# Development of a Small-Scale Supercritical $CO_2$ Turbine Power System


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# Objective

- **Develop a** “10kw SCO2 Turbine Power System” (**2016/ 01/ 01~2018/ 12/ 31**) ，including：
- 1. Indirect Heat Source SCO2 System

    for Waste Heat, Geothermal Source… ；
- 2. Direct Heating SCO2 System

    Oxyfuel Combustor Design & Preliminary test

*Joined with some heavy industries and Universities

# Industry Consortium

## China Steel

- Onsite available waste heat
- Agree to provide heat source to test
- Matching fund of 7.5%

## CSIST

- Provide Turbomachinery assistance

## MIRDC

- SCO2 Fluid Properties and System Monitoring

# Waste Heat in Taiwan

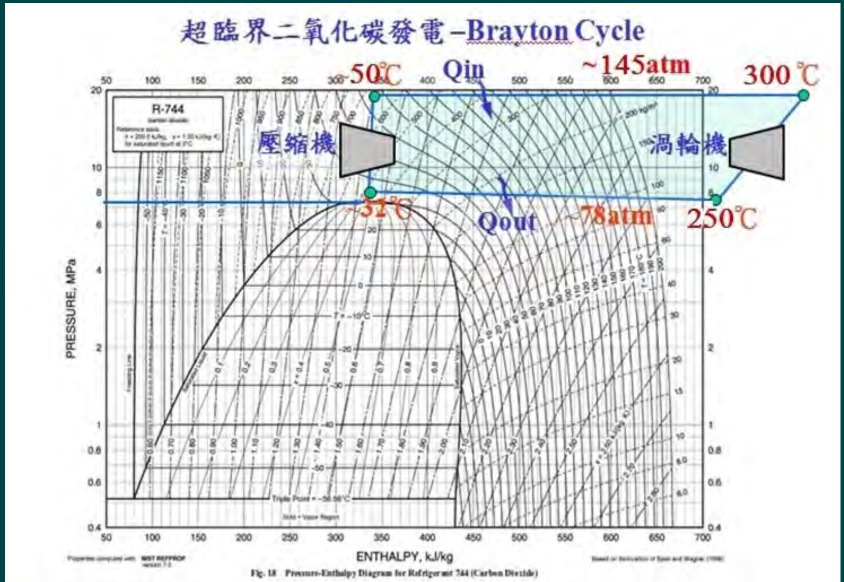
- High temperature waste heat recovery from cogeneration and boiler
- < 250°C waste heat recovery using ORC (μ=10~15%)
- Current heat recovery suffers from **cost** , **footprint** , **efficiency**

# Main Tasks

a. Design and Analysis of the SCO2 System Thermal Cycle；
b. Design and Fabricate of the Turbine & Compressor Subsystem;
c. Alternator (ISG) Design and Assembly;
d. 10 Kw SCO2 Power System Integration & Test
e. Oxyfuel Combustor Simulation, Design and Fabricate

# 10 Kw SCO2 System Specifications

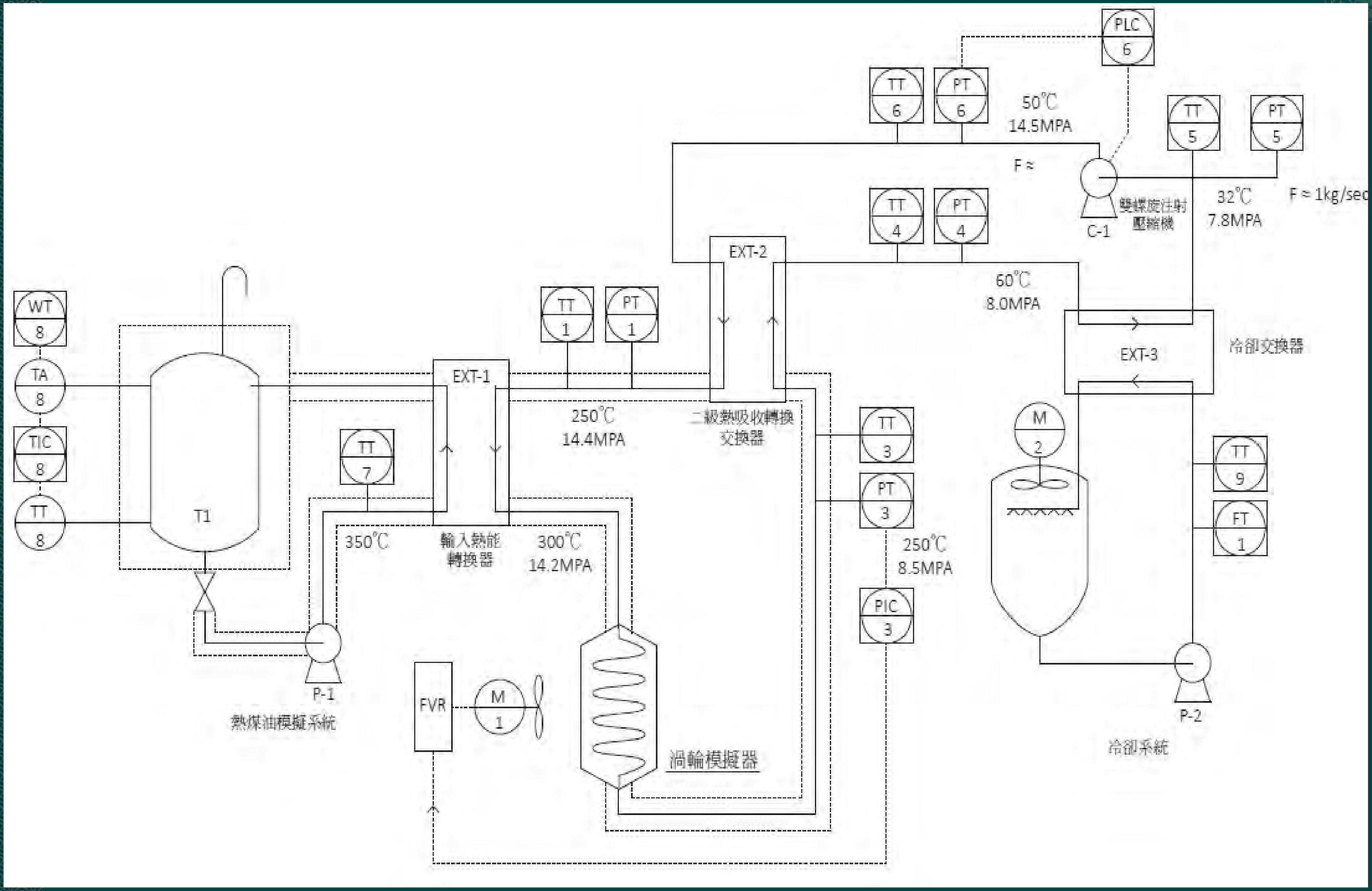
- a. Turbine Inlet Temp.~300 C, Pressure~14.1 Mpa.
- Turbine Outlet Temp. ~250 C, Pressure ~8.5 Mpa.
- Compressor Inlet Temp.~32 C, Pressure~7.8 Mpa.
- Compressor outlet Temp.~50 C, pressure~14.5 Mpa.
- Heat Exechanger Temp. difference(△T =50 C~150C),
- Pressure Loss each Step (△P~0.1Mpa )
- b. Compressor Outer Radius~4.0 cm,
- Turbine Outer Radius~4.0 cm.
- c. System SCCO2 flow rate~3.0 Kg/sec.
- e. Turbine Shaft RPM~30,000 rpm.
- f. Heat Source Temp.~350 C





1. ASHRAE Handbook, 2009.
2. Span, R. and W. Wagner, 1996."A new equation of state for carbon dioxide covering fluid region from triple-point temperature to 1100 K at pressures up to 800 Mpa. J. of physical and Chemical Reference Data 26: 1509-1596.
3. Robert Z. Litwin, "Supercritical CO2 turbine for use in solar power plants, US patent 7,6851820 B2 Mar. 2010.

# 10 kw SCO2 System Spec. & Design

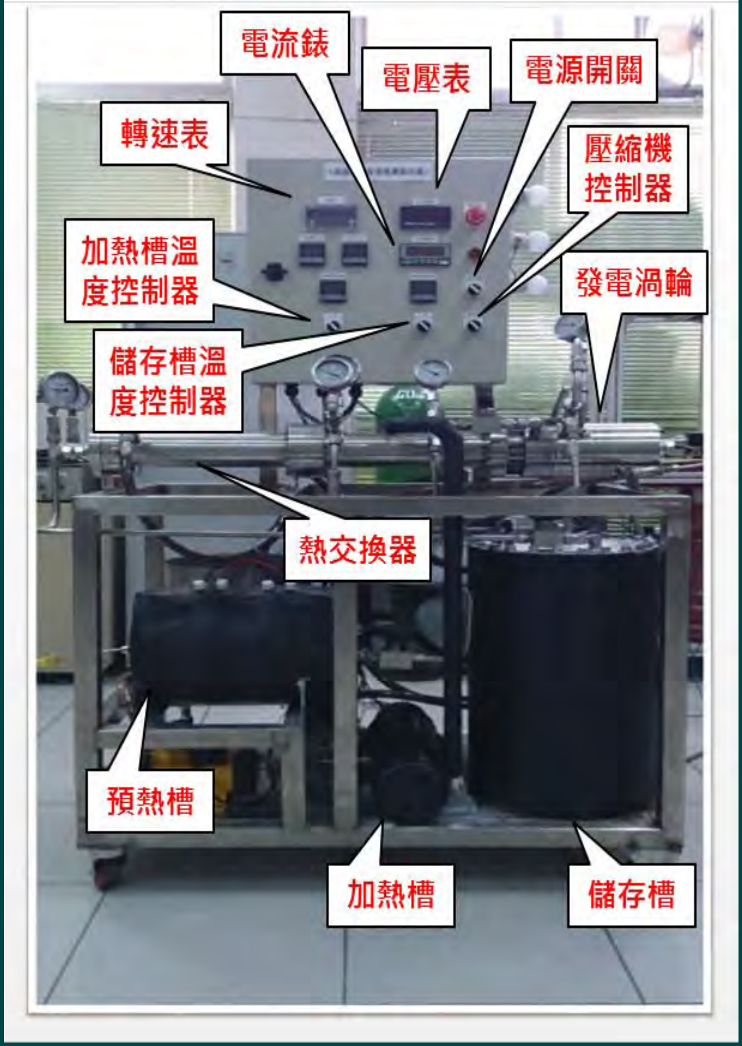


SCO2

# Power System Development Approach

# (1 kw→10kw → 250kw → Mw)

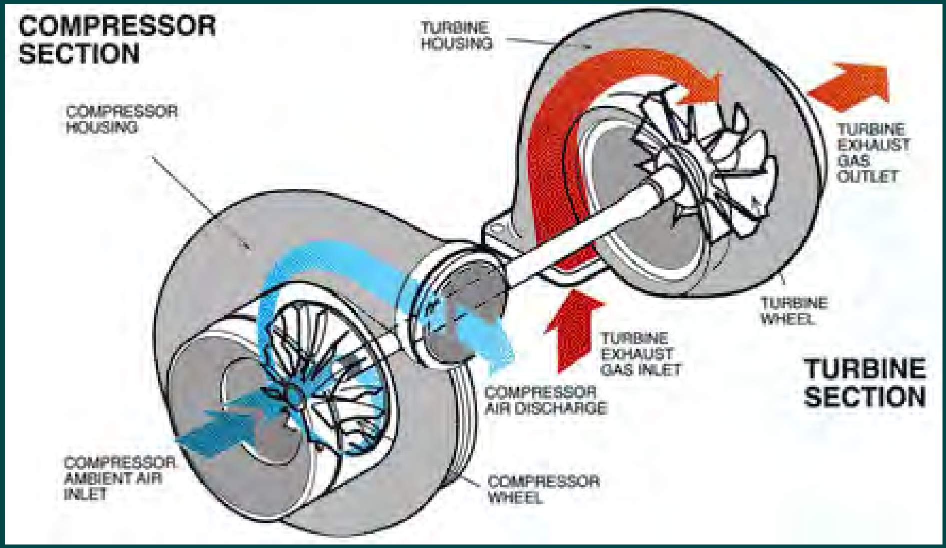
- Small Prototype R&D :
- I Kw power output from Waste Heat
- Using Brayton power cycle
- CFD Analysis of Compressor and Turbine Performance in SCCO2 Flowfield
- Design and Fabricate a Portable System
- Test and Assess the following technologies required



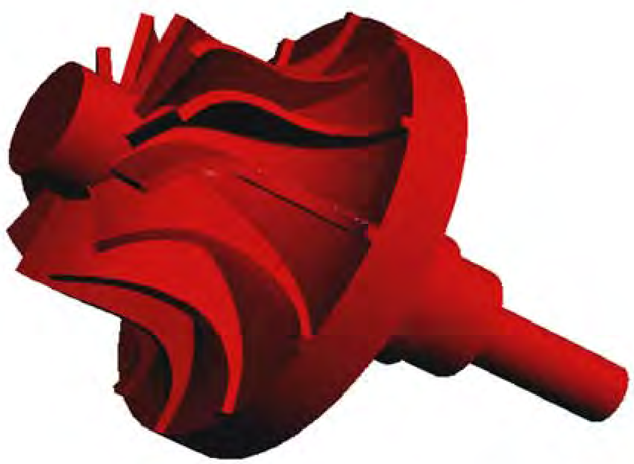
# TAC Component

渦輪與壓縮機結合發電機組合圖

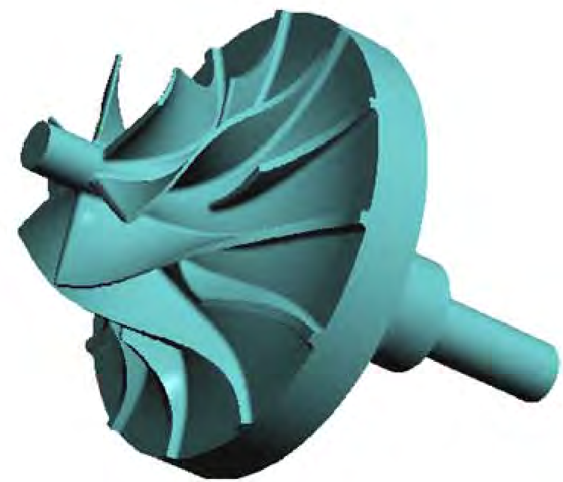
渦輪與壓縮機安裝組合圖



# Designed Compressor & Turbine



3D渦輪及製造圖



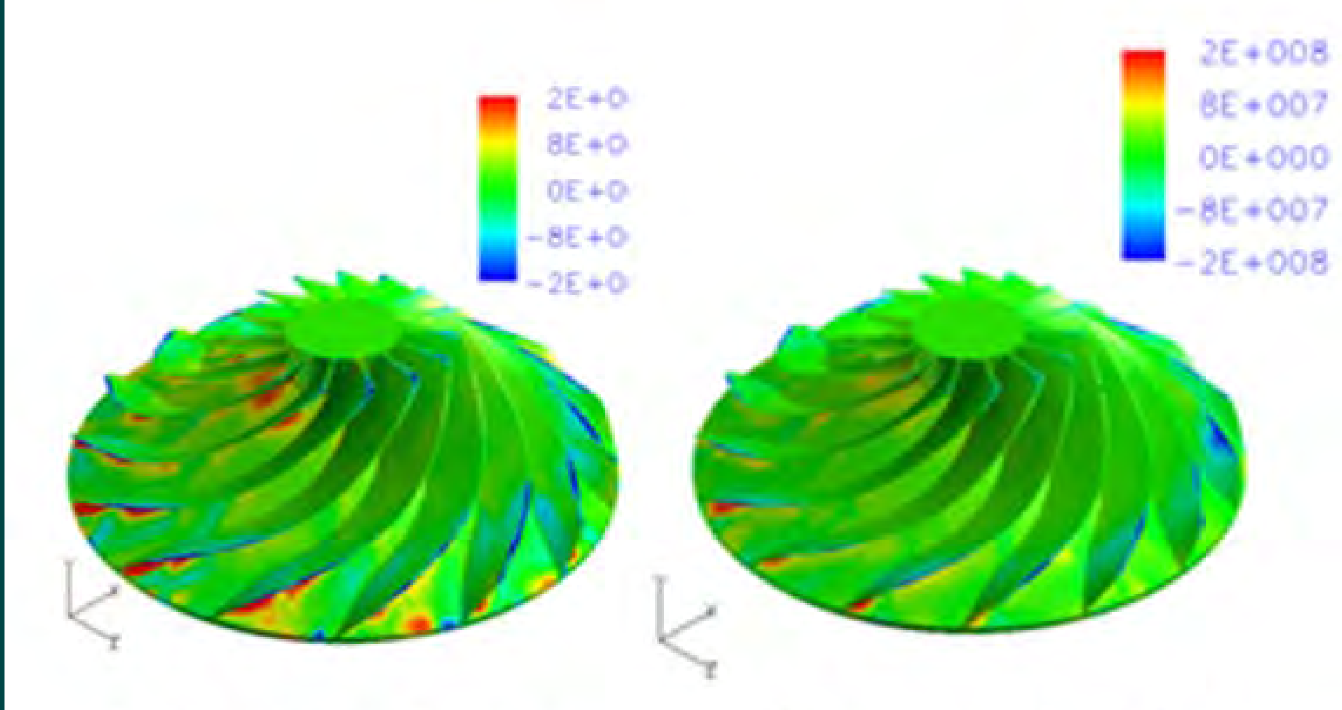
壓縮器3D製造圖

# CFD Simulation of Compressor & Turbine Flowfield

- Governing Equation:
- Mathematical Model Adopt Time-Dependent Reynold's Navier-Stokes Equations；
- Using discrete finite-volume Method coupled with Compressible Implicit Approaching Scheme，

