# Preliminary design study on a Multi-Megawatts Fossil-based Supercritical $CO_2$ Recompression and Reheat Integral Test Facility

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TPRI

# Motivation

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Advanced 620 ℃ Supercritical CO2 Brayton Cycle
28Mpa/620℃/620℃

The most state of the art USCW coal based utility, ST600℃, **Plant efficiency 44.5%。How to improve?**

Supercritical $CO_2$ Brayton Cycle

**ASCBC at 620℃ could achieve equivalent plant efficiency of SCW at 700 ℃ >50%?**

CSP and Nuclear high temperature sources; **GTCC&IGCC bottoming cycle;** Industrial Waste Heat recovery;

Advanced700 ℃USCW
36.65Mpa/700℃/720℃

Advanced 600 ℃USCW with double Reheat
33Mpa/600℃/620℃/620 ℃

Advanced 600 ℃ USCW
28Mpa/600℃/620℃

Supercritical Steam Rankine Cycle

**Nickel-based 700 ℃ Alloys**
Capital and technology intensive; time-consuming ;
Coupon tests failed in Europe
layout of 700℃ furnace and turbine.

# What is $SCO_2$-Brayton Cycle?

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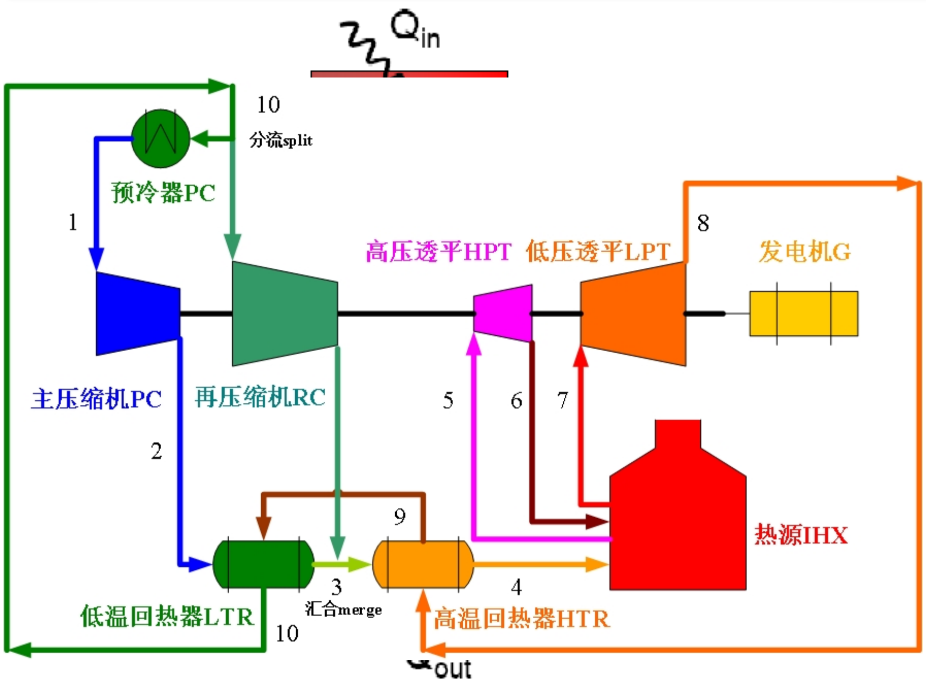
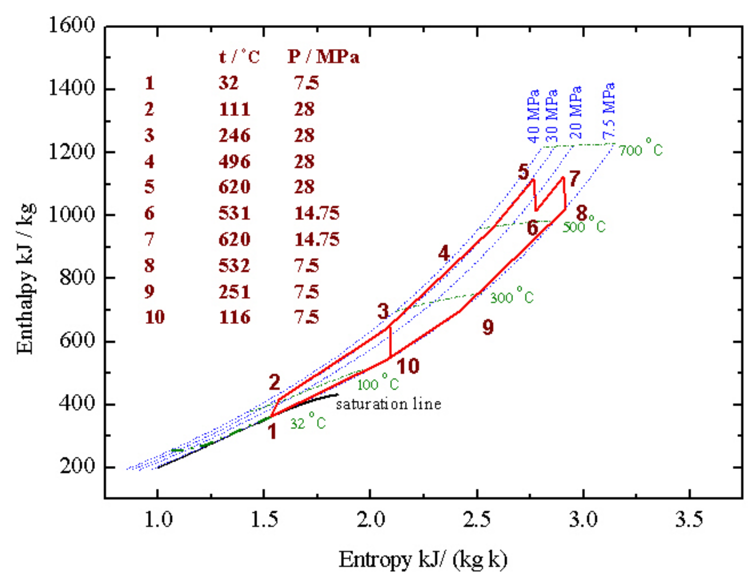
| | Steam Rankine Cycle | IG Brayton Cycle | $SCO_2$ Brayton Cycle |
|---|---|---|---|
| Compress | Pump | Compressor | Compressor |
| Heating | Boiler | Combustion Chamber | IHX |
| Expand | Turbine | Gas turbine | $SCO_2$ turbine |
| Cooling | Condenser | Ambiance | Precooler / Recuperator |



