# *Exergy analysis of a 1000MW single reheat supercritical $CO_2$ coal-fired power plant*

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# Outline

- **Background**
- Model & Methodology
- Results & Discussions
- Conclusions

# 1、Background: Why do we need S-$CO_2$ coal fired power plant?

| Double reheat ultra-supercritical technology | 700℃ ultra-supercritical technology |
|---|---|
| Vapor parameters of 33 MPa/600℃/620℃/620℃ | Vapor parameters of 36.65Mpa/700℃/720℃ |
| Unit efficiency of 47.82% | Unit efficiency of 51.92% |
| Difficult to arrange the heating exchange surface | Weak material development, high investment cost |

**Steam Rankine cycle (SRC)**

**S-$CO_2$ Brayton cycle**

- **Nuclear energy**
- **Solar energy**
- **Waste heat energy**
- **Coal-fired energy**

Advantages:

- High thermal efficiency
- Excellent inheritance of materials
- Compact turbine size

S-$CO_2$ coal-fired power plants **(SCO2PP)** have a broad prospect of development and application

# 1、Background: Progress of SCO2PP development

**2013 and 2016, Yann Le Moullec, initial concept design by EDF, France**

- Conceptual design and economic evaluation
- Short cut design of the boiler: Reheat cooling wall (RCW) layout

[1] Le Moullec Y. Conceptual study of a high efficiency coal-fired power plant with CO2 capture using a supercritical CO2 Brayton cycle[J]. Energy. 2013, 49(1): 32-46.
[2] Mecheri M, Le Moullec Y. Supercritical CO2 Brayton cycles for coal-fired power plants[J]. Energy. 2016, 103: 758-771.

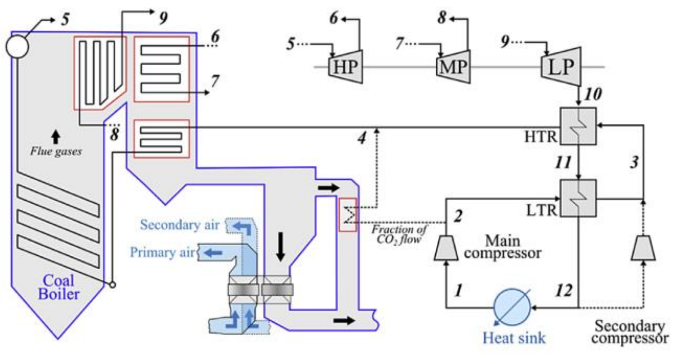
**2018，Jinliang Xu, by North China Electric Power University, China**

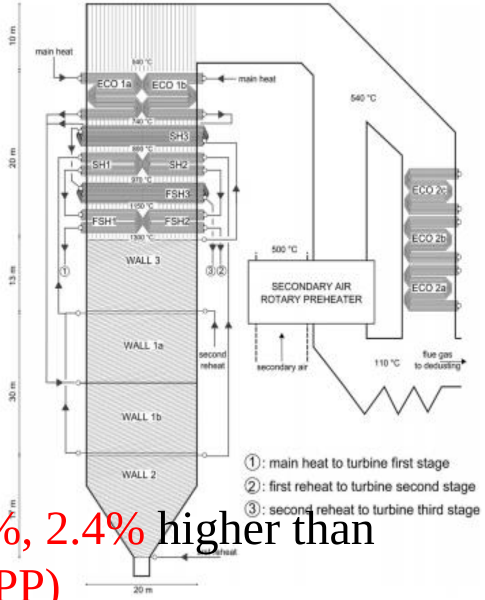
- S-CO2 boiler module design: Partial flow strategy (PFS)
- Efficiency is further improved based on Energy analysis

[3] Xu J, Sun E, Li M, et al. Key issues and solution strategies for supercritical carbon dioxide coal fired power plant[J]. Energy. 2018, 157: 227-246.

***Simplified schematic of double reheat S-CO2 boiler using* Reheat cooling wall (RCW) layout**

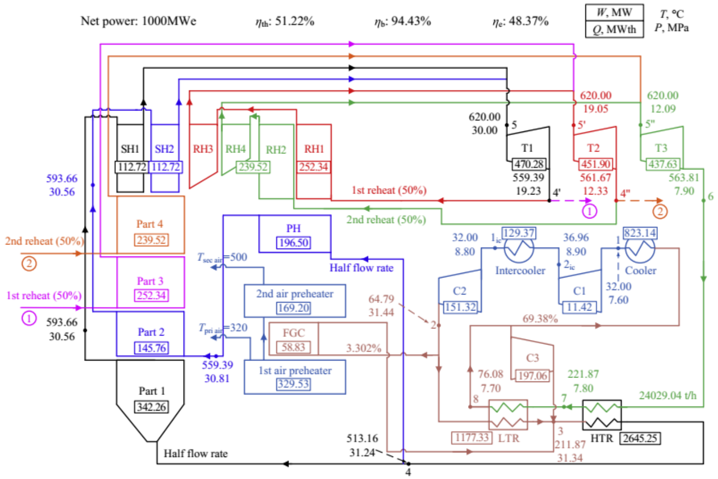
620°C/30MPa :

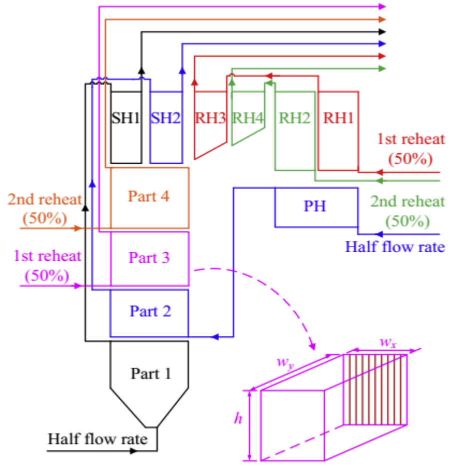



Overall plant net efficiency: 47.8%, 2.4% higher than traditional steam power plant (TSPP)

***Schematic of double reheat S-CO2 power plants using Partial flow strategy (PFS) module design***




Overall plant net efficiency: 48.3%

# 1、Background: Progress of S-CO2 coal-fired power plants development

**2016，Yu Yang, by Xi'an Thermal Power Research Institute, China**

- Numerical simulation of the coupled heat transfer between combustion and fluid heating
- Design of the heating surface of S-CO2 boiler

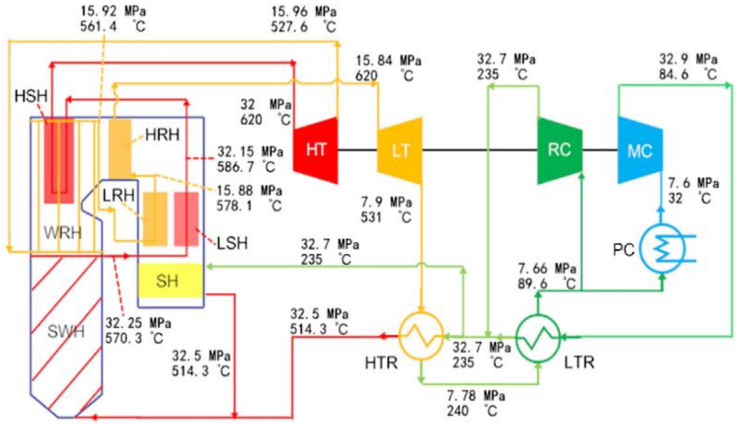
[4] Yang Y, Bai W, Wang Y, et al. Coupled simulation of the combustion and fluid heating of a 300 MW supercritical CO 2 boiler[J]. Applied Thermal Engineering. 2017, 113: 259-267.

