Development of a Small-Scale Supercritical CO2 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

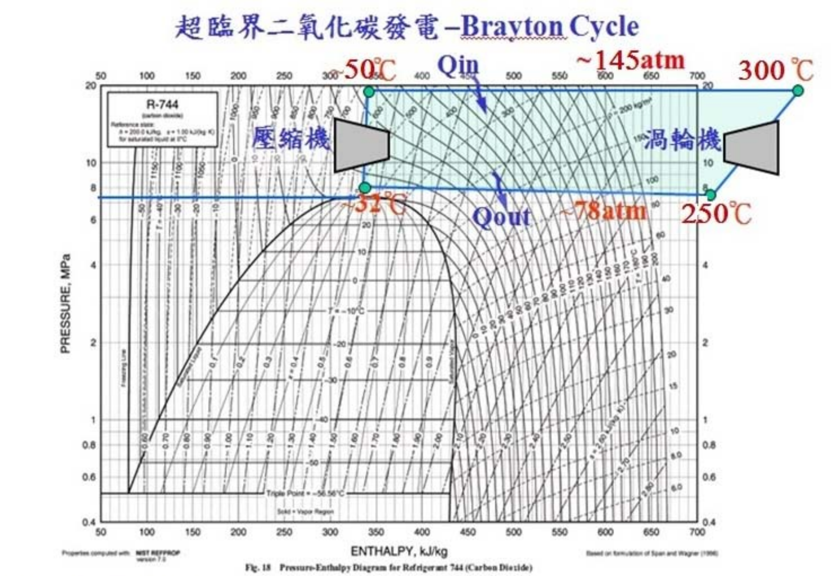
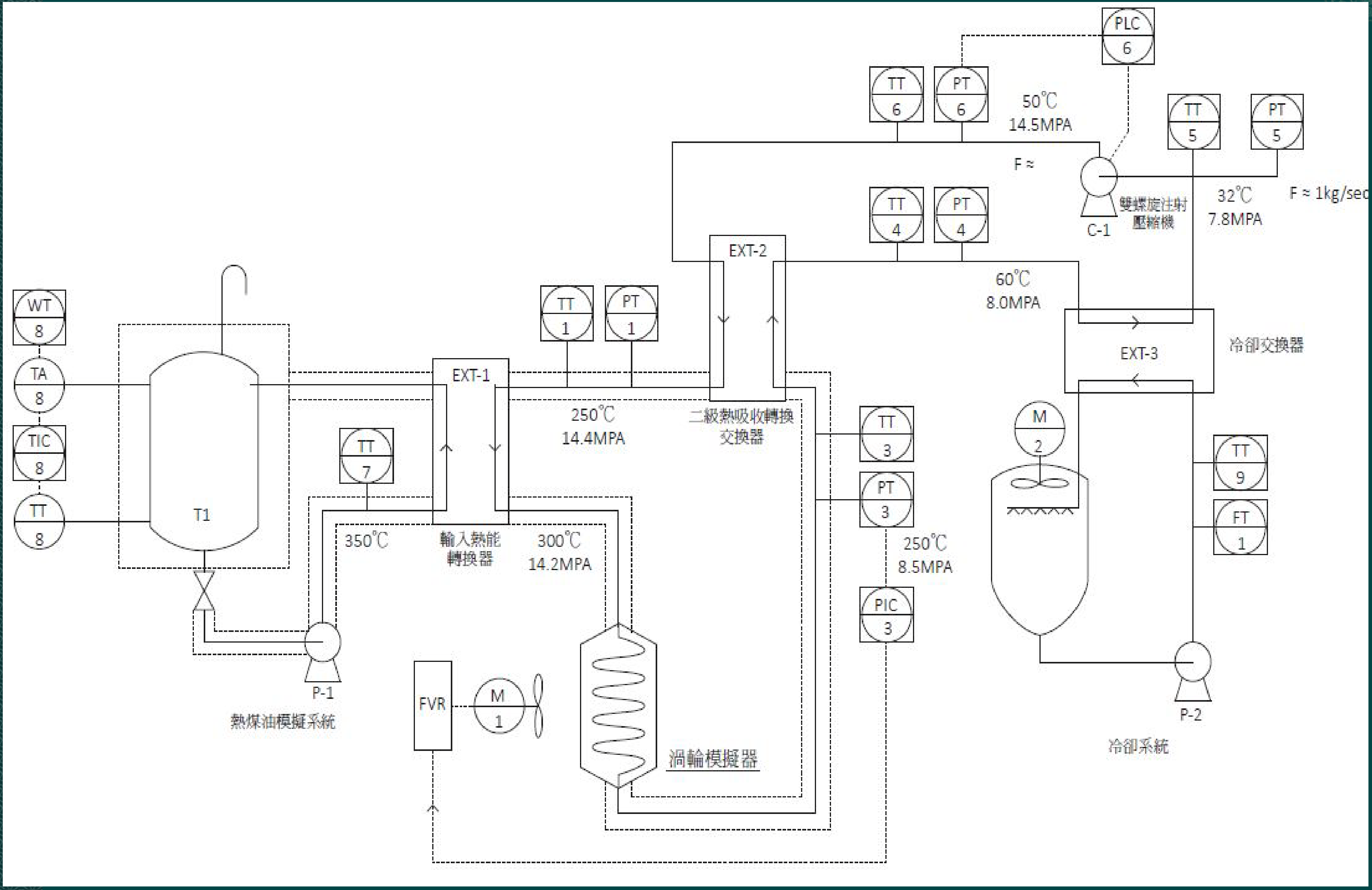


Fig. 18 Pressure-Enthalpy Diagram for Refrigerant 744 (Carbon Dioxide)

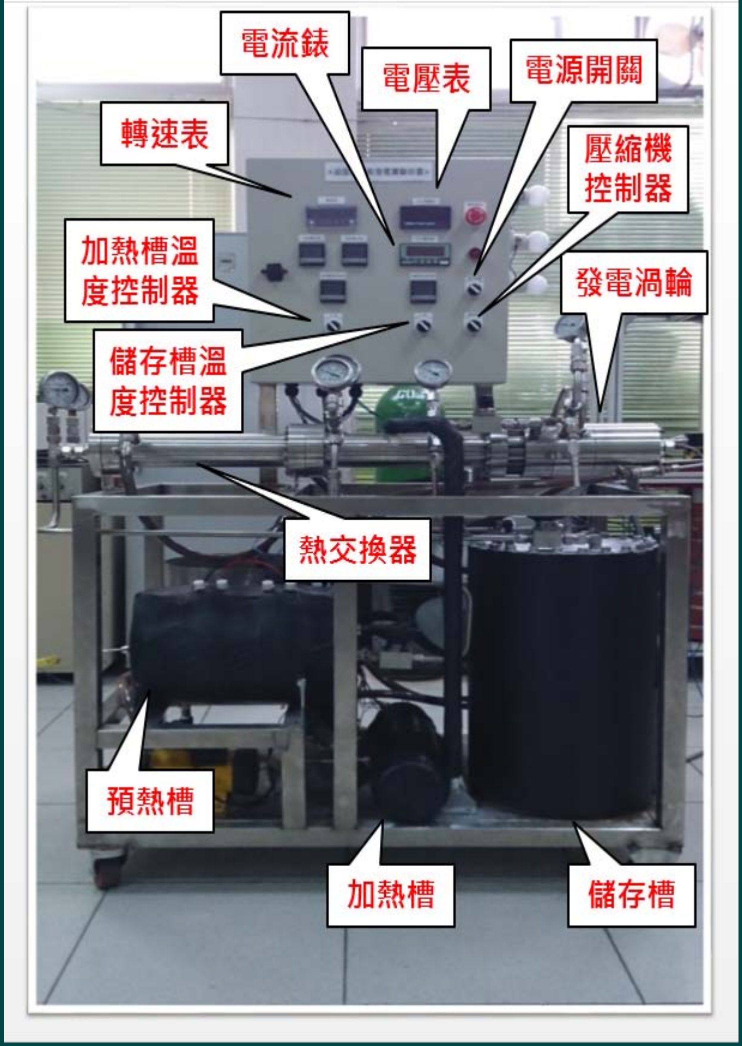
1. ASHRAE Handbook, 2009.
2. Span, R. and W. Wagner, 1996."Anew equation of state for carbon dioxide covering fluid region from triple-point temperature to 1100 K at pressures up to 800 Mpa. J. of physical and Chemical Reference Data 26: 1509-1596.
3. Robert Z. Litwin, "Supercritical CO2 turbine for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

10 kw SCO2 System Spec. & Design



Power System Development Approach (1 kw→10kw → 250kw → Mw)

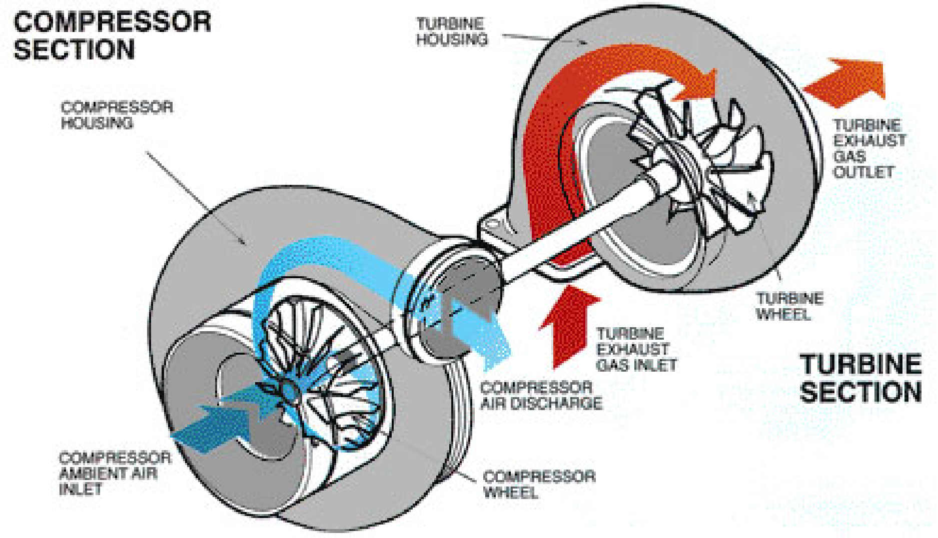
- **Small Prototype R&D :**
- **I Kw power** output from Waste Heat
- Using Brayton power cycle
- **CFD Analysis** of Compressor and Turbine Performance in SCCO2 Flowfield
- **Design and Fabricate a Portable System**
- **Test and Assess** the following technologies required