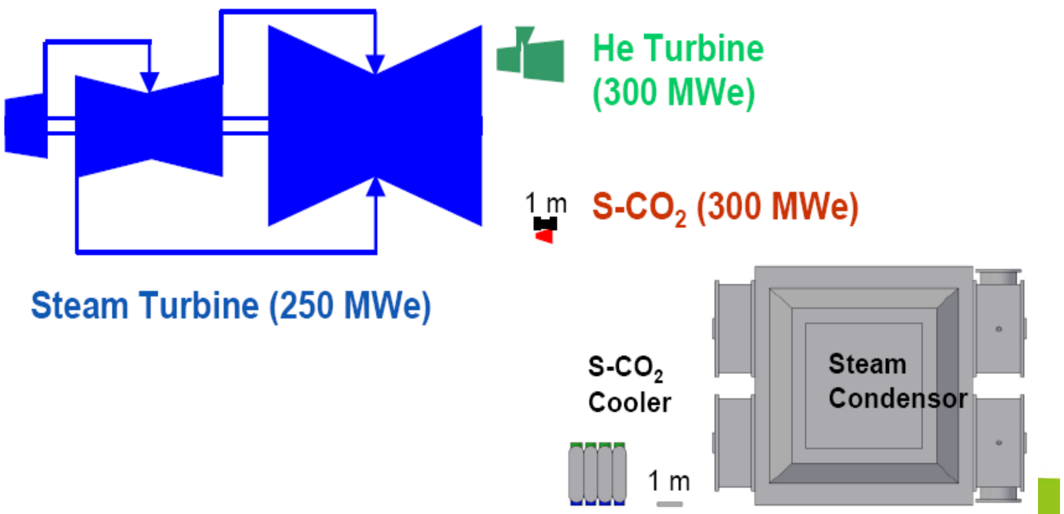
# Why $SCO_2$ ?