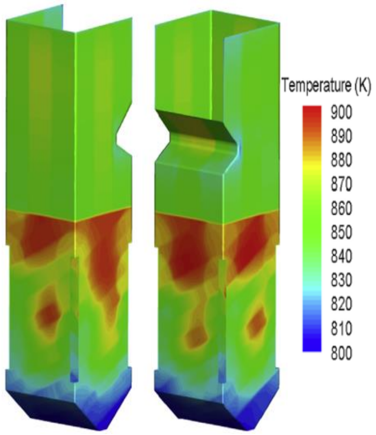
**2018，our previous study, Jun Xiang, by SKLCC, China**

- Parameter and configuration (Economizer and Compression) optimization based on exergy analysis
- A comprehensive optimized model for S-CO2 coal-fired power plant is established.

[5] Zhou J, Zhang C, Su S, et al. Exergy analysis of a 1000 MW single reheat supercritical CO2 Brayton cycle coal-fired power plant[J]. Energy Conversion and Management. 2018, 173: 348-358.

***Schematic of a 300MW single reheat S-CO2 coal-fired power plant and temperature distribution of heating surface in S-CO2 boiler:***

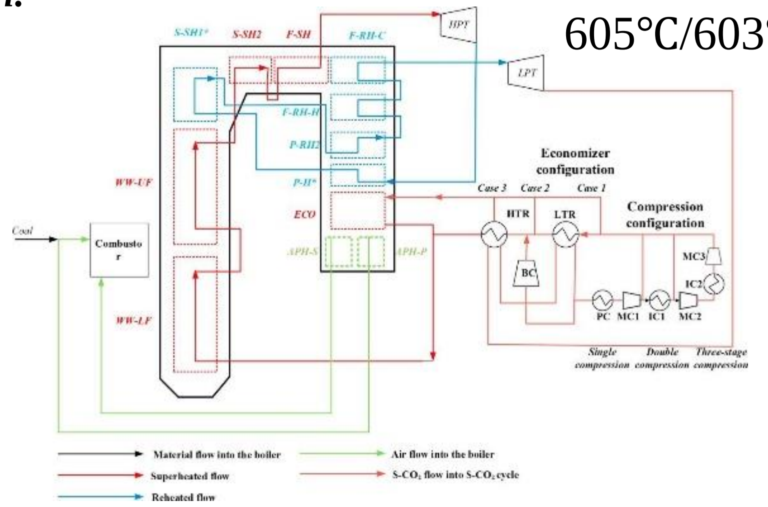



Reheat cooling wall (RCW) layout

***Schematic of single reheat S-CO2 power plants using exergy analysis optimization:***

605°C/603°C/27.4MPa




Overall plant exergy efficiency: 45.4%, improved by 3.5% compared with TSPP

# 1、Brief summary

- **S-CO2 Brayton cycle system  remains undetermined**

  System efficiency needs to be improved.

- **Energy analysis        Exergy analysis**

  It can accurately characterize the work potential for high-parameter system.

- **S-CO2 coal-fired power plants has potential for improvement**

  Optimization method and strategy should be presented and analyzed.

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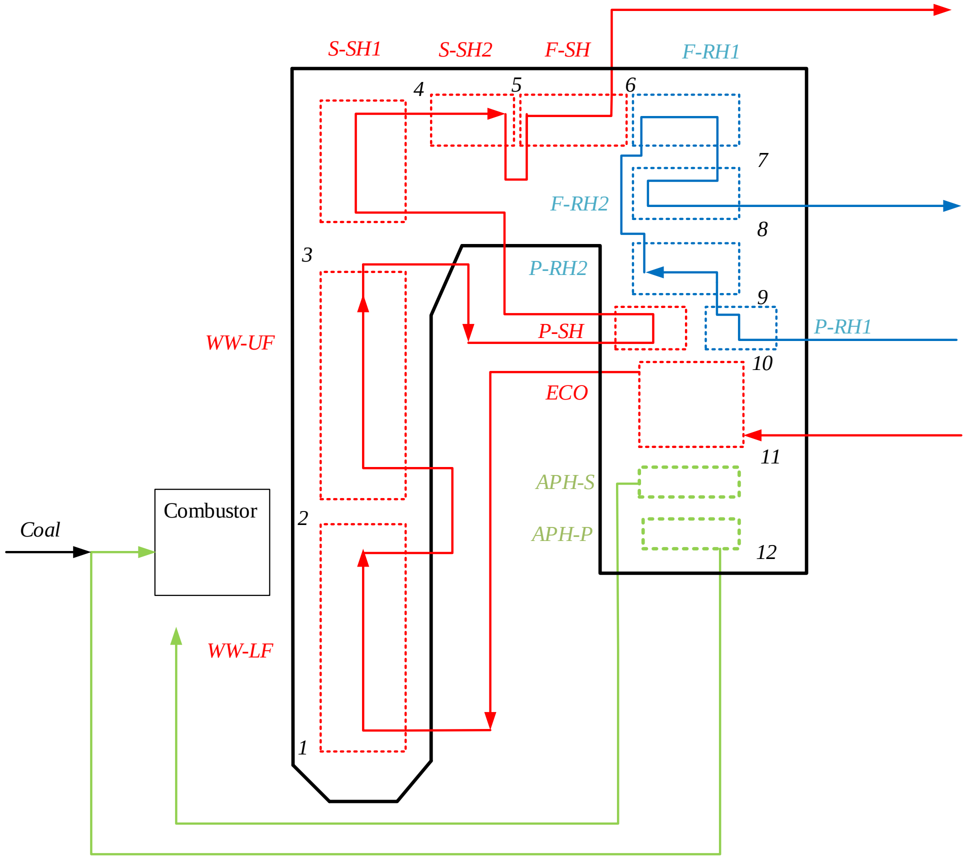
# 2.1 Model

## 1、 Traditional steam power plants (TSPP)




WW-LF: WaterWall of lower furnace
WW-UF: Cooling Wall of upper furnace
P-SH: Primary superheater/ Primary reheater3
S-SH1: Screen superheater1/ Screen reheater1
S-SH2: Screen superheater2
F-SH: Final superheater
F-RH1: Final reheater1
F-RH2: Final reheater2
P-RH2: Primary reheater2
P-RH1: Primary reheater1
ECO: Economizer
FGC: Flue gas cooler
APH-S: Secondary air preheater
APH-P: Primary air preheater