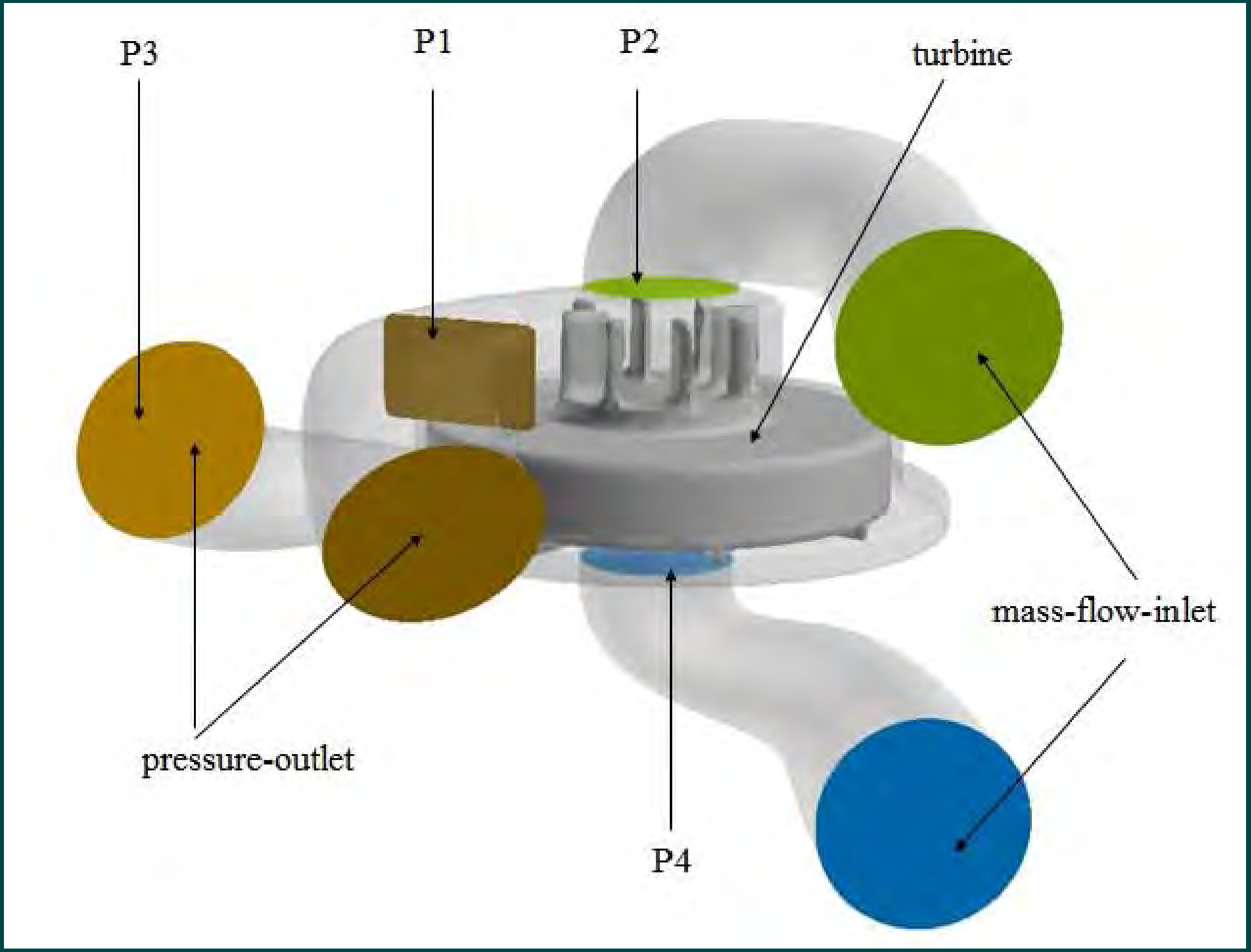
$$\frac{\partial}{\partial t}\iiint_{\Omega} U d\Omega + \oiint_{S} \vec{\Phi} \times d\vec{S} = 0$$