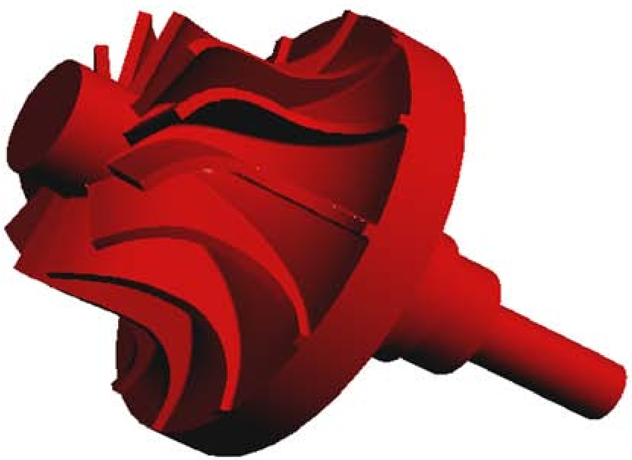
TAC Component

渦輪與壓縮機結合發電機組合圖

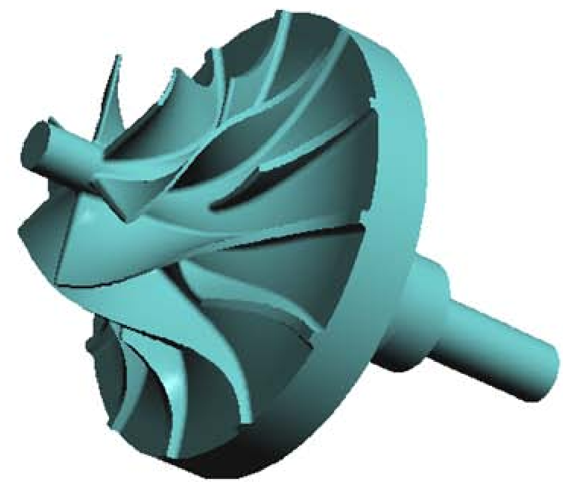
渦輪與壓縮機安裝組合圖



Designed Compressor & Turbine



3D渦輪及製造圖



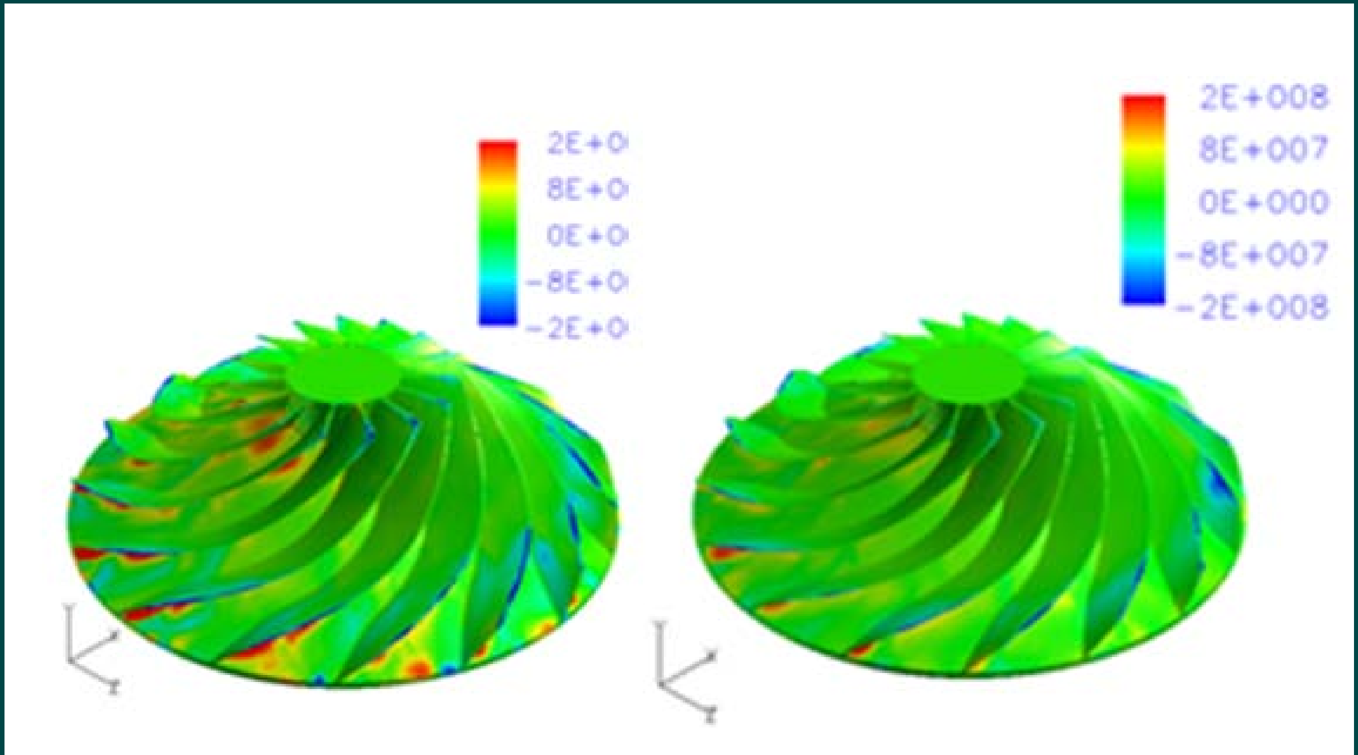
壓縮器3D製造圖

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，

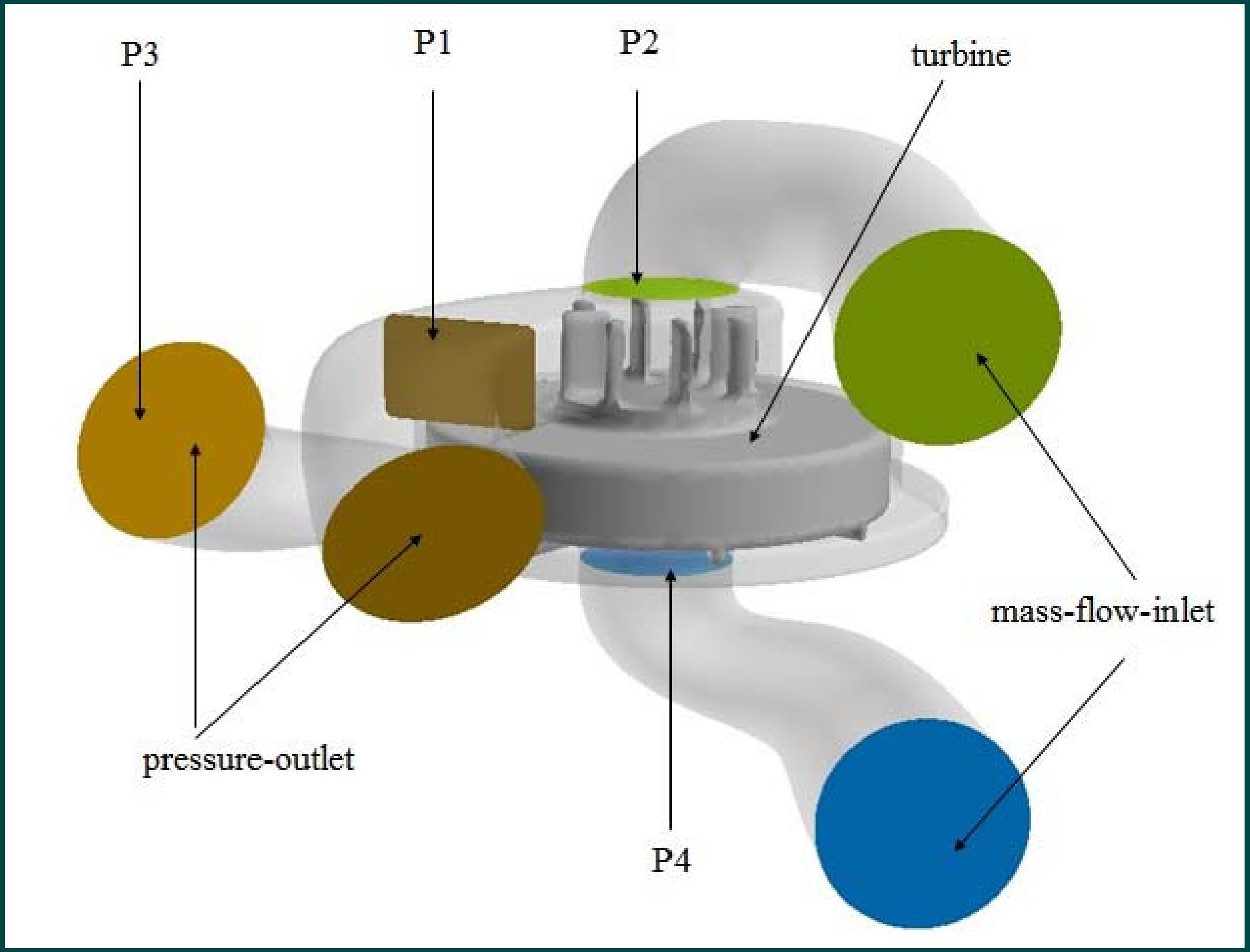
$$\frac{\partial}{\partial t}\iiint_{\Omega} U d\Omega + \oiint_{S} \vec{\Phi} \times d\vec{S} = 0$$

