 95%)





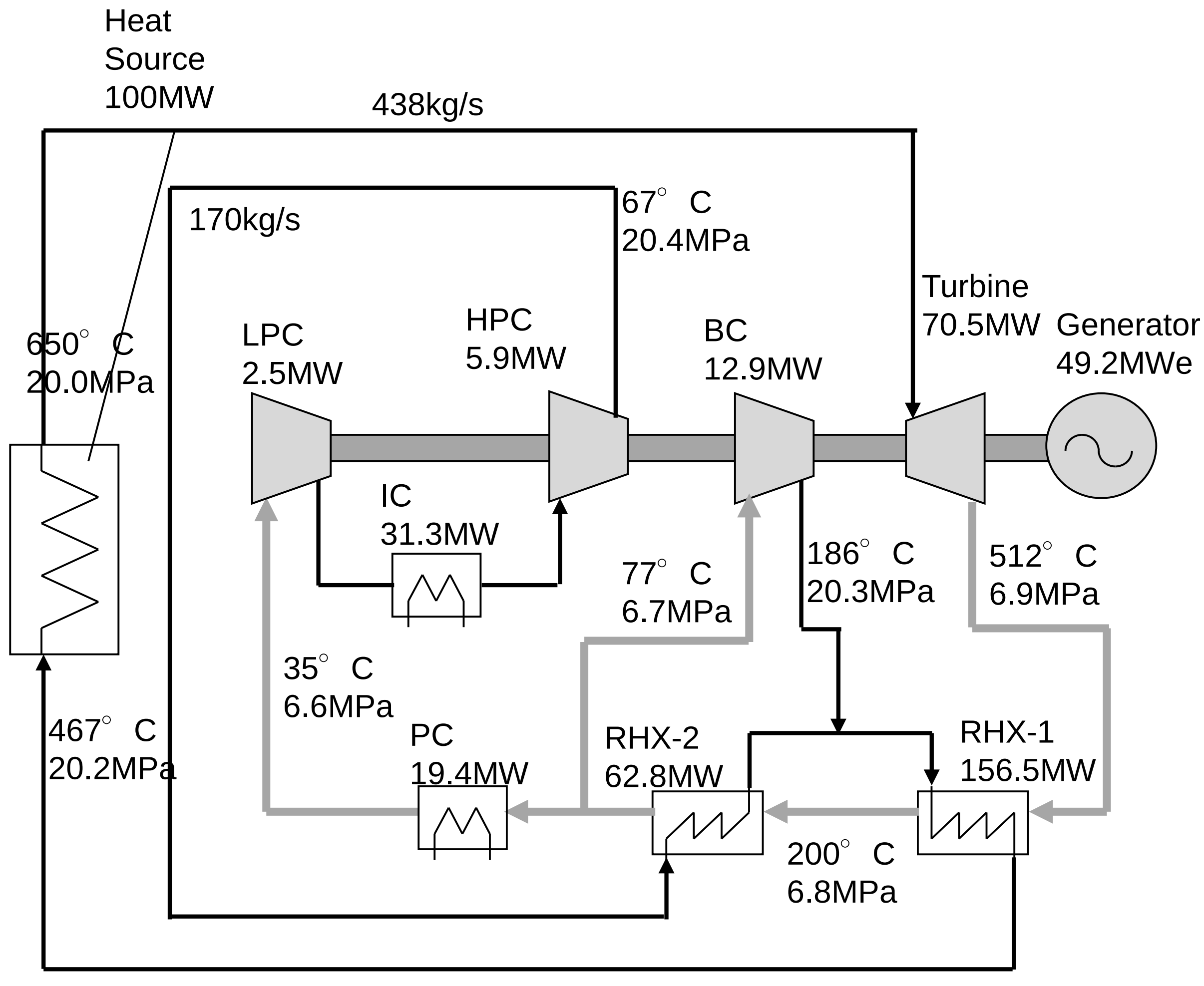
Supercritical CO_2 GT Cycle

Assumptions

- Turbine adiabatic efficiency 92%
- Compressor adiabatic efficiency 88%
- Pressure loss (ratios over the inlet pressure)

① Heat source 1.0%
② Recuperator high temperature side 1.2%
③ Recuperator low temperature side 0.4%
④ Precooler 1.0%
⑤ Intercooler 0.8%