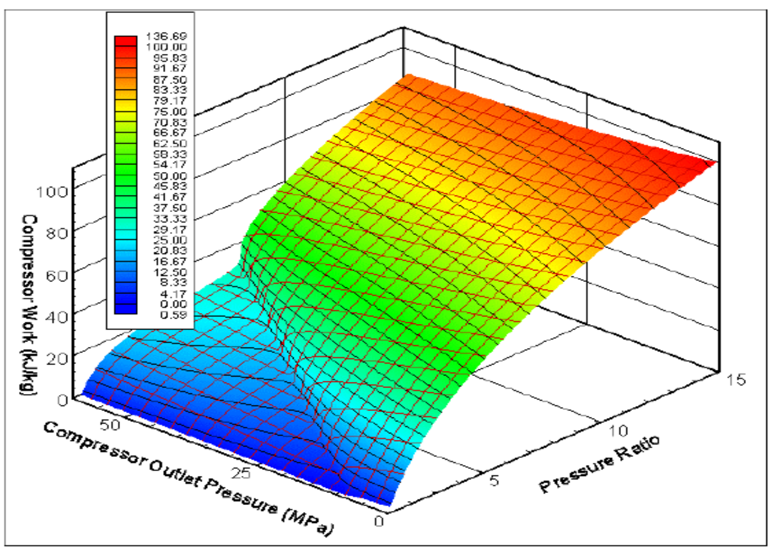


## ◆ $SCO_2$ is an attractive working fluid

- **moderate critical parameters**
  **7.29MPa, 30.98℃; accommodate a large range of temperatures;**
- **combined liquid and gas properties**
  **large density with relative low viscosity; condensed gas;**
- **less corrosive and environmentally friendly**
  **no need for water quality control and treatment support;**
- **higher power density**
  **significantly reduced component size;**
- **almost incompressible near critical point**
  **reduced compressor work;**

## Why $SCO_2$ Can Displace Steam ?



# Why $SCO_2$ ?

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## ◆ $SCO_2$ BC is a high efficiency and cost effective cycle

- ➢ high efficiency at moderate temperature
  Thermal efficiency > 50% possible @ 28MPa / 620 ℃ / 620 ℃;
- ➢ no phase change
  simple cycle layout and small plant footprint;
- ➢ low pressure ratio and high power density
  small turbomachinery;
- ➢ High recuperative
  ~2/3 of the cycle energy is recuperative heat;

| Lower Capital cost | | Lower O&M cost | | Lower LCOE |
|---|---|---|---|---|
| civil;<br>equipment;<br>installation; | + | fuel;<br>personnel;<br>Water treatment; | = | 15-20% off |

# Existing and Ongoing ITF

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| | | |
|---|---|---|
| 1 | Sandia National Lab | 7.68-13.84MPa；32℃-342℃，240kWe；31.5%；50000RPM；turbine efficiency 68% |
| 2 | Bechtel Marine Propulsion | 9.03-13.5MPa；36℃-299℃；100kWe；cycle efficiency 14.7%；60000RPM |
| 3 | Echogen | Waste heat 7MWe；TIT 275℃ |
| 4 | Tokyo Institute Technology | 30kWe small Test loop |
| 5 | DOE & NREL & SNL & BNL & UW & Echogen & EPRI &AB SOLAR | CSP 10MWe;8-28MPa;45-700℃; |
| 6 | SWRI & GE & Thar Energy | 1MWe simple loop; |
| 7 | KAIST/KAERI | 33.2℃；500℃; 7.78-20MPa |
| 8 | EDF/GE | 20MWe coal based pilot plant |
| 9 | NetPower & Toshiba | 50MWe Allam cycle |