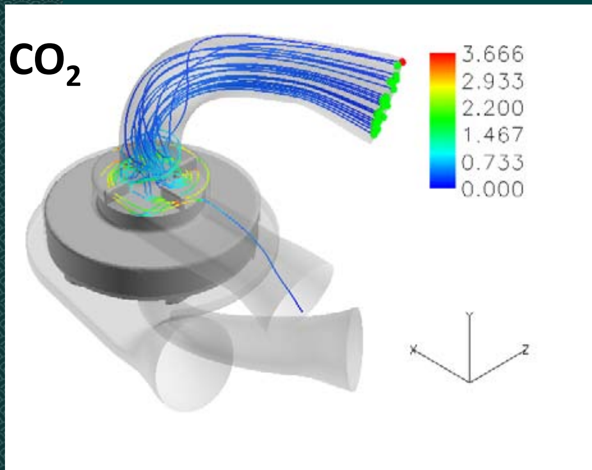
Turbine Surface Pressure Distribution

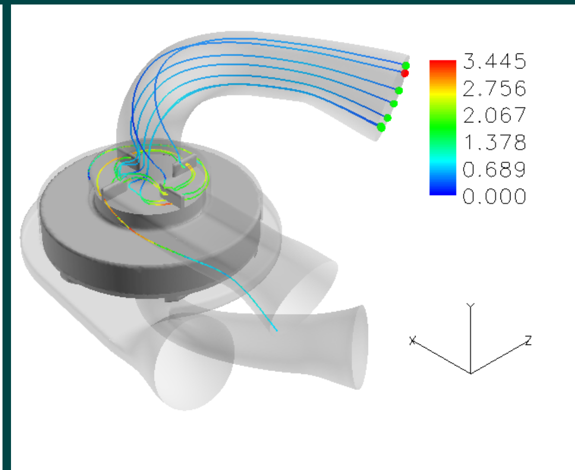


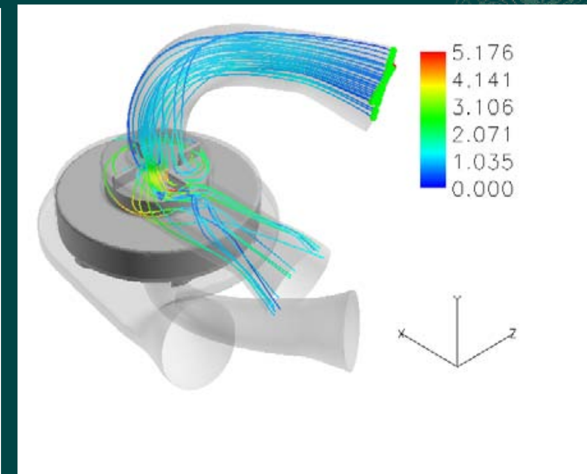
(a) air flow　　(b) scco2 flow

Compressor-Turbine System Flowfield Simulation





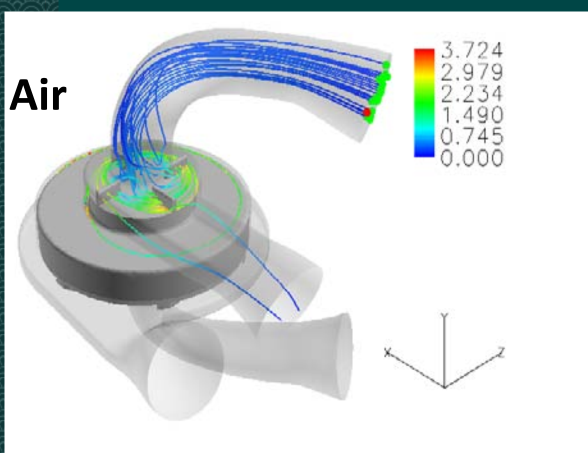


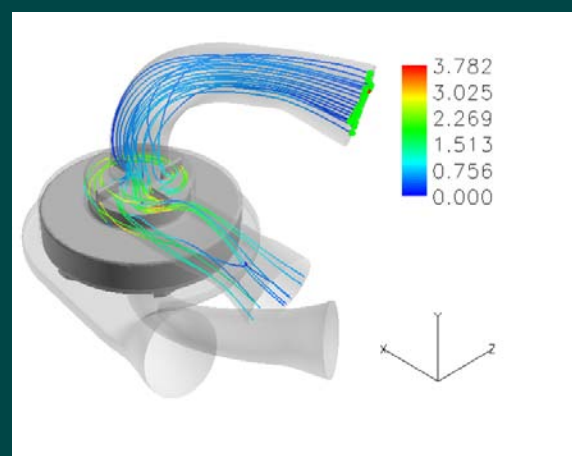


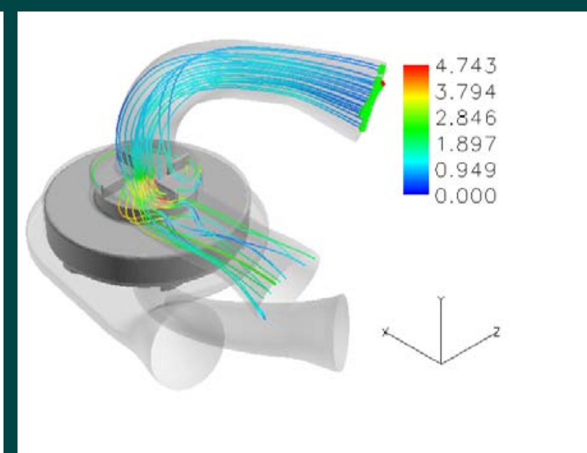
25Kgw/min

50 Kgw/min

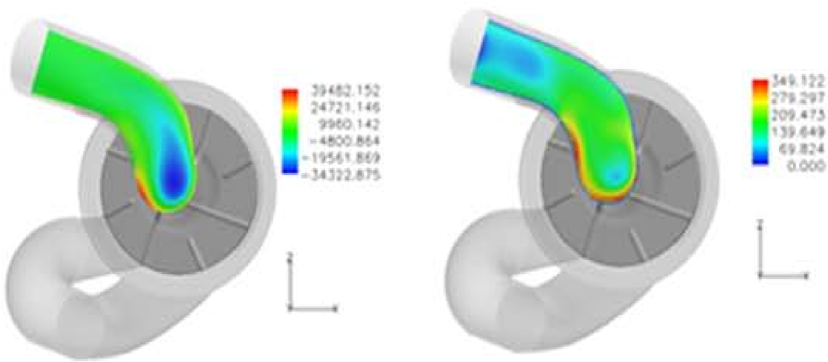
100 Kgw/min



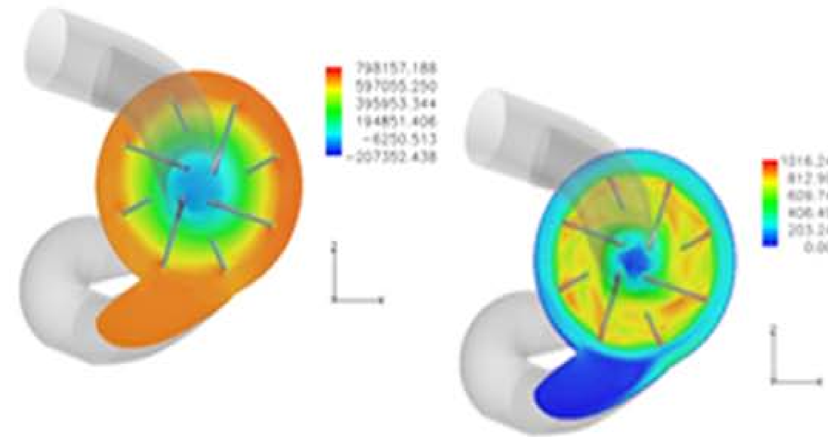




27,000 rpm

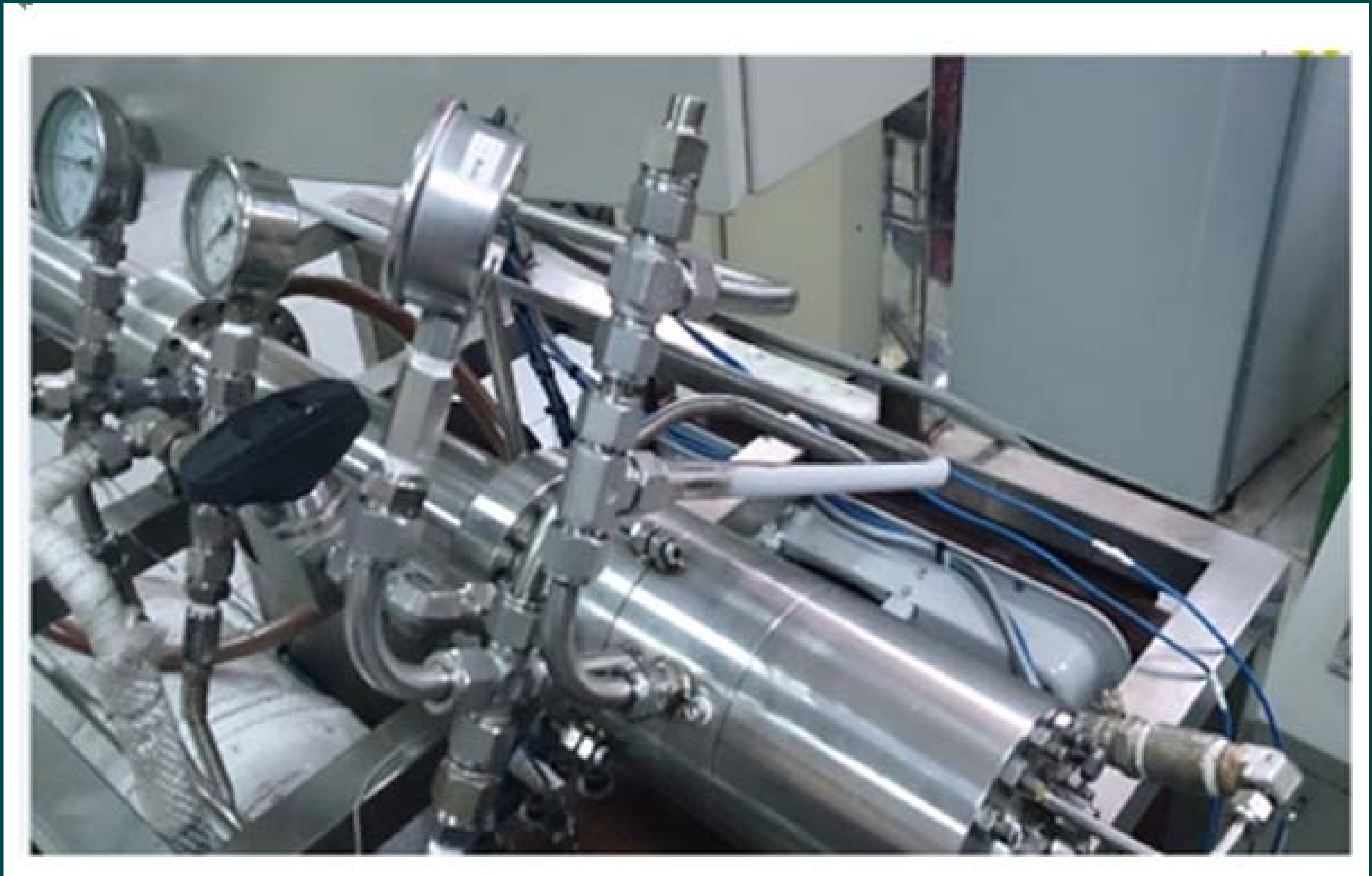


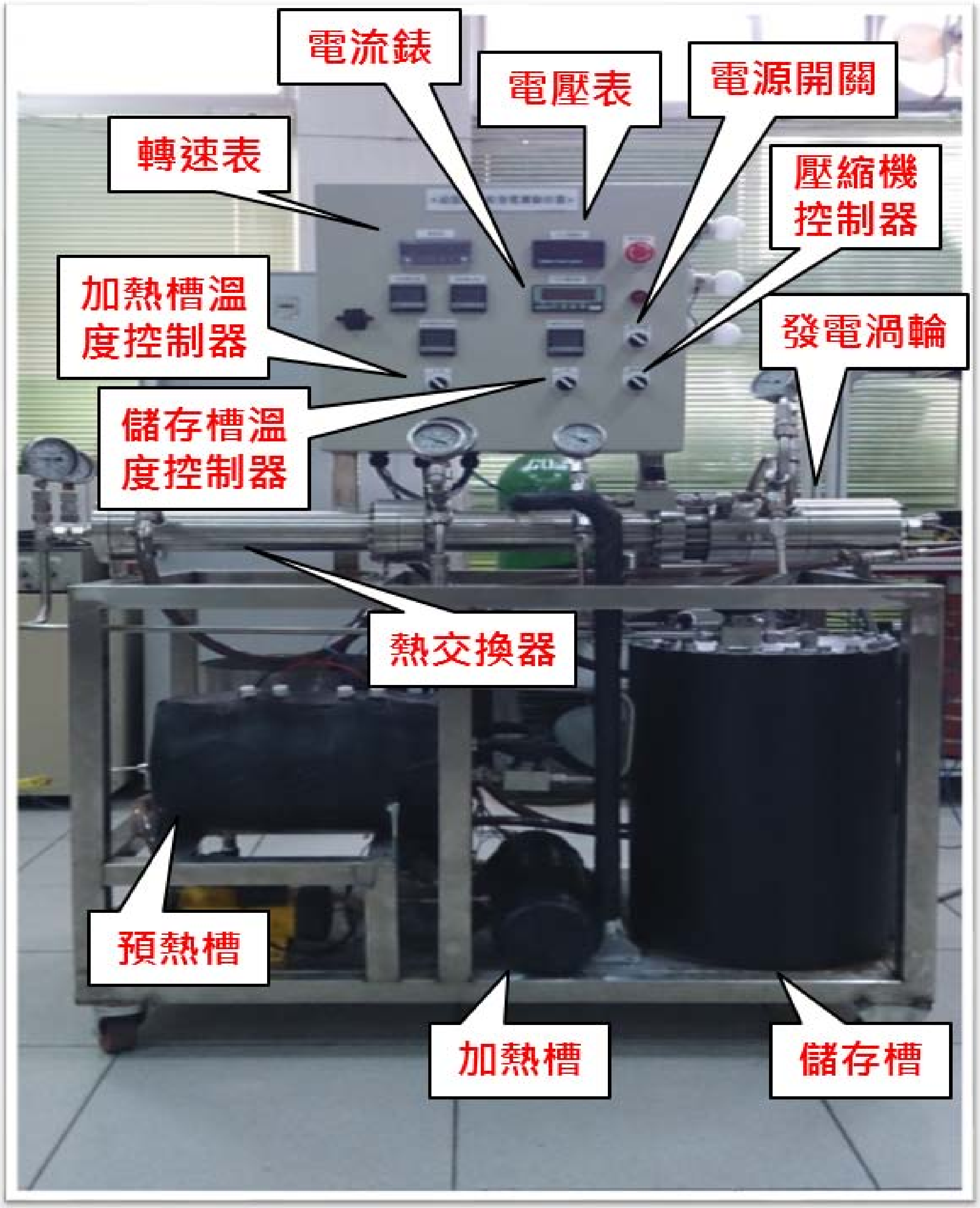
壓縮段進氣流道之壓力及流速分佈



壓縮段葉輪上表面切面壓力及速度分佈

Turbine-Alternator-Compressor Section





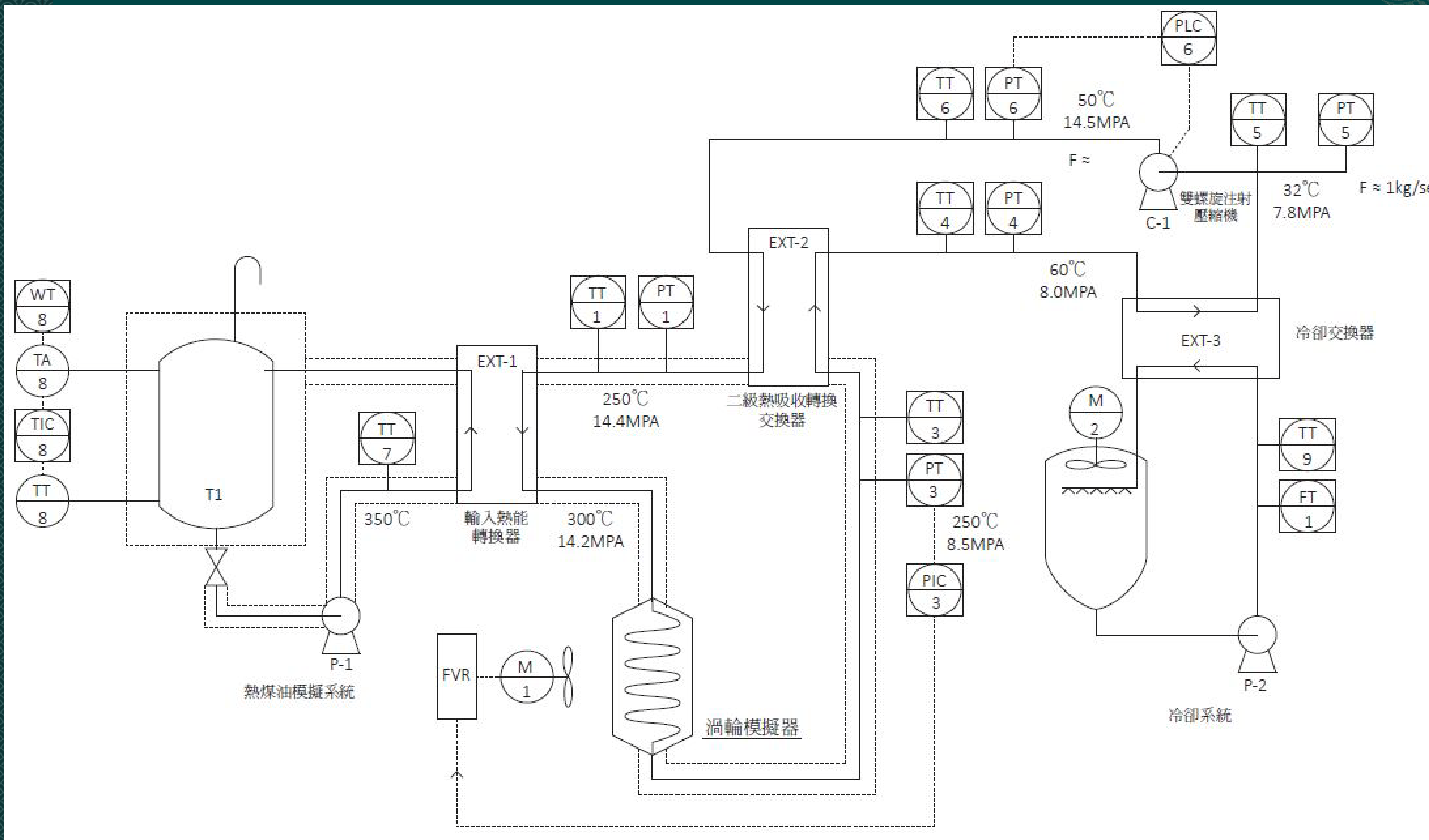
電流錶
電壓表
電源開關
轉速表
壓縮機
控制器
加熱槽溫
度控制器
發電渦輪
儲存槽溫
度控制器
熱交換器
預熱槽
加熱槽
儲存槽

Test Data showing Temperature, Current and Voltage

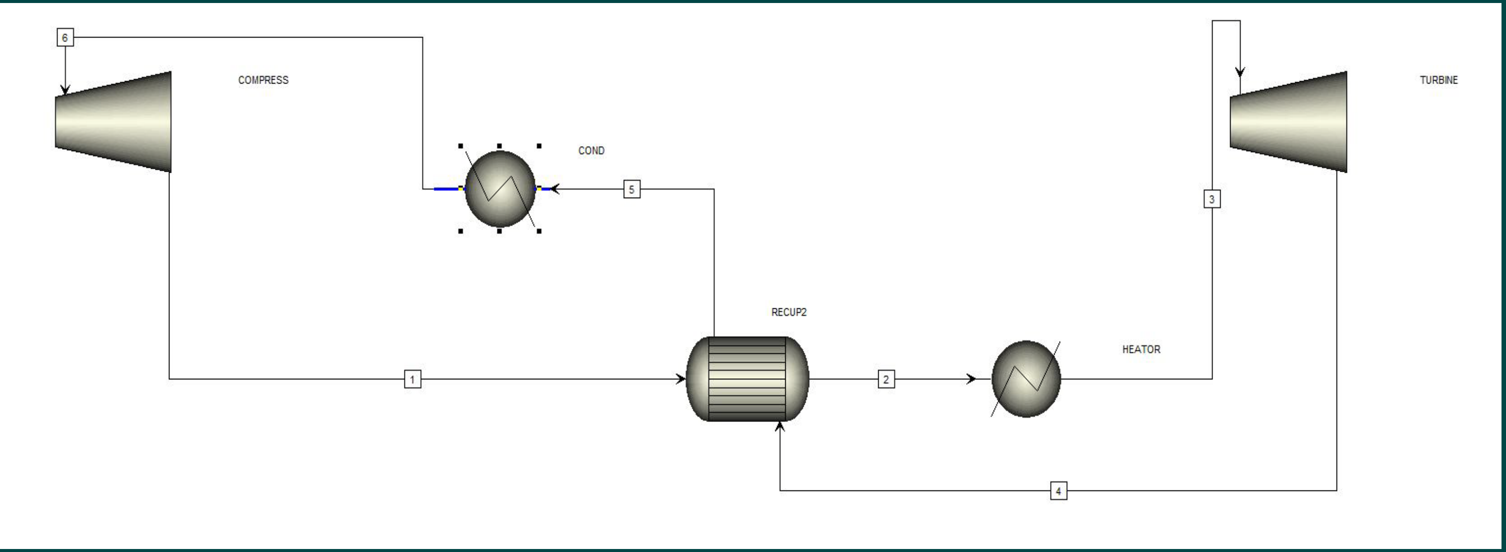
Results & Suggestions

- 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

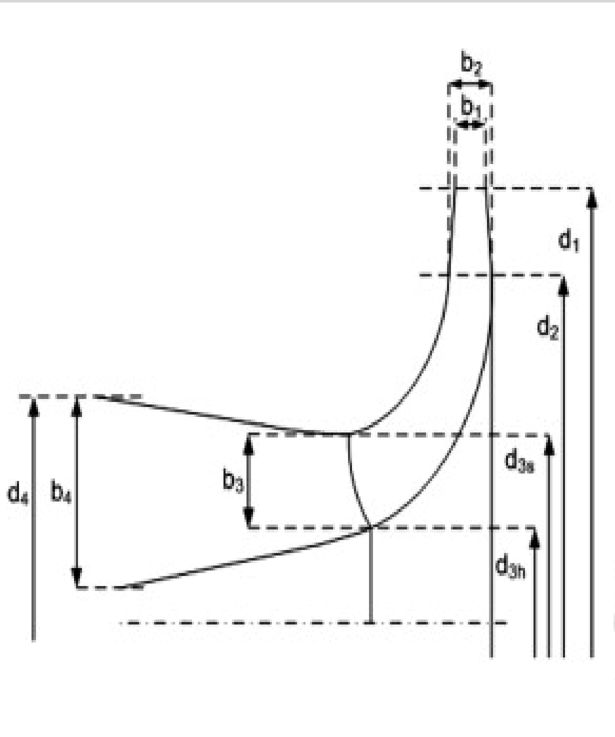
Mass flow: 1kg/s

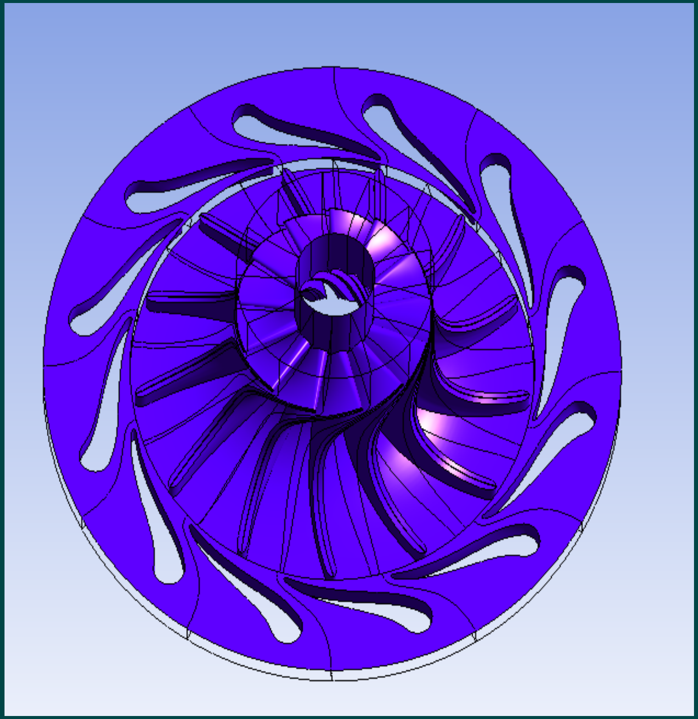
Rotation rate:

