3rd European supercritical CO_2 Conference
September 19-20, 2019, Paris, France

CSP Development in China and sCO_2 Research at Zhejiang University

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Paris, Sep. 20, 2019

Zhejiang University, Hangzhou, China

◆**Capital of Zhejiang Provence**

◆**1100km from Beijing**

◆**180 km from Shanghai**

Introduction of Hangzhou

- A historical and cultural city
- The most famous national tourist city in China

Spring

Summer

Autumn

Longest and Earliest man-made canal of world (Grand Canal: Beijing-Hangzhou)

Winter

World Cultural Heritage (West Lake, 2011)

Zhejiang University, Hangzhou, China

Hangzhou City

Zhejiang Provence

West Lake

7 campuses: 5 in Hangzhou, 1 in Zhoushan and 1 in Haining; ~50,000 Students

- Top 5 in Engineering of World (US News 2017)
- One of the Best Universities in China (C9 Union)

State Key Lab of Clean Energy Utilization @ Zhejiang University

Faculties and Students

- 50 faculties
- ~50 staffs
- ~500 graduated students

International Cooperation Centers

- **ZJU-Princeton Univ.**
  Jiont Research Center on Hydrogen Energy
- **ZJU-Standford Univ.**
  Jiount Research Center on Combustion Chemsitry
- **ZJU-UIUC** (University of Illinois at Urbana-Champaign)
  International Center for Bioenergy
- **ZJU-Leeds Univ.**
  International Center for Sustainable Energy Science and Tech.
- **ZJU-KTH**
  Jiont Research Center on Clean Energy Utilization
- **ZJU-Lund Univ.**
  International Center for Laser Diagnostics in Energy Science
- **ZJU-Purdue**
  International Center for Clean Energy Research Initiative
- **ZJU-Austrialia**
  BHP Billiton Jiont lab
- ....

Research fields

Energy

Combustion

Environment

Research Fields of Our Lab

Renewable Energy and Advanced Energy System

Simulations of Multiphase Reaction System

Clean Utilization of Low Grade Energy

High-efficiency Utilization of Fossil Fuel

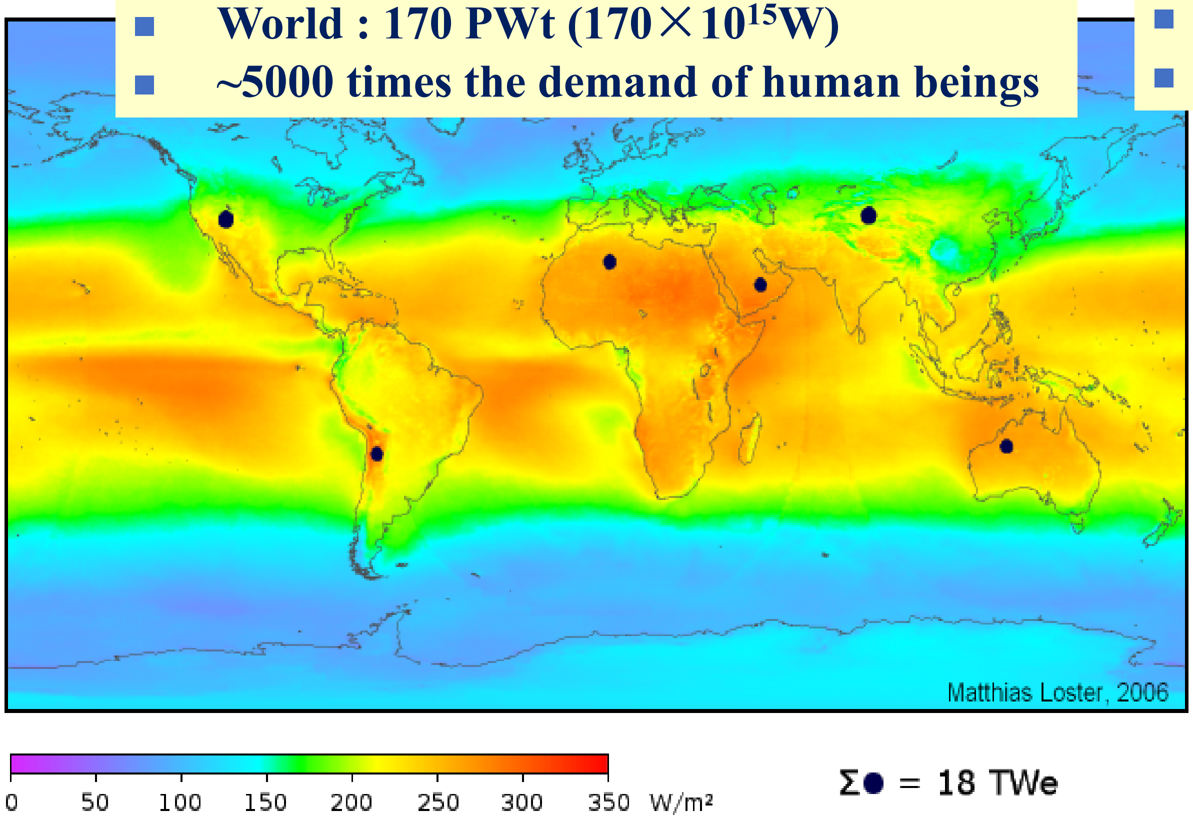
Pollution Control

Our research : CSP

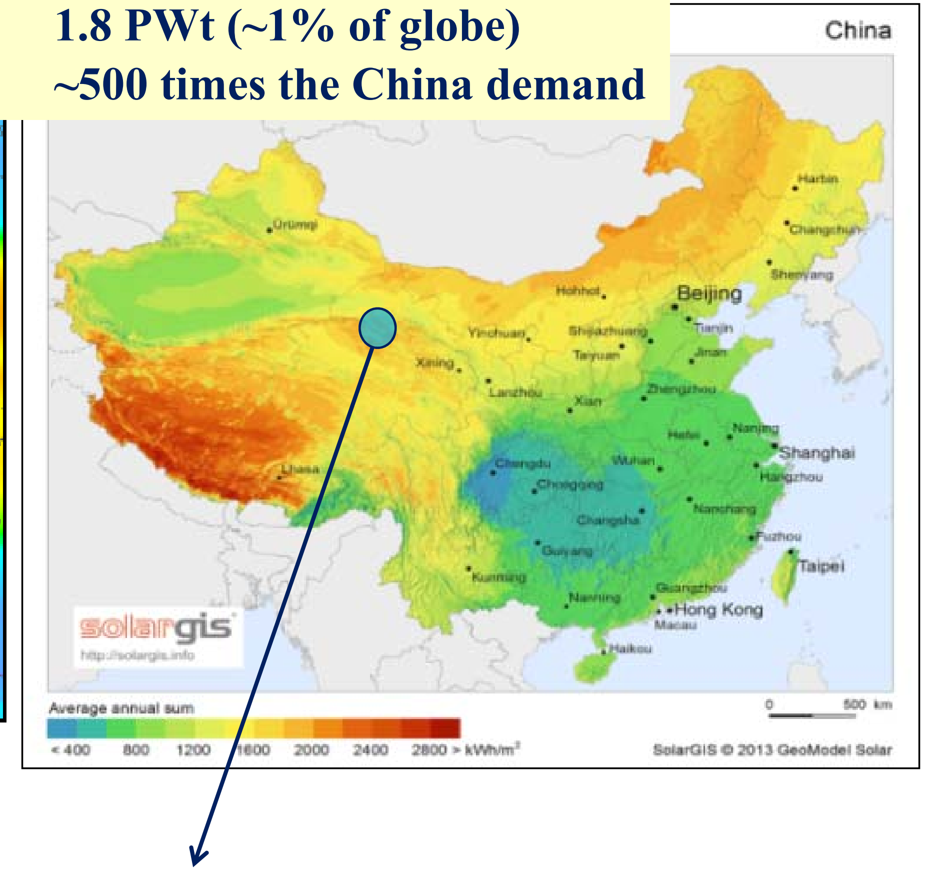
- **High-temperature reviver and storage**
  - ✓ Air/particle receiver
  - ✓ sensible/chemical storage
- **Advanced cycles**
  - ✓ Air Brayton
  - ✓ S-CO2 Brayton
  - ✓ Stirling cycle
  - ✓ PETE