# TPRI 5MWe Integral Test Facility

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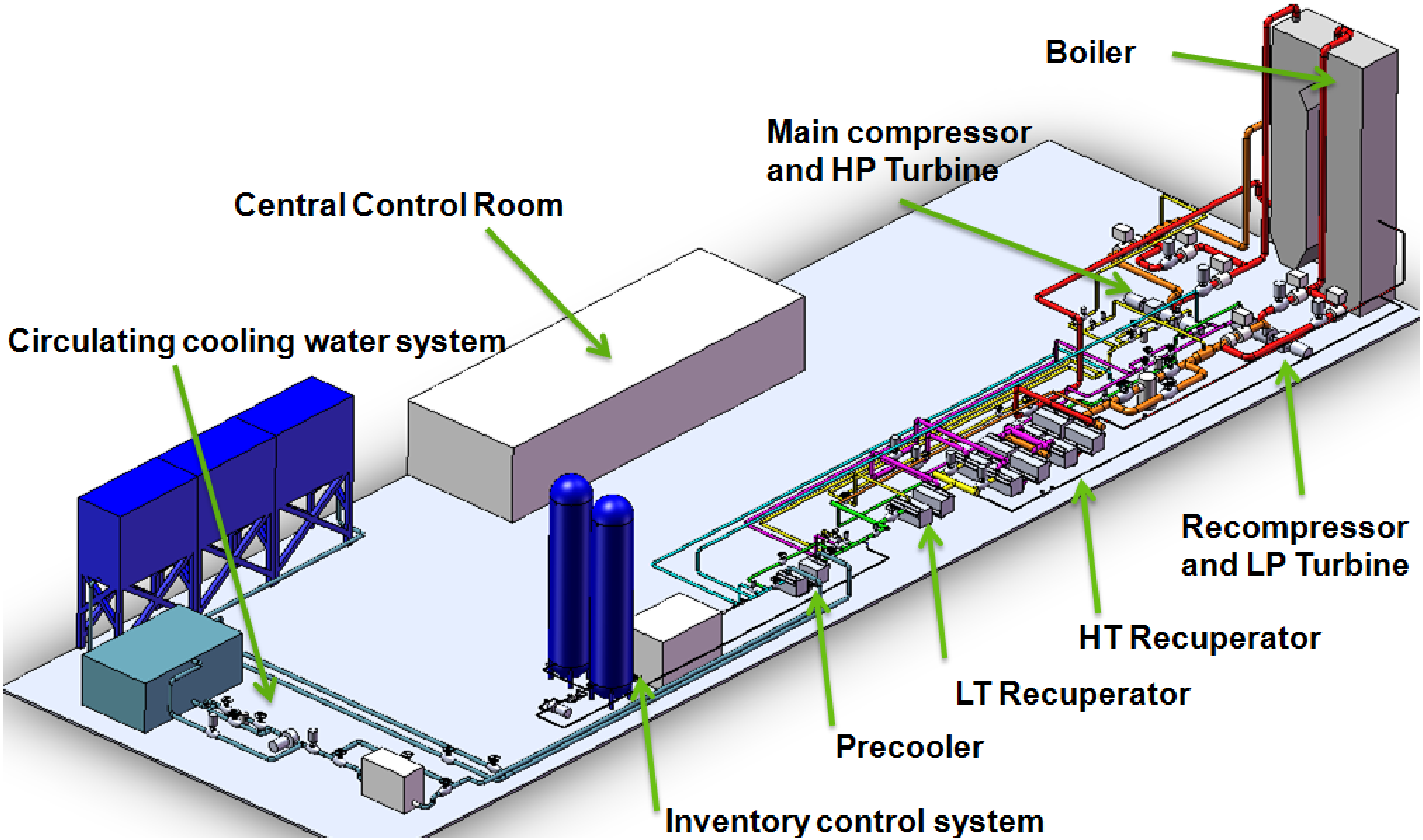

# System design

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| | | | | | |
|---|---|---|---|---|---|
| SR to Recompressor | / | 0.384 | HPT work | MW | 4.687 |
| SR to Economizer | / | 0.08 | LPT work | MW | 4.75 |
| HPT-IP | MPa | 20 | MC work | MW | 1.588 |
| HPT-IT | ℃ | 600 | RC work | MW | 2.643 |
| HP expansion ratio | / | 1.527 | Boiler duty | MW | 14.557 |
| LPT-IP | MPa | 12.69 | LTR duty | MW | 12.011 |
| LPT-IT | ℃ | 600 | HTR duty | MW | 34.586 |
| LP expansion ratio | / | 1.527 | PC duty | MW | 9.351 |
| MC-IP | MPa | 7.6 | Net capacity | MWe | 5 |
| MC-IT | ℃ | 32 | Boiler efficiency | % | 94 |
| MC PR | / | 2.816 | MC efficiency | % | 70 |
| RC-IP | MPa | 7.71 | RC efficiency | % | 72 |
| RC-IT | ℃ | 80.085 | LPT efficiency | % | 82 |
| RC PR | / | 2.737 | HPT efficiency | % | 80 |
| Mass Flow Rate | t/h | 304.37 | Cycle gross efficiency | % | 32.29 |