30000 rpm

Blade number: 13

Inducer number: 12



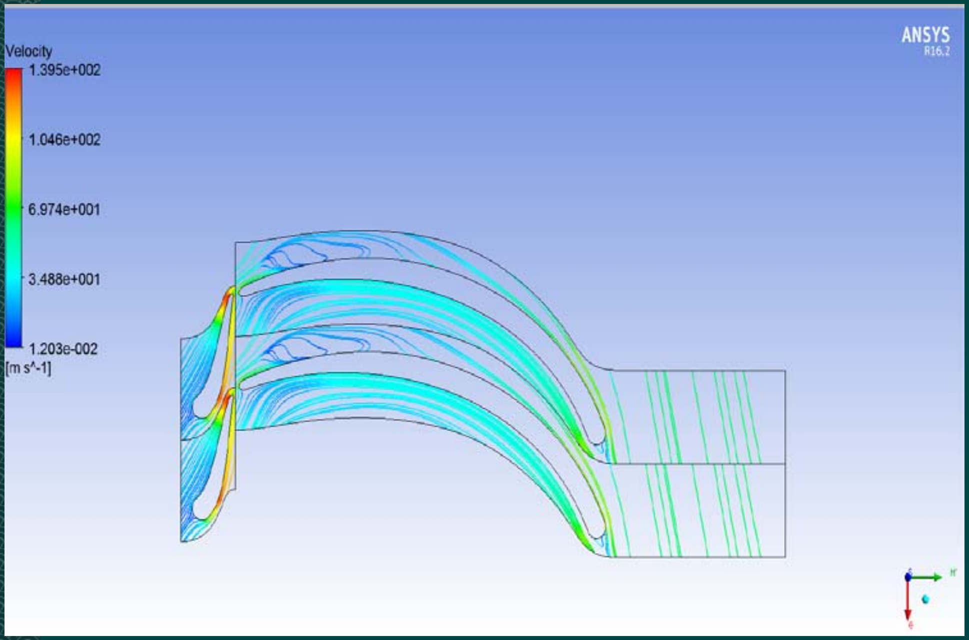


d_2=24

d_3=12

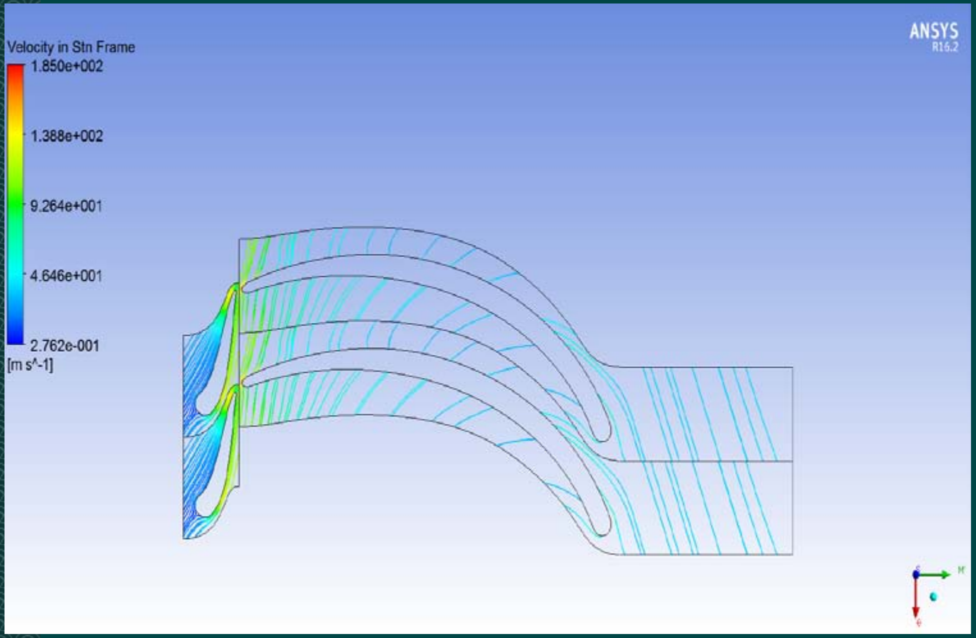
d_{3h}=4.8

b_1= b_2=3(mm)



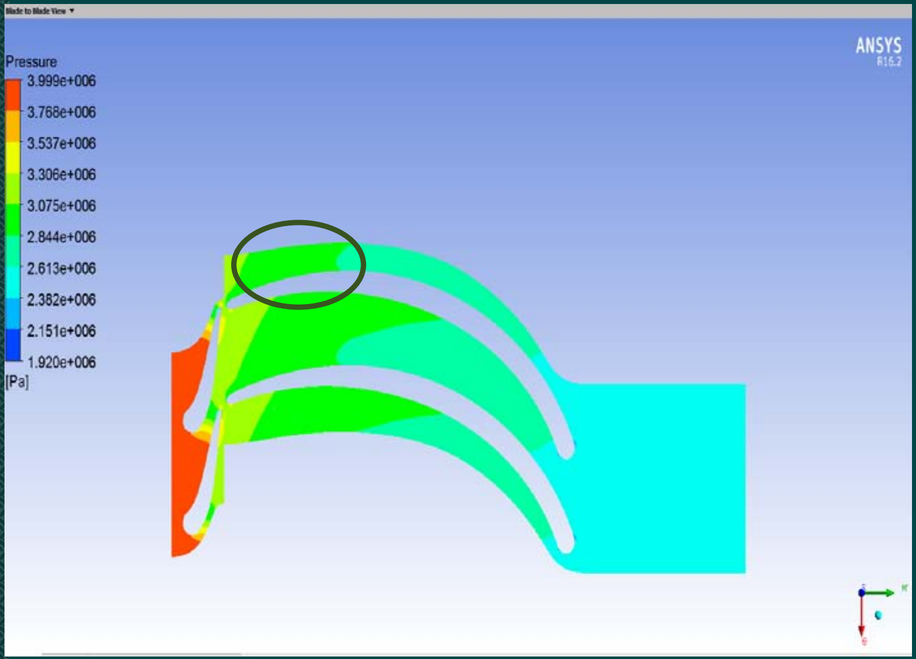
RFR frame

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



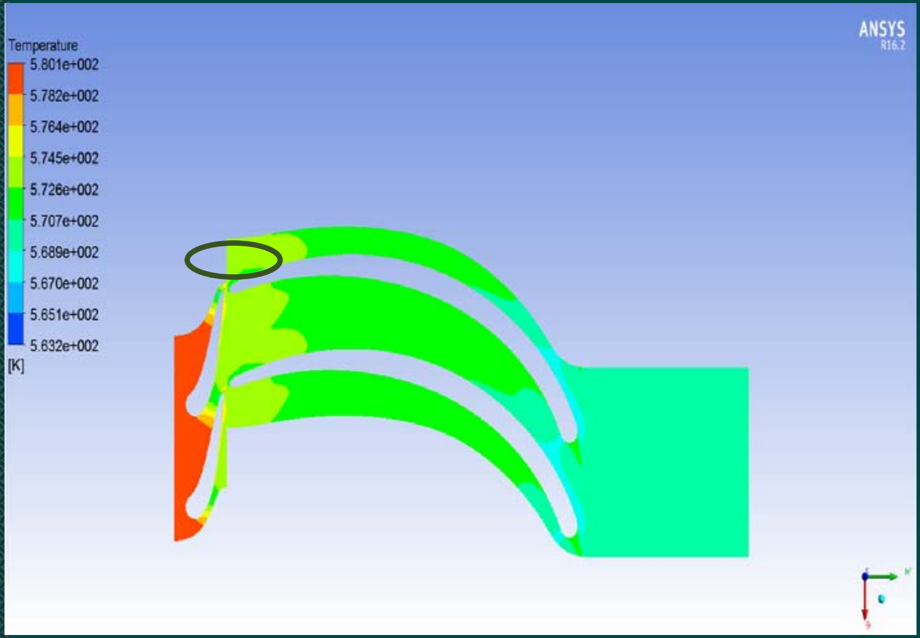
Stn frame

- Outlet streamline not axial direction
- Dynamic Energy loss



Model pressure

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



Model temperature

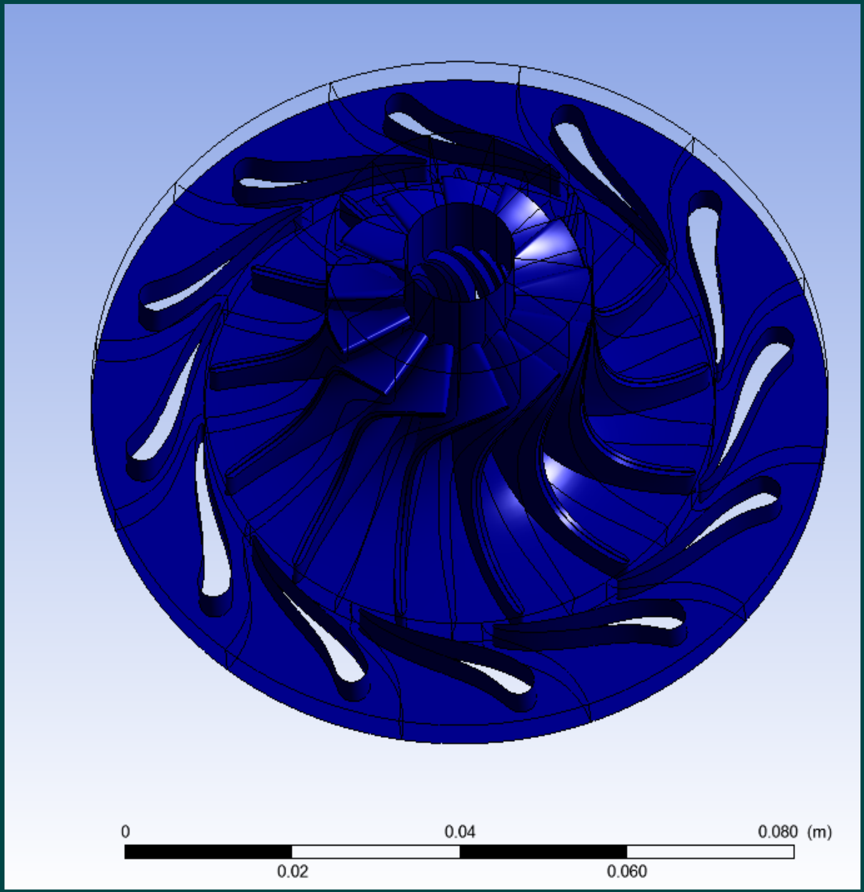
- Vortex also cause temperature non-continuous

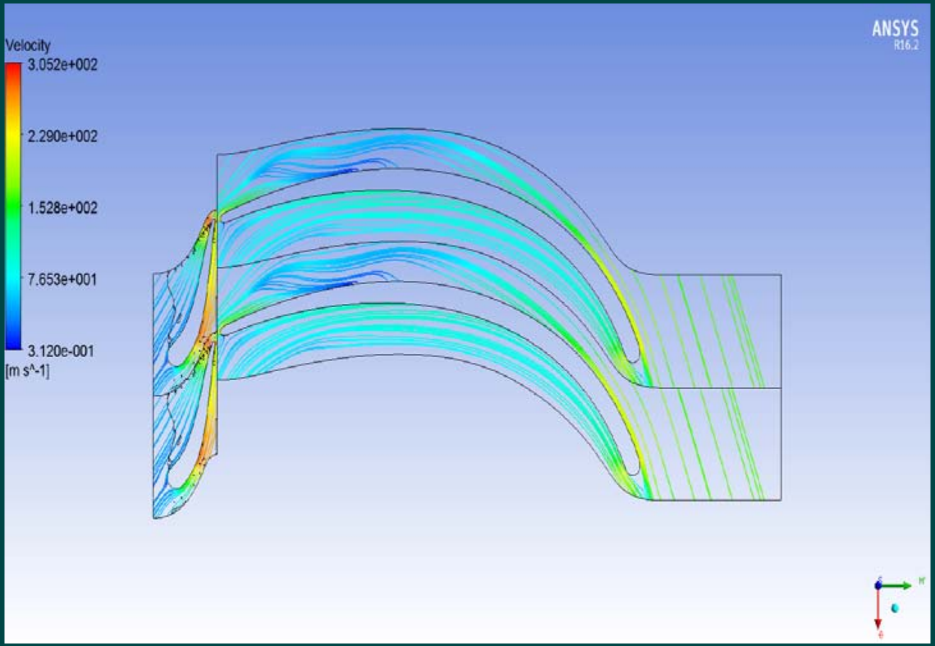
Modify the Design parameters

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

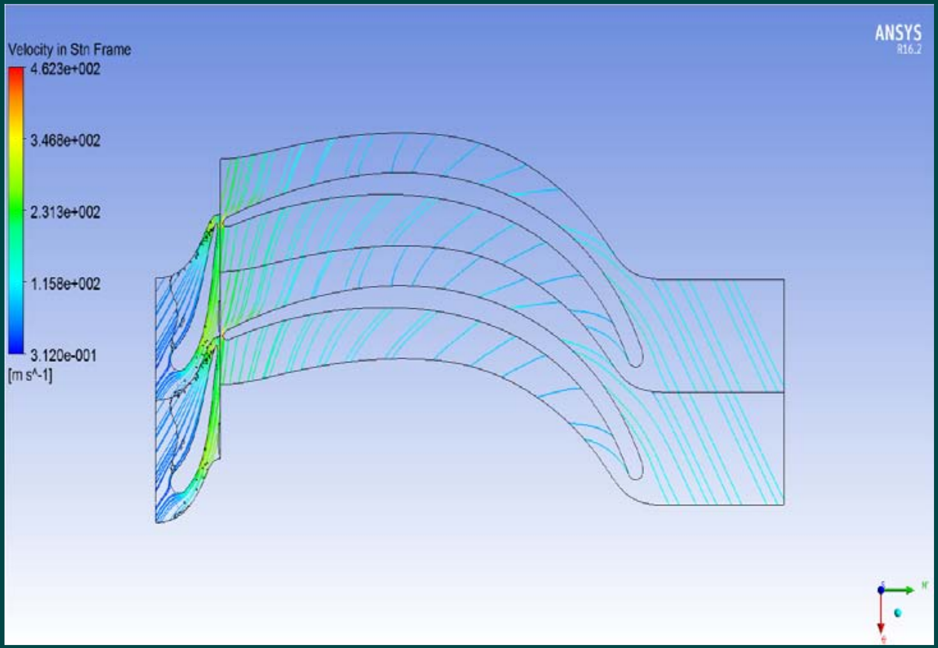
d_2=30
d_3=16
d_{3h}=6.6
$b_1 = b_2$=4(mm)