Solar resources: potential renewable energy

- World : 170 PWt (170×10^{15}W)
- ~5000 times the demand of human beings



- 1.8 PWt (~1% of globe)
- ~500 times the China demand



- The six pionts =
  the global electricity demand (@η 8%)

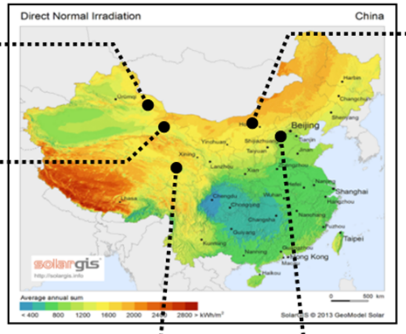
- 200,000 km² can afford the electricity demand of China in 2020

CSP Development in China

Hami,Xinjiang新疆(1)
1 molten salt tower

Dunhuang, Yumen, Gansu 甘肃(8)
3 molten salt towers
3 thermal oil troughs
1 molten salt trough
1 molten salt fresnel

Delingha, Gonghe, Qinghai 青海(3)
2 molten salt towers
1 thermal oil troughs



Wulate乌拉特，Inner Mongolia 内蒙 (1)
1 thermal oil troughs

Zhangjiakou, Hebei河北(3)
1 molten salt towers
1 molten salt trough
1 water Fresnel

16 projects are issued by Chinese government with the total capacity of ~1GW.

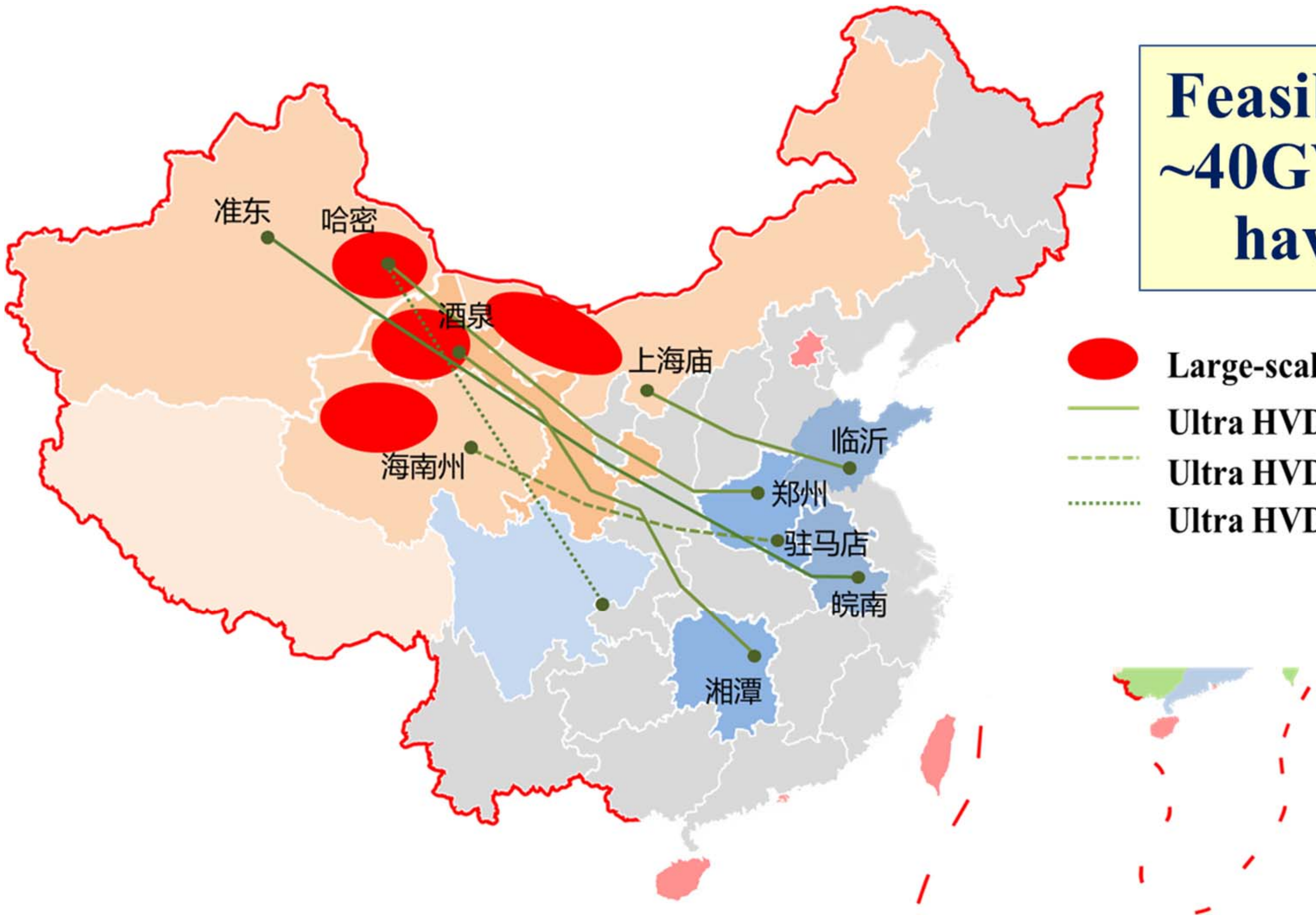
3 has been built, 5 will be completed in 2019, 8 will be finished in 2020

中广核CGN 50MW Parabolic Trough

首航Shouhang 100MW tower

中控Supcon 50MW tower

Electricity transmission from West to East of China



Feasibility reports of ~40GW CSP projects have been made

- Large-scale CSP parks -planning
- Ultra HVDC Transmission-operating
- Ultra HVDC Transmission- under construction
- Ultra HVDC Transmission-planning

UHVDC>800kV

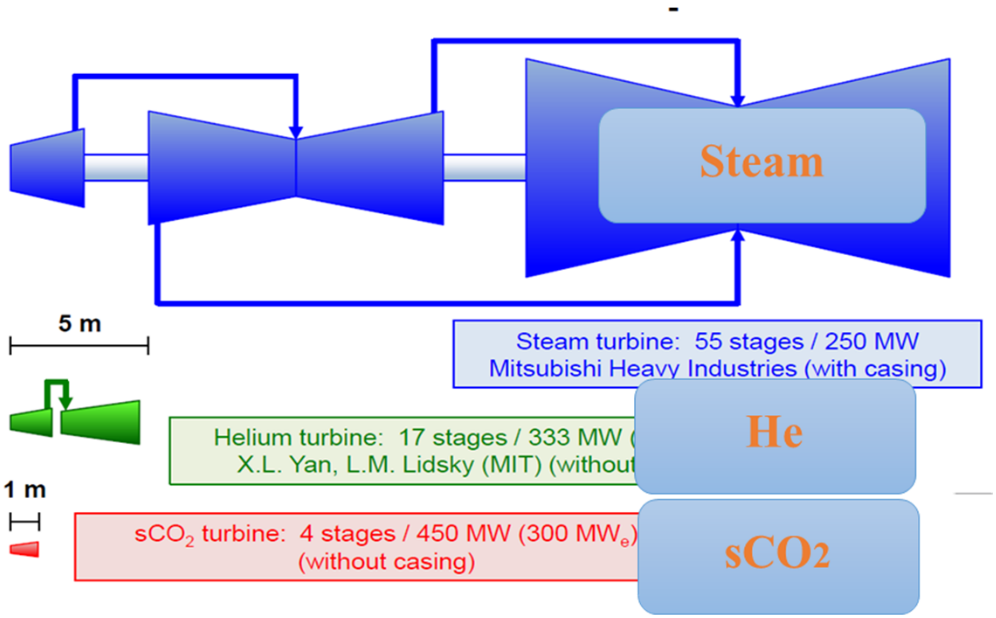
- ☐ Water is challenging
- ☐ Advanced technology is expected