# Inventory Control

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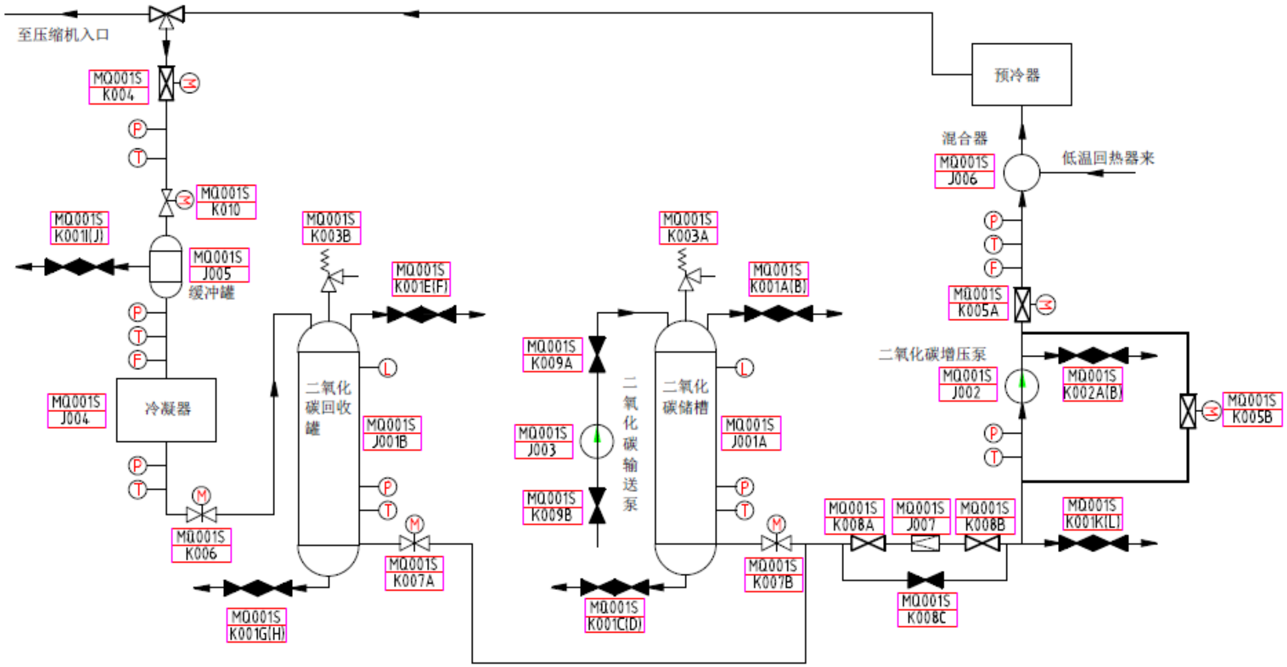
**Cryogenic storage for expansion tanks design widely used in industry**

**P=2.16MPa；T=-30℃；V=12m³**




# Turbomachinery

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| | Unit | MC | RC | HPT | LPT |
|---|---|---|---|---|---|
| mass flow rate | kg/s | 52.08 | 32.47 | 84.55 | 84.55 |
| work | MW | 1.58 | 2.64 | 4.68 | 4.75 |
| impeller diameter | mm | 140 | 200 | 120 | 200 |
| inlet pressure | MPa | 7.6 | 7.7 | 20 | 12.7 |
| inlet temperature | ℃ | 32 | 80 | 600 | 600 |
| inlet density | $kg/m^3$ | 557.5 | 152.4 | 116.7 | 75.26 |
| outlet pressure | MPa | 21.4 | 21.1 | 13.09 | 8.31 |
| outlet temperature | ℃ | 70.1 | 187.3 | 551.3 | 551.1 |
| outlet density | $kg/m^3$ | 684.6 | 288.58 | 82.4 | 52.76 |
| shaft speed | rpm | 30000 | 30000 | 30000 | 30000 |
| isentropic efficiency | % | 70 | 72 | 80 | 82 |