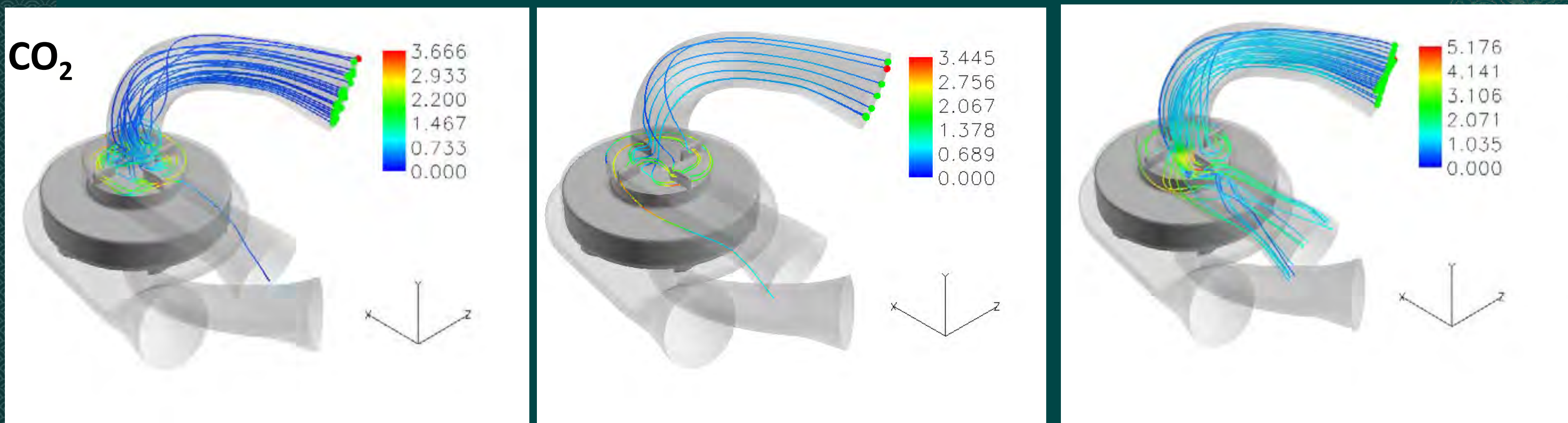
# Turbine Surface Pressure Distribution



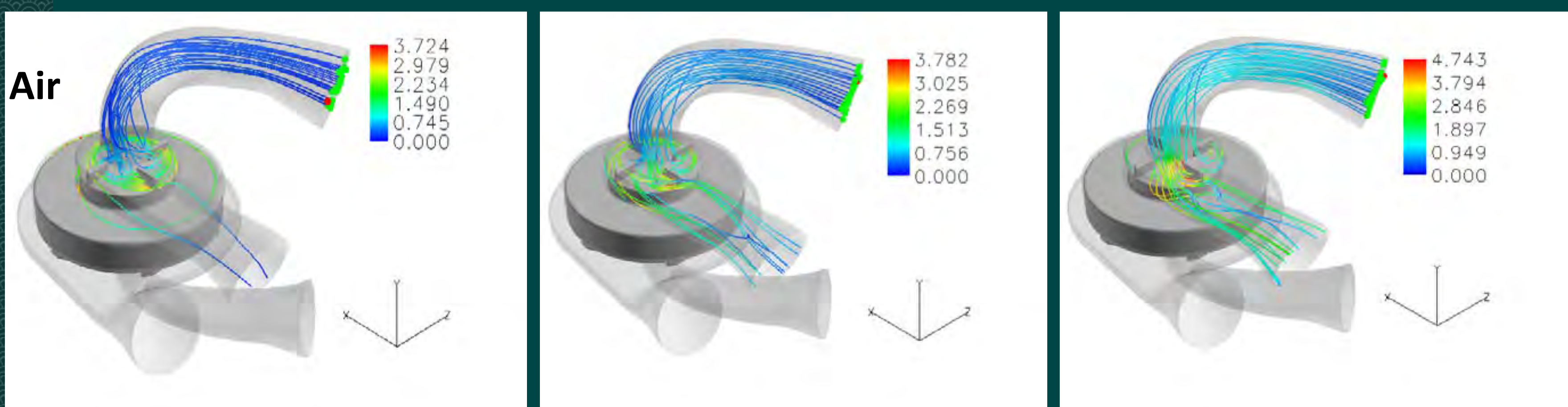

(a) air flow (b) scco2 flow

# Compressor-Turbine System Flowfield Simulation

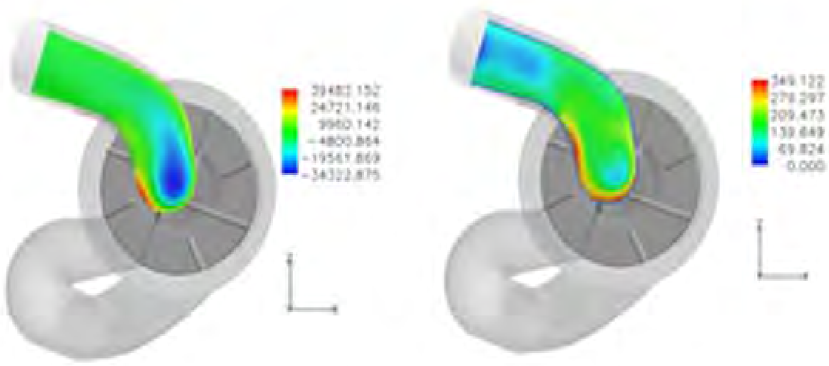




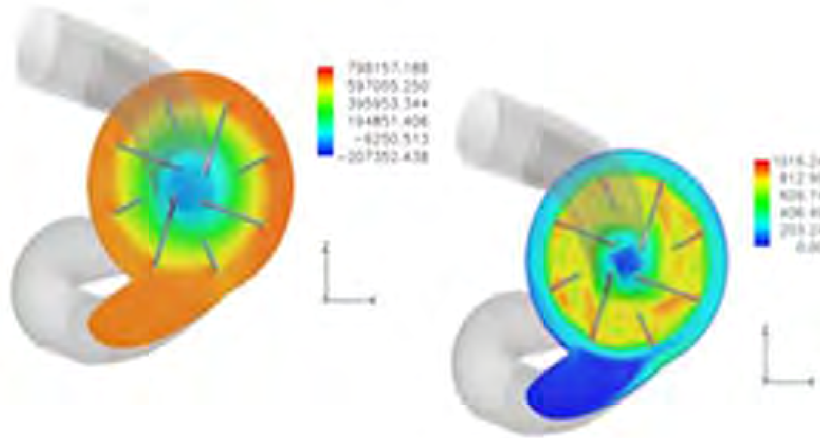

25Kgw/min 50 Kgw/min 100 Kgw/min




**27,000 rpm**

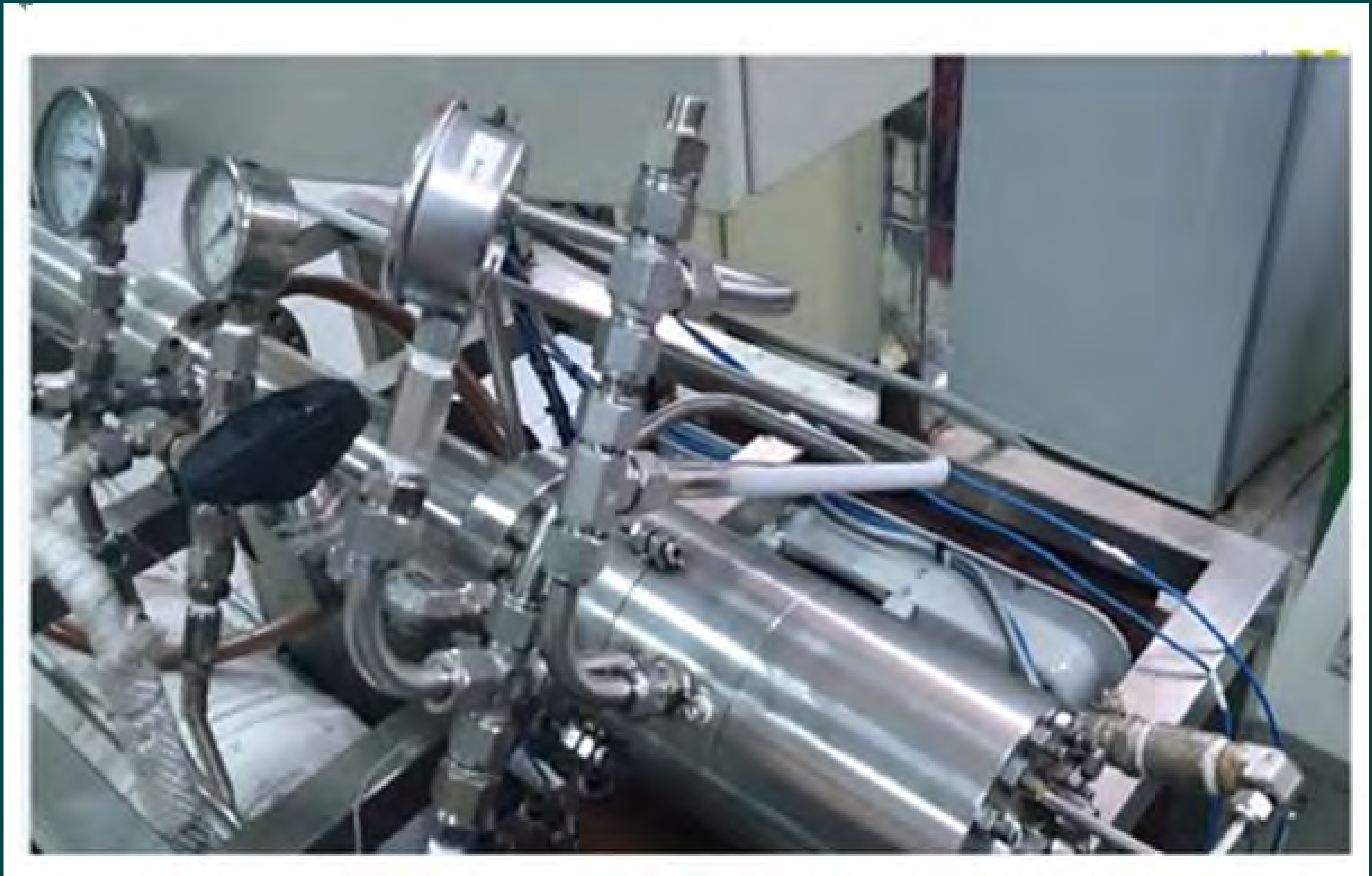


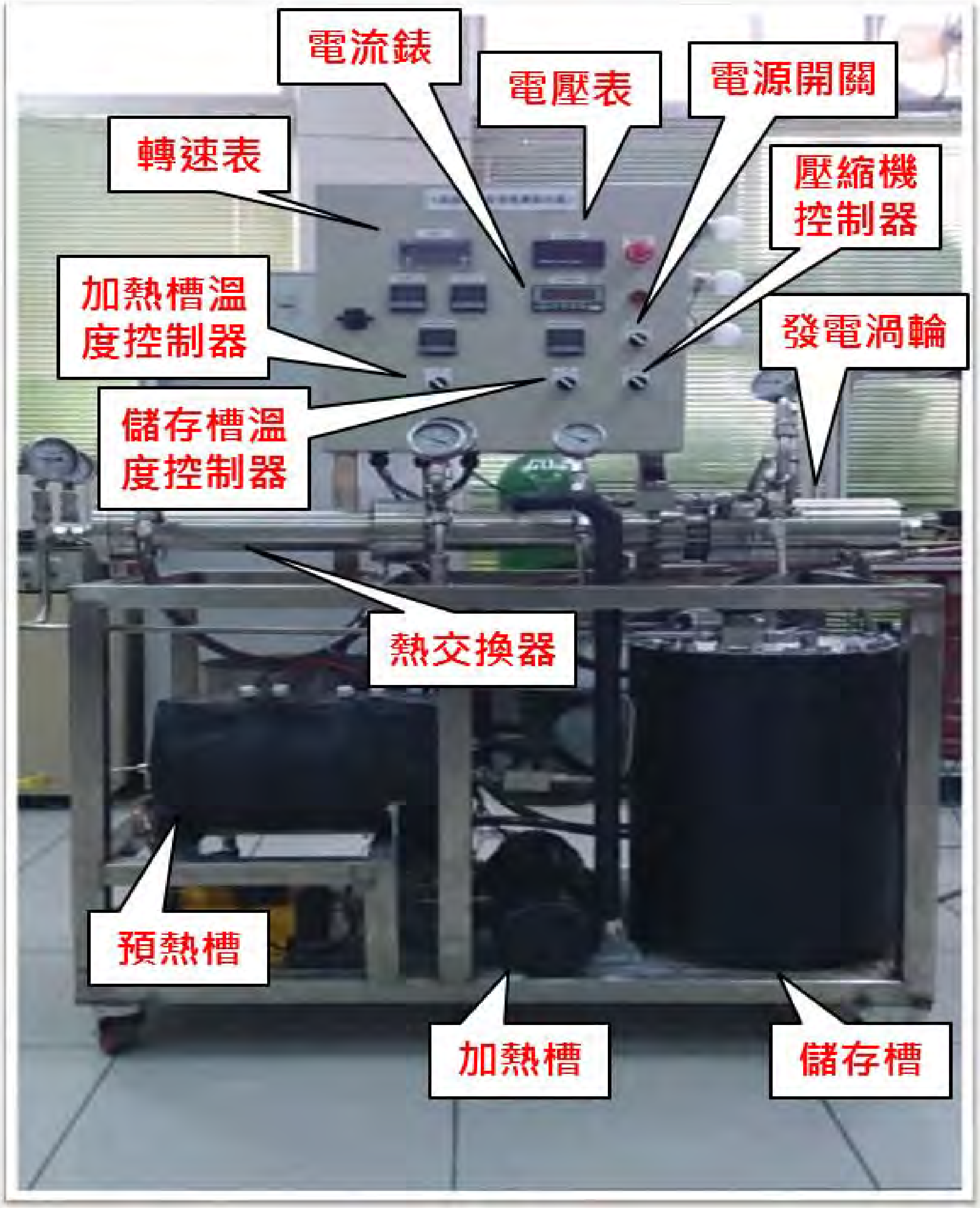

壓縮段進氣流道之壓力及流速分佈



壓縮段葉輪上表面切面壓力及速度分佈

# Turbine-Alternator-Compressor Section



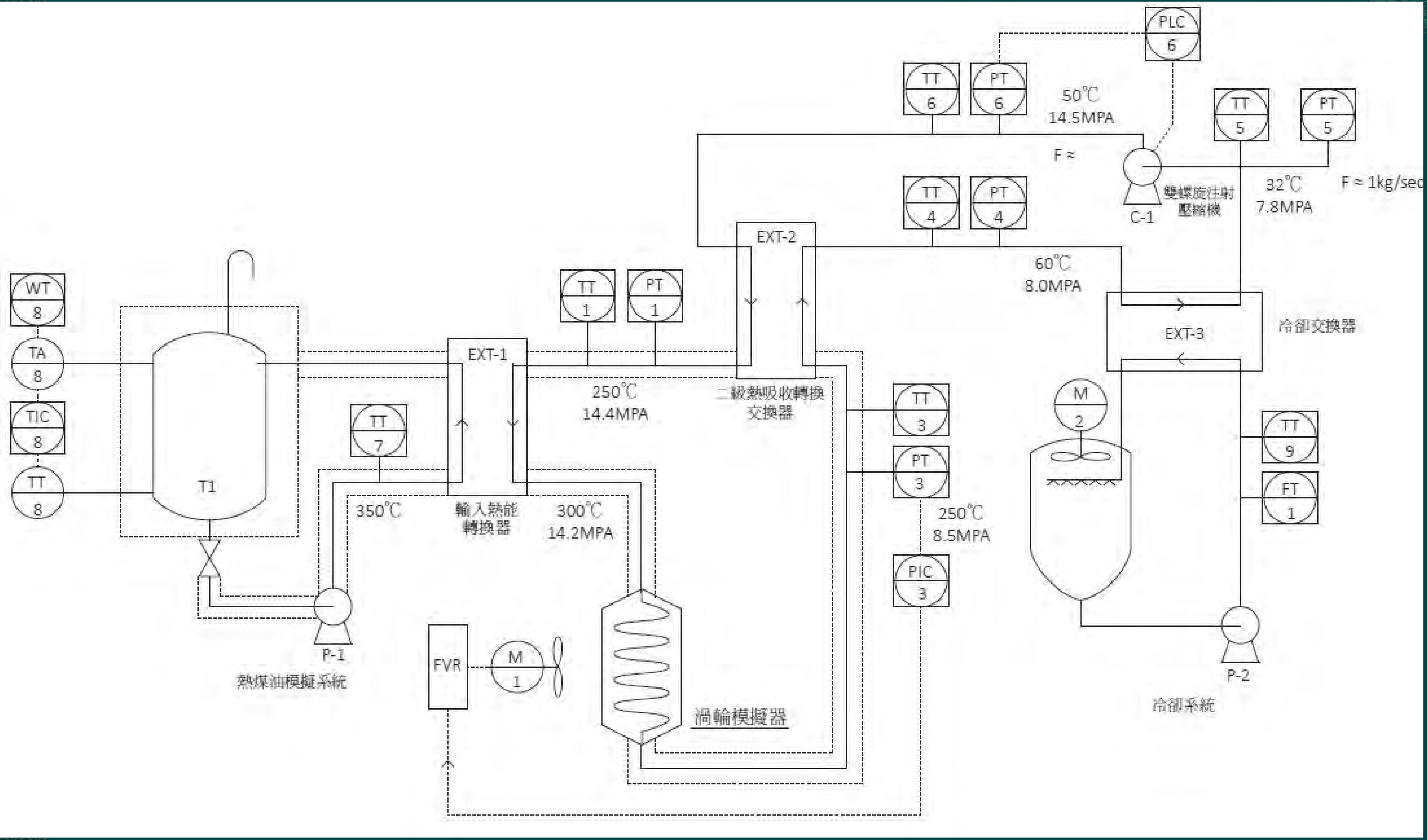

電流錶
電壓表
電源開關
轉速表
壓縮機
控制器
加熱槽溫
度控制器
發電渦輪
儲存槽溫
度控制器
熱交換器
預熱槽
加熱槽
儲存槽

# Test Data showing Temperature, Current and Voltage

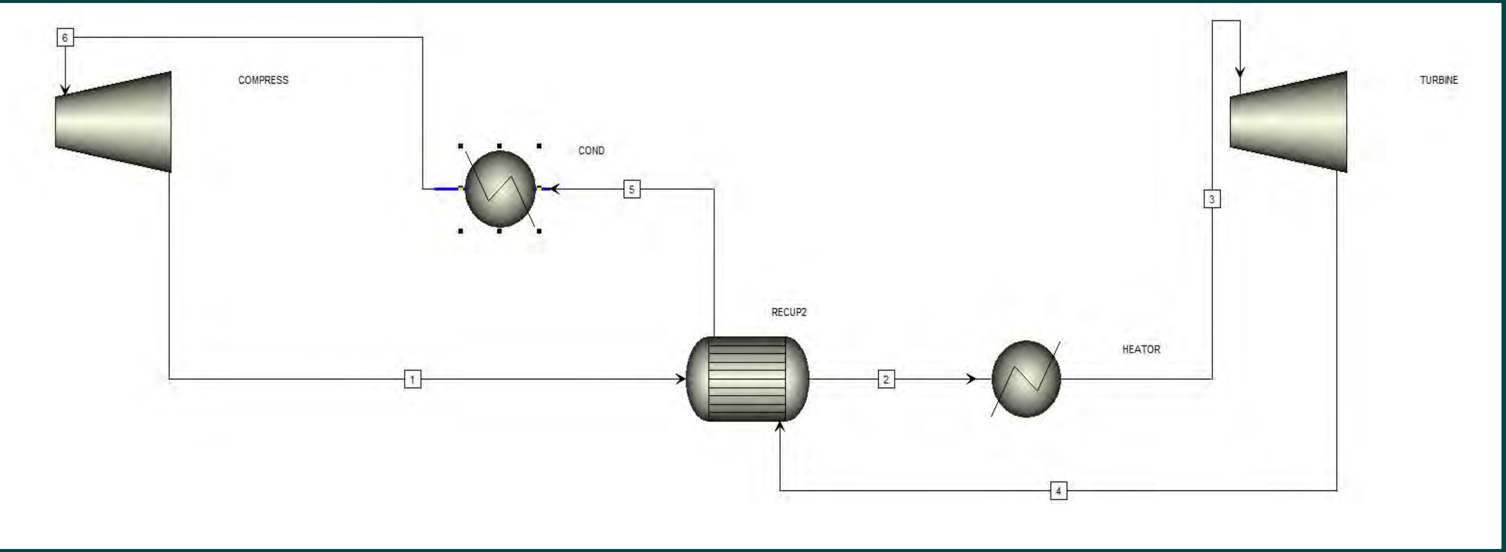
# Results & Suggestions

- As turbine inlet temperature T~150 C, and pressure difference ΔP between turbine inlet & outlet reaches ΔP > 30Kg/cm2, the system can start running.
- The maximum Voltage output is V~125 v, Current I~5 amp, Rotation speed R~10,000 rpm.
- The test condition is not stable and can not offer sustained power output yet.
- Estimated improvement includes: heat exchanger, heat source, compressor--turbine flow & system piping…

# 10 Kw System Aspen Plus Analysis & Flow chart



# Aspen Plus Simulation




## Reference results

| state | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Pressure (MPa) | 14.5 | 14.5 | 14.2 | 8.5 | 8 | 7.8 |
| T(K) | 323 | 475 | 580 | 523 | 330 | 305 |

## Simulation results

| state | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Pressure (MPa) | 14.5 | 14.5 | 14.2 | 8.5 | 8 | 7.8 |
| T(K) | 321.95 | 438.03 | 579.85 | 530.74 | 326.95 | 304.85 |

Turbine efficiency: 85% (assumed)

Compressor efficiency: 78% (assumed)

| | |
|---|---|
| Turbine output | 43.7kW |
| Net work output | 30.9kW |
| Heat to Power efficiency | 34.8% |
| Net efficiency | **27.6%** |

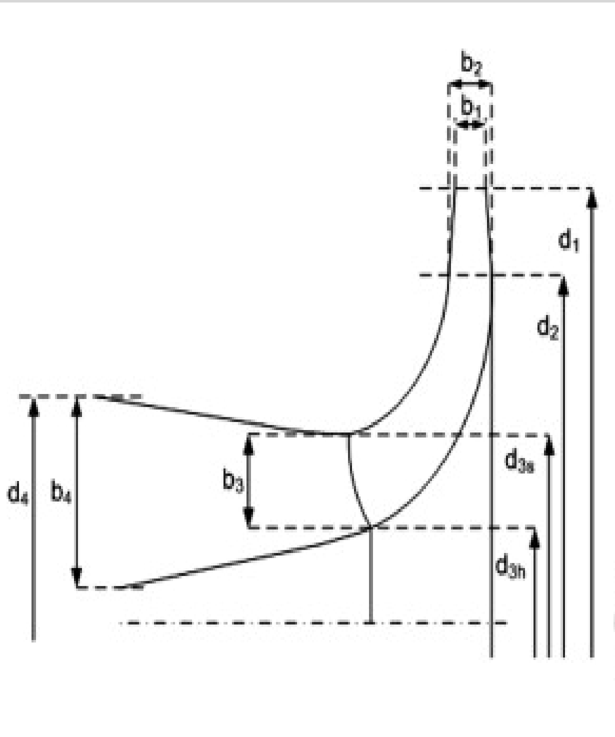
# Turbomachinery

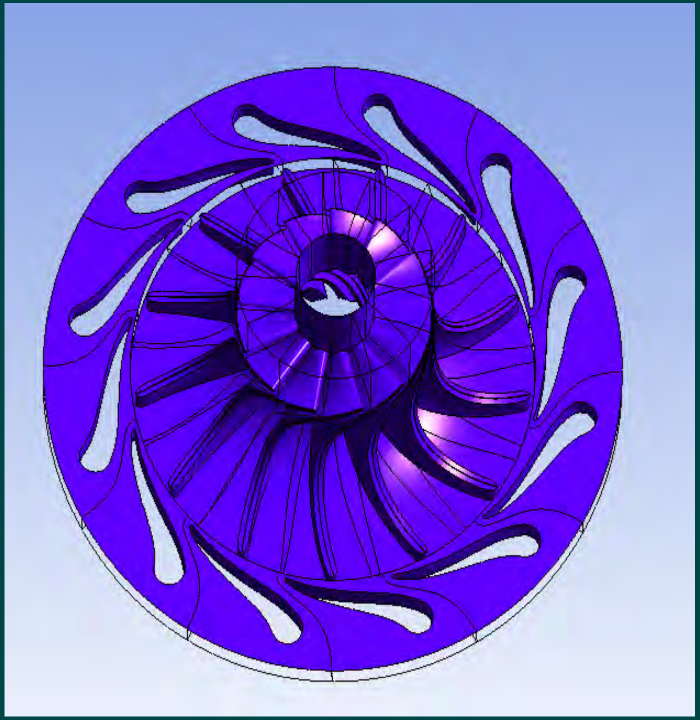
Mass flow: 1kg/s

Rotation rate: 30000 rpm

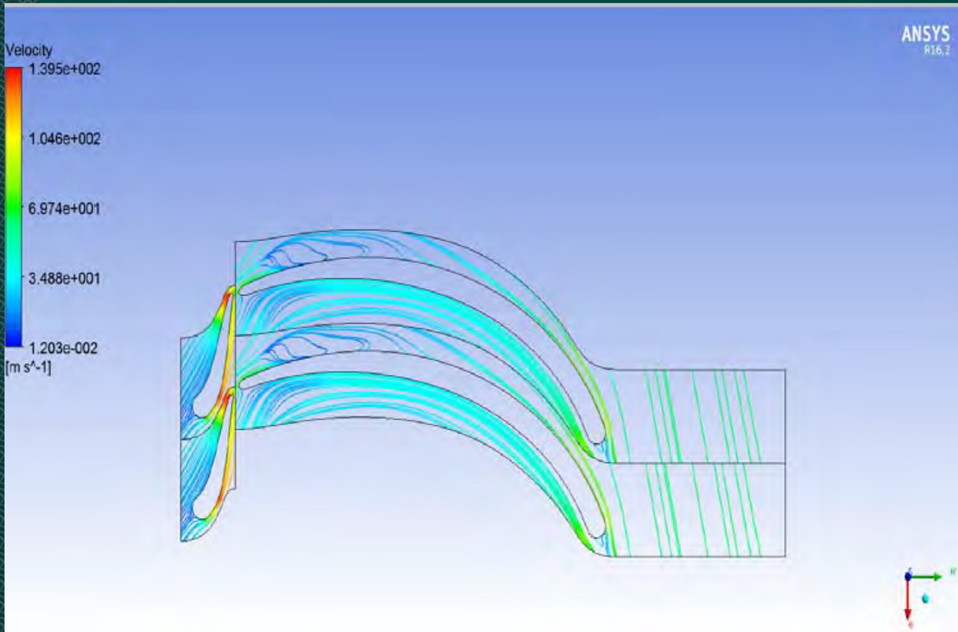
Blade number: 13

Inducer number: 12



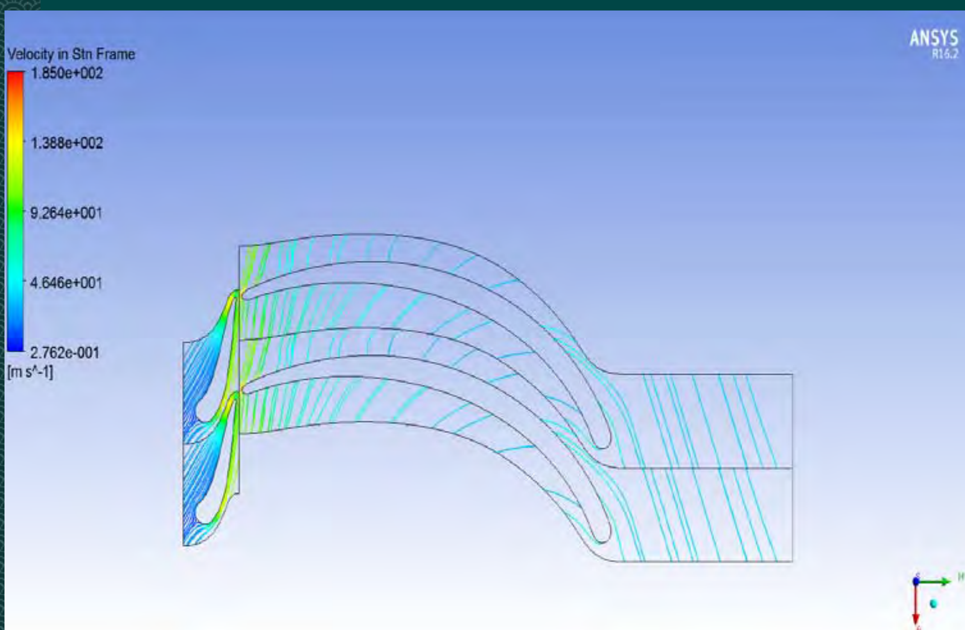



$d_2$=24
$d_3$=12
$d_{3h}$=4.8
$b_1$= $b_2$=3(mm)