- Recuperator average temperature effectiveness 91%



Cycle Thermal Efficiency = 49.2%

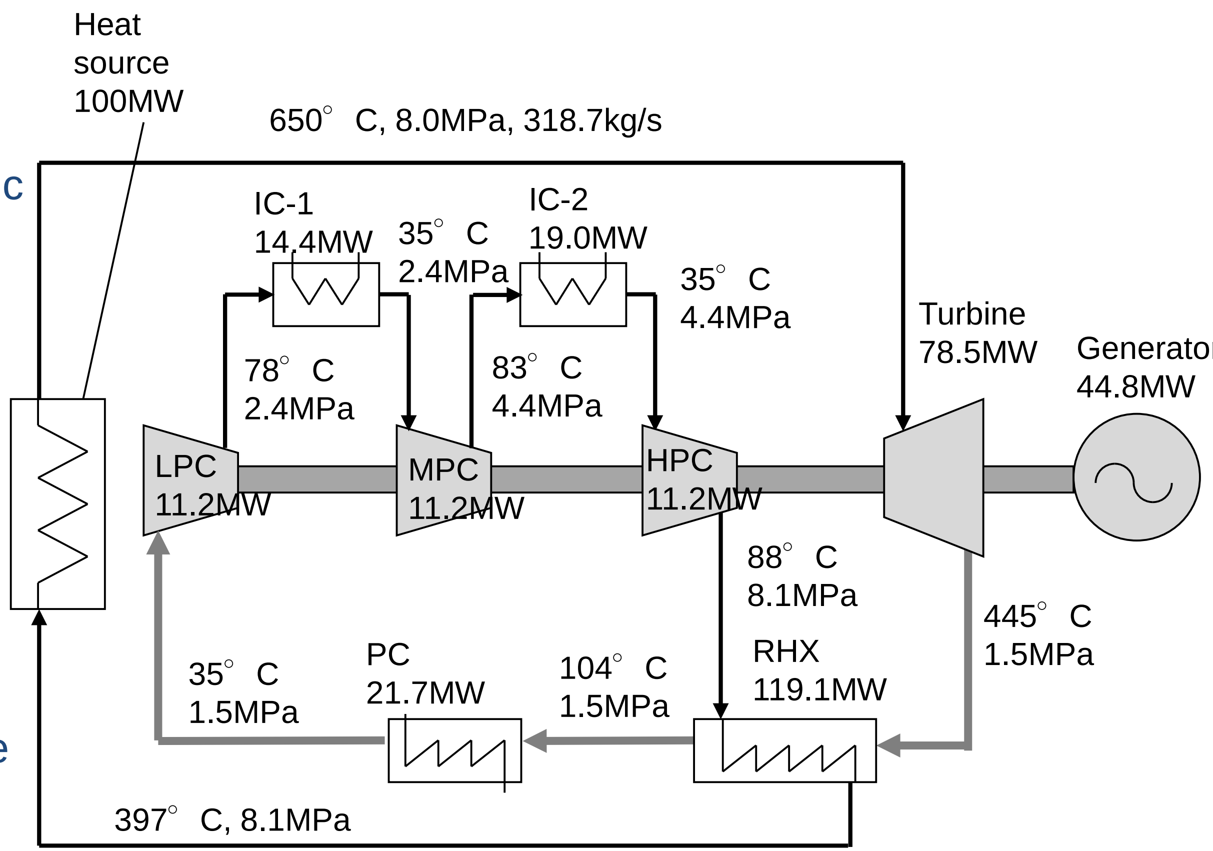
Brayton CO_2 GT Cycle

Assumptions

- Turbine adiabatic efficiency 92%
- Compressor adiabatic efficiency 88%
- Pressure loss (ratios over the inlet pressure)

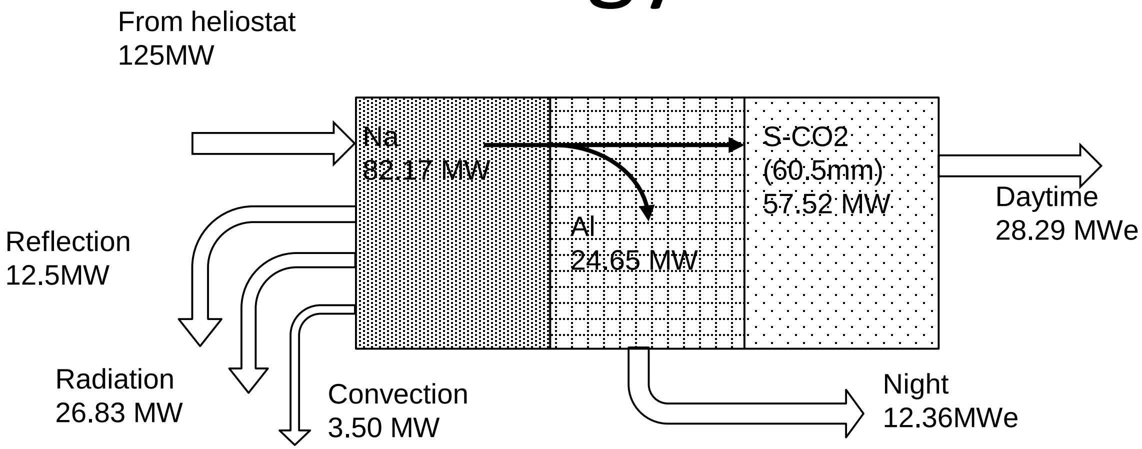
① Heat source 1.0%
② Recuperator high temperature side 1.2%
③ Recuperator low temperature side 0.4%
④ Precooler 1.0%
⑤ Intercooler 0.8%