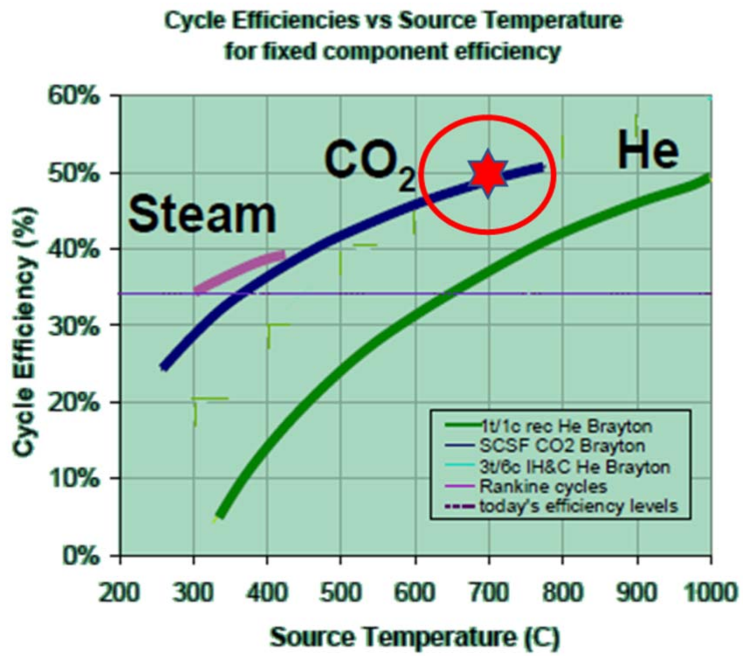
Challenges & next generation technologies

Items	Trough&Fresnel	Tower	Dish	……
Concentration ratio	60~130	400~600	500-1000	**400-2000**
Heat transfer	Oil/steam/MS	molten salt/DSG	H2/He	**gas/solid**
Working medium	water/steam	water/steam	H2/He	**gas/solid**
Cycle	Rankine	Rankine	Stirling	**Brayton/combined**
Temperature	<400°C	<580°C	700-800°C	**700-1400°C**
η_e	<15%	<20%	<32%	**25-40%**
Water kg/(kWh)	~0.3	~0.2	~0.01	**~0.01**

High temp.→high eff. & less water (flexible & suitable for adjusting the grid peaks)

sCO_2 Brayton is potential for next generation of CSP (compact、high efficiency)

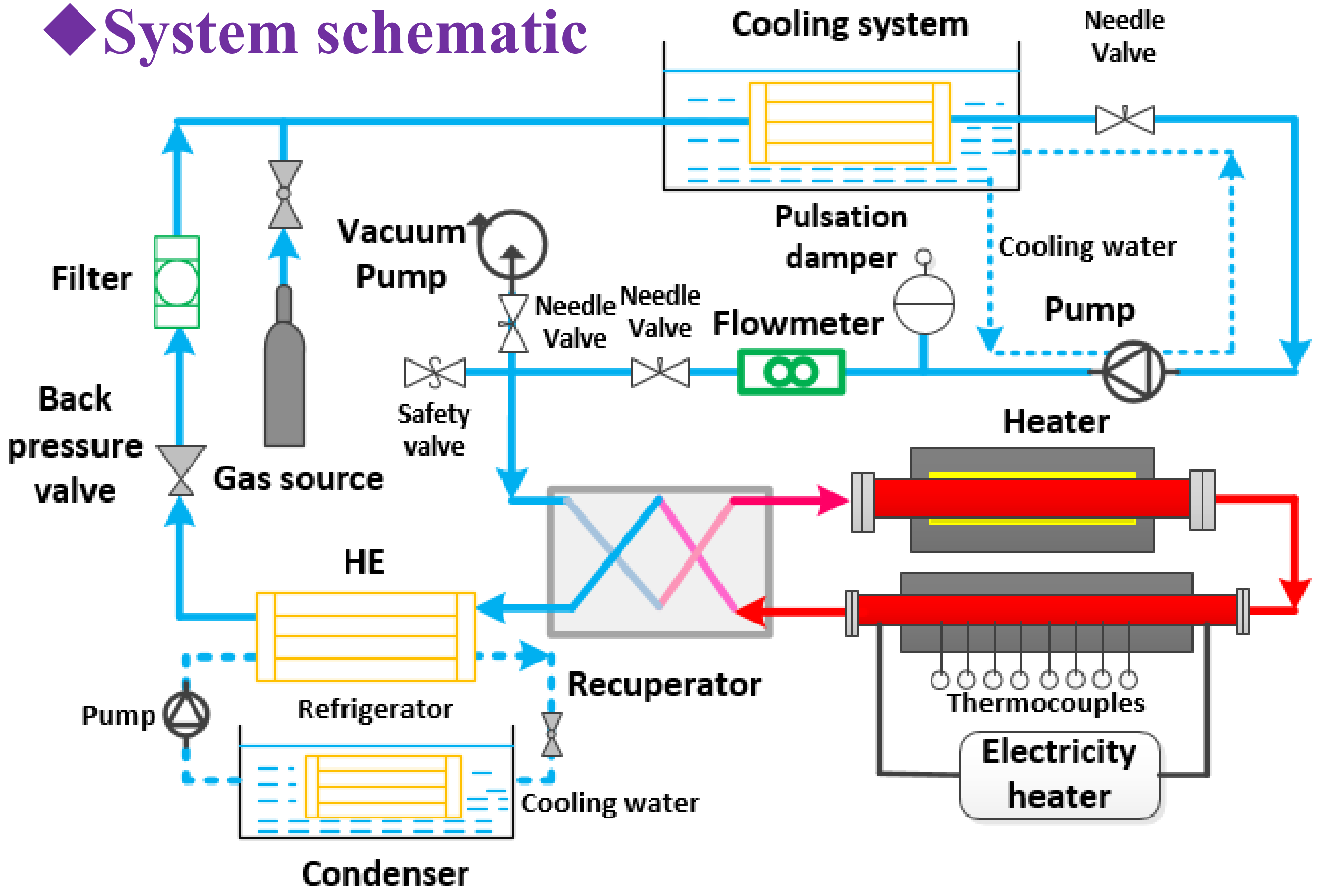




- **High efficiency (Cycle efficiency >50% when TIT is higher than 700℃).**
- **Compact (smaller than steam cycle).**
- **Low water consumption.**

sCO2 test loop at ZJU campus

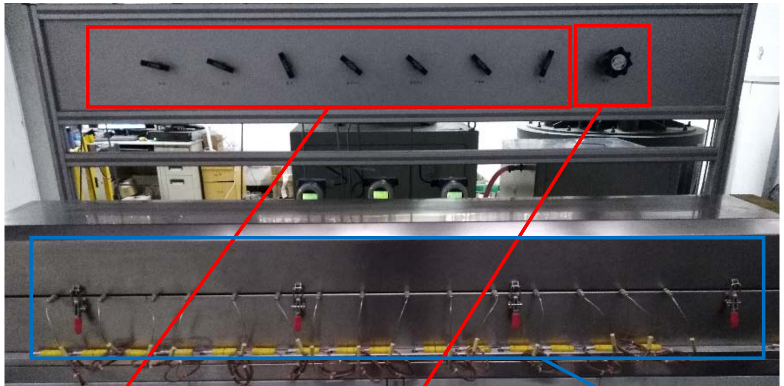
◆System schematic

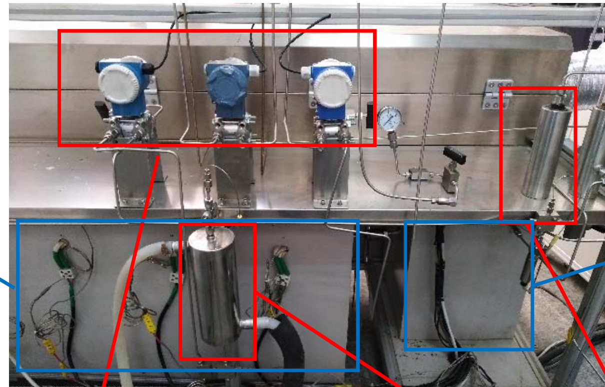


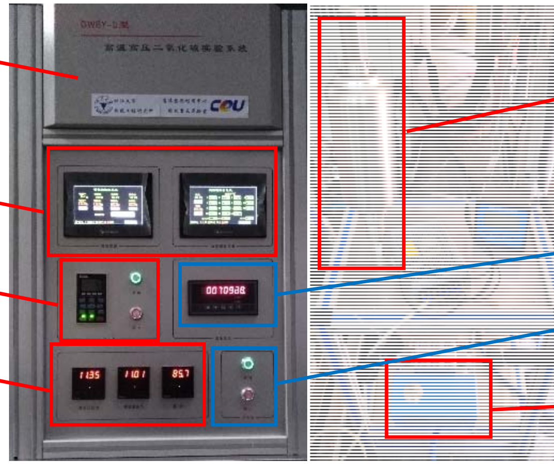
Parameter	Value
Mass flow rate	10~60 kg/h
Working temperature	30~500 °C
Working pressure	7~15 MPa

- The purpose of this work: investigate the dynamic performance of sCO_2 test loop.
- Three input variables for the system: the mass flow rate, the working temperature and the working pressure.
- Used the experiment results to develop simulation model.