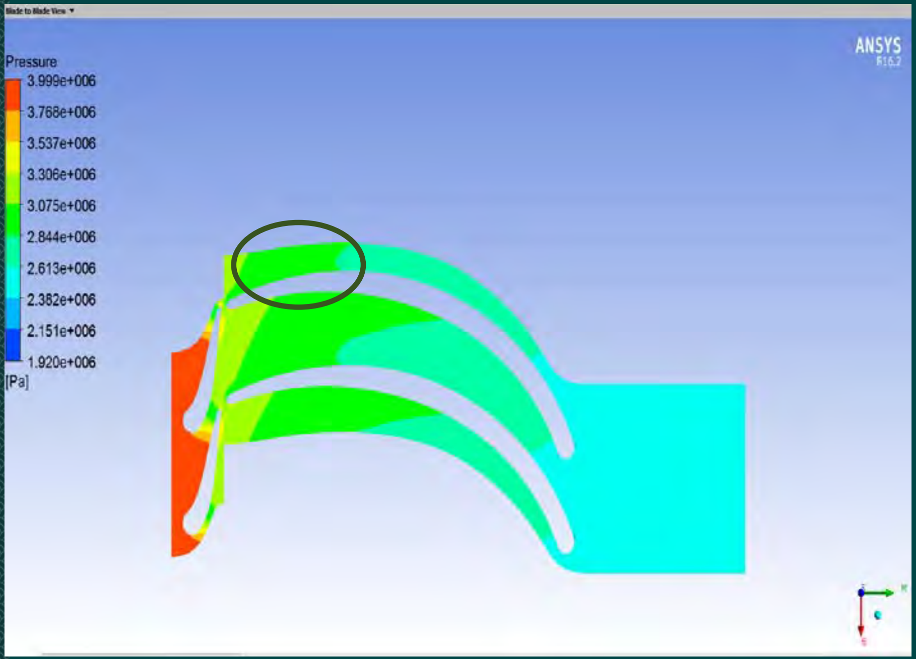

**RFR frame**

- Rotor entrance angle (~40°)
- Vortex affect dynamic movement



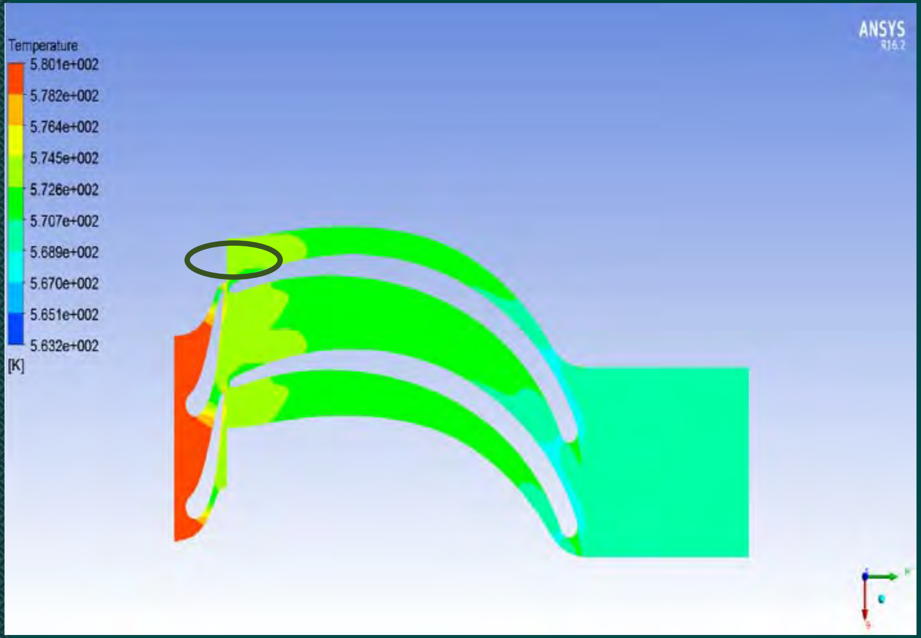

**Stn frame**

- Outlet streamline not axial direction
- Dynamic Energy loss




**Model pressure**

- Vortex cause pressure drop
- Pressure drop caused by large incident angle




**Model temperature**

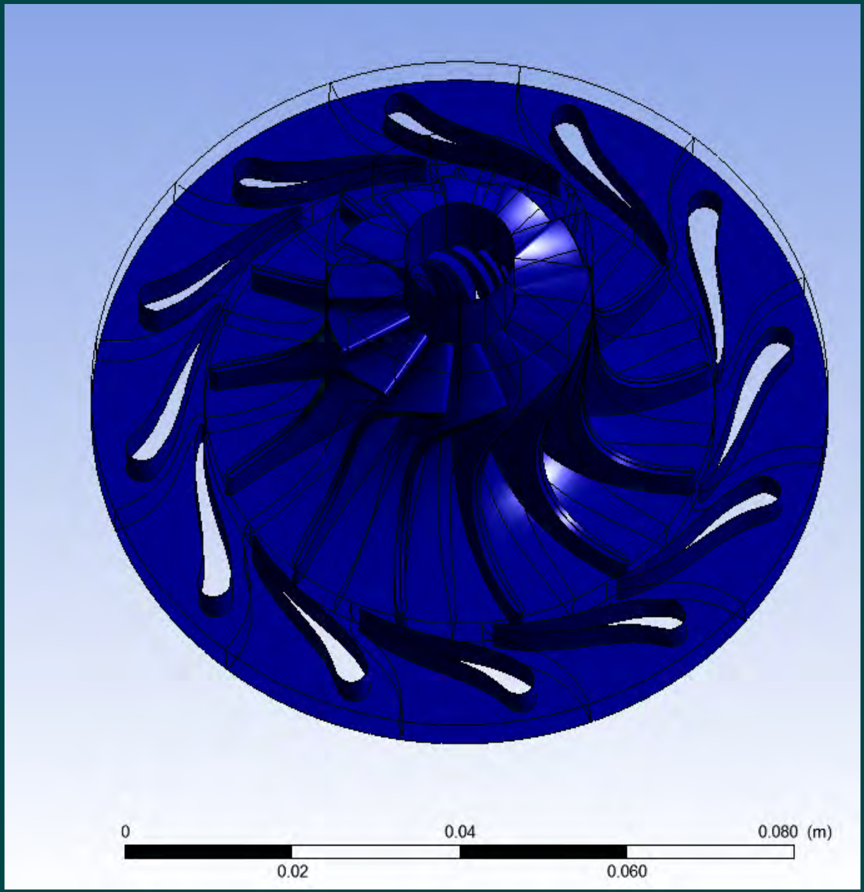
- Vortex also cause temperature non-continuous

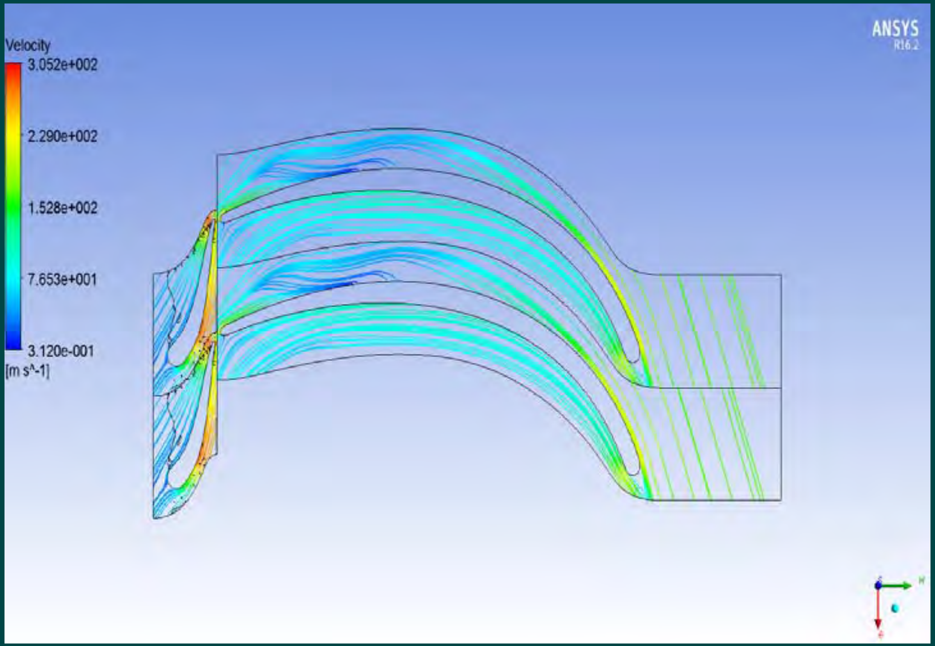
# Modify the Design parameters

Flow Rate increase to 3.1kg/s、
Rotation speed to 50000RPM

- Mass flow: 3.1kg/s
- Angular velocity: 50000 rpm
- Blade number:13
- Inducer number:12

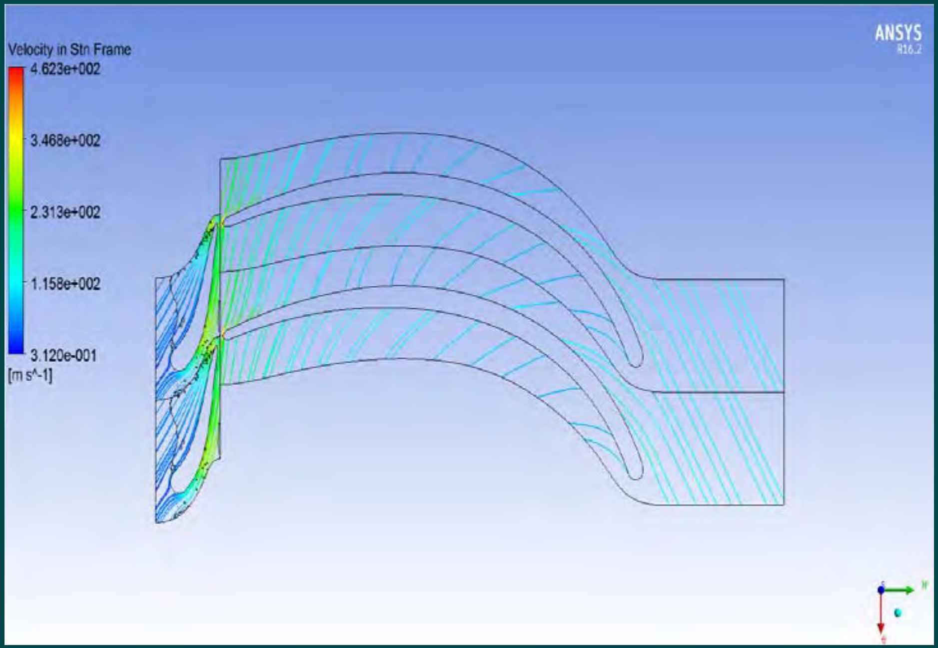
$d_2$=30
$d_3$=16
$d_{3h}$=6.6
$b_1$= $b_2$=4(mm)





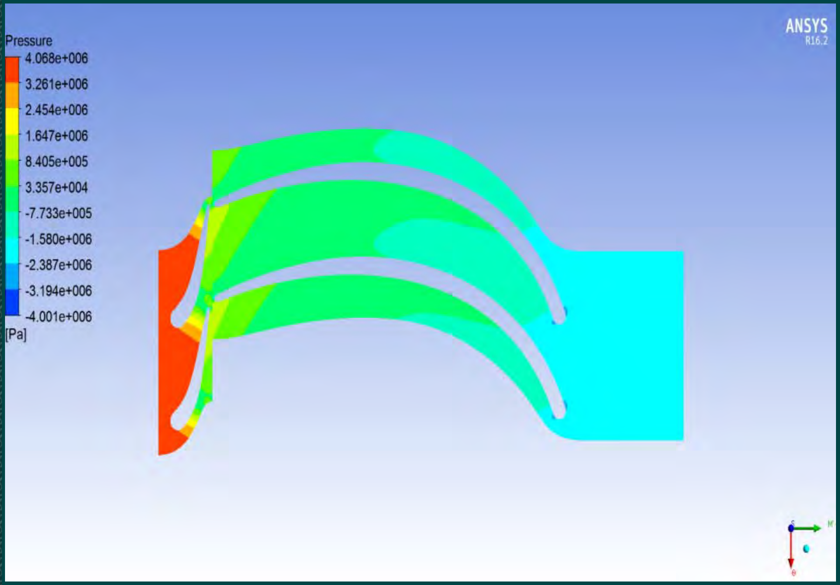

**RFR frame**

- Rotor entrance angle (~20°)
- Less vortex zone



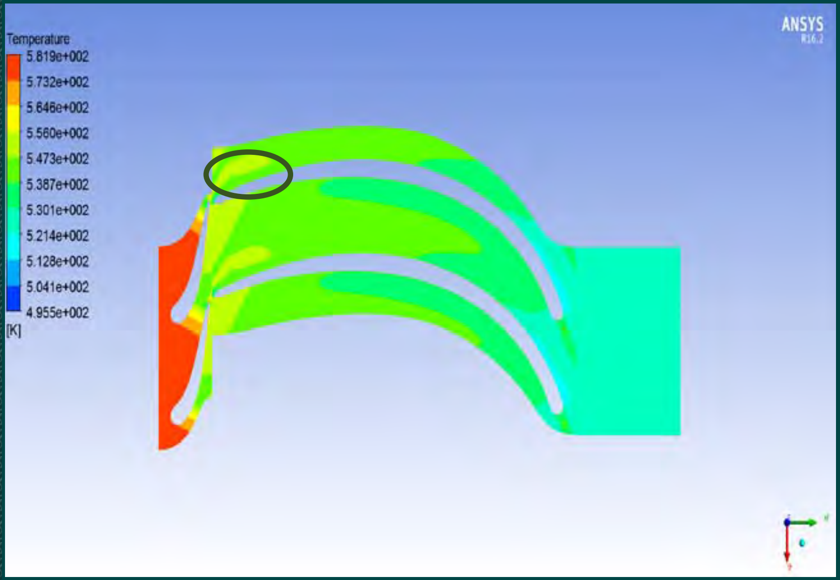

**Stn frame**

- Exit streamline direction need improved




**Model pressure**

- Less pressure drop zone
- 轉子壓降集中在葉片中後段

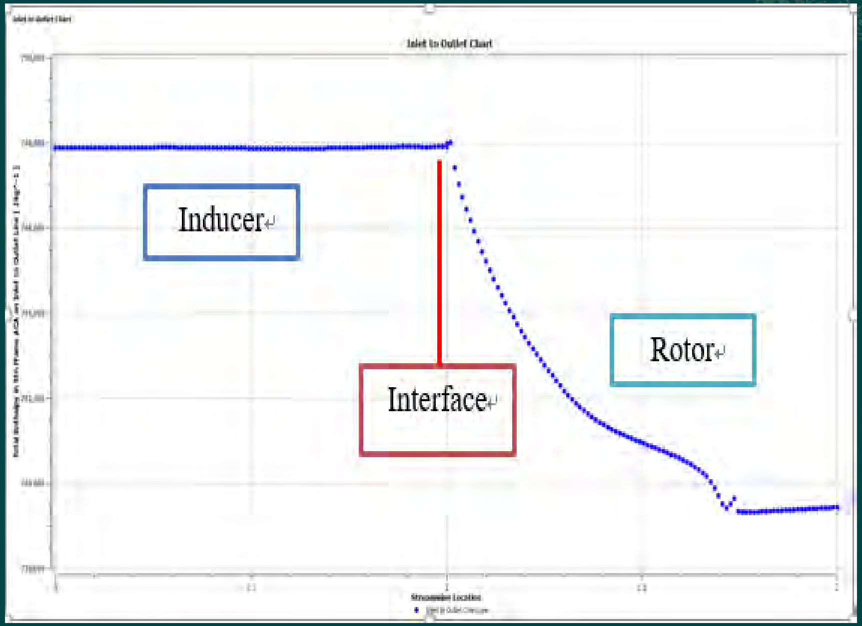



**Model temperature**

- Less temperature drop zone

| $\dot{m} = 3.7kg/s$ 50000RPM | Design model | | |
|---|---|---|---|
| | Inducer inlet | Interface | Rotor outlet |
| Static pressure (MPa) | 14 | 10.53 | 8.1 |
| Static temperature (K) | 580 | 550.5 | 528.8 |
| Velocity in Stn frame (m/s) | 42.8 | 236.1 | 109.7 |
| Density (kg/m$^3$) | 131.38 | 105.2 | 84.5 |

渦輪設計站位圖




**Total enthalpy chart**

# Development of a High-speed permanent magnet electrical machine

**Characteristics of the PMSM Specifications**

- High power density and high efficiency levels
- High power factor and thus power saving
- ability to provide starting torque
- Reduction of volumes
- Low rotor losses and low copper losses

| design parameter | technical value |
|---|---|
| rated speed | 30,000 rpm |
| output power | 10 kW |
| efficiency | >92% |
| supply frequency | 500 Hz |
| induced voltage | 220 V |

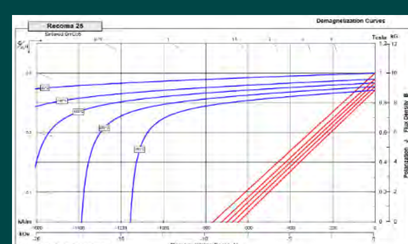
**Selection of silicon steel and permanent magnet for specific operating environment**

**Silicon steel : 10JNEX900**

- suitable for high-frequency condition
- low core loss
- High permeability
- low magnetostriction and stable quality

| material | thickness (mm) | specific resistance (μΩ.m) | saturation magnetization (T) | coreloss(400 Hz,1T) (W/kg) |
|---|---|---|---|---|
| 10JNEX900 | 0.1 | 0.82 | 1.8 | 5.7 |
| grain oriented Si steel | 0.1 | 0.48 | 2 | 6.4 |
| Fe base amorphous | 0.025 | 1.3 | 1.5 | 1.5 |

- suitable for high temperature environment
- high residual induction and coercive force

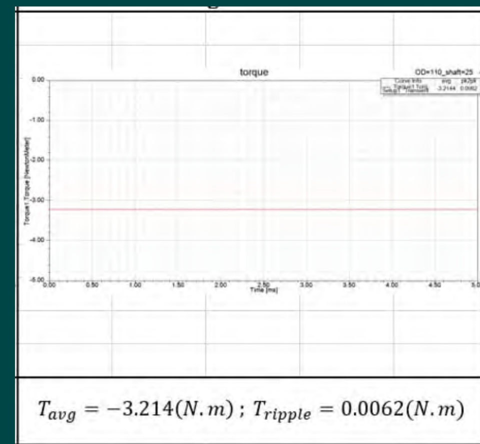



| | Characteristic | Units | min. | nominal |
|---|---|---|---|---|
| Magnetic Properties | **Br**, Residual Induction | Gauss | 9,700 | 10,000 |
| | | Tesla | 0.97 | 1.00 |
| | $H_{cB}$, Coercivity | Oersteds | 9,050 | 9,740 |
| | | kA/m | 720 | 775 |
| | $H_{cJ}$, Intrinsic Coercivity | Oersteds | 25,000 | 30,000 |
| | | kA/m | 2,000 | 2,400 |
| | **BHmax**, Maximum Energy Product | MGOe | 23 | 25 |
| | | $kJ/m^3$ | 180 | 200 |

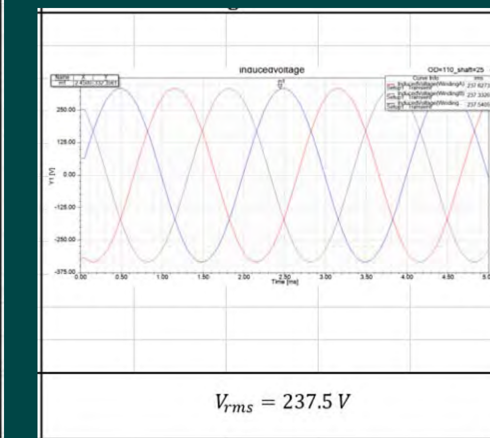
# Development of a High-speed Permanent Magnet Electrical Machine

**Design result**

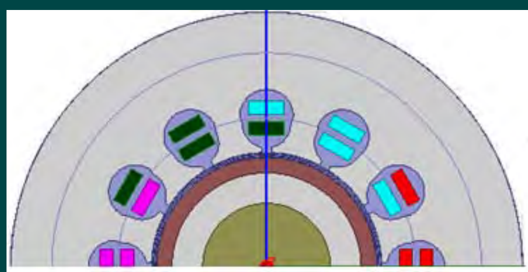
Taking the empirical analysis into consideration with the simulation of the **ANSYS EM Maxwell** software has led to the development of the model in figure 1.