# Turbomachinery

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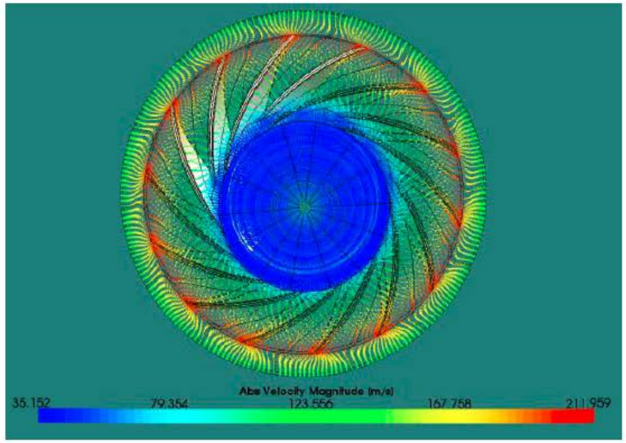
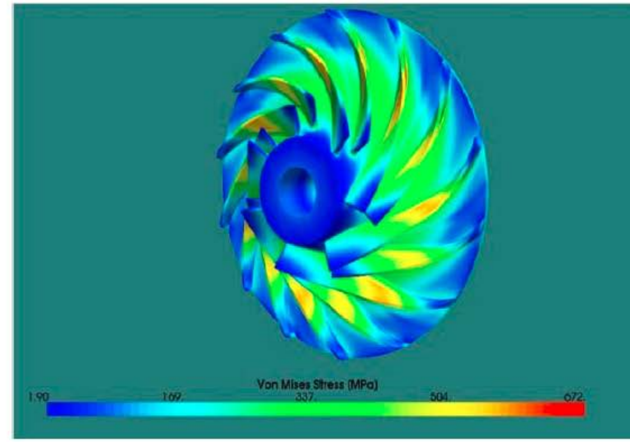
**Compressor:**
**Titanium alloy**