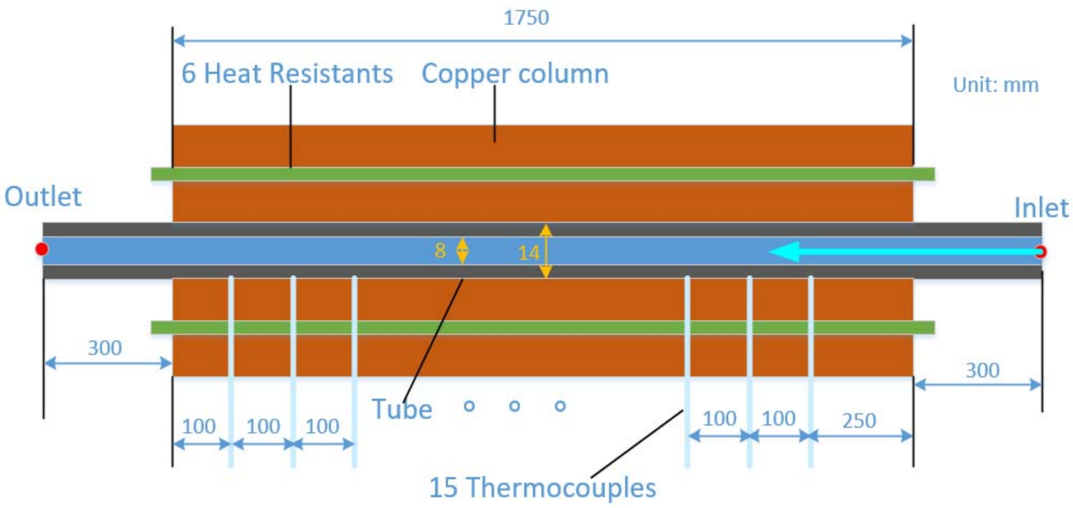
sCO2 test loop--System pictures







Experimental conditions



➢ Calculation method:

$$Nu = \frac{hd_i}{\lambda_{CO2}}$$

$$h = \frac{q}{LMTD}$$

$$LMTD = \frac{(t_{b,in} - t_{b,out})}{\ln\left(\frac{t_{b,in} - t_{w,i}}{t_{b,out} - t_{w,i}}\right)}$$

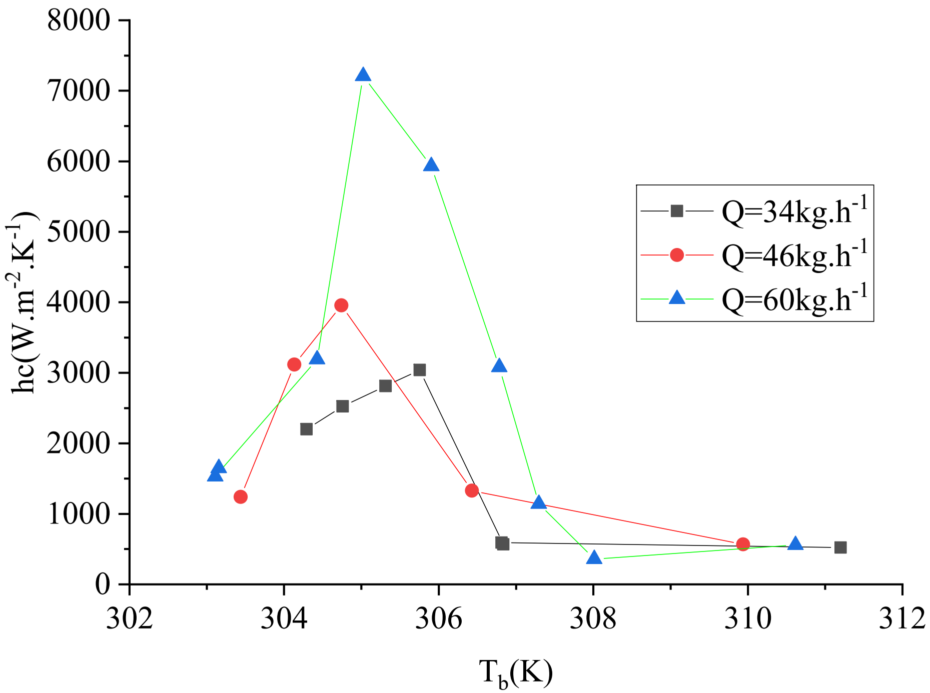
$$t_{w,o} = \frac{\left(\frac{\sum_{j=1}^{10} t_{w,i}}{10} + \frac{\sum_{j=3}^{13} t_{w,i}}{13}\right)}{2}$$

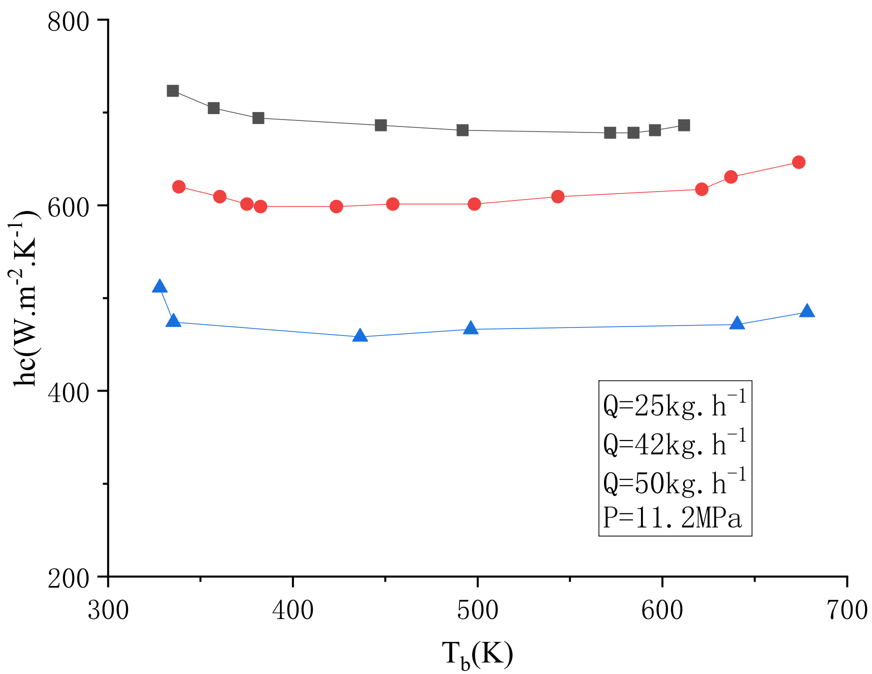
$$t_{w,i} = t_{w,o} + \frac{Q}{2\pi\lambda_c l} \ln\frac{d_o}{d_i}$$

$$t_b = \frac{t_{b,in} + t_{b,out}}{2}$$

Items	CO_2
Flow direction	Horizontal
Pressure	15MPa
Mass flow rate	20-60 kg/h
temperature	30~500 °C
Heat flux q	0~60kW/m^2
Reynolds number	2×10^4~1.1×10^5