Fiqure2.rated output torque in the PMSM




Fiqure3.induced voltage in the PMSM



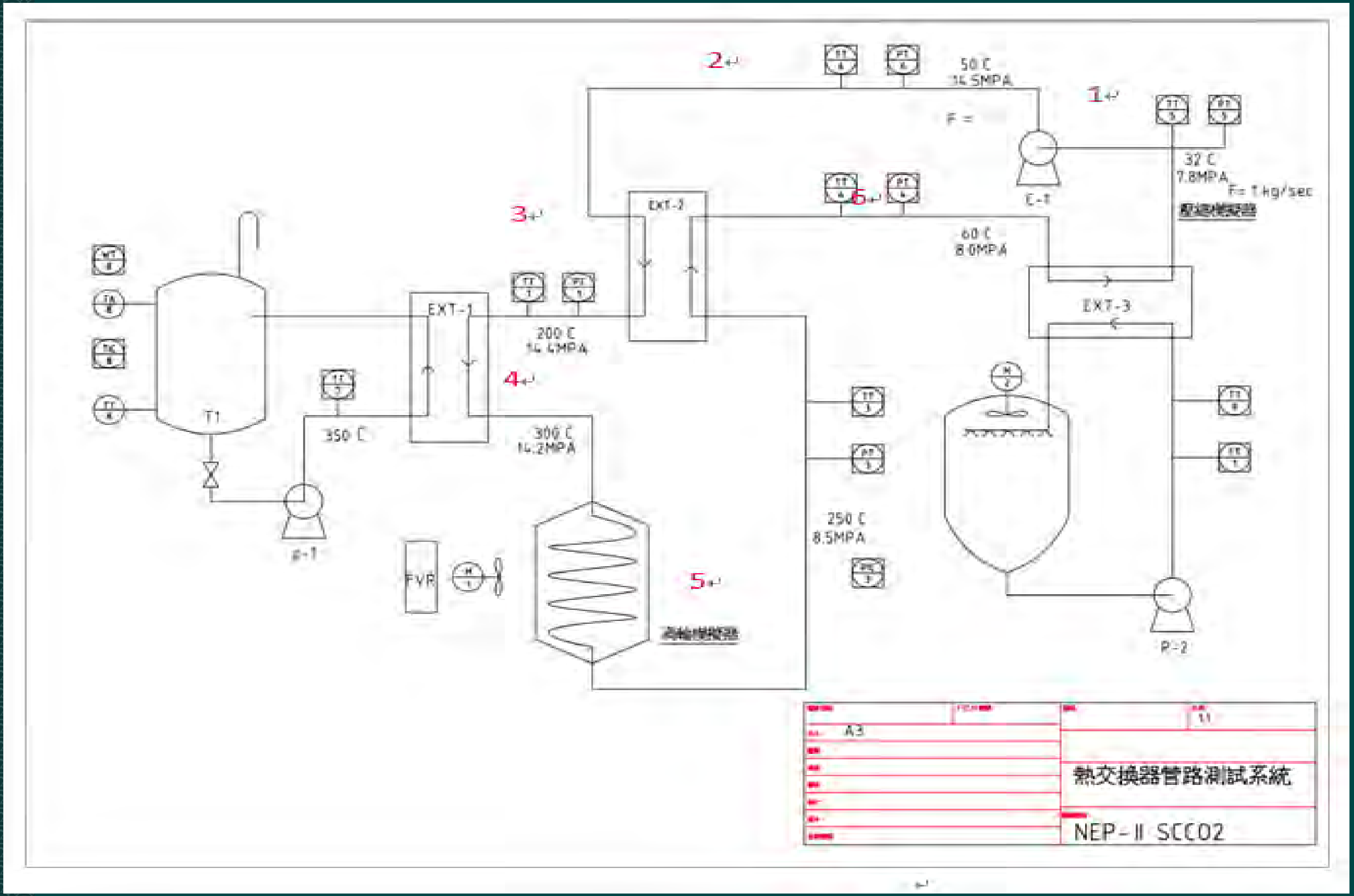
Fiqure 1. Model of the 50000 rpm 10 kw permanent magnet machine

Through simulation, the rated output torque and induced voltage of figure2. and figure3. was developed. It shows that the ripple torque were relatively small and smaller harmonic components.

**The most important geometrical data and details concerning simulations** are summarize in below.

| geometrical data | | simulation results | |
|---|---|---|---|
| outer stator diameter(mm) | 120 | speed(rpm) | 30,000 |
| outer rotor diameter(mm) | 50 | power(kW) | 10 |
| air gap(mm) | 1 | torque(N.m) | 3.2 |
| active length(mm) | 150 | voltage(rms)(V) | 237 |
| pole/slots | 2/12 | efficiency(%) | 92 |

# System Energy Balance Analysis



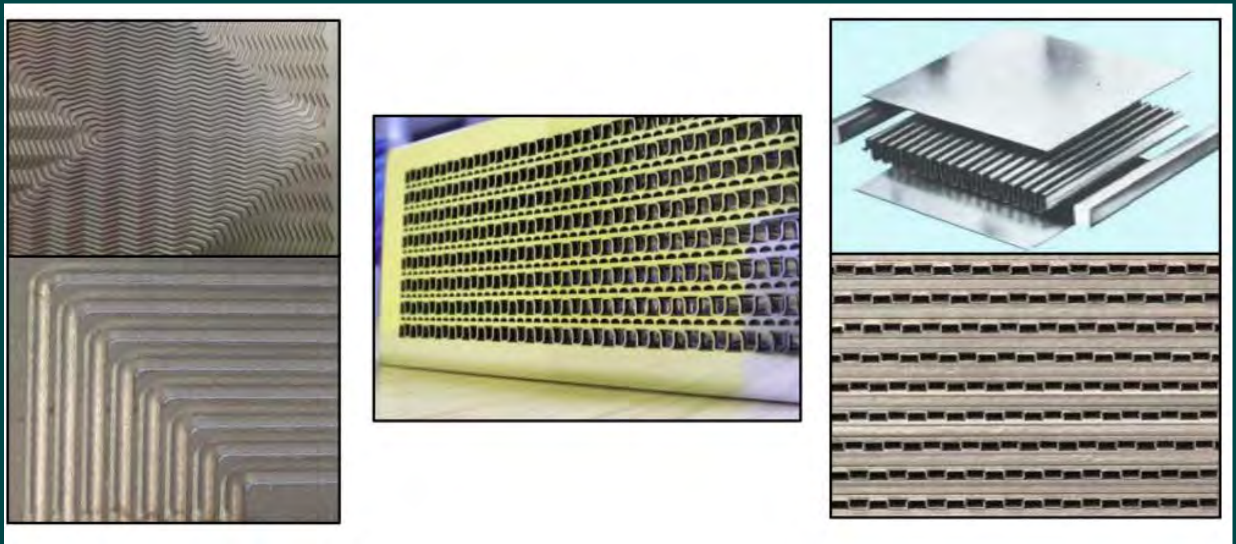
# Heat Exchanger Analysis

*Heat exchanger heat loads*

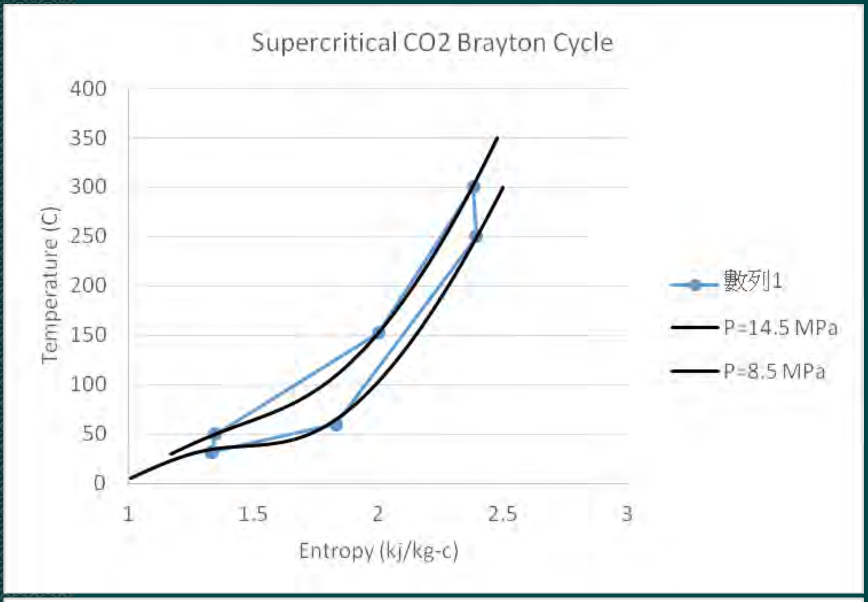
| | | | |
|---|---|---|---|
| *exchanger 1, heat load* | *Q EX,1* | *186.2* | *kW* |
| *Exchanger 3, heat load* | *Q EX,3* | *156.2* | *kW* |
| *exchanger 2, heat load* | *Q EX2* | *236.6* | *kW* |

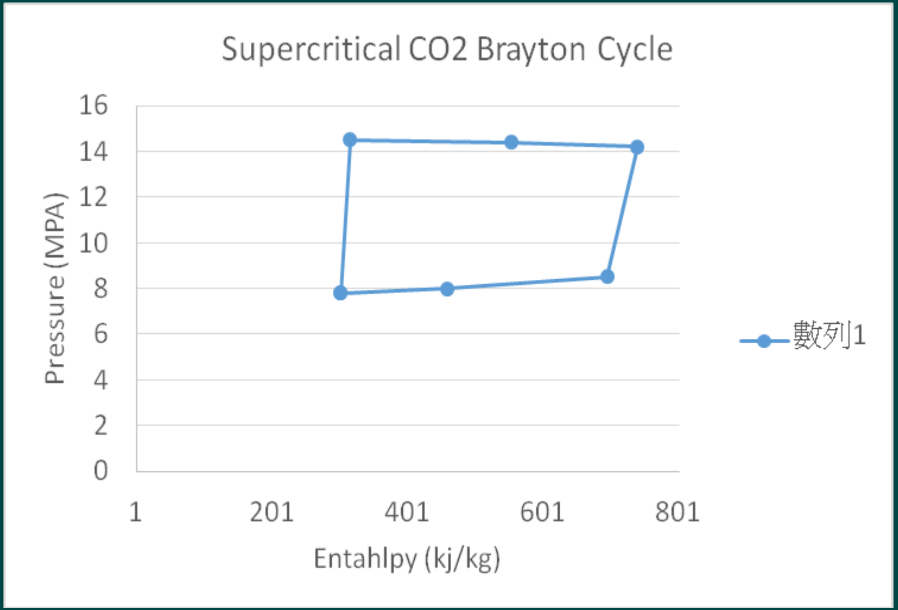
*Work input and output*

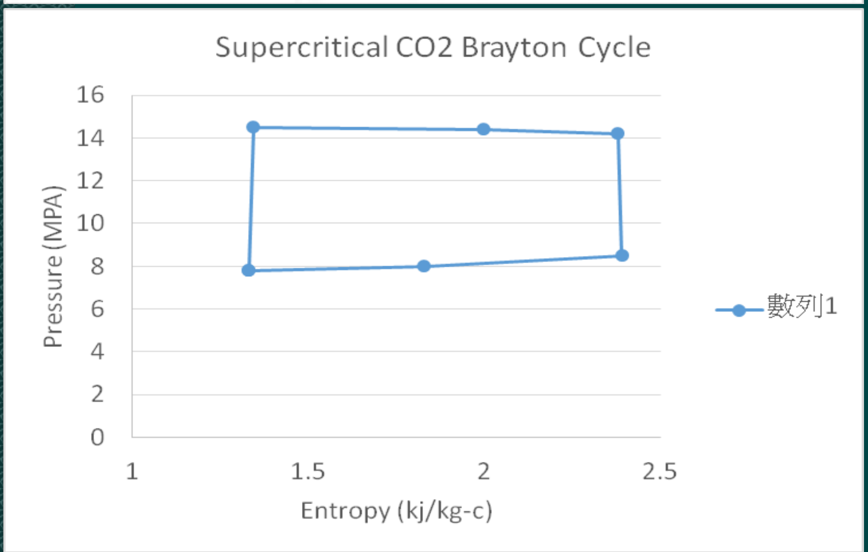
| | | | |
|---|---|---|---|
| *Compressor work input* | $W_{comp}$ | *10.2* | *kW* |
| *turbine work output* | $W_{tur}$ | *44.3* | *kW* |