1000MW single-reheat traditional steam coal-fired power plant

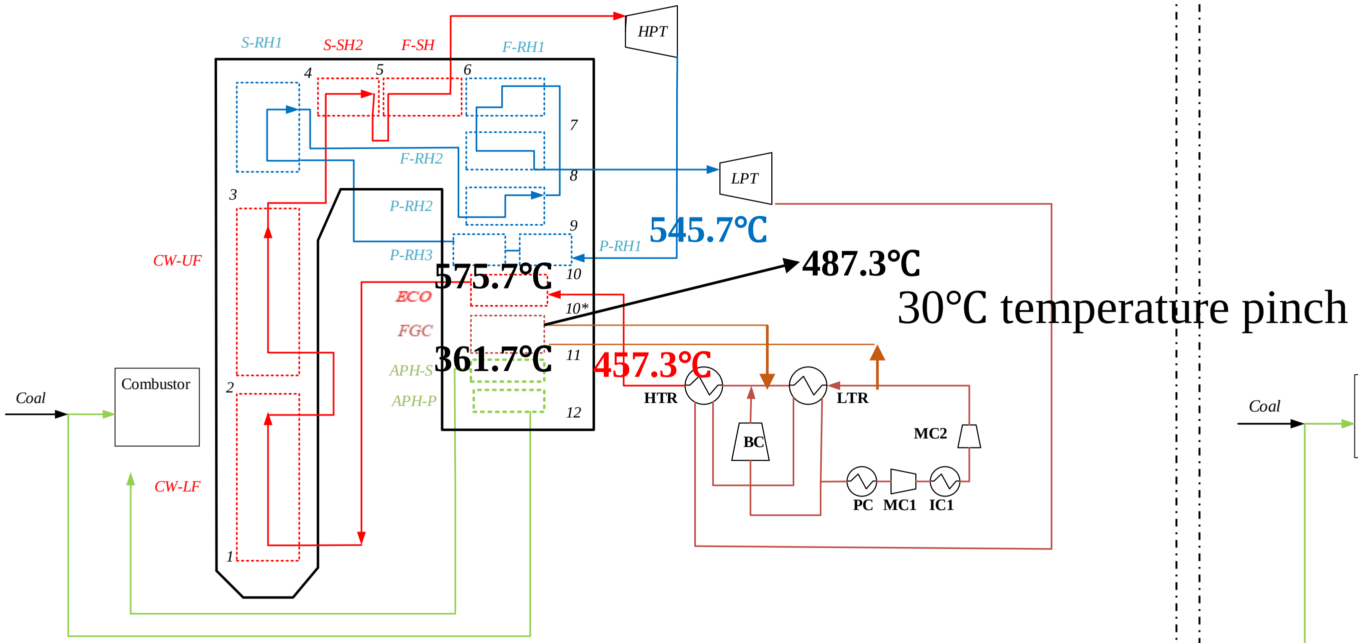
*Table 1. The main parameters for the simulation of a single-reheat boiler*

| Flue gas | Outlet temperature (°C) Referred values (TSPP) | Outlet temperature (°C) Simulation values (TSPP) | Error (%) |
|---|---|---|---|
| WW-LF | - | 1613.1 | - |
| WW-UF | - | 1225.9 | - |
| P-SH | 503.6 | 500.8 | −0.6 |
| S-SH1 | 1139.8 | 1119.6 | −1.8 |
| S-SH2 | 1037.8 | 1020.6 | −1.7 |
| F-SH | 938.2 | 923.7 | −1.5 |
| F-RH-H | 805.5 | 794.3 | −1.4 |
| F-RH-C | 839.9 | 828 | −1.4 |
| P-RH2 | 770.8 | 760.5 | −1.3 |
| P-RH1 | 456.7 | 455.1 | −0.4 |
| ECO | 358.9 | 358.5 | −0.1 |
| APH-S | 128.5 | 127 | −1.2 |
| APH-P | 128.5 | 130.3 | 1.4 |

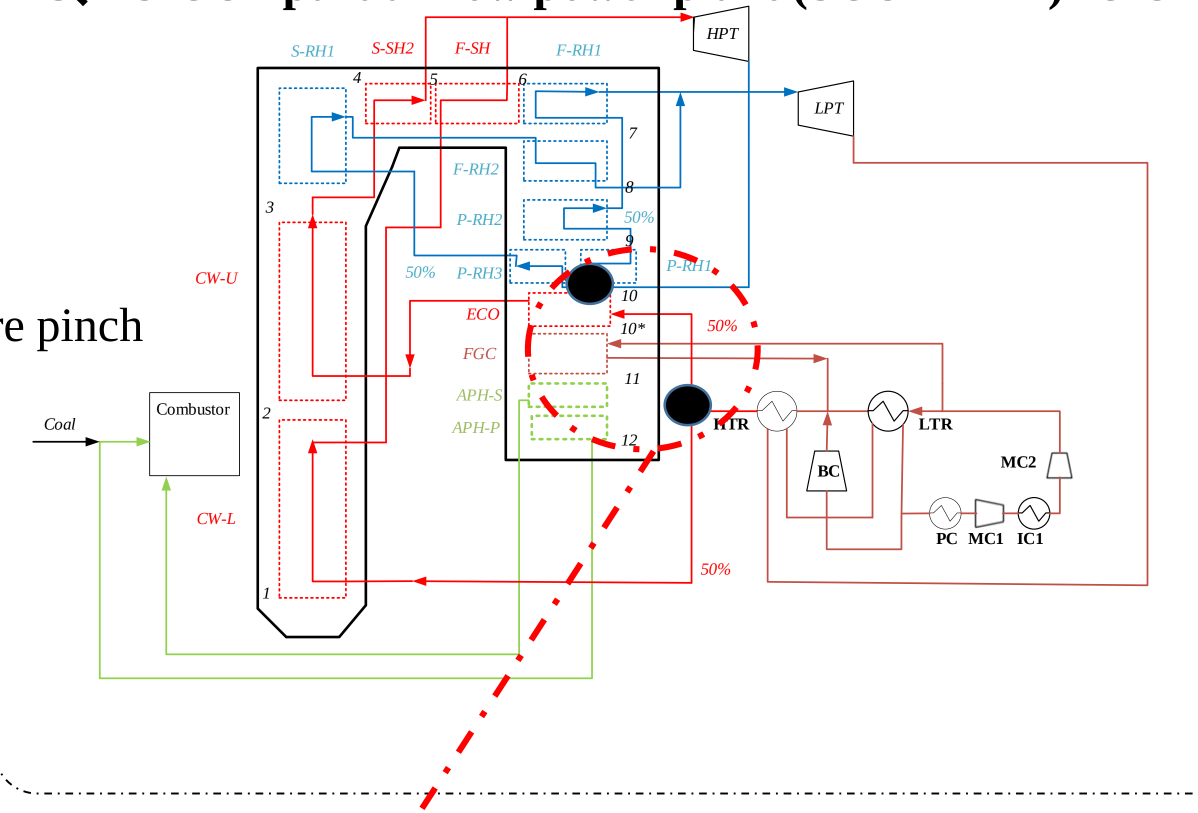
Less than 2% error

# 2.1 Model

## 2、 Basic single reheat S-$CO_2$ power plant (Basic SCO2PP )




## 3、 S-CO2 partial flow power plant (SCO2PFPP)+CISF




**Waste heat utilization ：**

Cycle internal split flow (CISF) method

**Boiler heating exchange surface layout:**

Flue gas cooler (FGC) under Economizer (ECO)