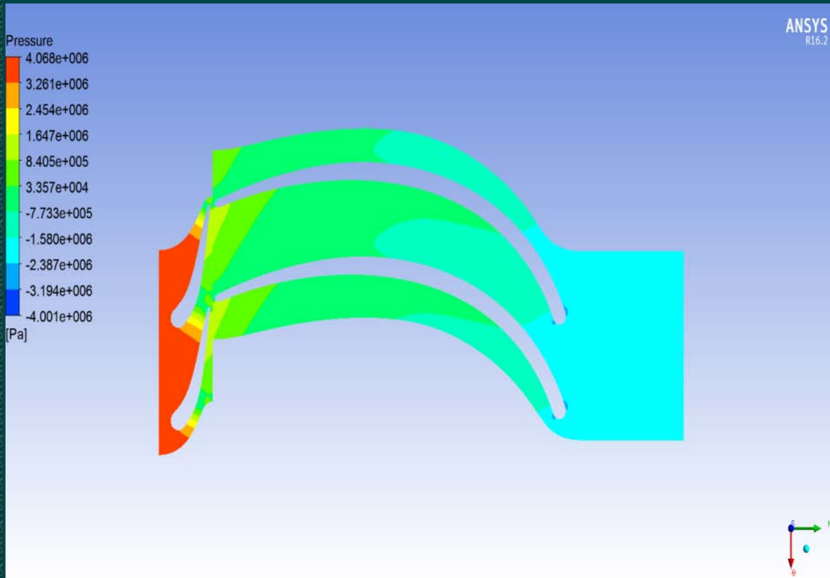
RFR frame

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



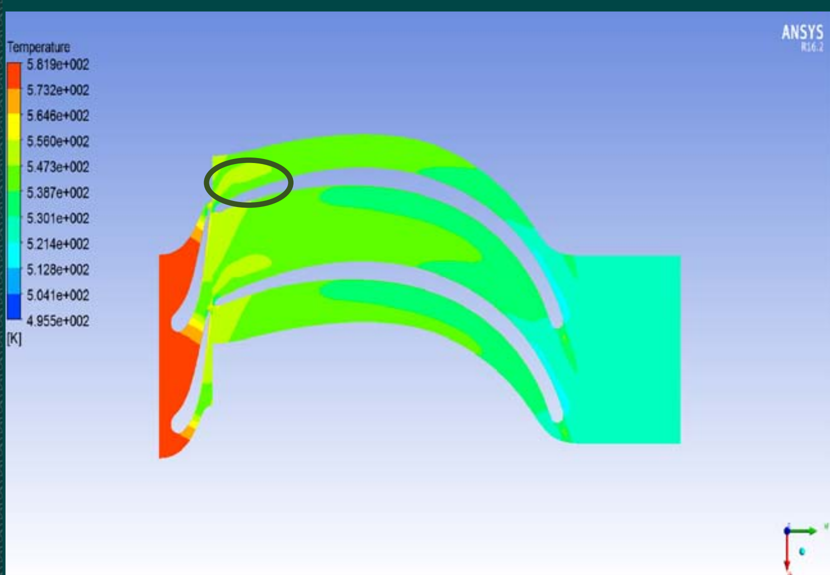
Stn frame

- Exit streamline direction need improved



Model pressure

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

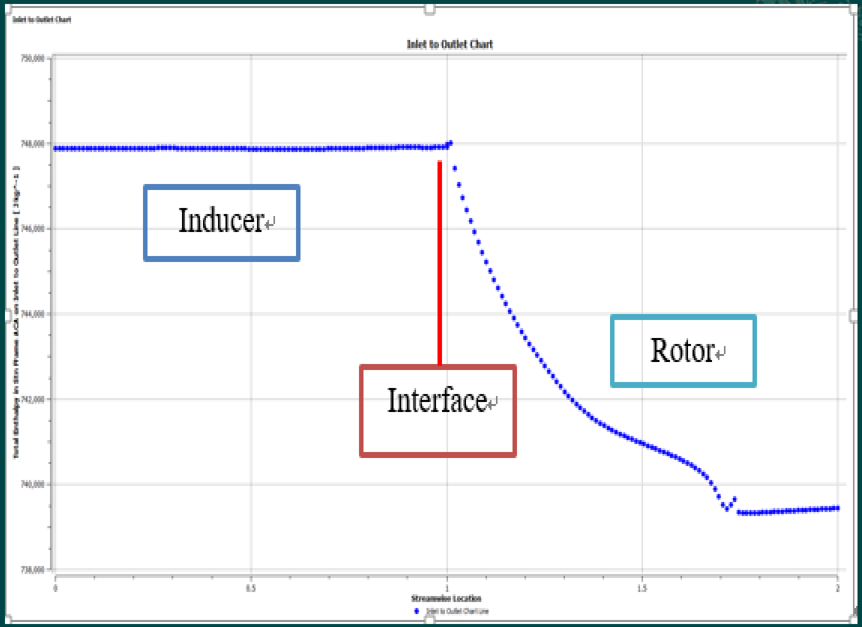


Model temperature

- 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

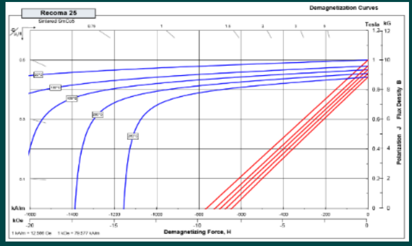
Selection of silicon steel and permanent magnet for specific operating environment

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

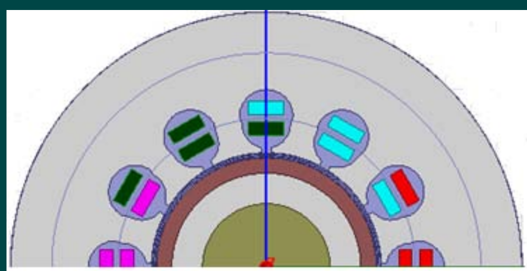


Magnetic Properties	Characteristic	Units	min.	nominal
	Br, Residual Induction	Gauss	9,700	10,000
		Tesla	0.97	1.00
	H_{cB}, Coercivity	Oersteds	9,050	9,740
		kA/m	720	775
	H_{cJ}, Intrinsic Coercivity	Oersteds	25,000	30,000
		kA/m	2,000	2,400
	BHmax, Maximum Energy Product	MGOe	23	25
		kJ/m^3	180	200

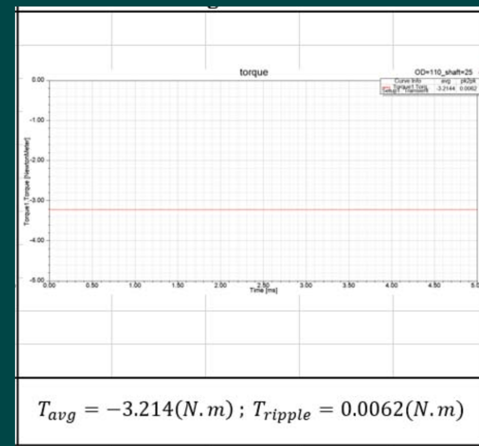
Development of a High-speed Permanent Magnet Electrical Machine

Design result

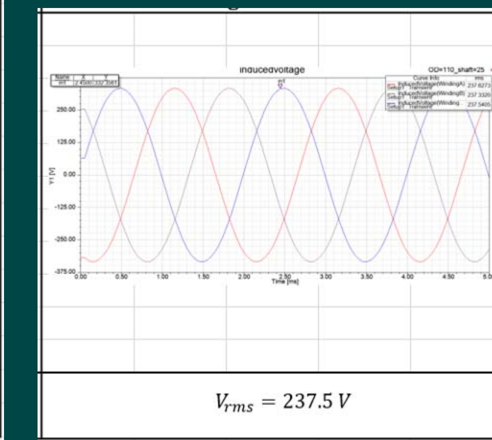
Taking the empirical analysis into consideration with the simulation of the **ANSYS EM Maxwell** software has led to the development of the model in figure 1.



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



Fiqure2.rated output torque in the PMSM



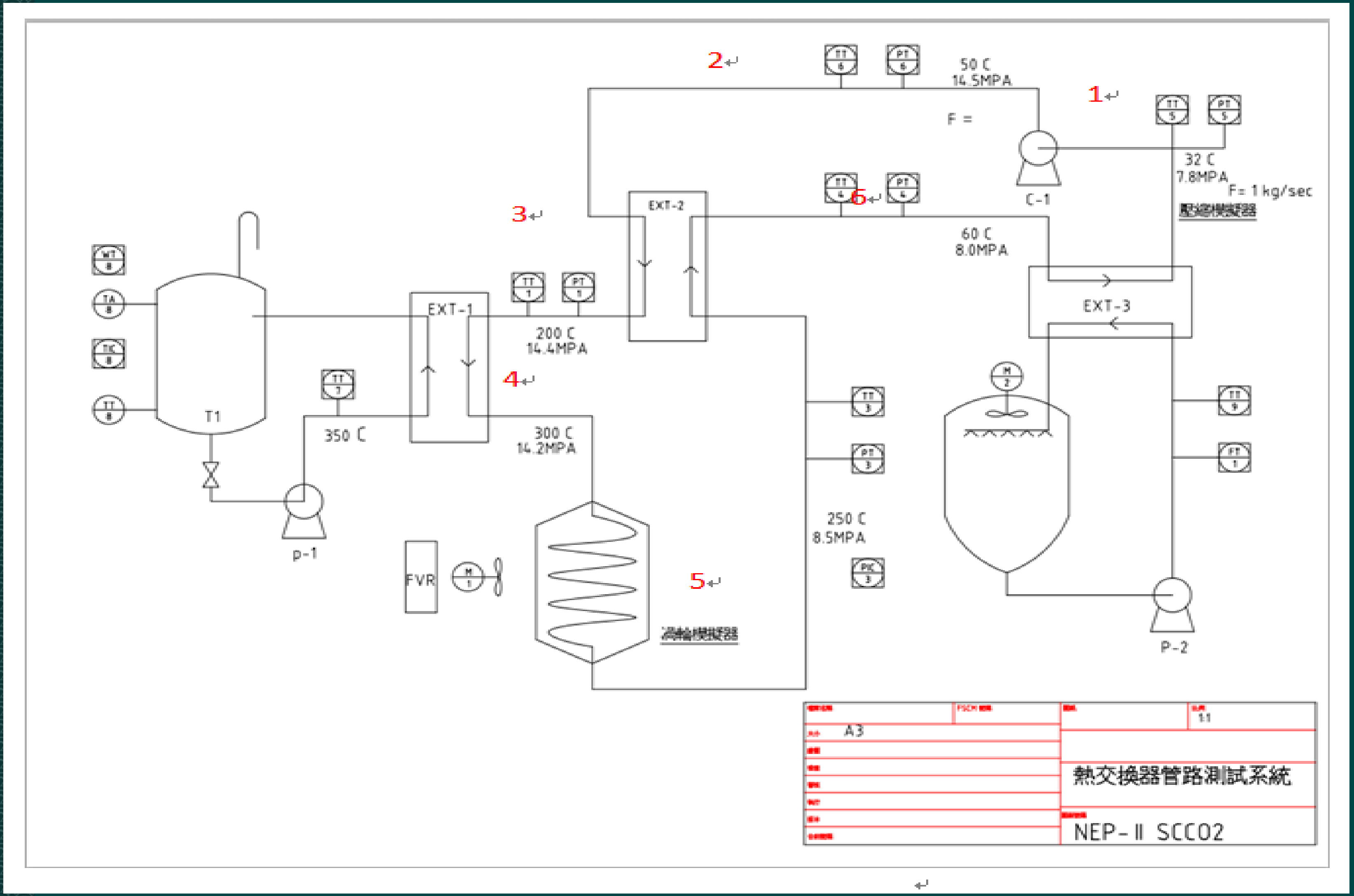
Fiqure3.induced voltage in the PMSM

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



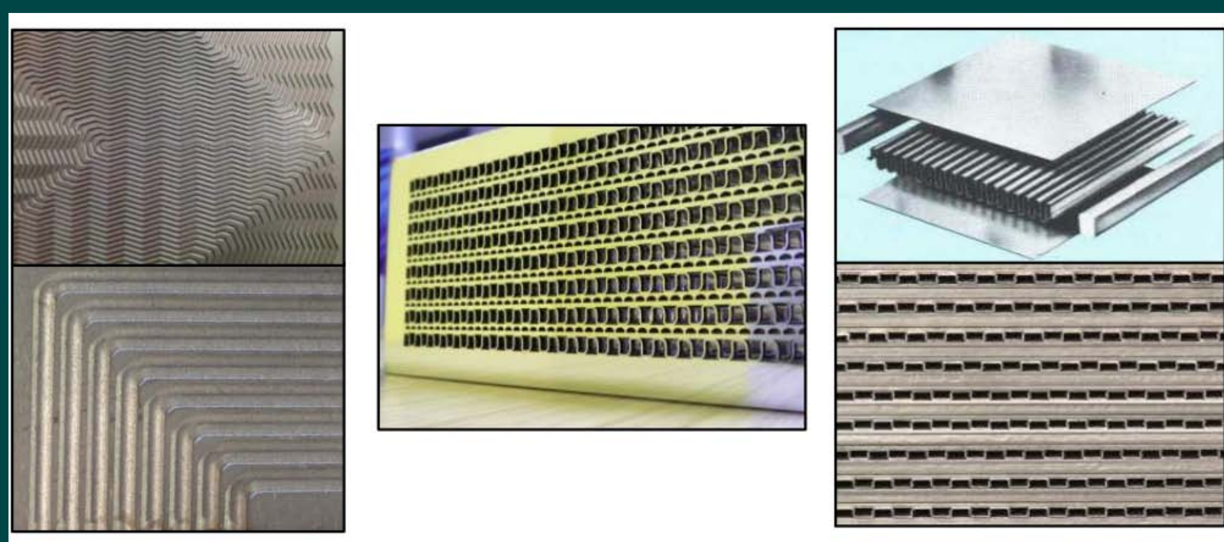
Heat Exchanger Analysis

Heat exchanger heat loads

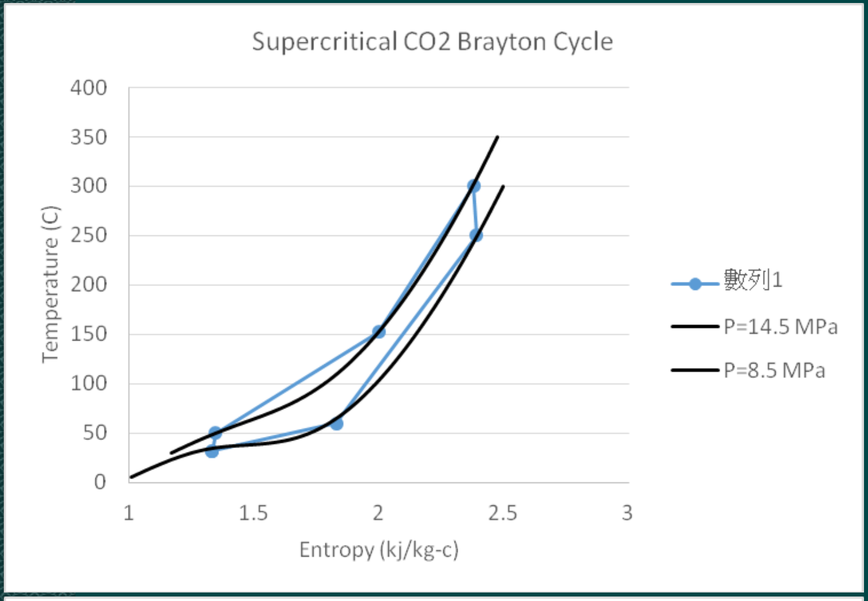
exchanger 1, heat load	*Q EX,1*	*186.2*	*kW*
Exchanger 3, heat load	*Q EX,3*	*156.2*	*kW*
exchanger 2, heat load	*Q EX2*	*236.6*	*kW*

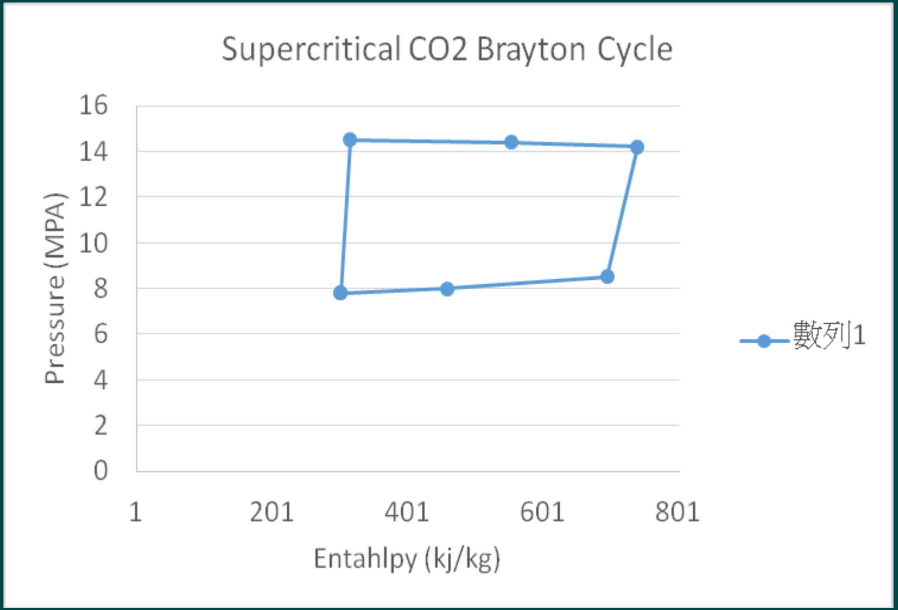
Work input and output

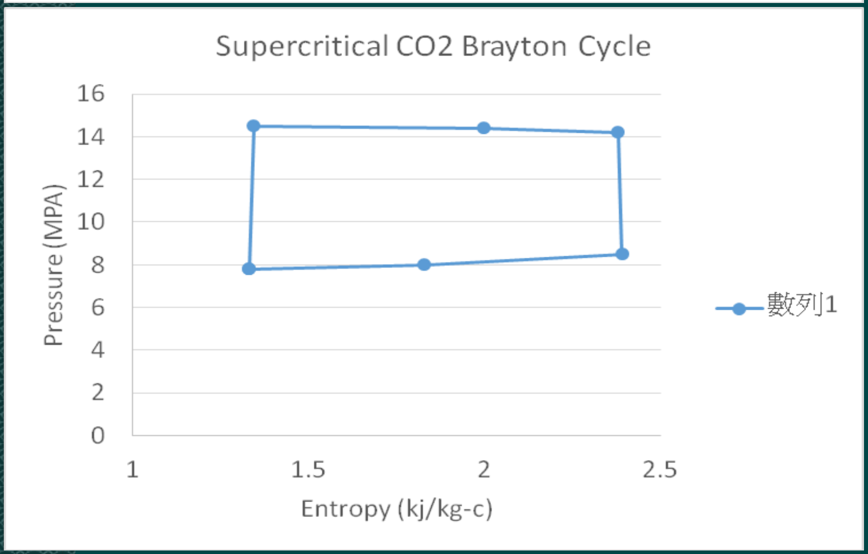
Compressor work input	W_{comp}	*10.2*	*kW*
turbine work output	W_{tur}	*44.3*	*kW*