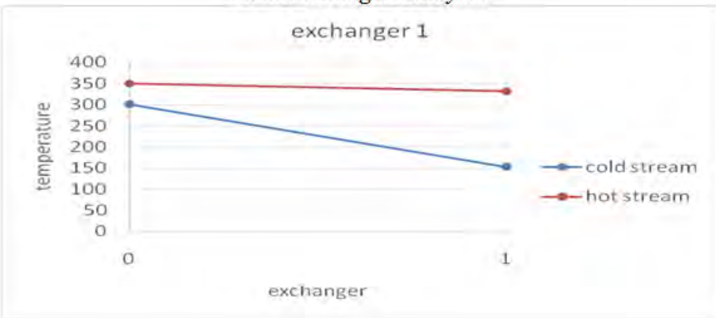
# SCO2 Brayton Cycle Graphs

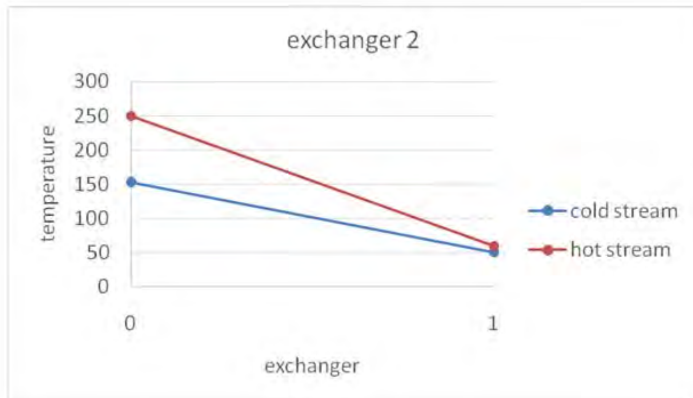


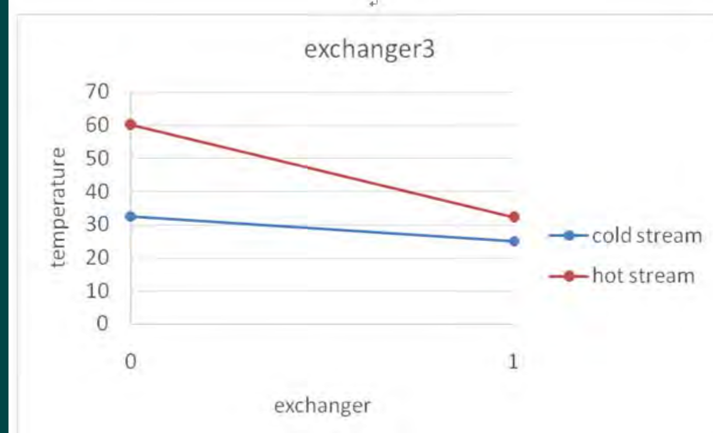



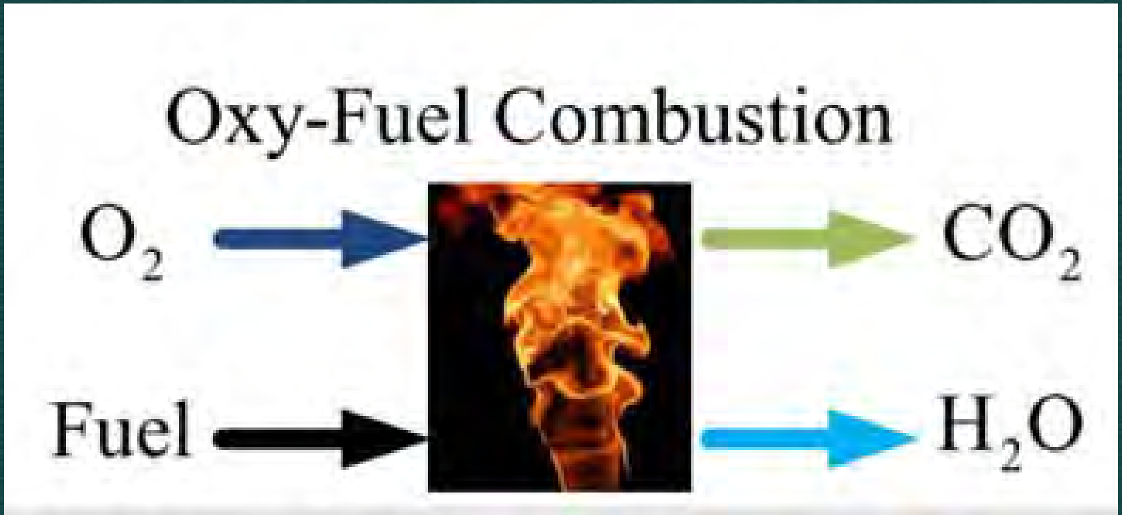
*Heat exchanger Analysis*



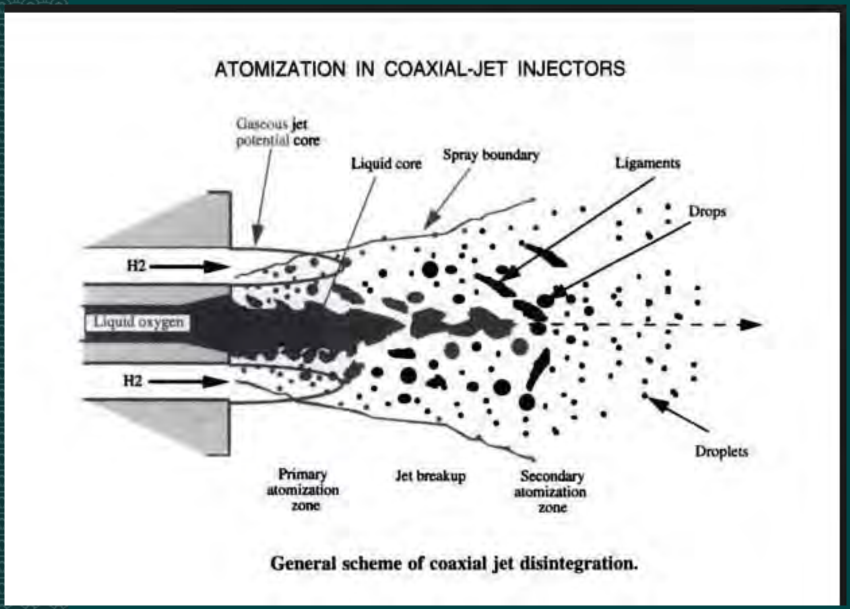



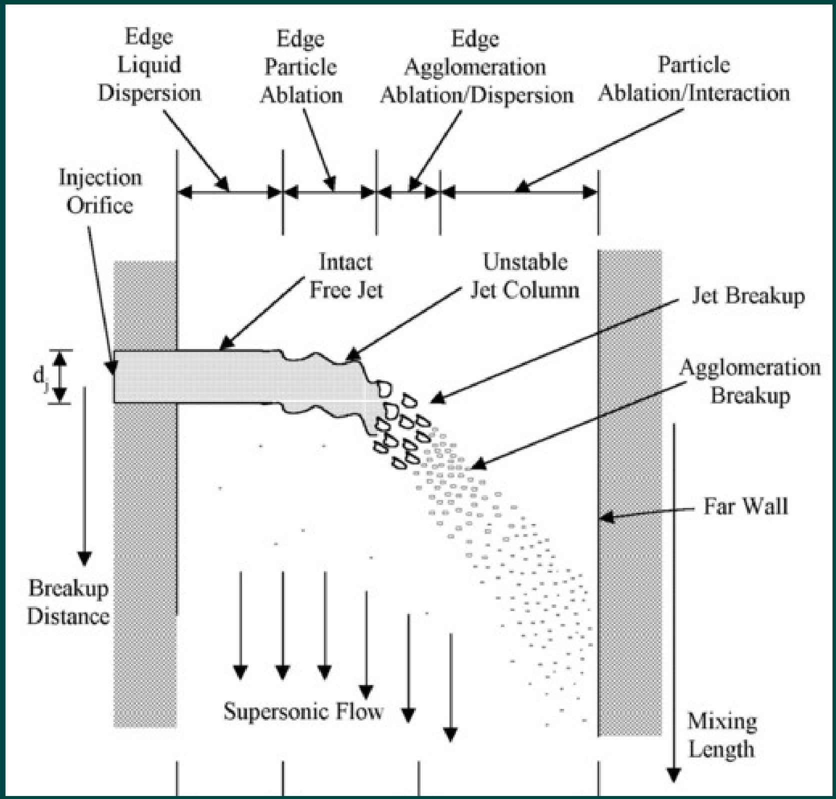
# SCO2 Oxyfuel Combustor Analysis

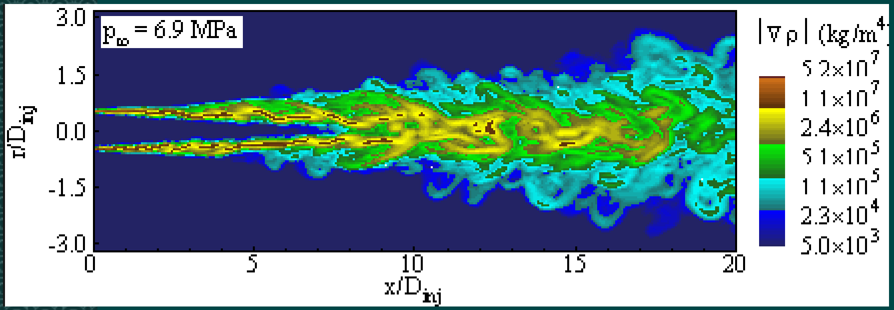


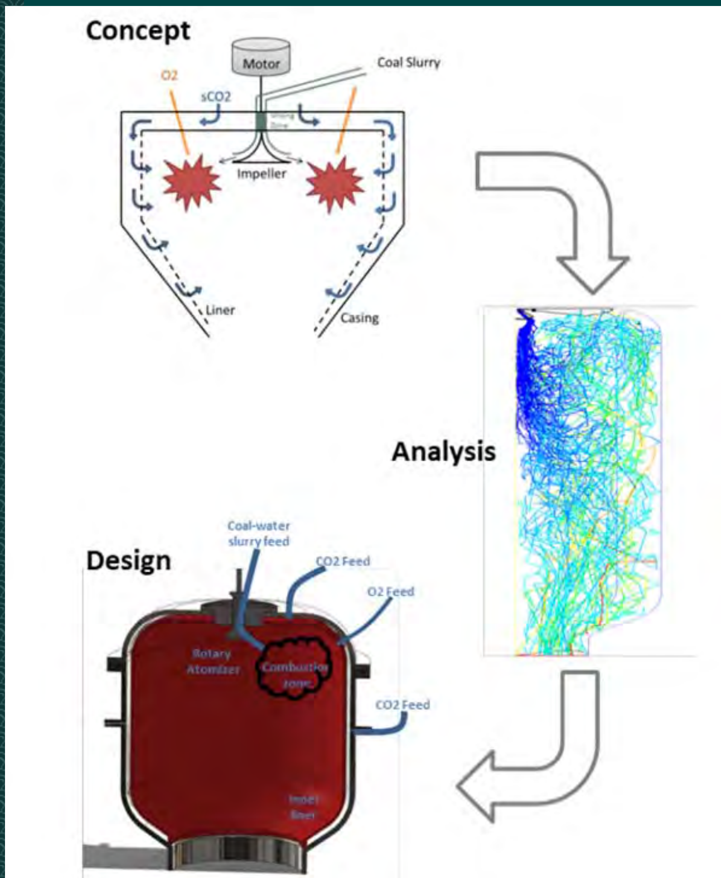
# Different types of Fuel Injector

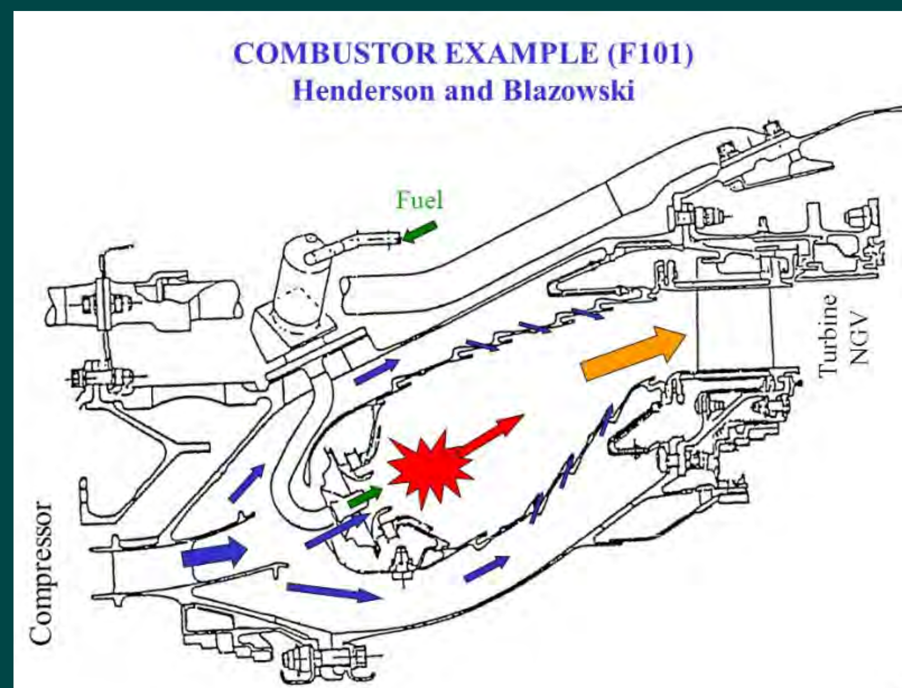


General scheme of coaxial jet disintegration.

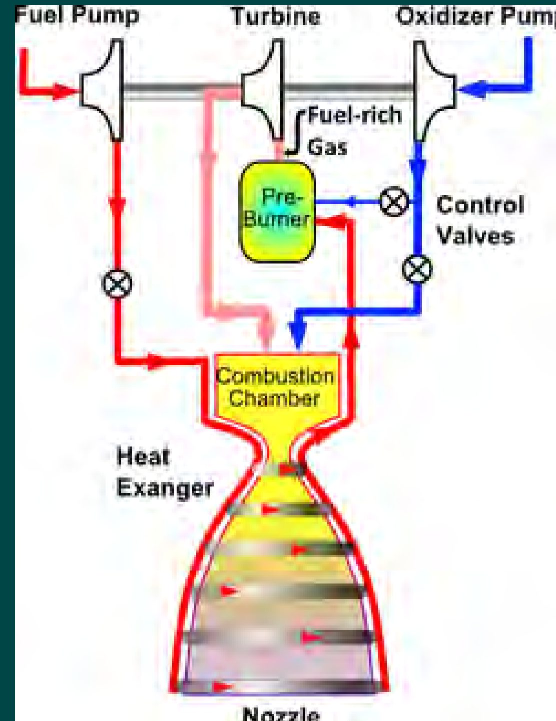



Concept
Motor
Coal Slurry
O2
sCO2
Impeller
Liner
Casing
Analysis
Design
Coal-water slurry feed
CO2 Feed
O2 Feed
Rotary Atomizer
CO2 Feed


COMBUSTOR EXAMPLE (F101)
Henderson and Blazowski
Fuel
Turbine NGV
Compressor

Liquid rocket engine (NASA 1963)

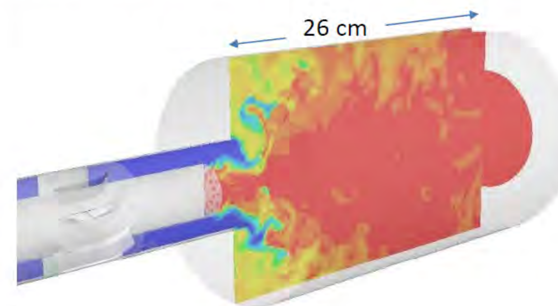



# Oxy-Fuel Combustor Modeling

***CFD exploration of high-pressure oxy combustion in a swirl stabilized non-premixed research combustor. What if???***

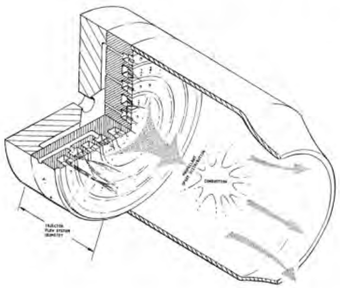
**P=300bar**
**20%O2/80%CO2**
**T=2050K**
**Mdot=72 kg/s**
**180 MW**

**3.3M Cells**
**LES (Dynamic Smagorinsky)**
**1-step mechanism**

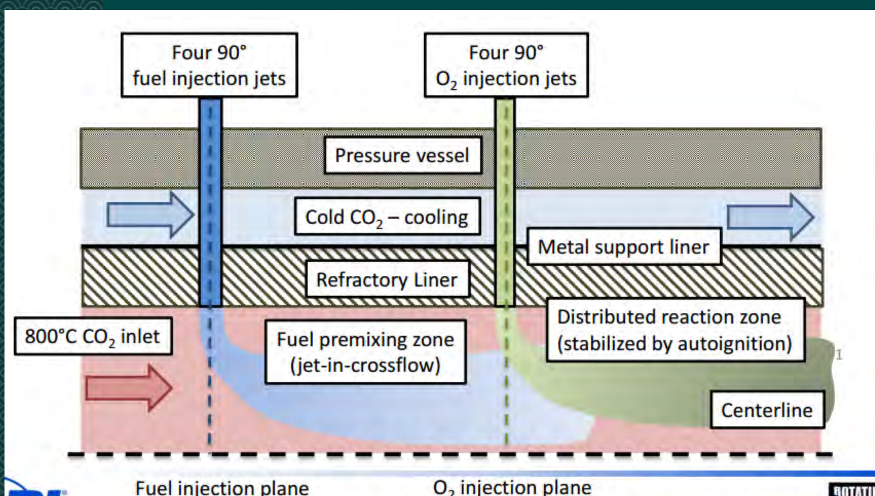


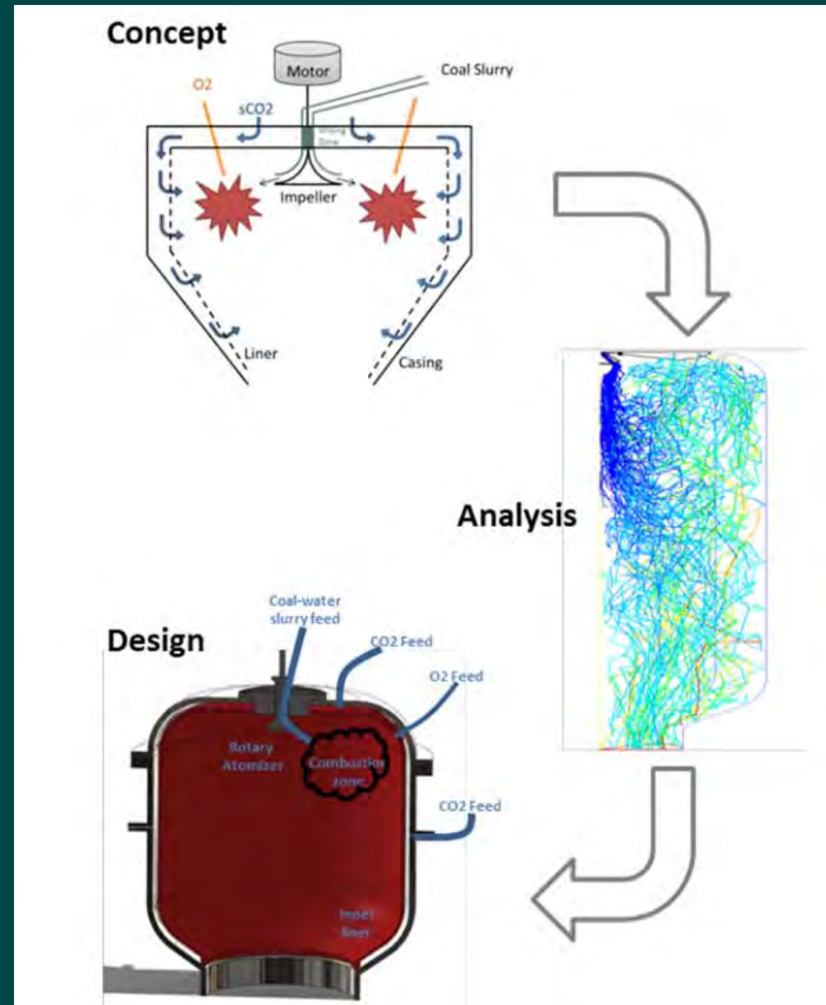

- Compressible LES formulation allows for simulation of combustion dynamics.