**Partial flow strategy (PFS)** to reduce the pressure drop

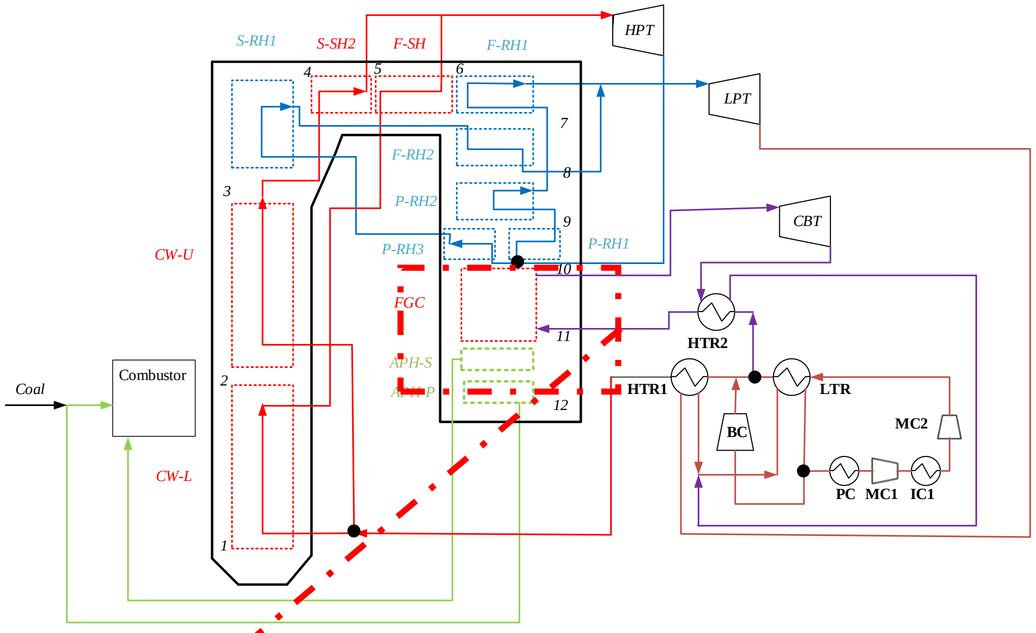
Divide into two halves, and pressure drop decreases by 1/8

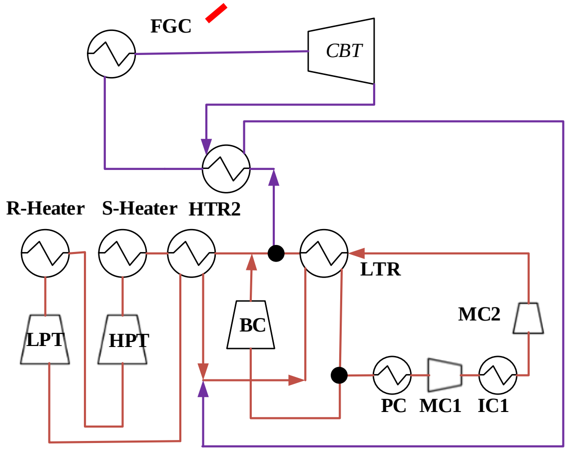
Heating length ↓ 1/2 Mass flow ↓ 1/2

**S-CO2 partial flow power plant (SCO2PFPP)**

# 2.1 Model

## 4、 SCO2PFPP+CTBC




Use this part of flue gas waste heat as the heat source of the bottom cycle

**Waste heat utilization：** Connected-Top-Bottom cycle (CTBC) method

*Table 2. Simulation values of four different coal-fired power plants*

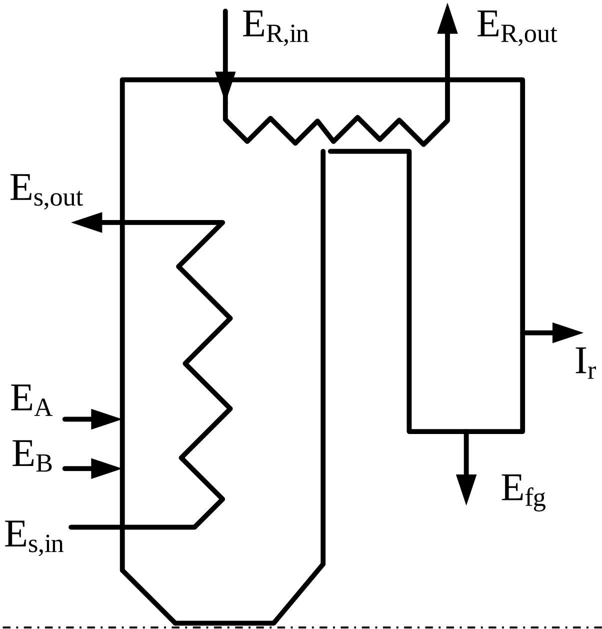
| Items | TSPP | Basic SCO2PP | SCO2PFPP +CISF | SCO2PFPP+ CTBC |
|---|---|---|---|---|
| Main inlet temperature into WW or CW / °C | 332.0 | 467.7 | 451.0 | 451.0 |
| $T_{10}$ / ℃ | 483.4 | 575.7 | 575.7 | 575.7 |
| $T_{10*}$ / ℃ | - | 487.0 | 487.0 | - |
| $T_{11}$ / ℃ | 361.7 | 361.7 | 361.7 | 361.7 |
| Mass flow rate / tonnes·h$^{-1}$ | 3101.8 | 29184.0 | 27890.9 | 26416.4 |
| Energy efficiency of the unit / % | 43.2 | 45.7 | 47.6 | 49.1 |

Main inlet temperature into CW of SCO2PP increases by 100~150℃

Mass flow rate of SCO2PP is 8~10 times compared with TSPP

# 2.2 Methodology

## ◆ S-CO2 boiler system exergy analysis method:




Boiler system exergy balance equation:

$$E_A + E_B + E_{s,in} + E_{R,in} = E_{s,out} + E_{R,out} + I_r + E_{fg}$$

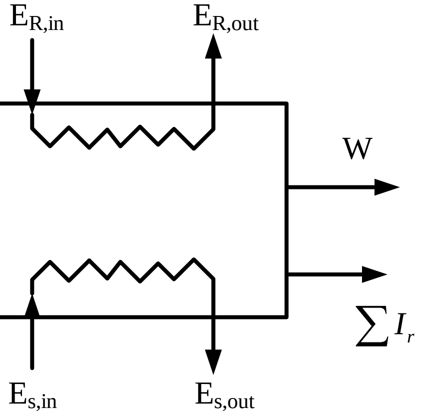
Boiler system exergy efficiency: $$\eta_b^e = \frac{\left(E_{s,out} - E_{s,in}\right) + \left(E_{R,out} - E_{R,in}\right)}{E_A + E_B}$$

Fuel exergy: $$e_B = LHV\left(1.0064 + 0.1519\frac{H}{C} + 0.0616\frac{O}{C} + 0.0429\frac{N}{C}\right)$$

Heating exchange exergy loss: $$I_r^e = \left(E_{in}^h - E_{out}^h\right) - \left(E_{out}^c - E_{in}^c\right) = QT_0\left(\frac{1}{\overline{T}_c} - \frac{1}{\overline{T}_h}\right)$$

Flue gas exergy loss: $$I_g = Q\left(1 - \frac{\overline{T}_0}{\overline{T}_h}\right)$$