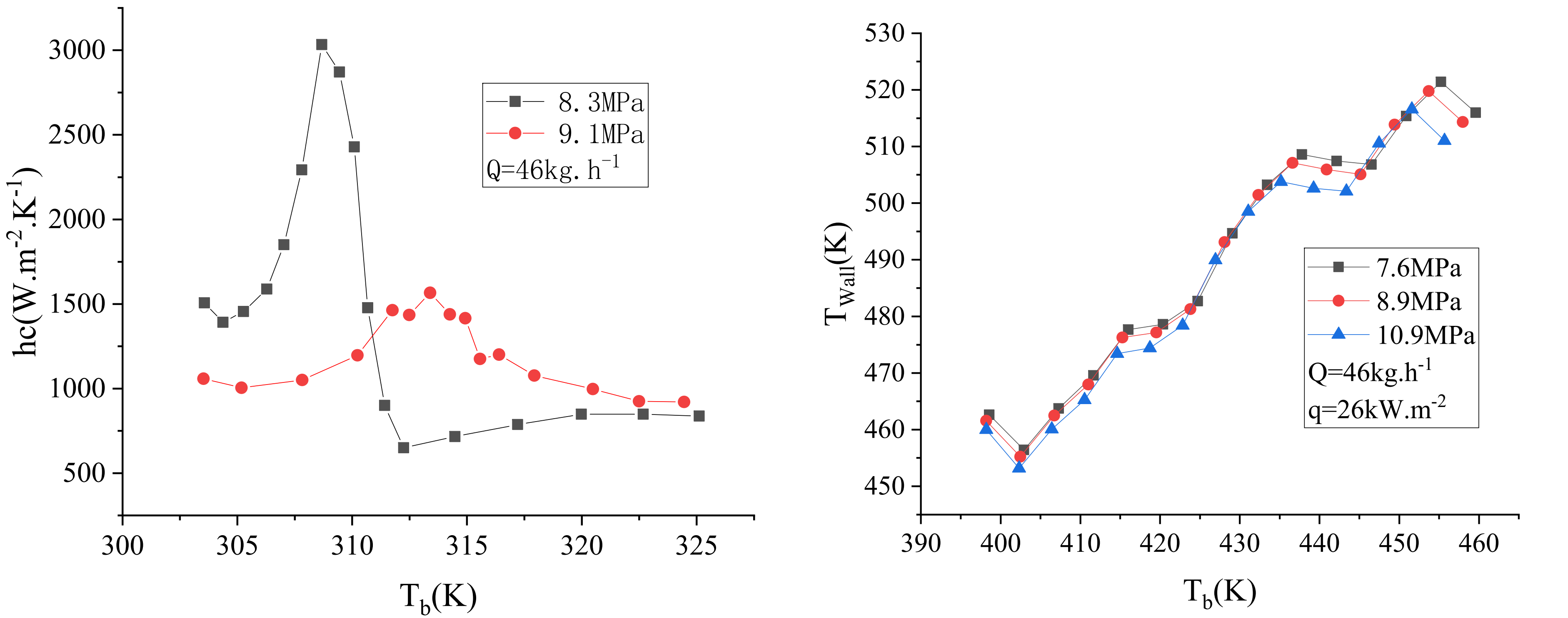
Effect of mass flux





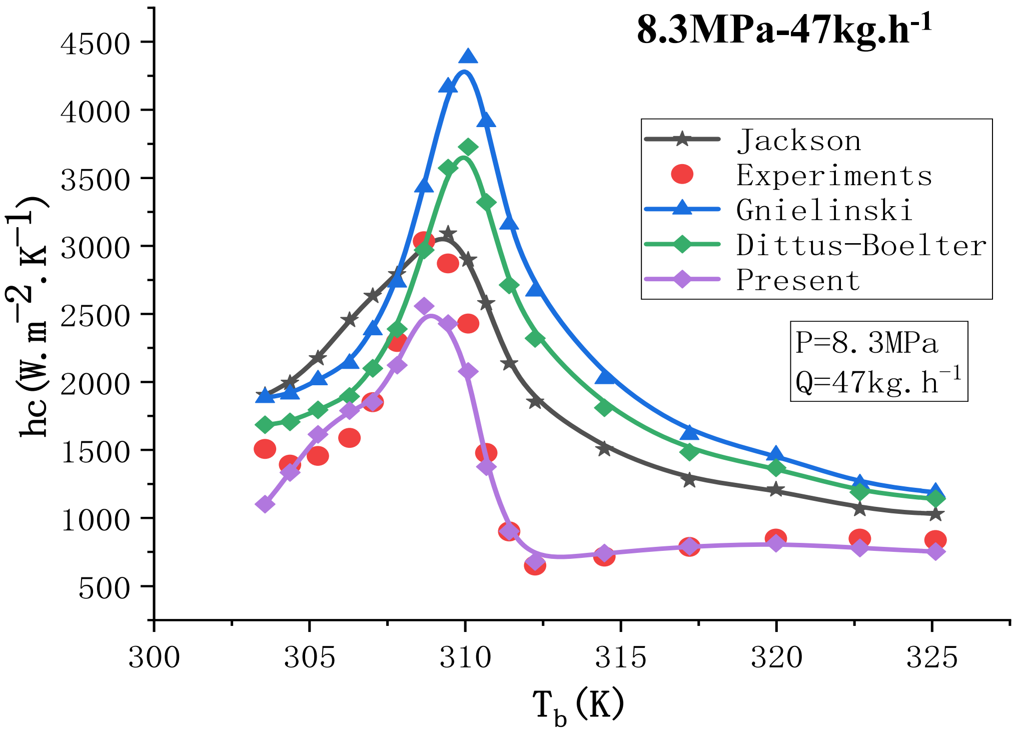
- As Q increases, the HTC increases too.
- Near the pseudo-critical temperature, heat transfer coefficient (HTC) reaches the peak point;
- For temperature >100°C, HTC is quite stable.

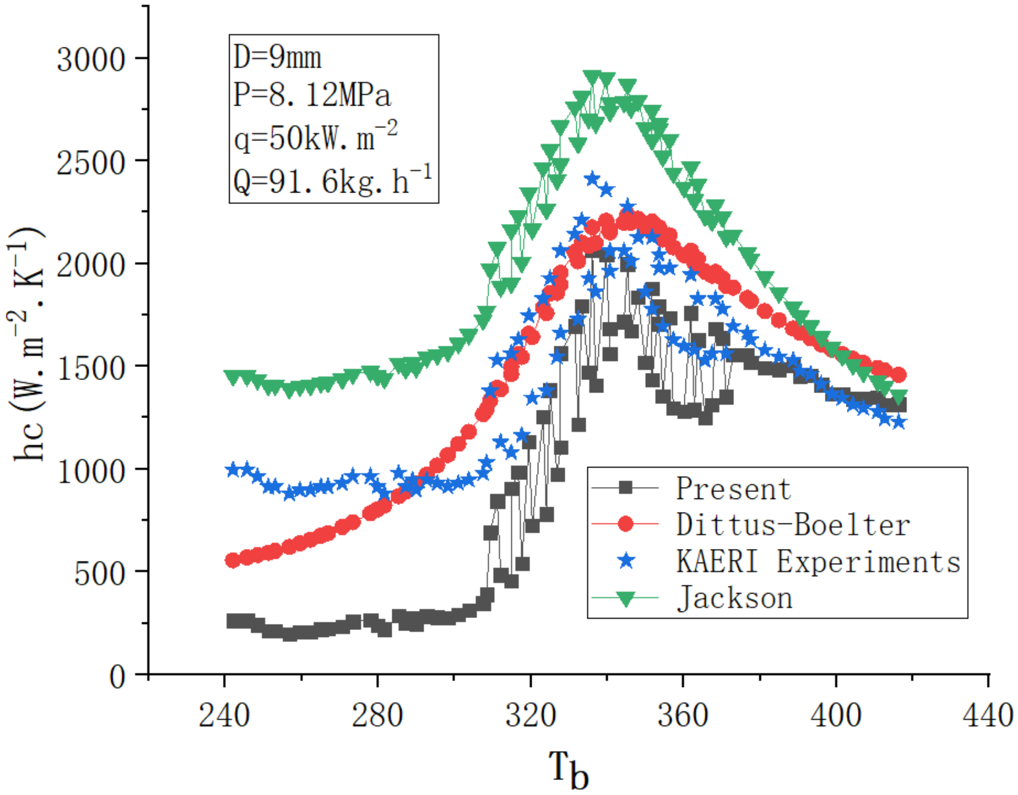
Effect of Pressure



- The higher pressure resulted in the lower HTC peak;
- when T >100 °C, the effect of pressure is not significant.