- Recuperator average temperature effectiveness 91%



Cycle Thermal Efficiency = 44.8%

Energy Balance

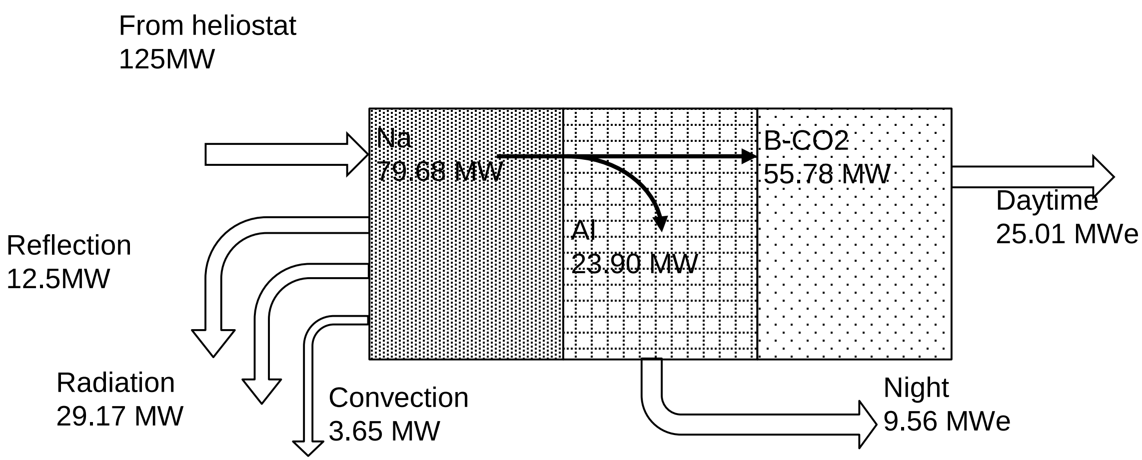


$$\frac{28.29\ MW}{125.0\ MW} = 22.6\%$$

Daytime only

$$65.73\% \times 49.19\% = 32.33\%$$

Supercritical CO_2 Cycle (60.5mm)