## ◆ S-CO2 cycle system exergy analysis method:




S-CO2 cycle system exergy balance equation:

$$E_{s,out} + E_{R,out} = E_{s,in} + E_{R,in} + \sum I_r + W$$

S-CO2 cycle system exergy efficiency: $$\eta_{sc}^e = \frac{W}{\left(E_{s,out} - E_{s,in}\right) + \left(E_{R,out} - E_{R,in}\right)}$$

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# 3.1.1 Exergy distribution analysis of different 1000MW coal-fired power plants

*Table 3. Exergy distribution analysis of different coal-fired power plants*

| Items | Exergy loss (MW) TSPP | Exergy loss (MW) Basic SCO2PP | Exergy loss (MW) SCO2PFPP +CISF | Exergy loss (MW) SCO2PFPP +CTBC | Exergy loss ratio (%) TSPP | Exergy loss ratio (%) Basic SCO2PP | Exergy loss ratio (%) SCO2PFPP+CISF | Exergy loss ratio (%) SCO2PFPP+CTBC |
|---|---|---|---|---|---|---|---|---|
| Input exergy to the unit | 2444.8 | 2444.8 | 2444.8 | 2444.8 | - | - | - | - |
| Furnace combustion | 662.5 | 662.5 | 662.5 | 662.5 | 46.7 | 48.7 | 50.4 | 51.8 |
| Heat exchanger surface in boiler | 472.6 | 402.0 | 403.3 | 357.9 | 33.3 | 29.6 | 30.7 | 28.0 |
| Traditional steam cycle or S-$CO_2$ cycle | 246.8 | 232.7 | 224.0 | 234.9 | 17.4 | 17.1 | 17.1 | 18.4 |
| Others | 36.4 | 62.3 | 23.6 | 22.7 | 2.6 | 4.6 | 1.8 | 1.8 |
| Sum of exergy loss | 1418.3 | 1359.5 | 1313.4 | 1278.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Output effective exergy | 1027.0 | 1085.3 | 1131.4 | 1166.8 | - | - | - | - |
| Exergy efficiency of the boiler (%) | 52.1 | 53.9 | 55.4 | 57.3 | Boiler | | | |
| Exergy efficiency of the cycle (%) | 80.7 | 82.4 | 83.5 | 83.2 | - | Cycle | - | - |
| Exergy efficiency of the unit (%) | 42.0 | 44.4 | 46.3 | 47.7 | - | Unit | - | - |

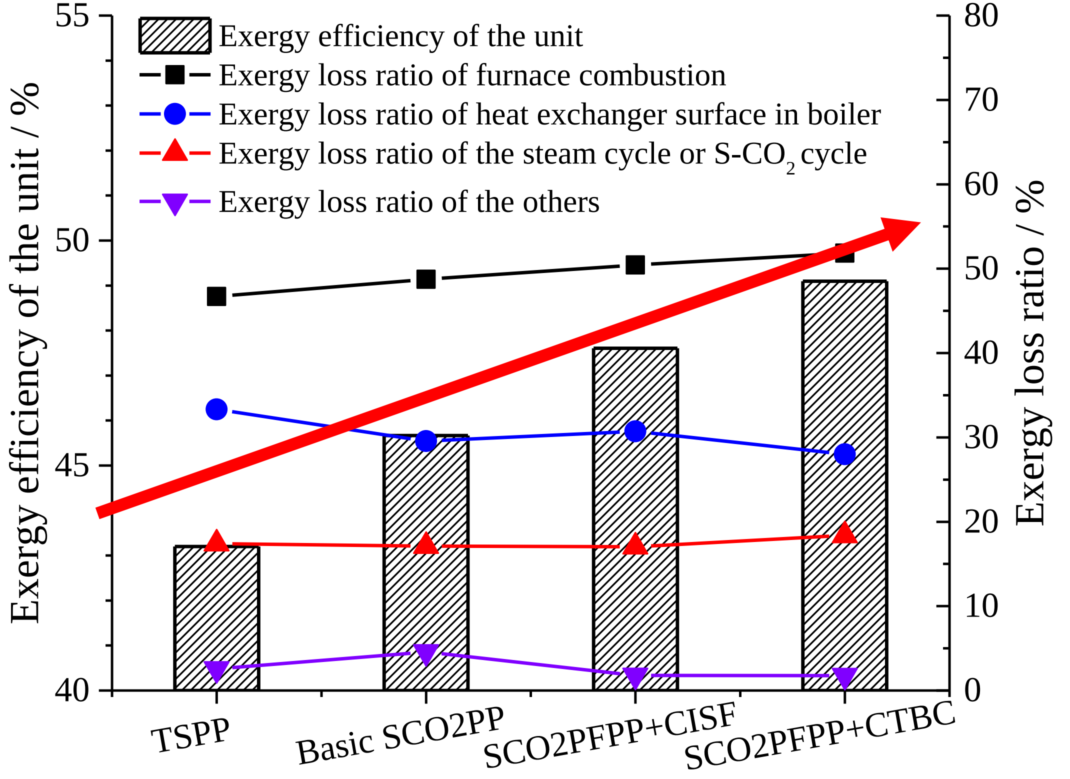
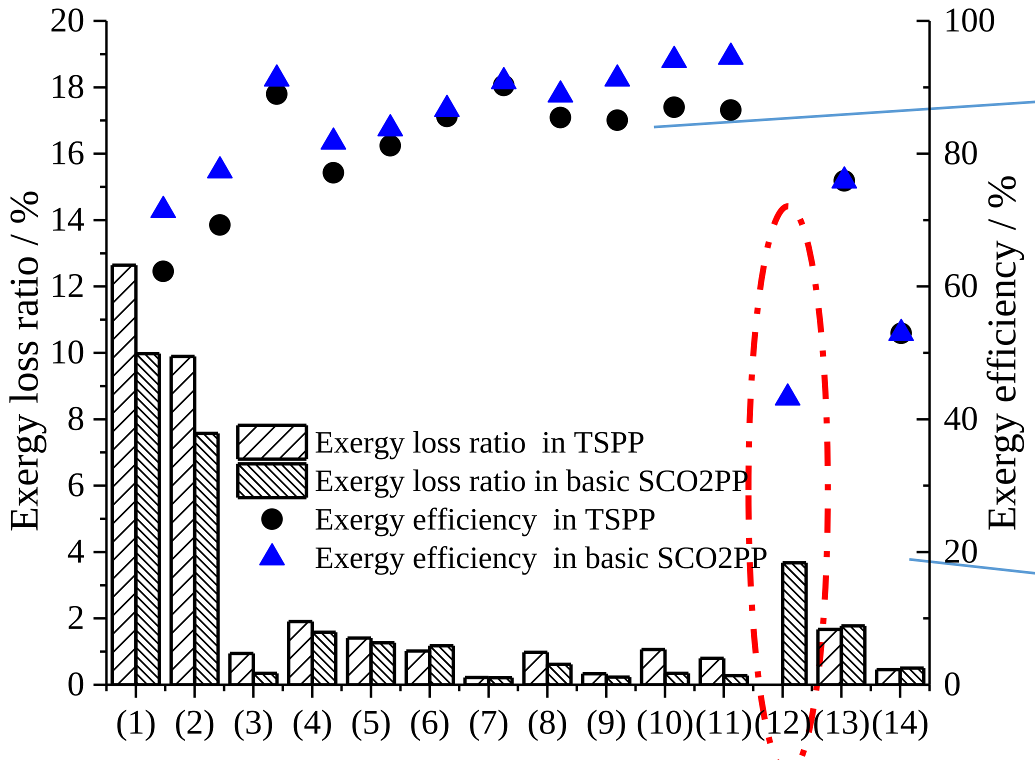



***Fig. 1. Exergy analysis of different coal-fired power plants***

- SCO2PFPP(CTBC) has better comprehensive performance, including higher exergy efficiency of the boiler and S-CO2 cycle due to its lowest exergy loss ratio of heat exchange surface.
- The exergy loss ratio of the S-CO2 boiler system is as high as about 82%, in which the exergy loss ratio of the furnace combustion accounts for about 50% and the heat exchange surface for about 29%.
- The exergy loss of the heat exchange surface has more remarkable effect on the unit exergy efficiency.