# Oxy-Combustion



- Oxygen + reactant
- Direct fired sCO2 combustors have a third inert stream
- Challenge:
  - Mix and combustor fuel with out high temperature

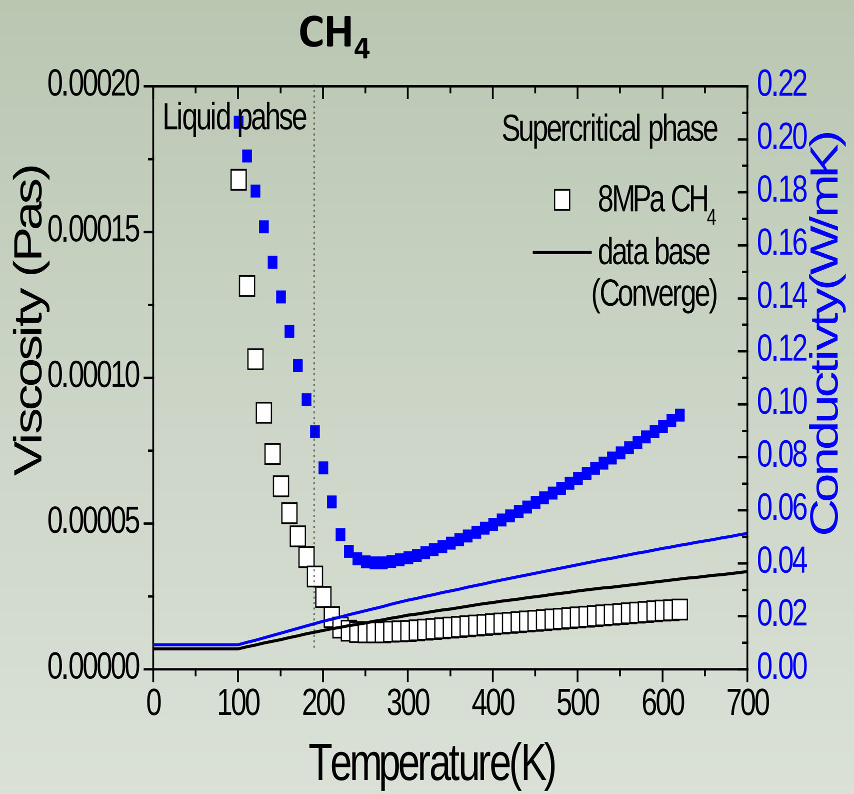


1. Collect $CH_4$, $CO_2$, $H_2O$, $O_2$,CO, $N_2$ and $H_2$ Gas Properties
2. Using "Converge" Scheme Simulate CO2 ,CH4 & O2 Combustion

*Reference: J. Delimont, A. McClung, "Simulation of a Direct Fired Oxy-Fuel Combustor for sCO2 Power Cycles", SwRI, 2016.

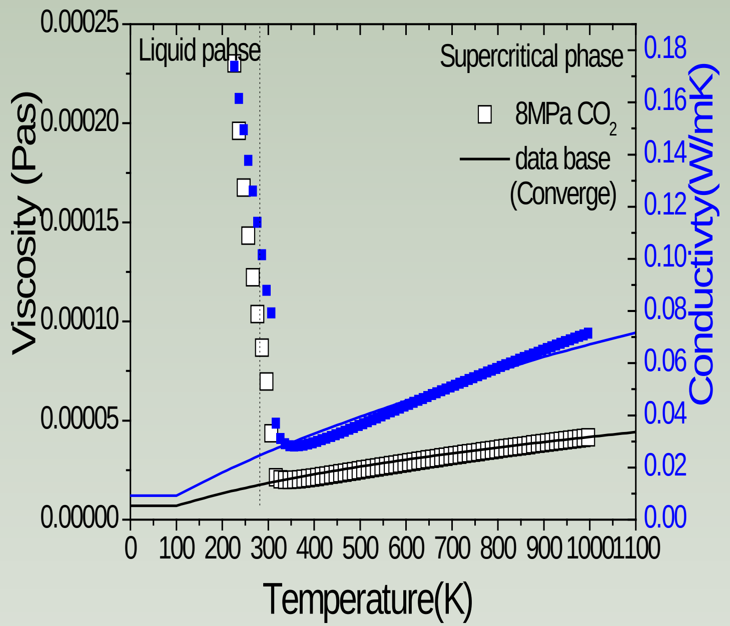
# Task 1 Results: Gas property [$CH_4$ and species critical T and P]



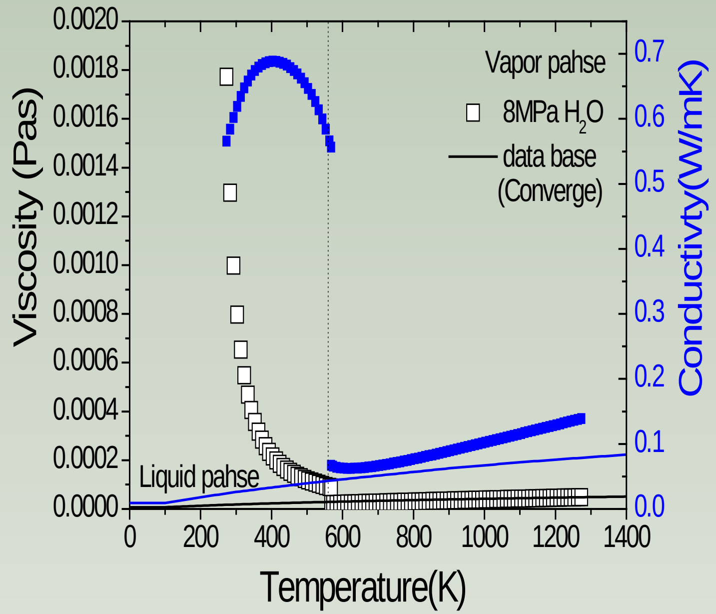

| Species | $T_c$(K) | $P_c$(MPa) |
|---|---|---|
| $CH_4$ | 190.56 | 4.59 |
| $CO_2$ | 304.12 | 7.38 |
| $H_2O$ | 647.10 | 22.06 |
| $H_2$ | 33.15 | 1.30 |
| $O_2$ | 154.58 | 5.04 |
| CO | 132.86 | 3.50 |
| $N_2$ | 126.19 | 3.40 |

# Task 1 Results: Gas property [$CO_2$ and $H_2O$]

**$CO_2$**




**$H_2O$**



# Governing equation

- 質量守恆方程 $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$

- 物種傳輸方程 $$\frac{\partial \rho \phi_k}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i \phi_k - \Gamma_k \frac{\partial \phi_k}{\partial x_i}\right) = S_{\phi_k} \quad k = 1, \ldots, N$$

  $\Gamma_k$和$S_{\phi_k}$為擴散係數和來源項。

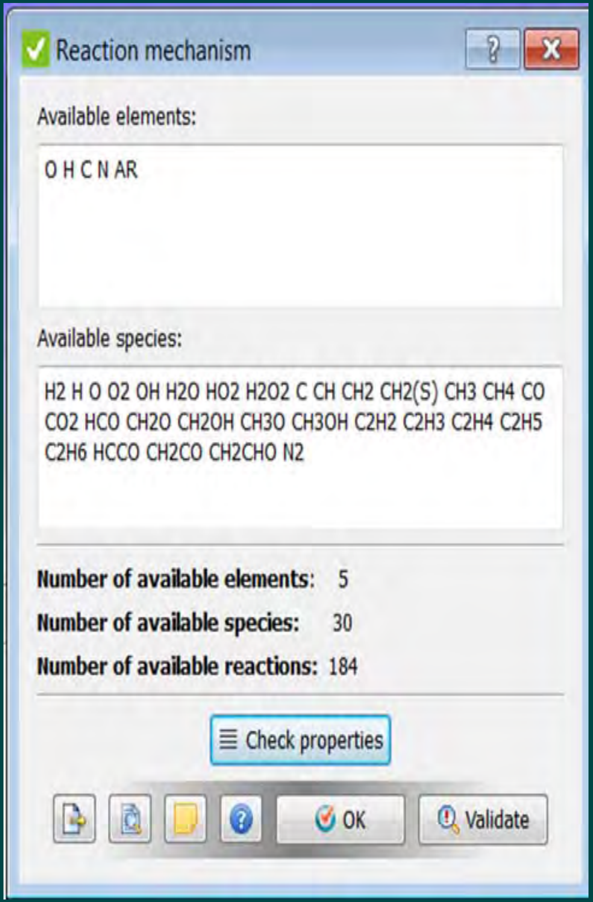
- 動量守恆方程 $$\frac{\partial \rho}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F}$$

  $\bar{\bar{\tau}}$應力張量，$\bar{\bar{\tau}} = \mu\left[\left(\nabla\vec{v} + \nabla\vec{v}^T\right) - \frac{2}{3}\nabla \cdot \vec{v} I\right]$

- 能量守恆方程 $$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = -\nabla \cdot \left(\sum_j h_j J_j\right) + S_h$$

# Combustion modeling: CEQ

- Simplify combustion modeling base on chemical equilibrium.
- When **chemical time-scales are faster than the fluid time-scales**, CEQ are used for the combustion modeling.
- The CEQ solver is ensure for any combination of gas species.
- This solver uses data in "***therm.dat***" and "*mech.dat*" to calculate the equilibrium concentration.
- We use the 30 species in Lu & Law's methane skeletal mechanism and thermodynamic data based on GRI 3.0 for this simulation.

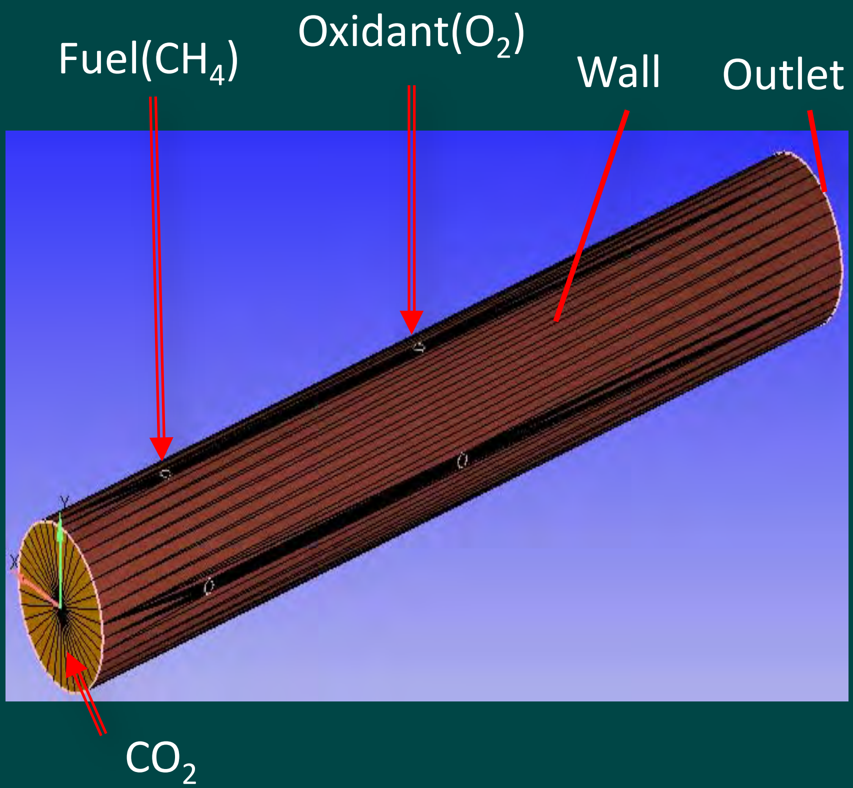




Reference:
Tianfeng Lu and Chung K. Law, "A criterion based on computational singular perturbation for the identification of quasi steady state species: A reduced mechanism for methane oxidation with NO chemistry," Combustion and Flame, Vol.154 No.4 pp.761–774, 2008.

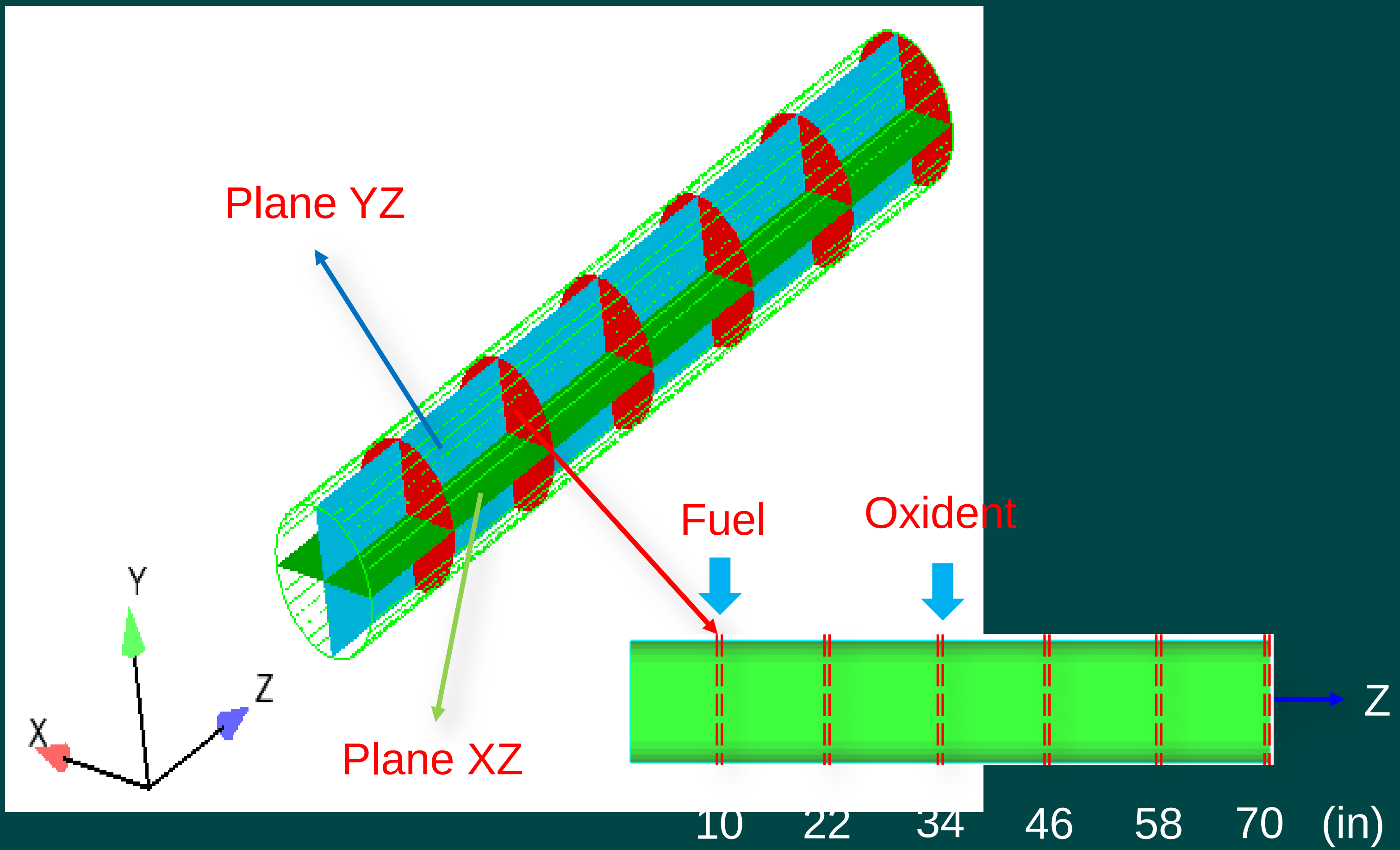
# Boundary condition

| Boundary ID | Type | Setting Parameter | Value | Unit |
|---|---|---|---|---|
| Fuel | INFLOW | velocity | 10 | m/s |
| | | temperature | 313 | K |
| Oxygen | INFLOW | velocity | 20 | m/s |
| | | temperature | 313 | K |
| $CO_2$ | INFLOW | velocity | 20 | m/s |
| | | temperature | 1073 | K |
| Outlet | OUTFLOW | pressure | 7.4 | MPa |
| Wall | WALL | temperature | 313 | K |