$$\frac{25.01\ MW}{125.0\ MW} = 20.0\%$$

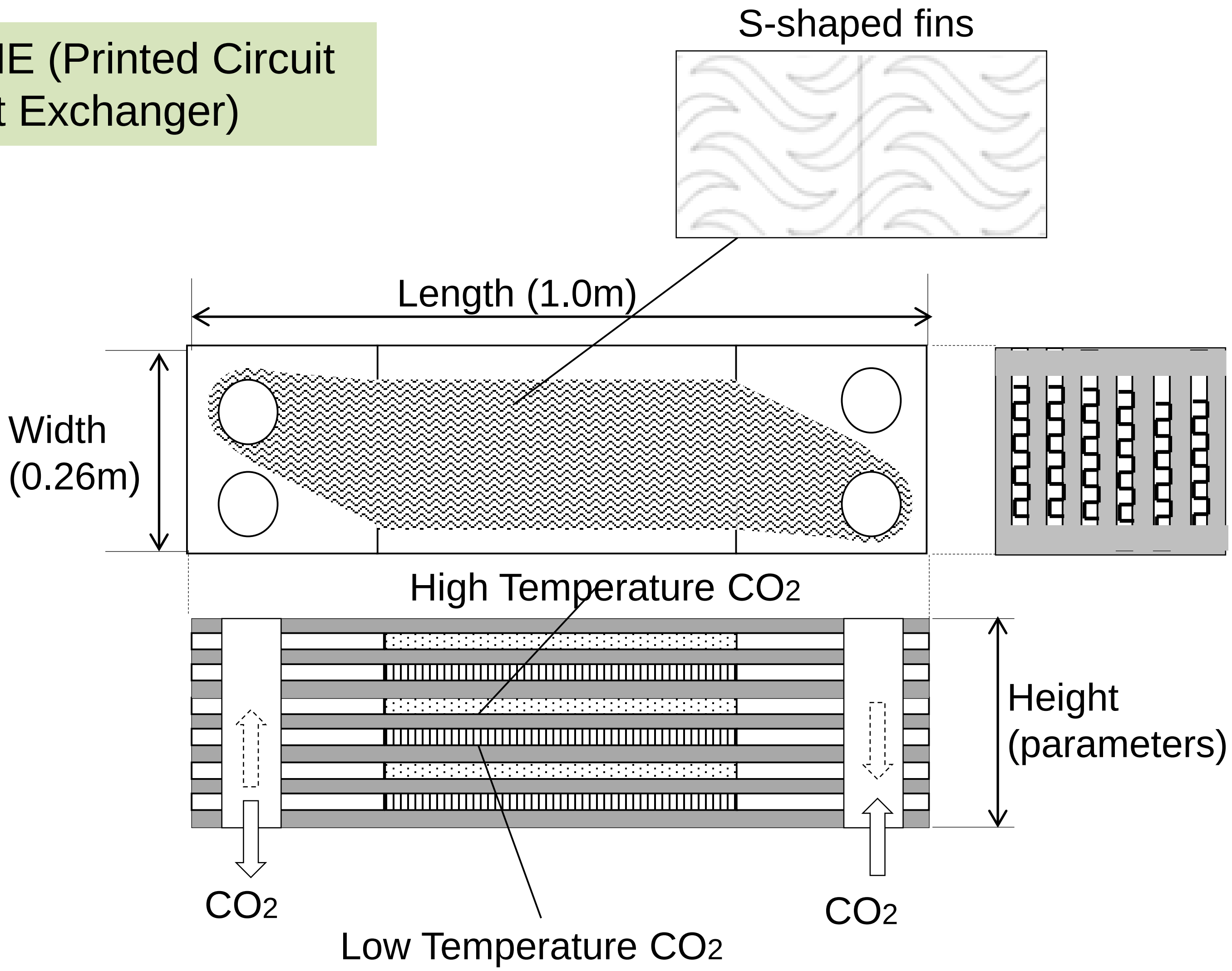
Daytime only

$$63.75\% \times 44.83\% = 28.58\%$$

Brayton CO_2 Cycle

Recuperator Designs

PCHE (Printed Circuit Heat Exchanger)



Design Conditions of the Recuperators

Items		Supercritical CO_2 Gas Turbine		Brayton CO_2 Gas Turbine
		RHX-1	RHX-2	RHX
Recuperator effectiveness %		91	91	91
Number of modules		6	6	6
Heat load MW/modules		11.012	4.884	8.950
HT side	Flow rate kg/s	32.887	32.887	26.248
	Inlet temperature ℃	503.25	209.70	430.84
	Inlet pressure MPa	6.410	6.333	1.305
LT side	Flow rate kg/s	32.887	19.598	26.248
	Inlet temperature ℃	196.69	67.39	92.67
	Inlet pressure MPa	20.283	20.365	8.113

Results of the Recuperator Designs

Items		Supercritical CO_2 Gas Turbine		Brayton CO_2 Gas Turbine
		RHX-1	RHX-2	RHX
Width × Length m/module		0.26 × 1.0	0.26 × 1.0	0.26 × 0.88
Height m/module		5.72	3.25	4.54
Weight ton/module		10.66	6.25	15.19
Total weight ton		64.0	37.5	91.1
Heat transfer capacity MW		11.023	4.892	8.967
Pressure loss ratio (dP/Pinlet)	HT side %	0.227	0.383	0.931
	LT side %	0.252	0.040	0.074

The total weight of recuperators for the supercritical CO_2 gas turbine cycle is equivalent with that for the Brayton CO_2 gas turbine cycle.

Conclusions

In the solar thermal power plant provided with the tower type receiver cooled by Na, a Na-Al-CO_2 heat exchanger and two CO_2 GT cycles, i.e., “20 MPa supercritical CO_2 GT cycle” and “8 MPa Brayton CO_2 GT cycle” , effects of the receiver inlet Na temperature were examined. The ratio of heat storage to the total thermal energy was assumed 30%, which means Al inventory of 3,000 ton.

The following conclusions were obtained.

1. The values of the receiver efficiency decreases with the Na inlet temperature.
2. The values of the receiver efficiency corresponding to the Al melting area of 30% were 600°C, 610°C and 640°C for the supercritical CO_2 cycle (60.5 mm and 48.6 mm) and the Brayton cycle, respectively.
3. Appropriate and then selected values of the turbine inlet pressure are 20 MPa and 8 MPa for the supercritical CO_2 cycle and the Brayton CO_2 cycle, respectively.
4. In these pressure, values of the cycle thermal efficiencies are 49.2% for the supercritical CO_2 cycle and 44.8% for the Brayton CO_2 cycle.
5. The values of the thermal efficiency of the total system are 22.6% and 20.0% for the supercritical CO_2 cycle and for the Brayton CO_2 cycle, respectively.
6. The recuperator weight for the supercritical CO_2 cycle is equivalent to that for the Brayton CO_2 cycle.