# 3.1.2 Exergy analysis of the heating exchange surface between TSPP and basic SCO2PP

**Compared with TSPP, the increase in exergy efficiency of basic SCO2PP is mainly due to the decreasing exergy loss ratio of the heat exchange surface.**




1. Waterwall or cooling Wall of lower furnace
2. Waterwall or cooling Wall of upper furnace
3. Primary superheater/ Primary reheater3
4. Screen superheater1/ Screen reheater1
5. Screen superheater2
6. Final superheater
7. Final reheater1
8. Final reheater2
9. Primary reheater2
10. Primary reheater1
11. Economizer
12. Flue gas cooler
13. Secondary air preheater
14. Primary air preheater

*Fig. 2. Exergy analysis of the heating exchange surface between TSPP and basic SCO2PP*

- Exergy loss ratio of almost all the heat exchange surface of basic SCO2PP is lower than that of TSPP due to their relatively higher exergy efficiency, except Flue gas cooler (FGC).
- The exergy loss ratio of FGC is as high as 3.7%, which takes up relatively high proportion. And its exergy efficiency is lowest.

# 3.1.3 Exergy analysis of CISF and CTBC units

**Between SCO2PFPP+CISF and SCO2PFPP+CTBC, the main variations occur in the heat exchange surface and the S-CO2 cycle.**

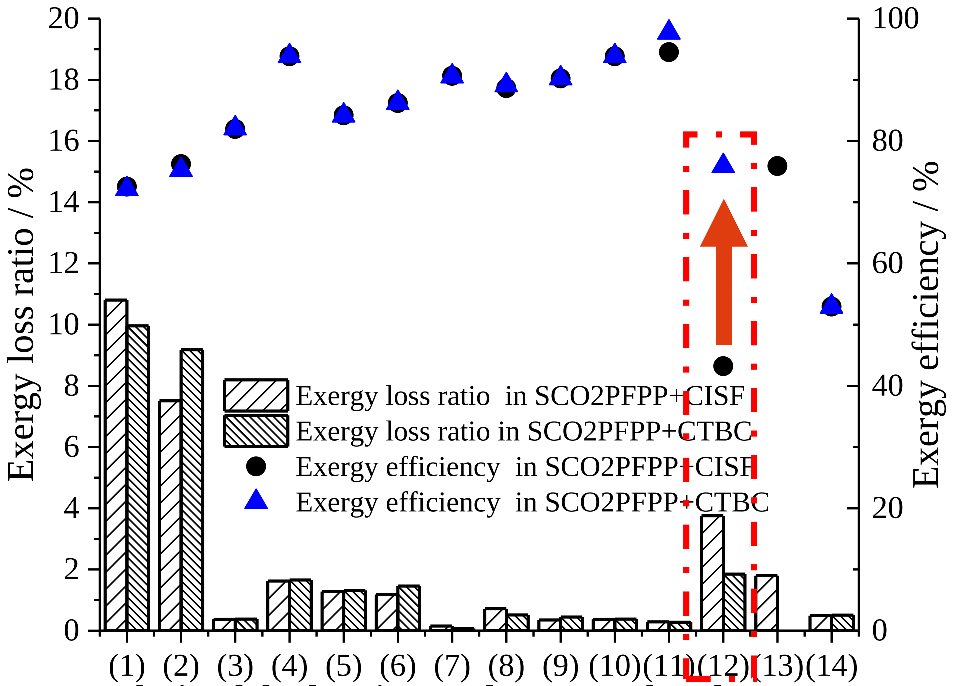



*Fig. 3. Exergy analysis of the heating exchange surface between CISF and CTBC units*

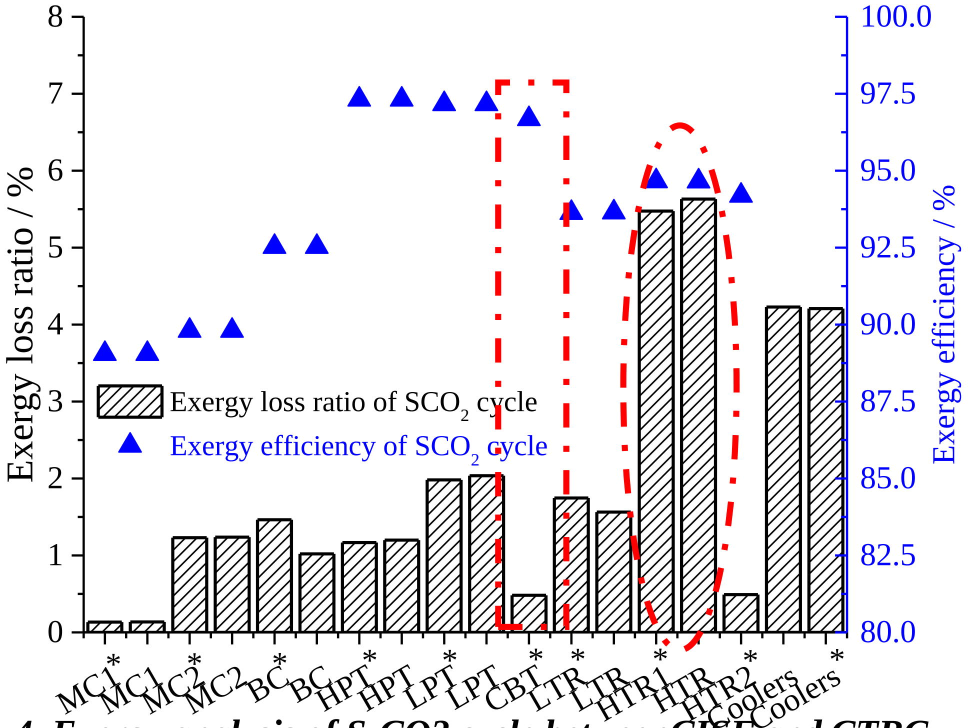
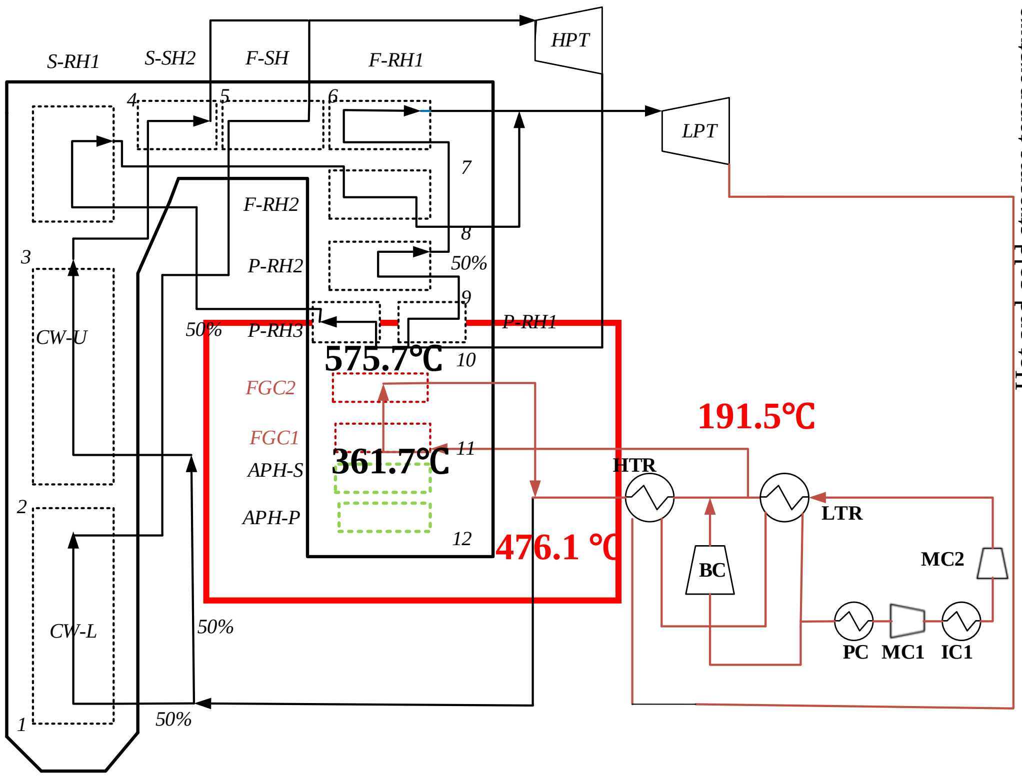