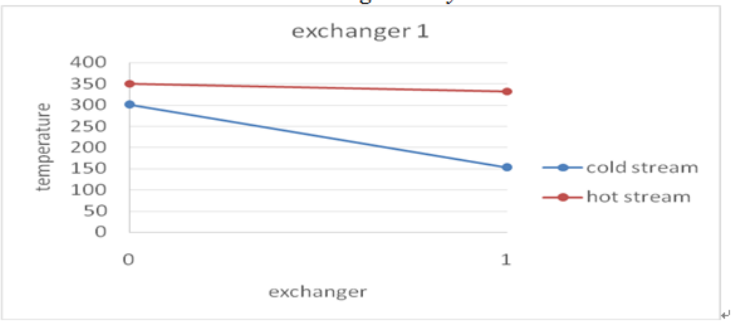
SCO2 Brayton Cycle Graphs

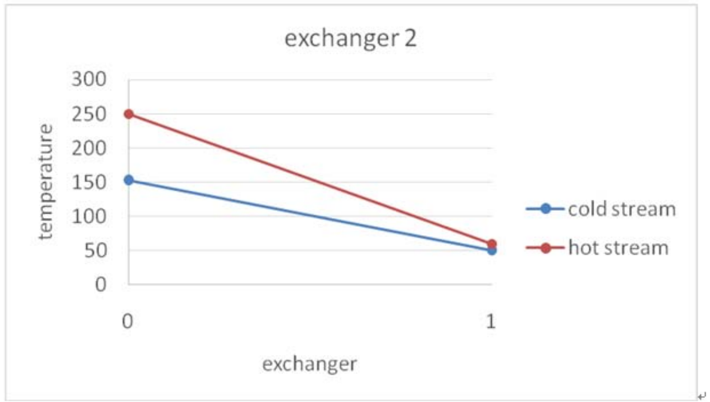


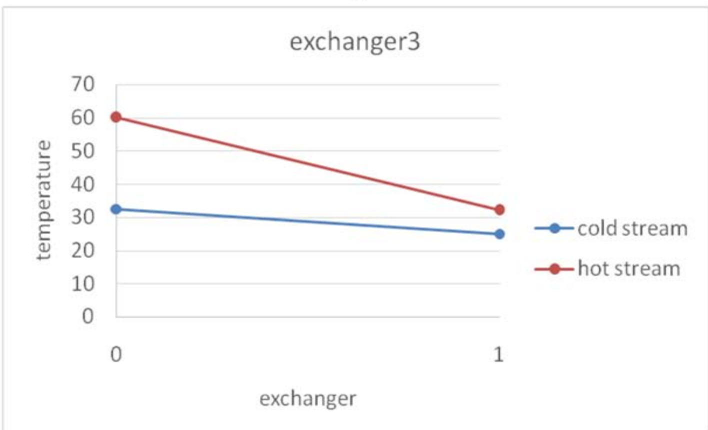




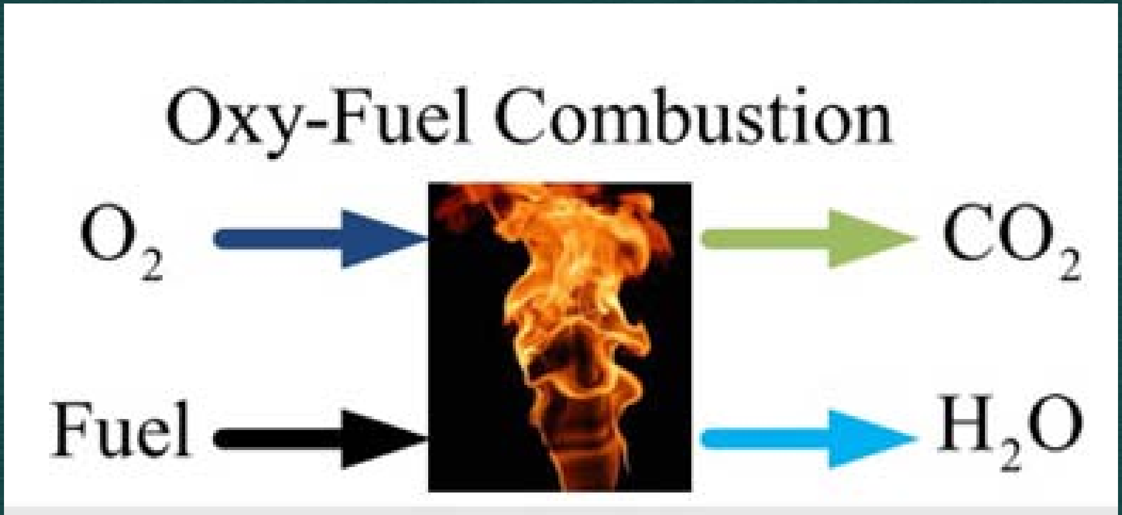
Heat exchanger Analysis



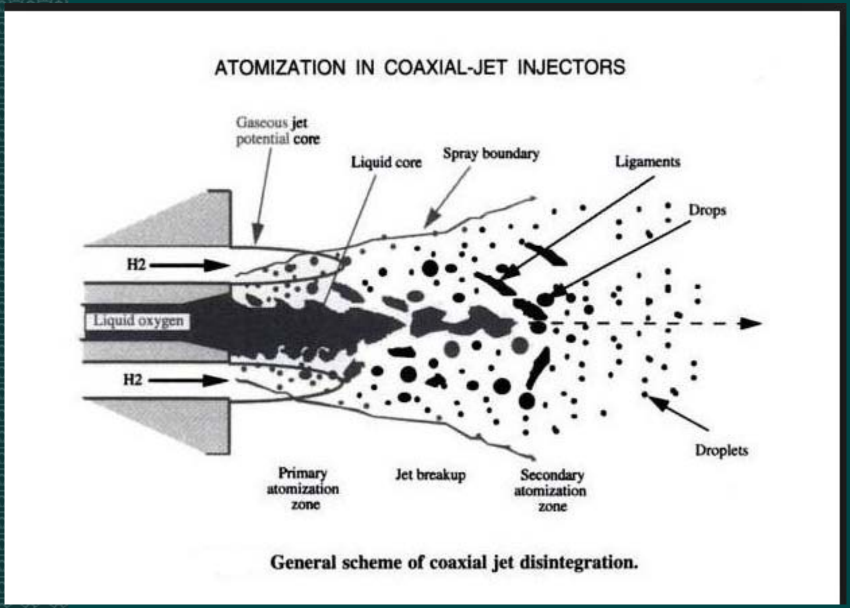




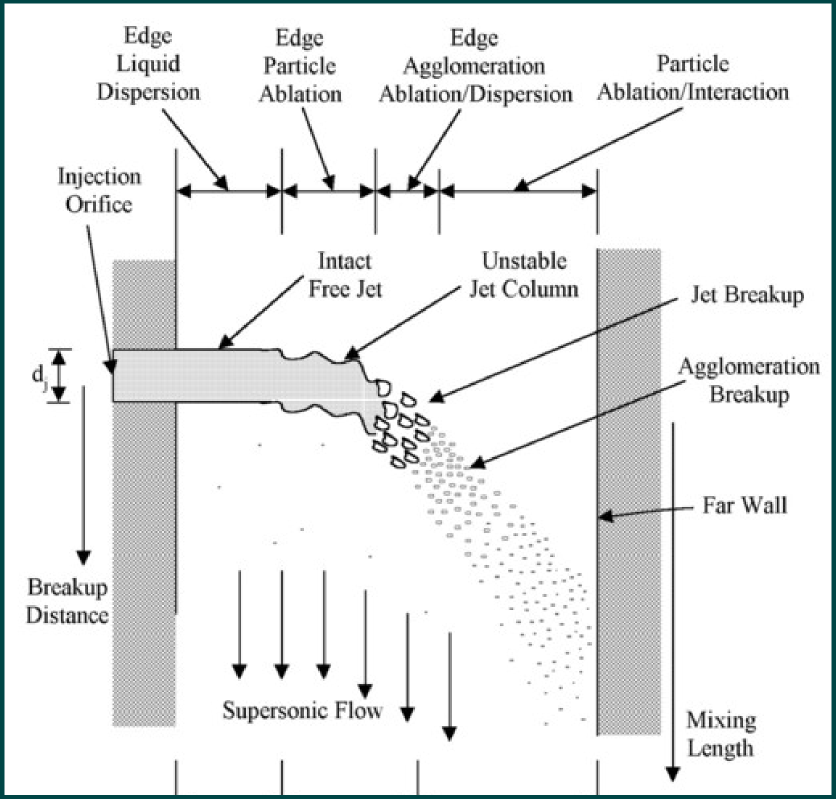
SCO2 Oxyfuel Combustor Analysis

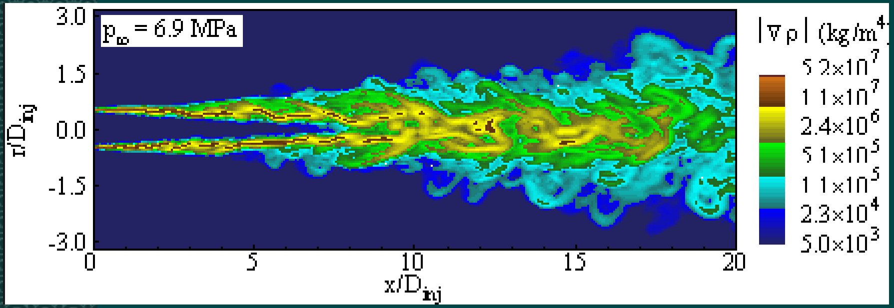


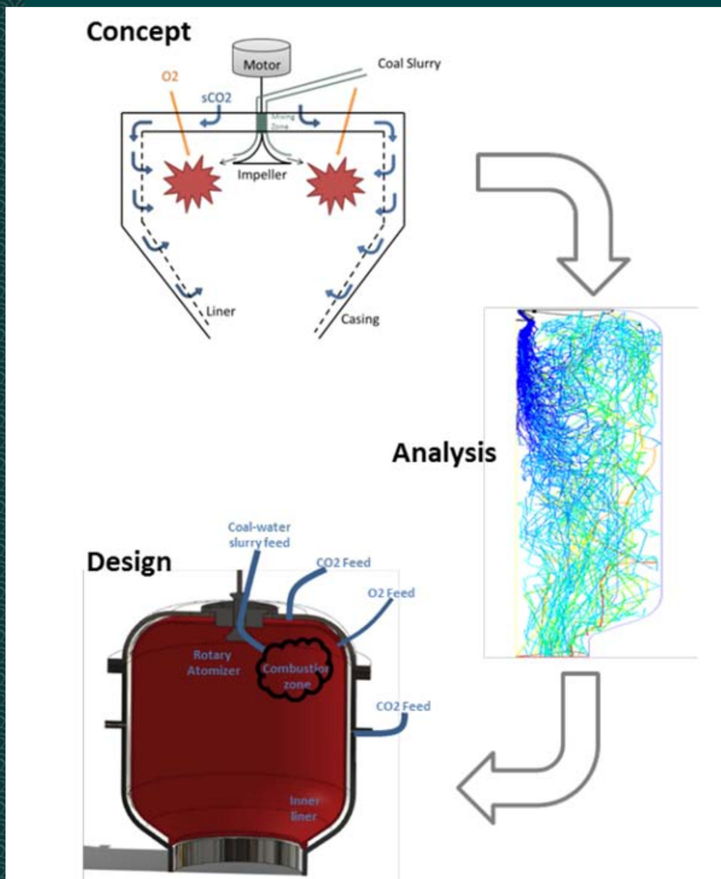
Different types of Fuel Injector

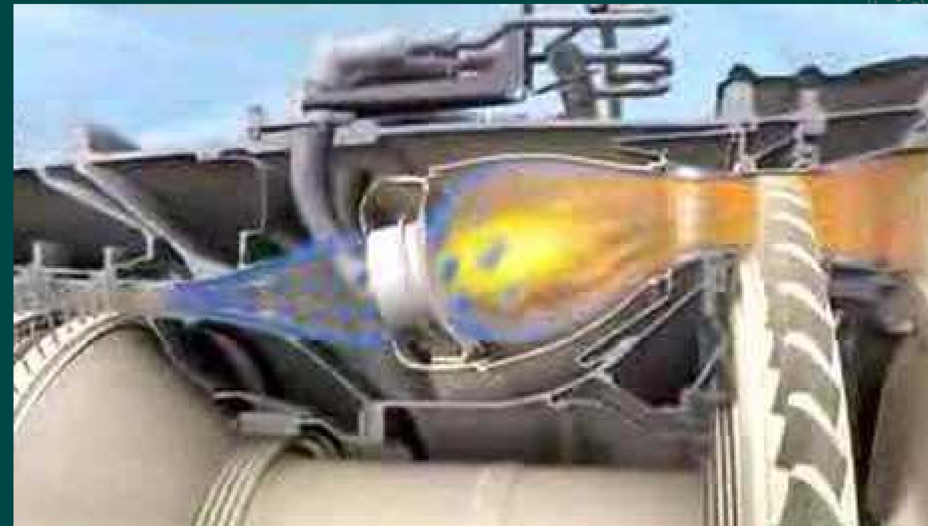


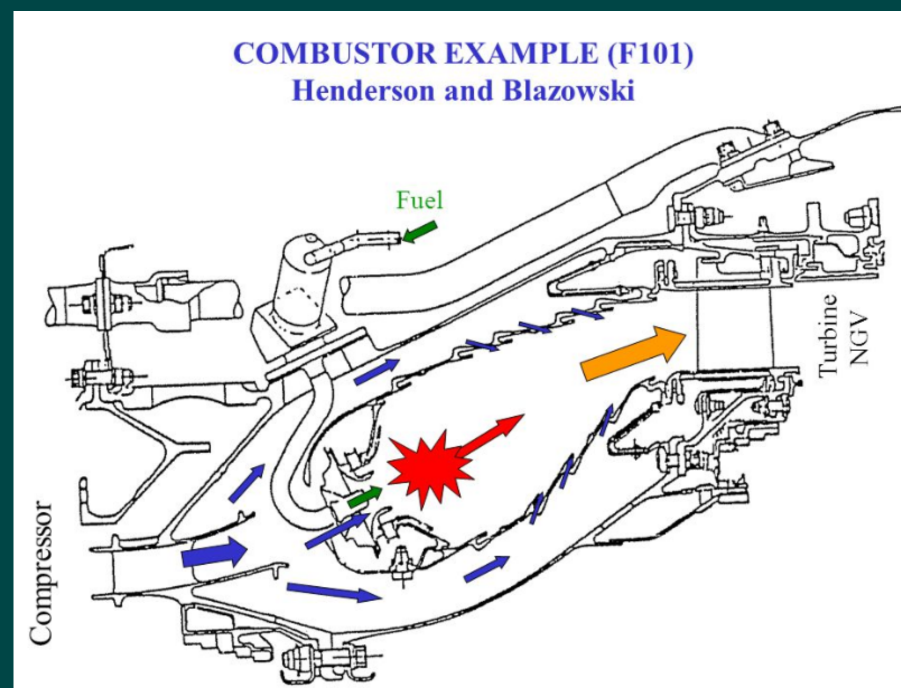
General scheme of coaxial jet disintegration.