Correlations comparison



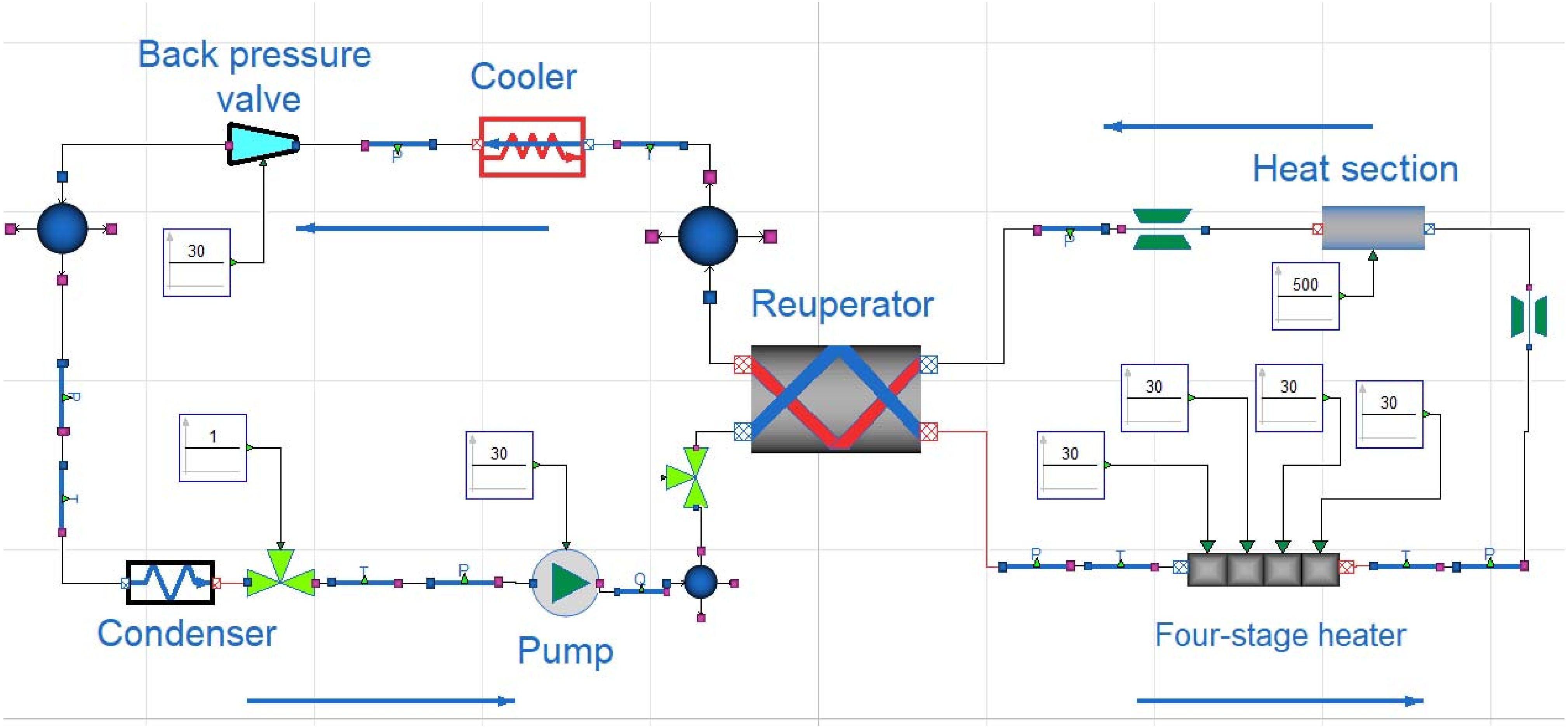


Concluded correlation:

$$Nu = 32.39 \mathrm{Re}_b^{1.0084} \mathrm{Pr}_b^{1.9876} \left(\frac{\rho_w}{\rho_b}\right)^{2.2123} \left(\frac{\overline{c_{p,w}}}{c_{p,b}}\right)^{0.7389} q^{+0.9935} c_t^{6.1590}$$

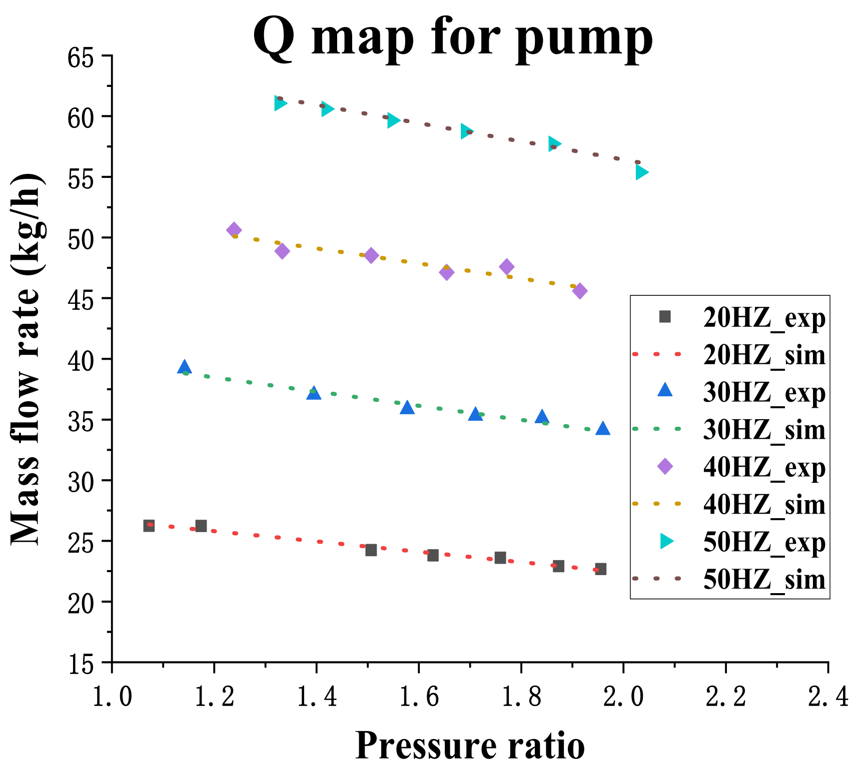
Data from: Bae Y-Y, Kim H-Y. Convective heat transfer to CO2 at a supercritical pressure flowing vertically upward in tubes and an annular channel. Experimental Thermal and Fluid Science. 2009;33:329-39.