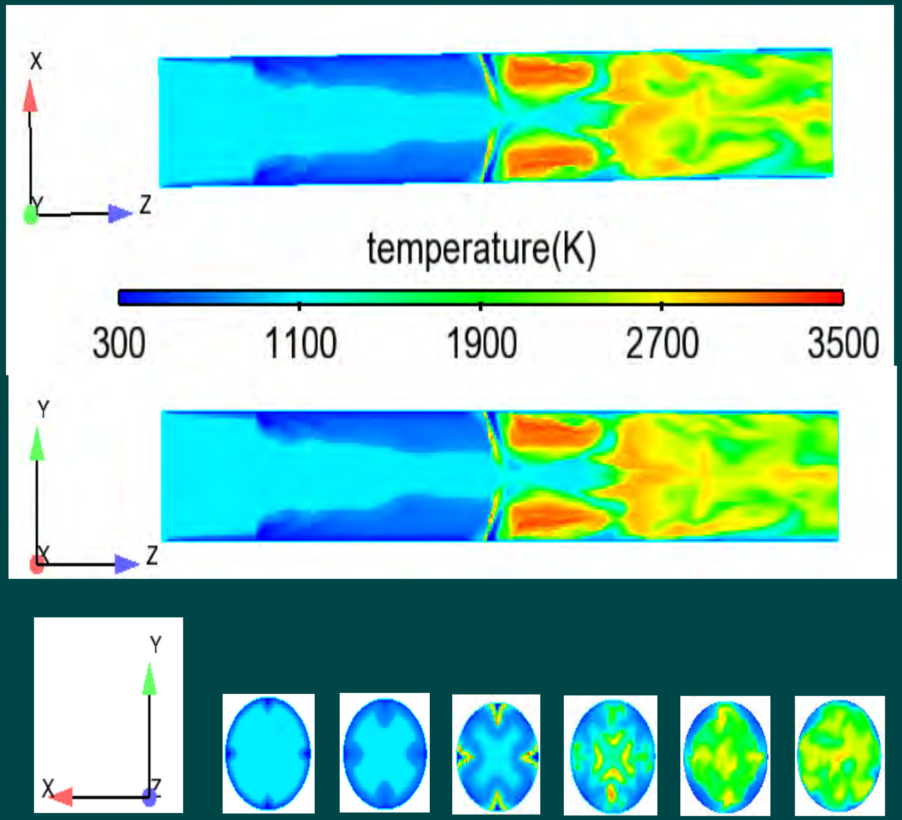



- 壁面設為313 K等溫邊界模擬Cold $CO_2$ cooling 的影響。
- 總釋熱率為33.55 MW。

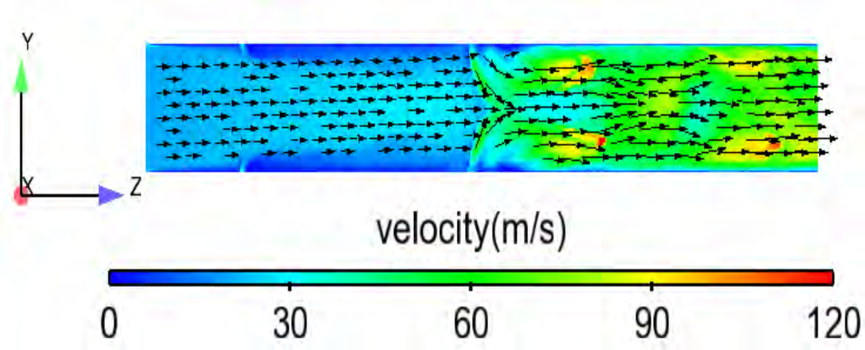
# Observed Sectors Profile

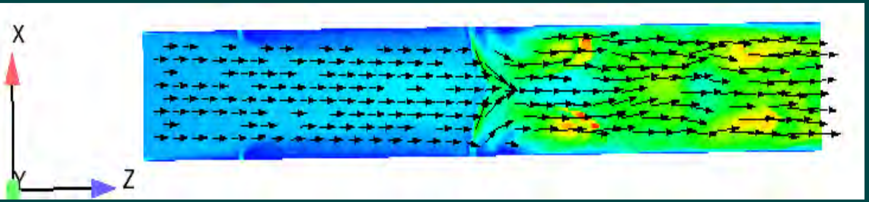


# Results: Temperature (K)

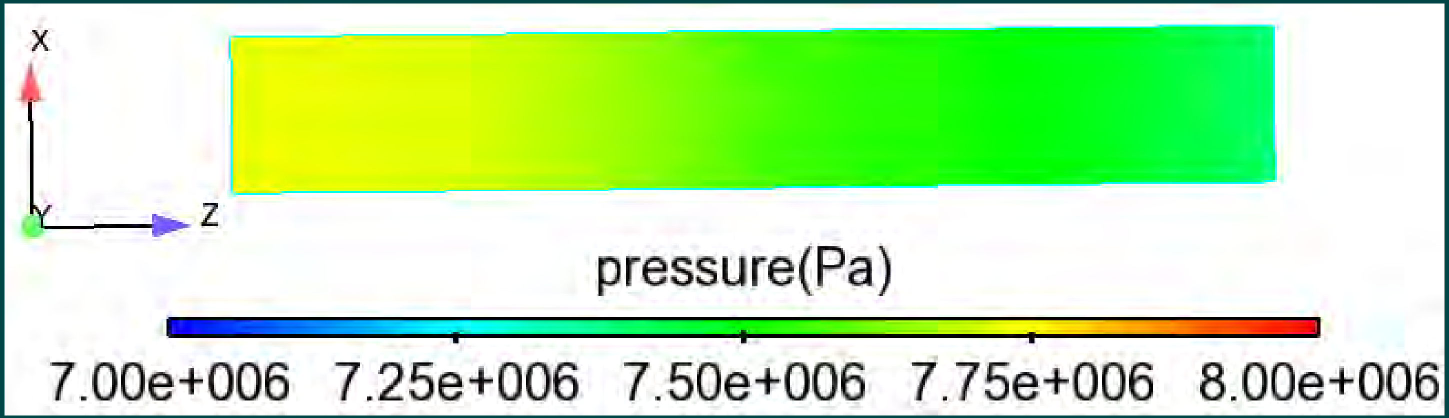


# Results:  Velocity Vector (m/s)

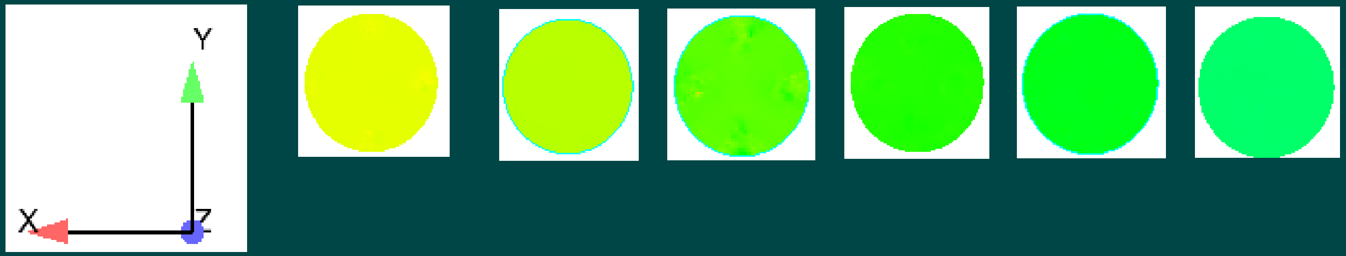


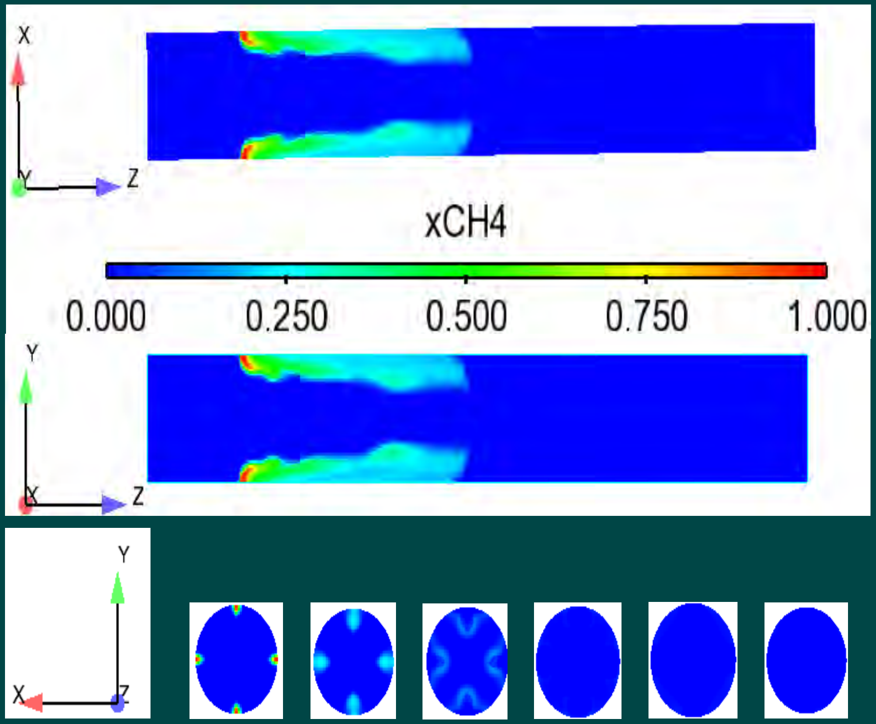
# Task 2 Results: Pressure (Pa)



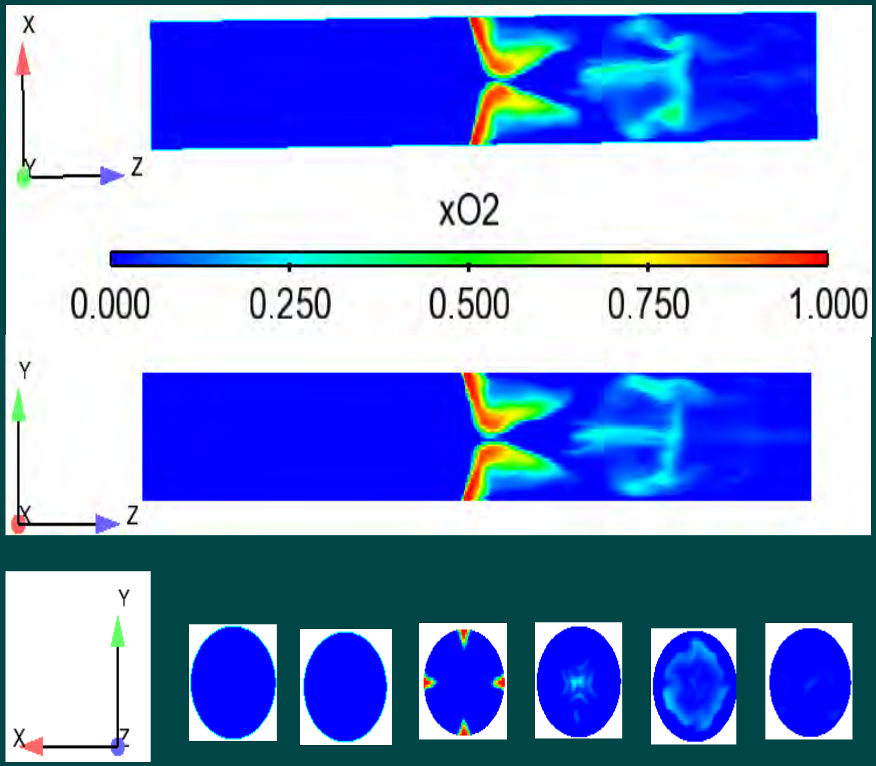




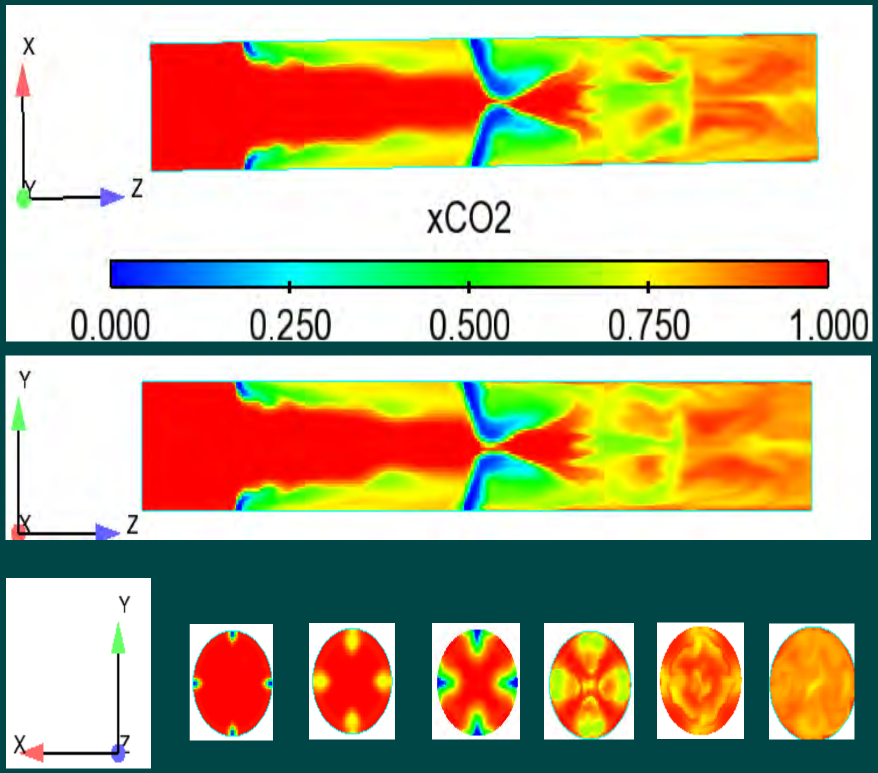
# Task 2 Results: Mole fraction of $CH_4$



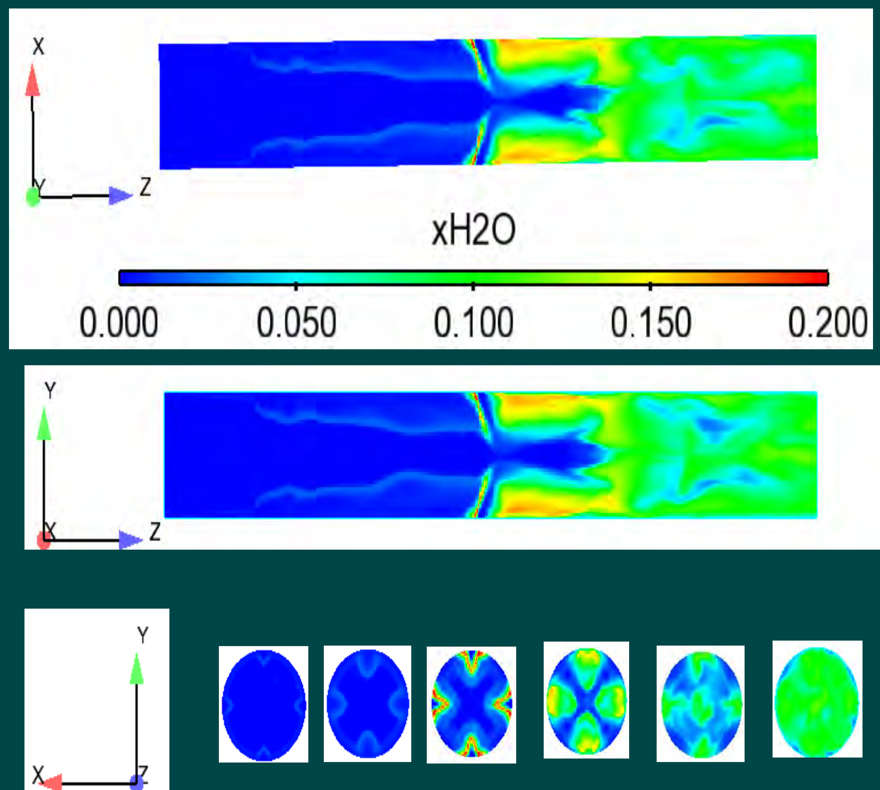
# Task 2 Results: Mole fraction of $O_2$



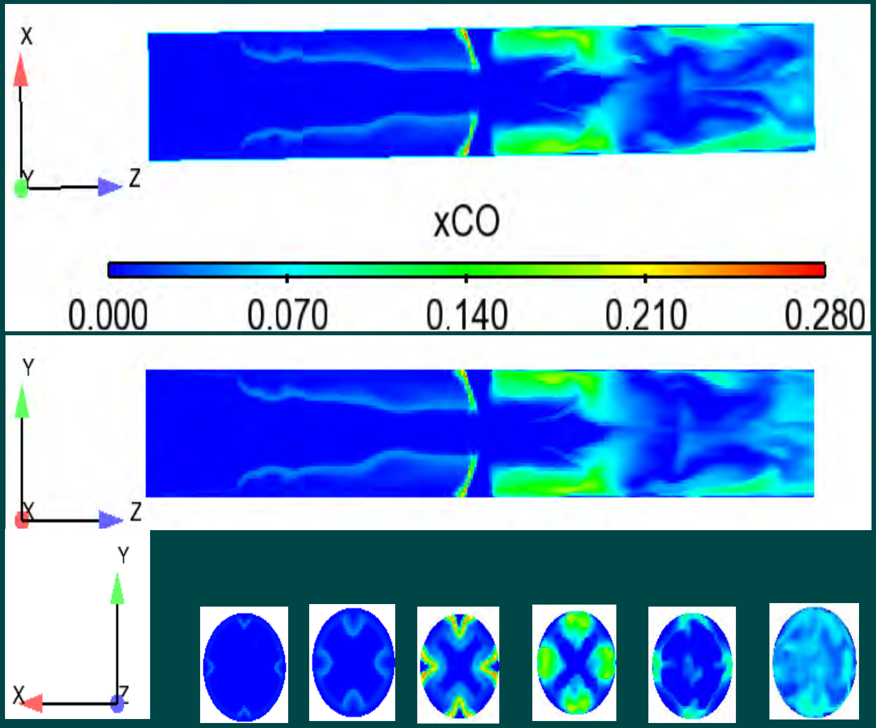
# Task 2 Results: [Mole fraction of $CO_2$ ]



# Task 2 Results:  Mole fraction of $H_2O$



# Task 2 Results: Mole fraction of CO



# Task 2 Results: Exhausted Gas Compositions

| Species | Percentage |
|---|---|
| xCO | 4.98% |
| xCO2 | 85.59% |
| xH2 | 0.15% |
| XH2O | 8.84% |
| xOH | 0.07% |
| xO2 | 0.28% |
| xCH4 | 0.08% |
| Total | 100% |

Exhausted gas temp.: 1959K

# Future works

- TAC(Turbine-Alternator-Compressor) Designed, Coupled and Fabricated
- ISG will Establish Current Wave Feedback Control Mechanism , in Sine Wave Form Distribution
- SCO2 Thermal and Fluid System Integrate & Test。
- SCO2 Oxyfuel Combustor Parameters Analysis, including, locations and flow rate of injectors, wall temperature, exhaust gas composition, etc. Then fabricate and test.