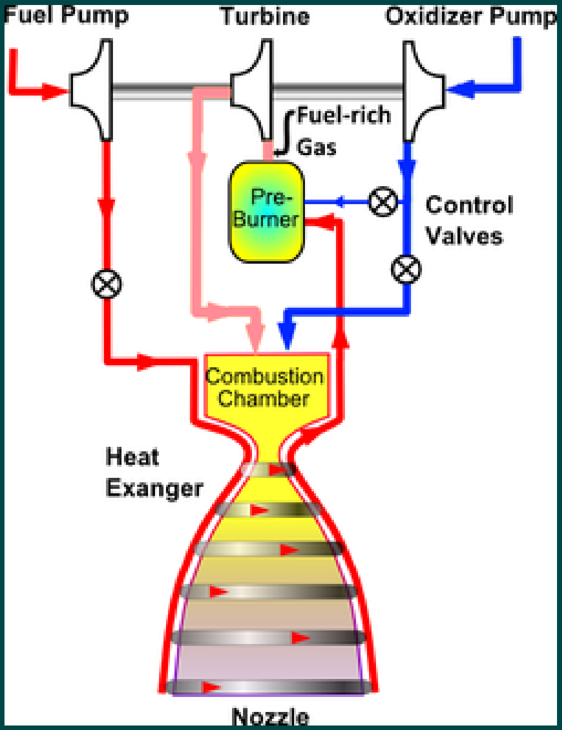



Concept
Motor
Coal Slurry
O2
sCO2
Impeller
Liner
Casing
Analysis
Design
Coal-water slurry feed
CO2 Feed
O2 Feed
Rotary Atomizer
Combustion zone
CO2 Feed
Inner liner




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

Liquid rocket engine (NASA 1963)

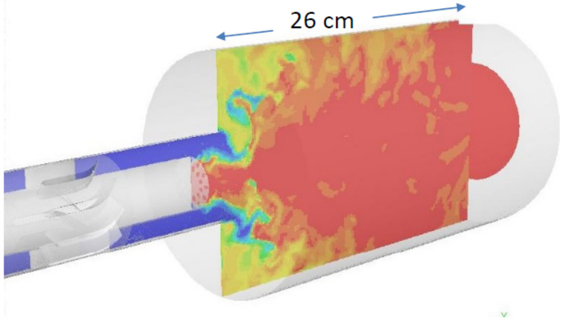


Oxy-Fuel Combustor Modeling

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

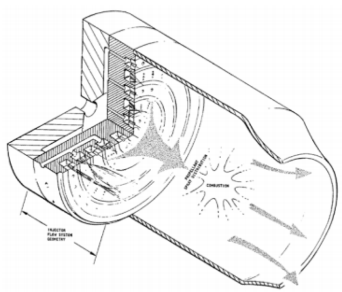
P=300bar
20%O2/80%CO2
T=2050K
Mdot=72 kg/s
180 MW

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

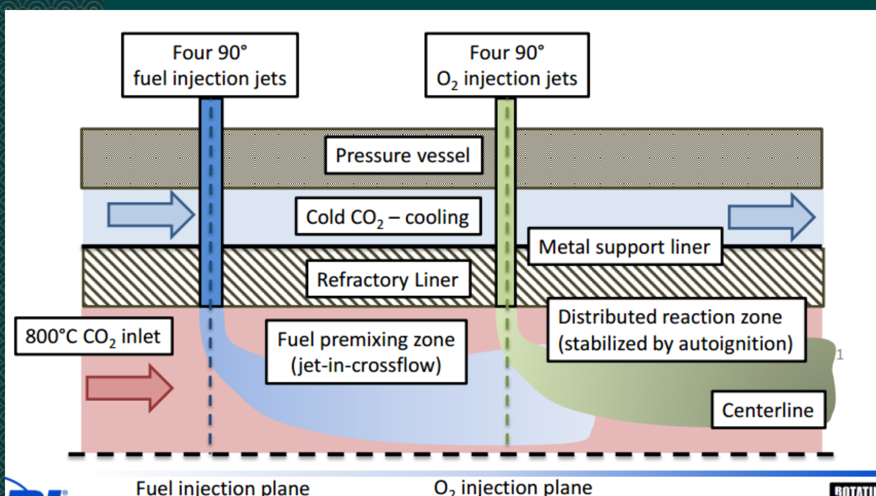


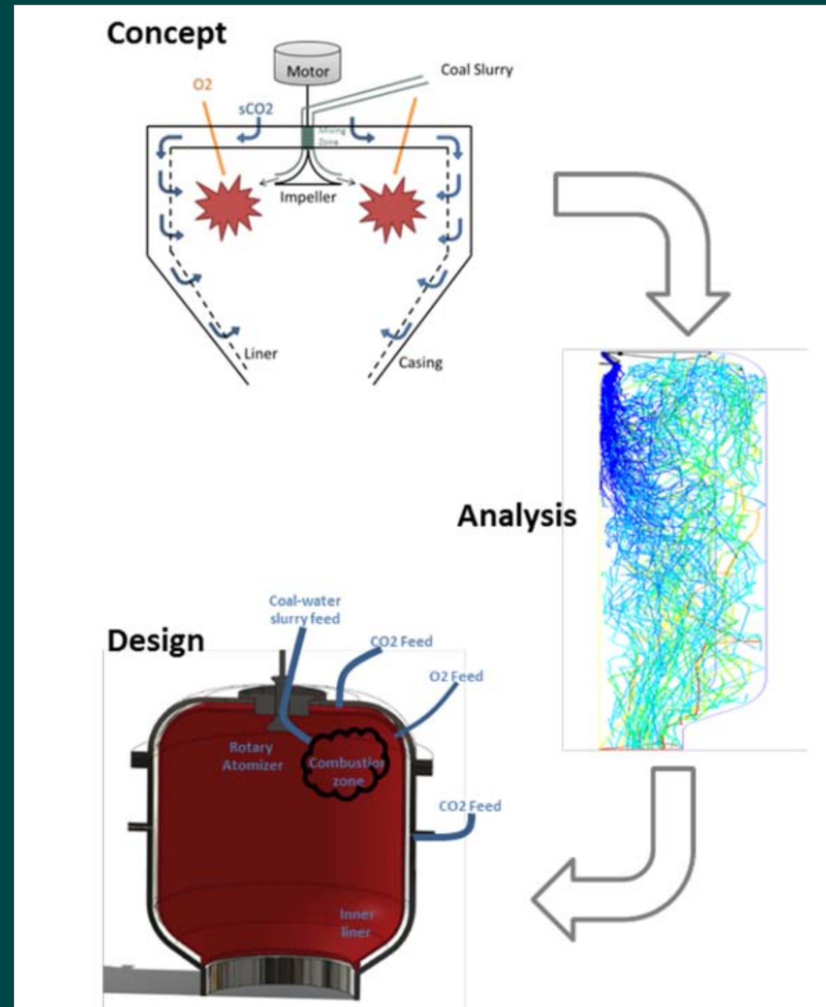
- Compressible LES formulation allows for simulation of combustion dynamics.

Oxy-Combustion



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

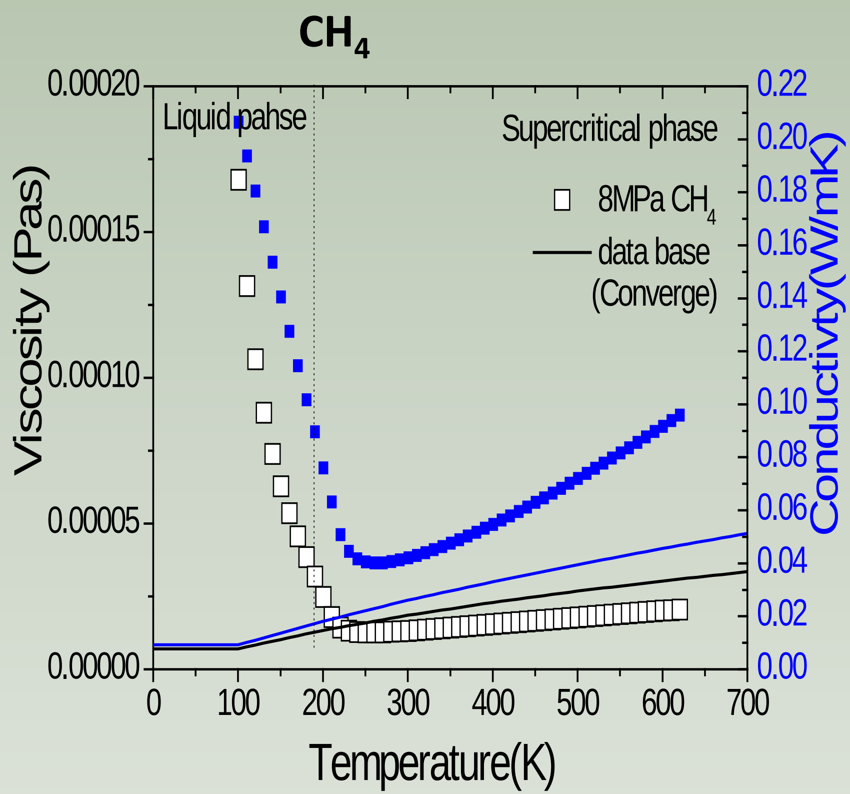




1. **Collect CH_4, CO_2, H_2O, O_2,CO, N_2 and H_2 Gas Properties**
2. **Using “Converge” Scheme Simulate CO2 ,CH4 & O2 Combustion**

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

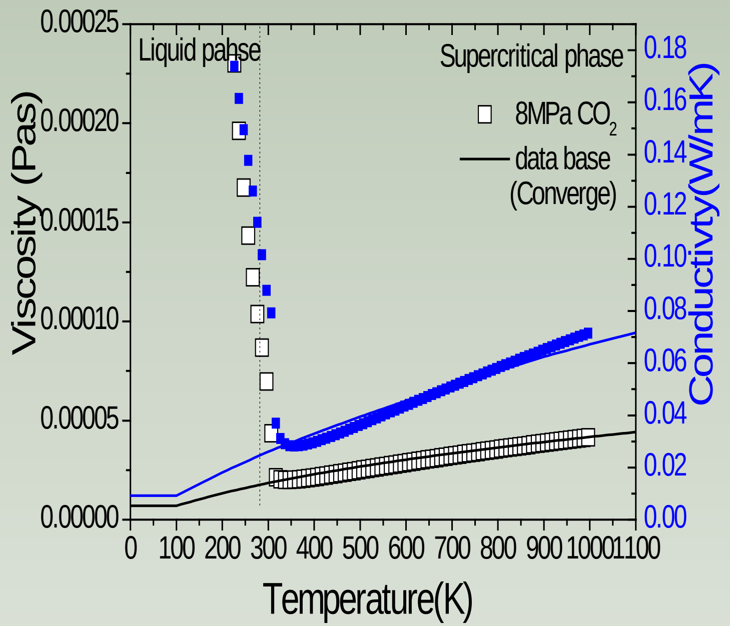
Task 1 Results: Gas property [CH_4 and species critical T and P]



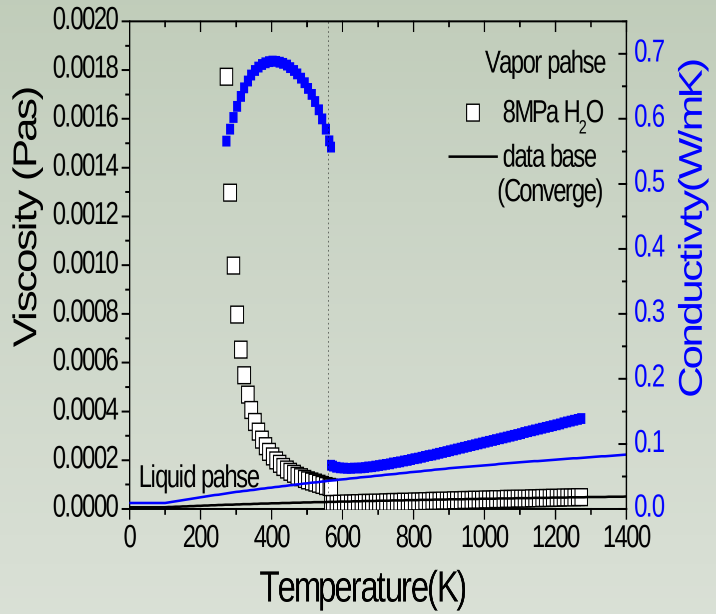
Species	T_c(K)	P_c(MPa)
CH_4	190.56	4.59
CO_2	304.12	7.38
H_2O	647.10	22.06
H_2	33.15	1.30
O_2	154.58	5.04
CO	132.86	3.50
N_2	126.19	3.40

Task 1 Results: Gas property [CO_2 and H_2O]

CO_2



H_2O



Governing equation

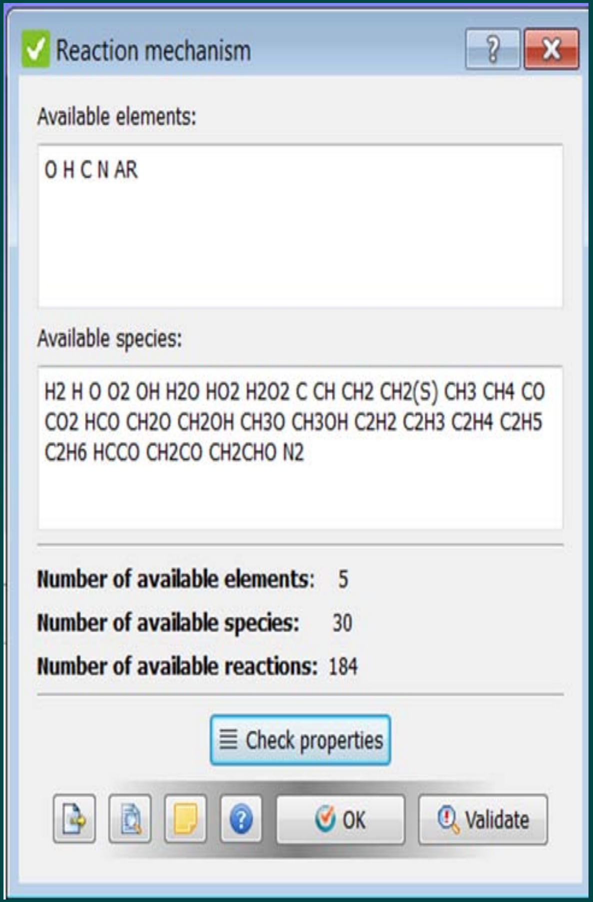
- 質量守恆方程 $\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{v})=0$
- 物種傳輸方程 $\frac{\partial\rho\phi_k}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\phi_k-\Gamma_k\frac{\partial\phi_k}{\partial x_i}\right)=S_{\phi_k}\quad k=1,\ldots,N$