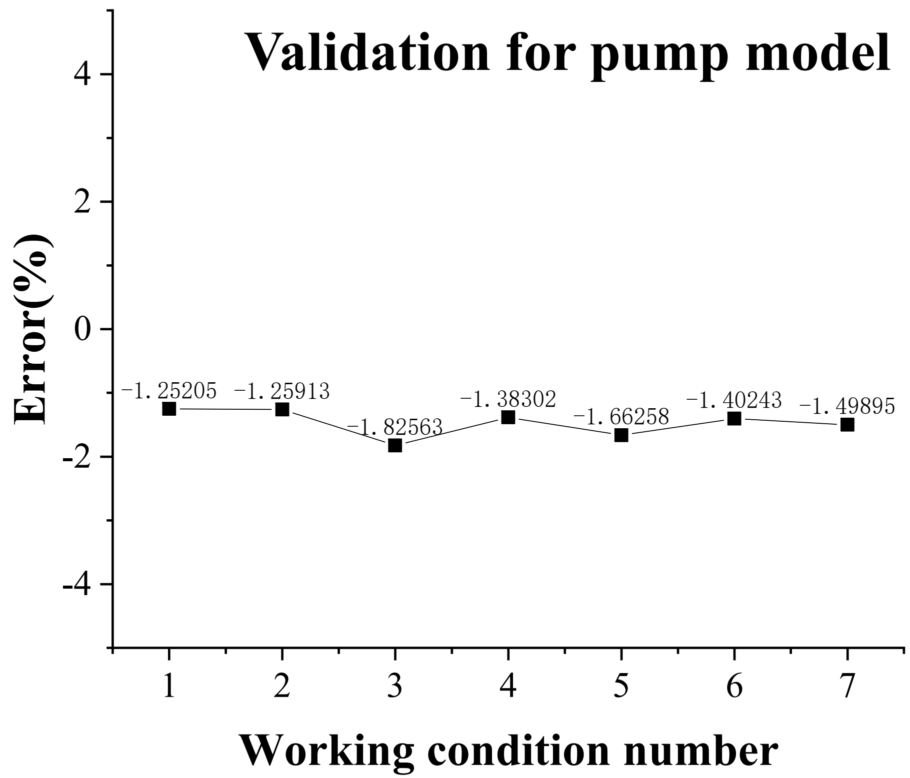
Simulation tool



Dymola-sCO_2 test loop model

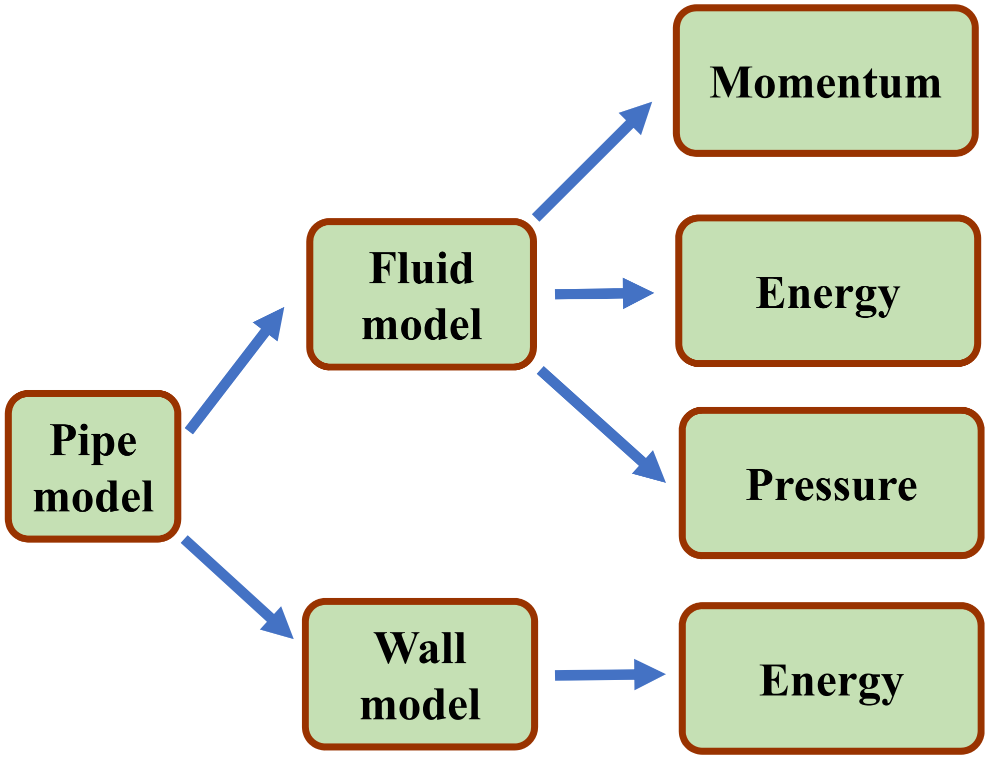
Pump model and steady state validation





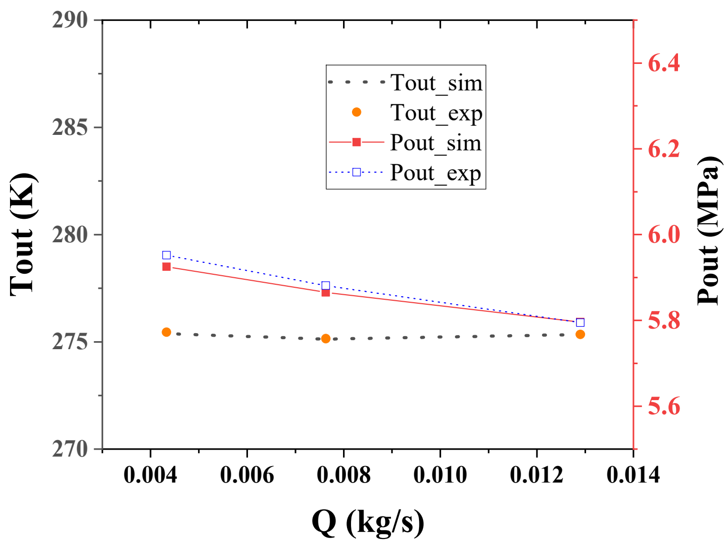
- The maximum error of the mass flow rate is ±1.67%.
- The maximum error for the outlet temperature is ±0.4%.

Pipe model

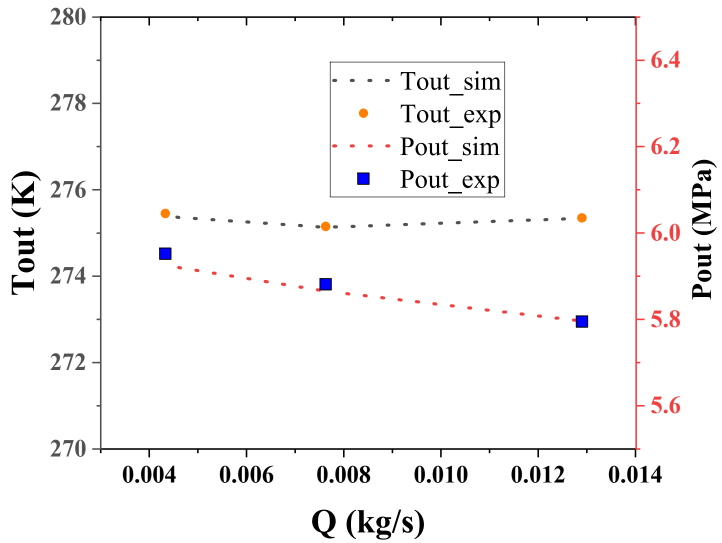


Heat exchanger	Pipe diameter Inner/Outer (mm)	Pipe length	Wall condition
recuperator	6/10	12	Normal heat loss to ambient (T_0=15 °C)
heater	6/10	12×4	Heating power (500W*4) PID control; Normal heat loss to ambient (T_0=15 °C)
Cooler	4/6	6	Heat loss to cooling water (T_0=0~10 °C)
Condenser	4/6	12	Heat loss to cooling water (T_0=-5~4 °C)
Heat section	8/14	2	Heating power (0~7.2 kW); Normal heat loss to ambient (T_0=15 °C)

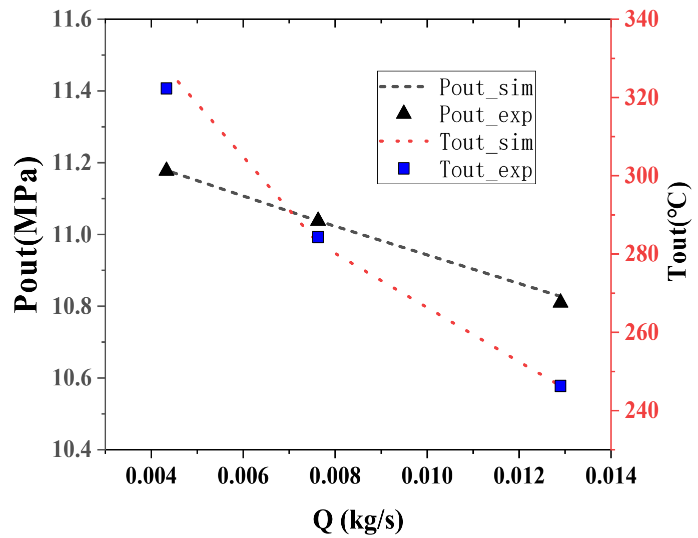
Steady state validation for components



P_{out}/T_{out}-cooler



P_{out}/T_{out}-condenser



P_{out}/T_{out}-test section

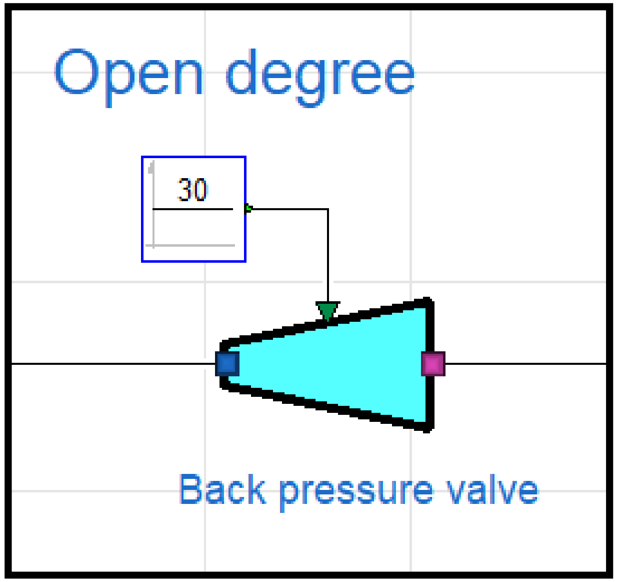
Components	Cooler		Condenser		Test section	
	Pout	Tout	Pout	Tout	Pout	Tout
Maximum Error (± %)	0.1	0.3	0.1	0.5	1.6	0.2