*Fig. 4. Exergy analysis of S-CO2 cycle betweenCISF and CTBC units*

- Exergy efficiency of the heat exchange surface between CISF and CTBC units is almost the same, except FGC.
- The exergy loss ratio of FGC in the CTBC unit suffers much lower than that of the CISF unit.
- The exergy loss ratio of HTR is the highest and takes up the majority of the S-CO2 cycle.
- Connected-bottom-cycle turbine (CBT) has relatively lower exergy efficiency compared with HPT and LPT in CTBC units , due to its lower inlet parameters.

## Optimization for SCO2PFPP +CISF




**Optimization method：**

Adjacent double flue gas cooler (**ADFGC**) layout

## Analyze HTR separately

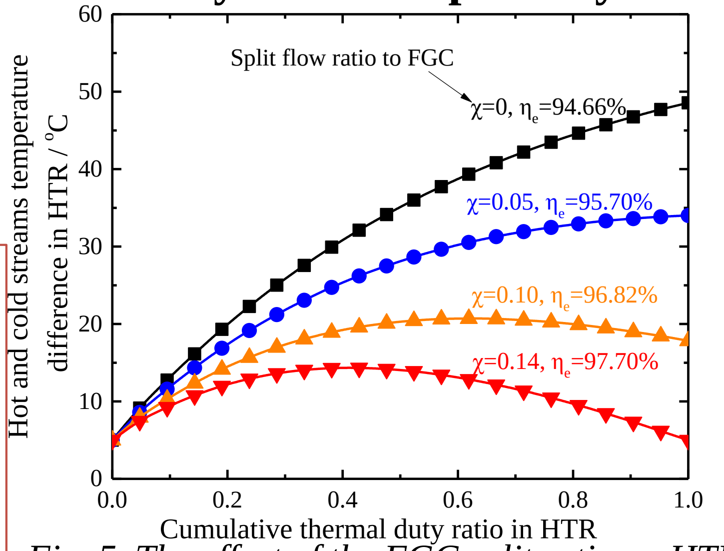



*Fig. 5. The effect of the FGC split ratio on HTR performance*

Split from the inlet high-pressure side of HTR

HTR temperature difference decrease

Improve HTR exergy efficiency

## Analyze the SCO2PFPP unit

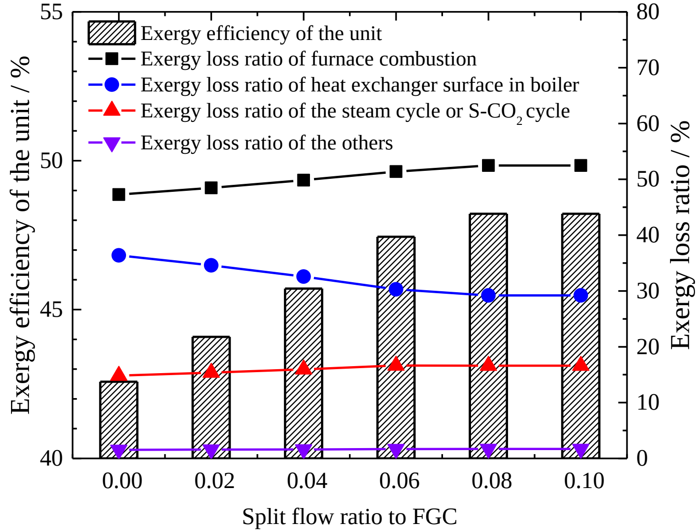


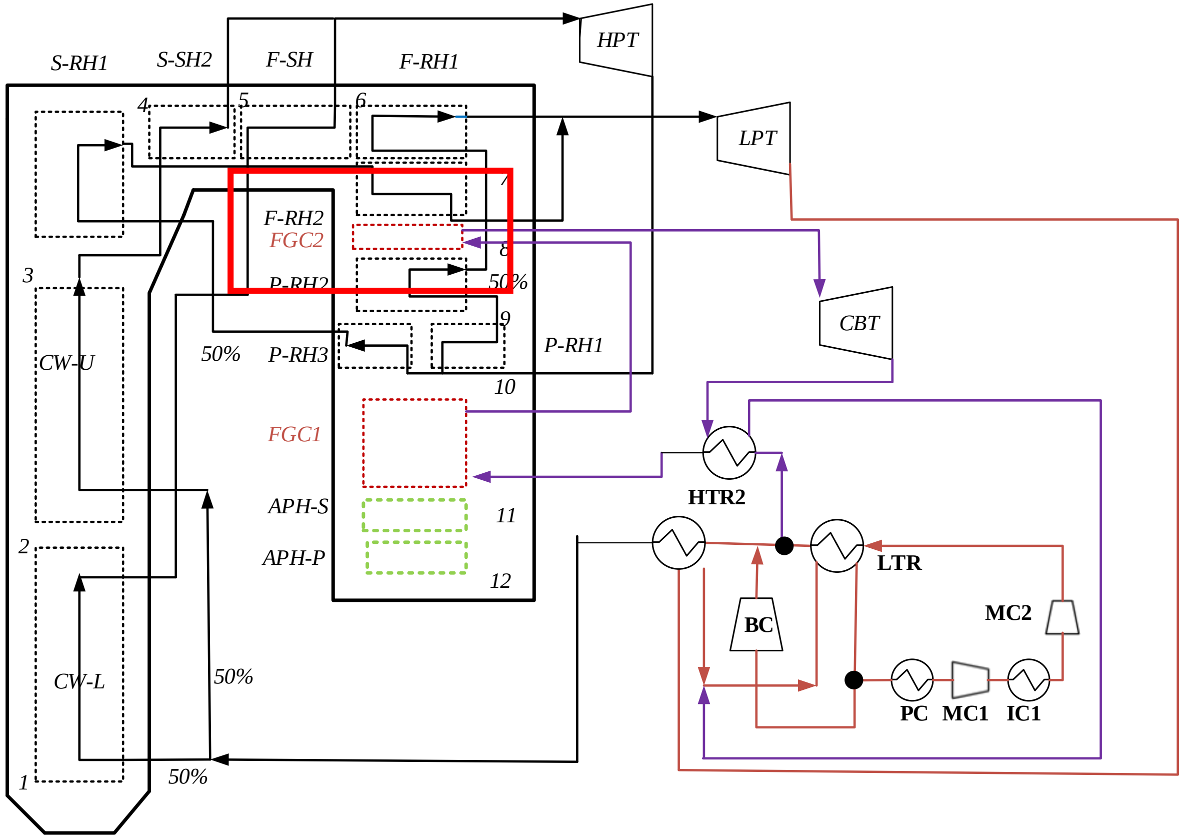

*Fig. 6. The effect of the FGC split ratio on unit performance*

**Exergy efficiency:48.22%**

**Improved by 1.94%**

# 3.2.2 SDFGC layout for SCO2PFPP+CISF

## Optimization for SCO2PFPP +CTBC



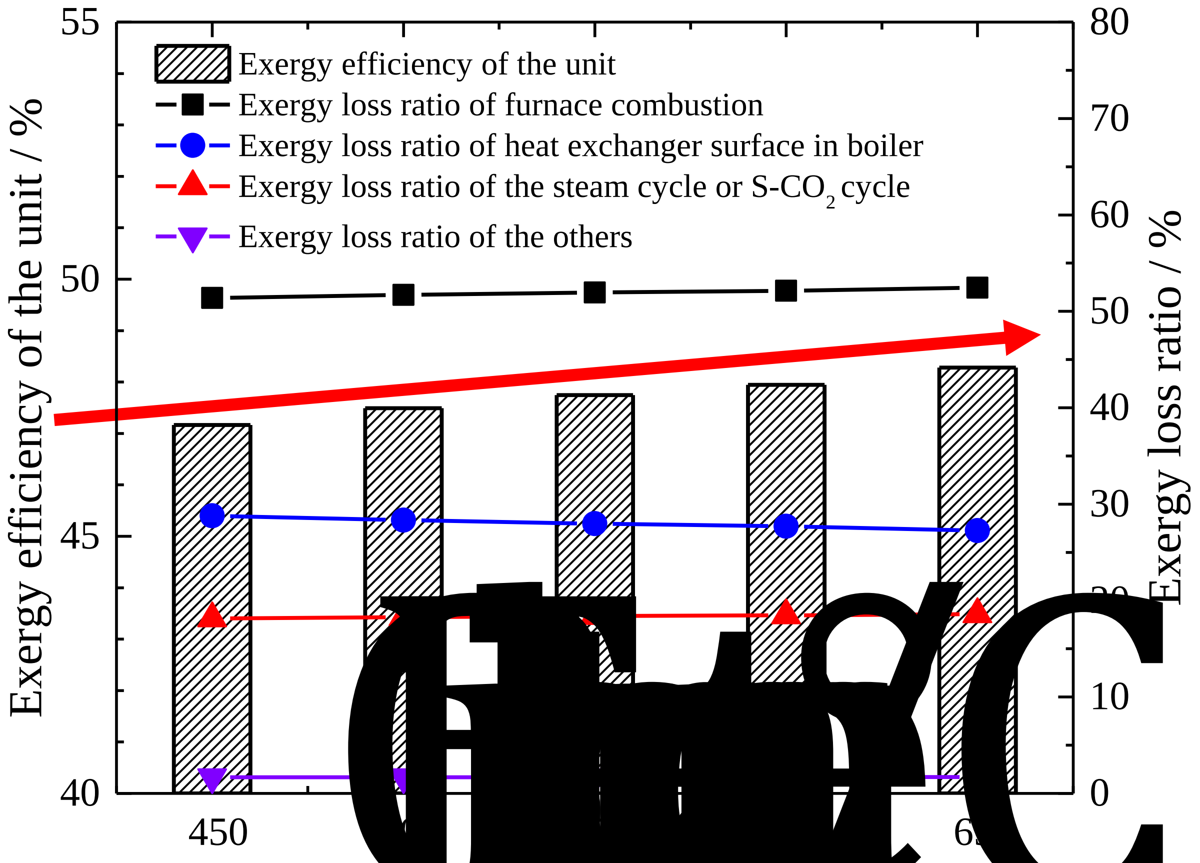




*Fig. 7. The effect of CBT inlet temperature on unit performance*

**Optimization method：**

Staggered double flue gas cooler (**SDFGC**) layout

**Exergy efficiency:47.95%（600℃）**

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# Conclusion

A comprehensive exergy analysis and optimization method for S-CO2 partial flow power plant (SCO2PFPP) using cycle-internal-split-flow (CISF) and connected-top-bottom-cycle (CTBC) method are constructed.