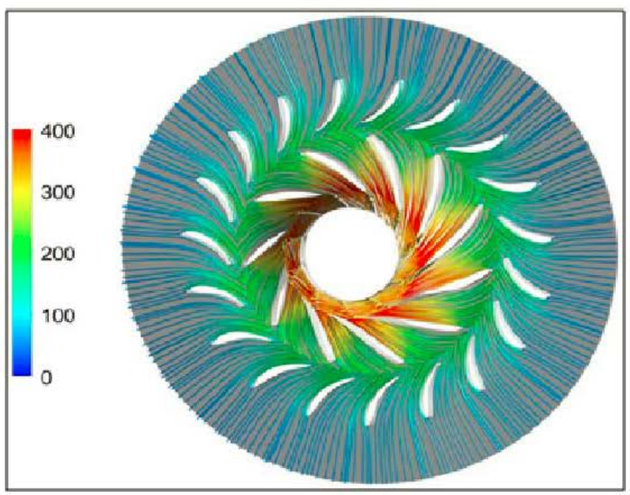
**Max Von Mises stress is 622MPa**

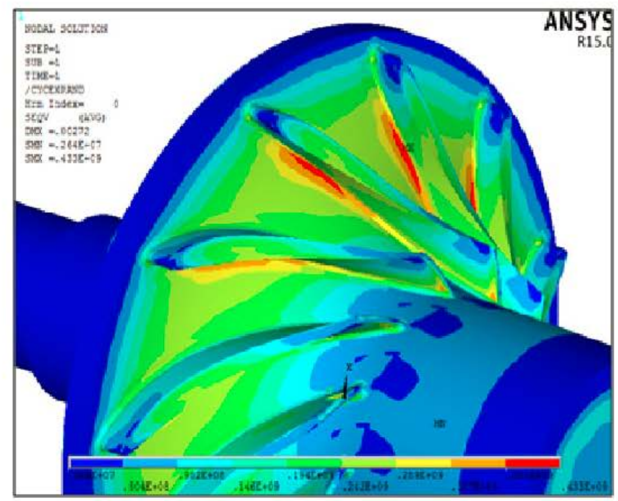



**Turbine:**
**Inconel 718**

**Max Von Mises stress is 433MPa**



# Recuperators and Precooler

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| | | HT Recup | | LT Recup | | PC | |
|---|---|---|---|---|---|---|---|
| | | Hot | Cold | Hot | Cold | Hot | Cold |
| heat duty | MW | 34.58 | | 12.01 | | 9.5 | |
| heat transfer area | $m^2$ | 2460 | | 837.4 | | 360.59 | |
| unit size | m | 0.6×0.6×1.35 | | 0.6×0.6×1.35 | | 0.6×0.6×1.35 | |
| number of unit | / | 8 | | 2 | | 1 | |
| U | $W/(m^2K)$ | 978.6 | | 1215.4 | | 2463.6 | |
| average DT | K | 15.84 | | 12.31 | | 25.83 | |
| Volume | m3 | 1.4 | | 0.52 | | 0.14 | |
| Weight | t | 38 | | 10.6 | | 2.25 | |
| WF | | CO2 | CO2 | CO2 | CO2 | CO2 | H2O |
| MFR | kg/s | 84.55 | 77.78 | 84.55 | 52.08 | 52.08 | 110 |
| PI | MPa | 8.31 | 21.1 | 8.01 | 21.4 | 7.71 | 0.2 |
| PO | MPa | 8.01 | 20.8 | 7.71 | 21.1 | 7.6 | 0.11 |
| TI | ℃ | 551.1 | 187.3 | 197.4 | 70.1 | 80.1 | 20 |
| TO | ℃ | 197.4 | 540.1 | 80.1 | 187.3 | 32 | 32.5 |

# $SCO_2$ heat transfer model

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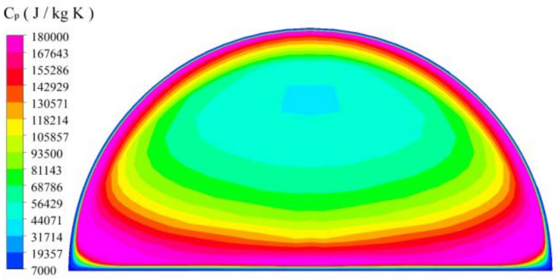
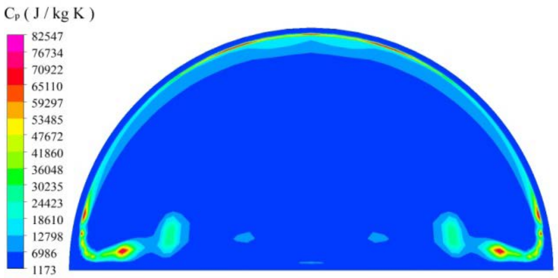
20 kW/m²



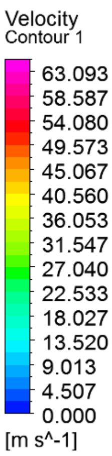

90 kW/m²




$$Nu_{b,pdf} = C\,Re_{b,pdf}^{m}\,Pr_{b,pdf}^{n}\left(\frac{\rho_{w,pdf}}{\rho_{b,pdf}}\right)^{p}\left(\frac{\overline{Cp}_{pdf}}{Cp_{b,pdf}}\right)^{q}$$