Valve models

Back pressure valve

Pressure drop:

$$\Delta P_f = \frac{Q^2}{2\rho} K \qquad K = signal.10^{12}$$

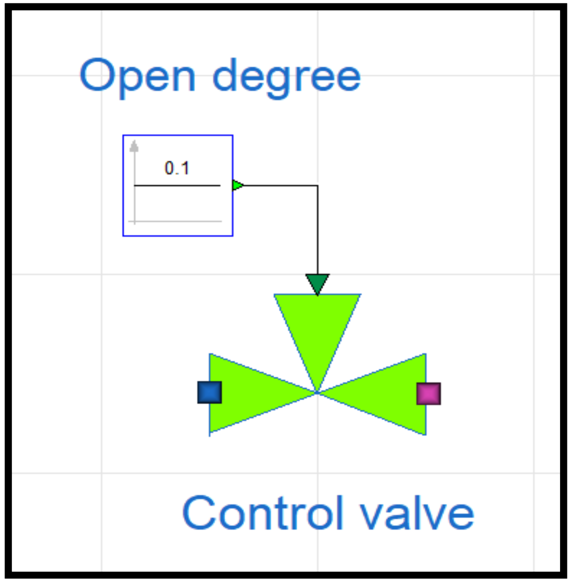


Control valve

Pressure drop:

$$\Delta P C v^2 = K \frac{Q^2}{\rho^2} \qquad Cv = Cv_{\max} signal$$

$K=1.733 \times 10^{12}$ Cvmax=8005.42



Conclusion

- The HTC reaches the peak value near the pseudo-critical temperature, but is stable when T> 100 °C.
- A new correlation is concluded for the working conditions in this test loop. It is used in the test loop simulation model to give a better prediction of HTC.
- The steady state validation for the main components have been done. The error between simulation and experiment results are ranged from ±0.1 % to ± 1.67%.

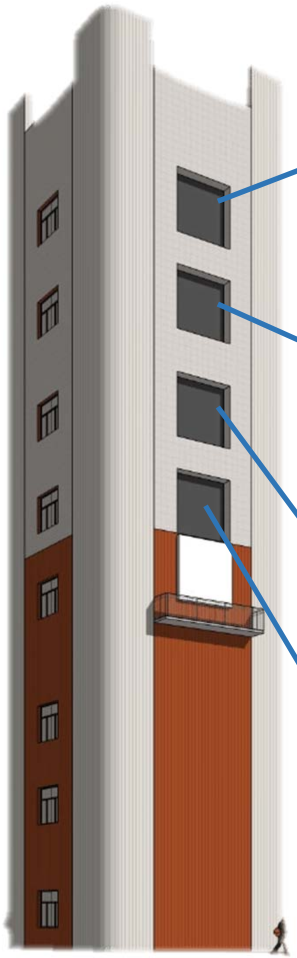
Future work

- **More comprehensive steady state validation.**
  - All components should be validated with more experiment results.
- **More Experimental and simulation work on dynamic conditions.**
  - Start-up and shut-down operations for the sCO_2 test loop.
  - Smart control strategies
- **To Build a 150 kW sCO_2 Brayton test loop combined with a MWth solar tower built in Zhejiang University.**

1MWth solar tower test platform

- Solar thermal power: 1 MW_{th}
- Tower height: 40 m
- Heliostats area: 2000 m^2 （100*20m^2）
- High temperature receiver > 900 °C
- Thermal storage > 800 °C
- Brayton cycle (air, sCO_2)
- Stirling cycle
- PETE(photon enhanced thermionic emission)

MWth solar tower test platform



Gas turbine system, Air receiver and **Thermochemical storage**.
Height: 34.85m

- Air Brayton cycle:
  1) Power output:100 kW
  2) Efficiency: 30%

Particle receiver and storage, **S-CO_2** system.
Height: 30.35m

- S-CO2 system:
  1) Power output: 150 kW
  2) Efficiency: ~30%

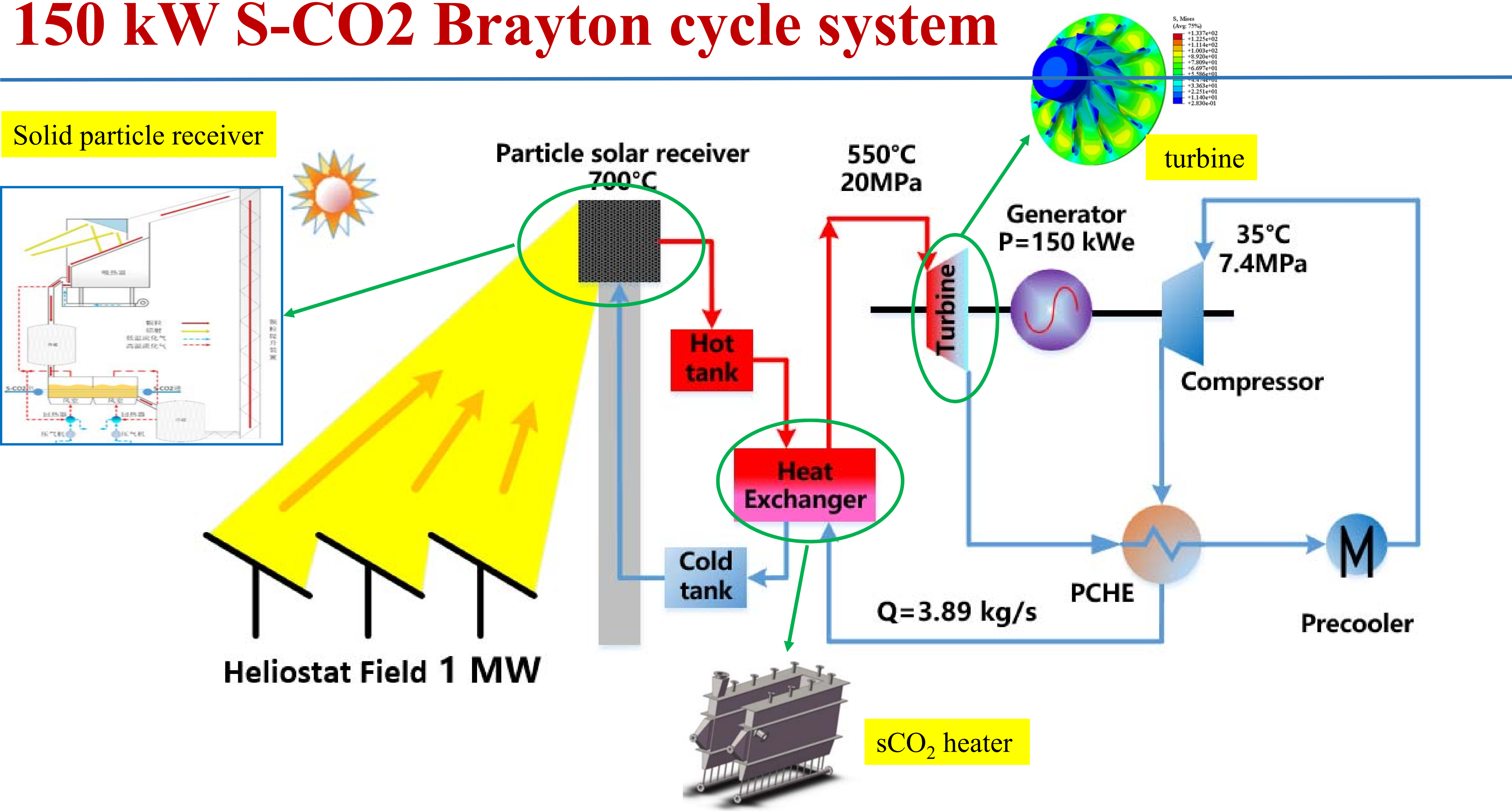
Molten salt system and Receiver.
Height: 25.35m

- Molten salt system:
  1) T_{in}: 290 ℃
  2) T_{out}: 560 ℃

PETE and **Stirling** engine.
Height: 20.85m

- Stirling engine:
  1) 1~30kW
  2) Efficiency: 20-30%

150 kW S-CO2 Brayton cycle system



Thank you!

Thanks to EDF (China)