- The exergy loss ratio of S-CO2 power plants units from high to low is mainly concentrated on furnace combustion, furnace heat transfer surface, followed by S-CO2 cycle and exhaust gas waste heat.
- The CISF and CTBC method can solve the waste heat utilization of the S-CO2 boiler. However, the exergy loss of FGC and HTR takes up considerably high percentages in CISF unit and connected-bottom-cycle turbine (CBT) has relatively lower exergy efficiency in CTBC unit.
- For optimization of SCO2PFPP+CISF, an innovative adjacent double flue gas cooler (ADFGC) layout is presented. The unit exergy efficiency is 48.22%, improved by 1.94%.
- For optimization of SCO2PFPP+CTBC, an innovative staggered double flue gas cooler (SDFGC) layout is presented. The unit exergy efficiency is 47.95% as the CBT inlet temperature is 600℃.

# Acknowledgments

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***Thanks for listening!***

# A:Model input parameter and logic framework

*Table 1. Main input parameters during the simulation of the single-reheat S-CO2 power plants*

| Parameter | ValueS |
|---|---|
| HPT inlet pressure/temperature | 274bar/605°C |
| LPT inlet pressure/temperature | 177bar/603°C |
| MC1 inlet flow pressure/temperature | 76bar/32°C |
| MC2 inlet flow pressure/temperature | 90bar/32°C |
| Optimum split ratio to BC | 0.28 |
| Components' pressure drop of S-$CO_2$ cycle | 0.1 |
| Superheat or reheat exchange surface's pressure drop in boiler | 1.0 |
| Compressor isentropic efficiency | 89.00% |
| Compressor motor efficiency | 99.60% |
| Turbine isentropic efficiency | 93.00% |
| Recuperator pinch temperature difference | 5°C |
| Flue gas and CO2 pinch temperature difference | 30°C |
| Flue gas outlet temperature | 129°C |