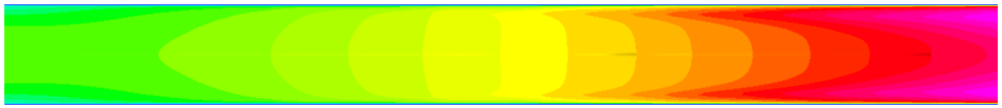
| | C | m | n | p | q |
|---|---|---|---|---|---|
| heating | 0.0281 | 0.729 | 0.675 | 0.466 | 0.532 |
| cooling | 0.0937 | 0.627 | 0.608 | 0.203 | 0.522 |

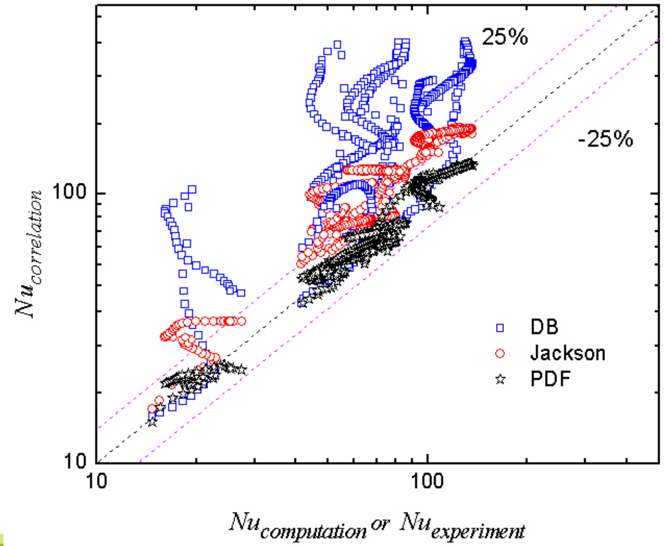
$$\phi(T) = \frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(T-\overline{T})^2}{2\sigma^2}}$$




Acceleration effect

“M-shaped” velocity profile





## Boiler

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| | | FWSH | FWRH | SH | RH | ECO | APH |
|---|---|---|---|---|---|---|---|
| Heat Duty | kW | 4809 | 3983 | 1590 | 989 | 3005 | 1746 |
| Heating surface Area | m2 | 39.6 | 32.8 | 63 | 89 | 315 | 1403 |
| flue gas IT | ℃ | | | 1012.7 | 854.6 | 733.8 | 351.1 |
| flue gas OT | ℃ | | | 854.6 | 733.8 | 351.1 | 118.7 |
| CO2/air IT | ℃ | 538.8 | 551.3 | 584.3 | 589.7 | 193.5 | 25 |
| CO2/air OT | ℃ | 584.3 | 589.7 | 600 | 600 | 538.7 | 290.8 |
| flue gas velocity | m/s | | | 14.89 | 13.27 | 12.57 | 10.7 |
| CO2 velocity | m/s | | | 23.67 | 19.78 | 4.95 | 5.83 |
| LMTD | ℃ | | | 334.4 | 194.6 | 175.7 | 63.2 |
| tube outside diameter | m | 25 | 25 | 42 | 42 | 38 | 38 |
| tube thickness | m | 5 | 4 | 5 | 4 | 4 | 2 |
| Outside wall temperature | ℃ | 621 | 611 | 605 | 590 | 550 | |
| volume | m3 | 0.212 | 0.225 | 0.384 | 0.612 | 1.865 | / |
| weight | t | 2.939 | 2.045 | 2.165 | 2.512 | 8.793 | 21.89 |

# Conclusions

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- $SCO_2$ power conversion technology has been extensively investigated around the world due to its compact components, simple plant layouts and the potential to significantly increase the efficiency.
- The existing laboratory scale integral demonstration test loops well verified the concept of the $SCO_2$ power cycle. However there are numerous hurdles need to address before the commercial scale achieve the efficiency benefits and reliable operation.
- TPRI are planning to build a $SCO_2$ R&R power cycle test loop with larger capacity and higher parameters aiming at the utility scale coal-based power plant.
- The initial system modeling and scaling as well as the key components preliminary design has been made for 5MWe ITF. The whole project was expected to accomplish at the end of 2017.

# Thanks for your attention!

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