  Γ_k和S_{ϕ_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

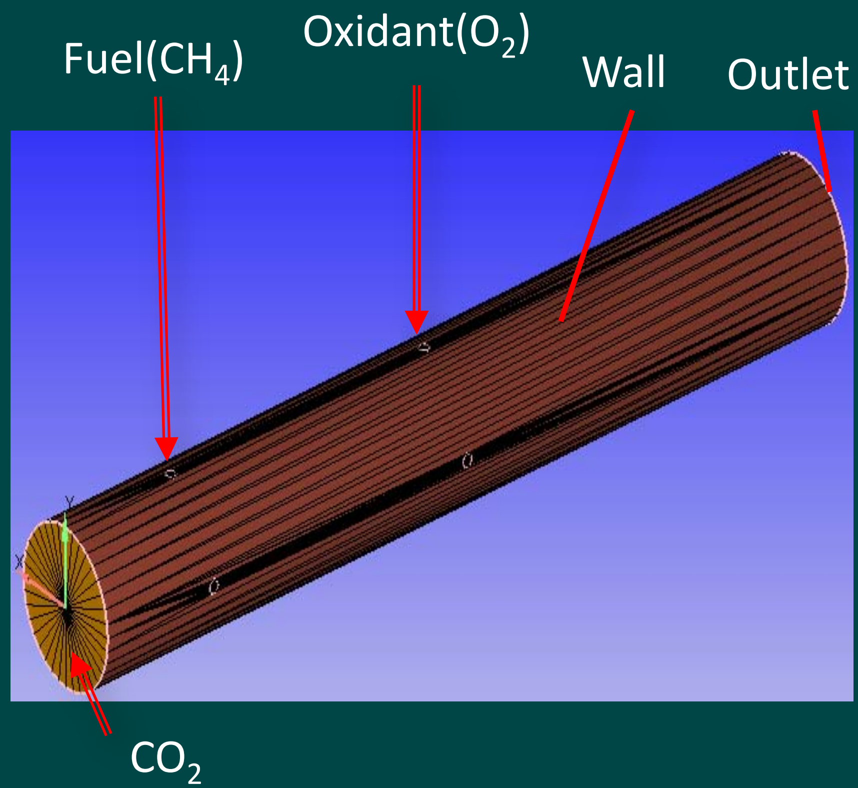
- Simplify combustion modeling base on chemical equilibrium.
- When **chemical time-scales are faster than the fluid time-scales**, CEQ are used for the combustion modeling.
- The CEQ solver is ensure for any combination of gas species.
- This solver uses data in "***therm.dat***" and "*mech.dat*" to 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.

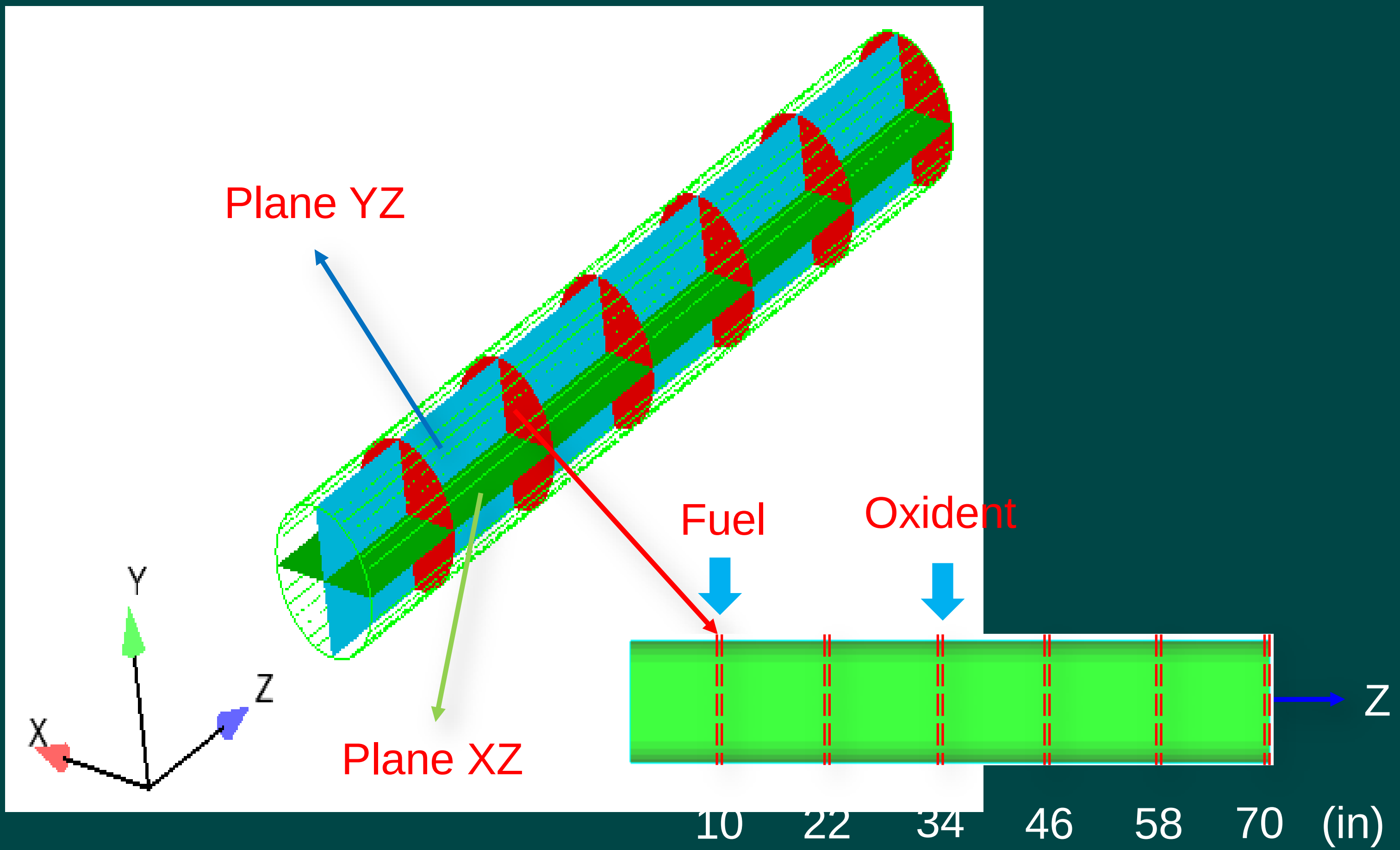
Boundary condition

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

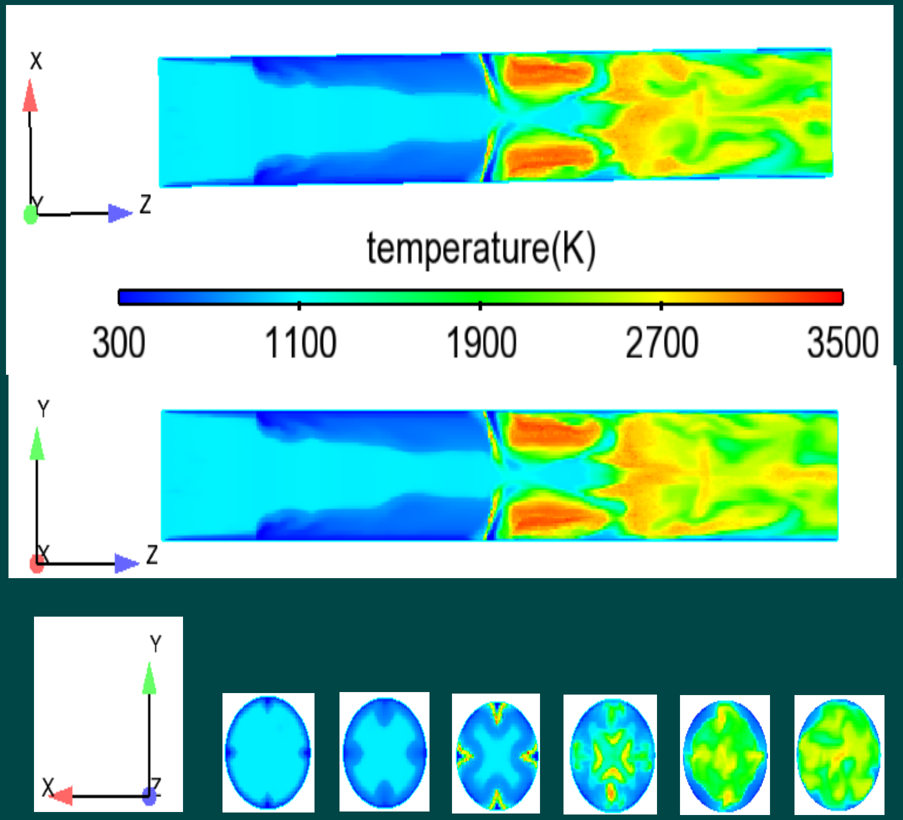


- 壁面設為313 K等溫邊界模擬Cold CO_2 cooling 的影響。
- 總釋熱率為33.55 MW。

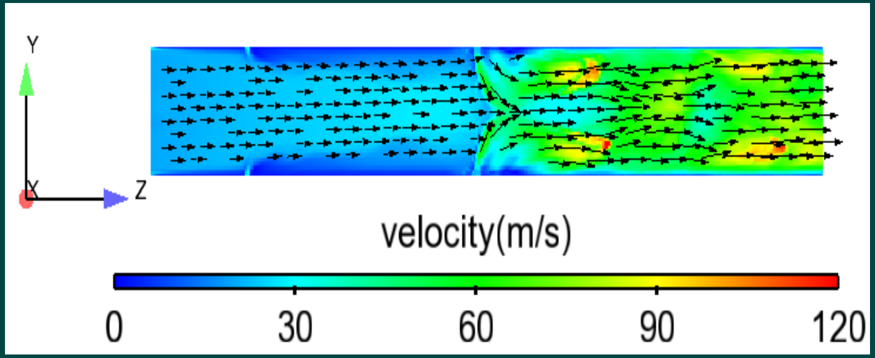
Observed Sectors Profile

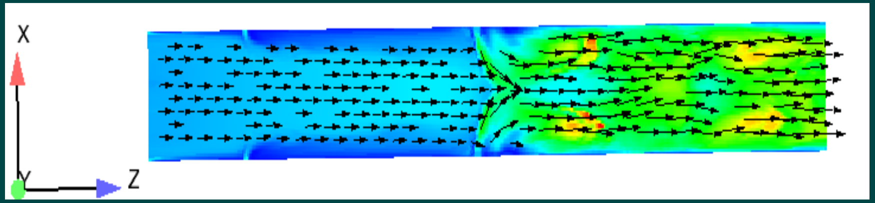


Results: Temperature (K)

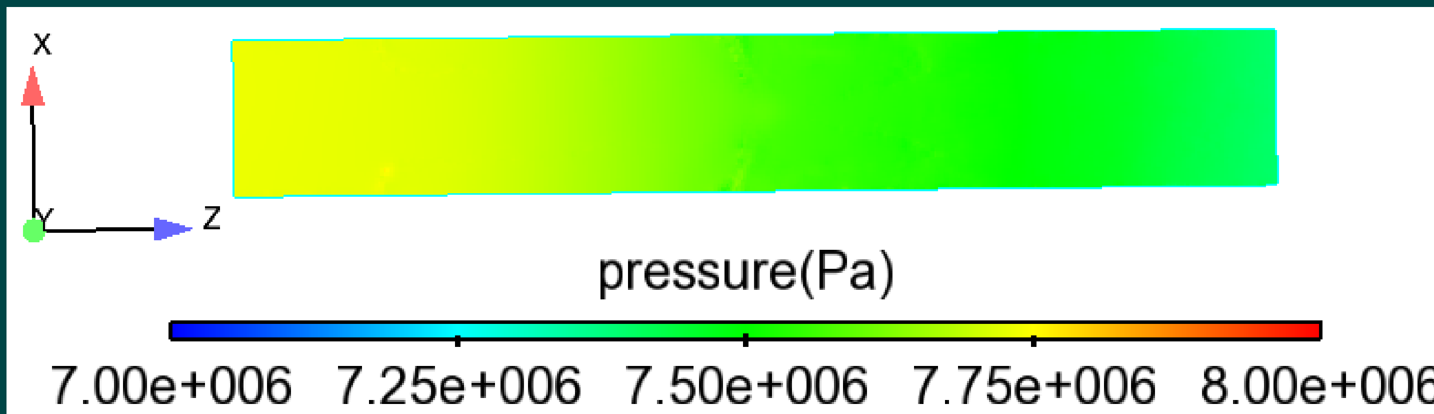


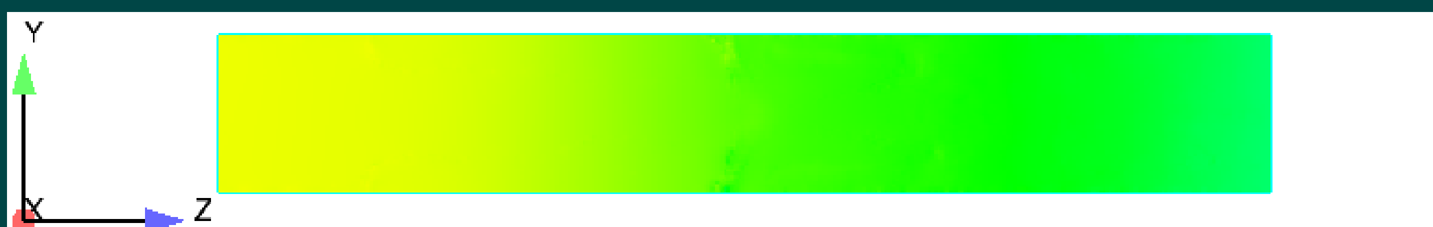
Results: Velocity Vector (m/s)

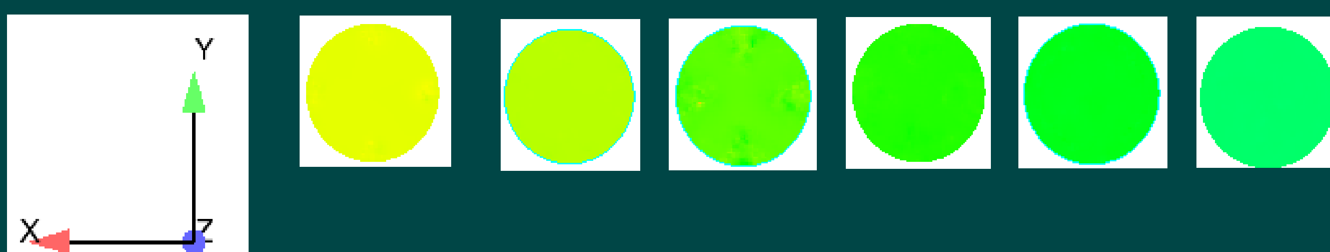




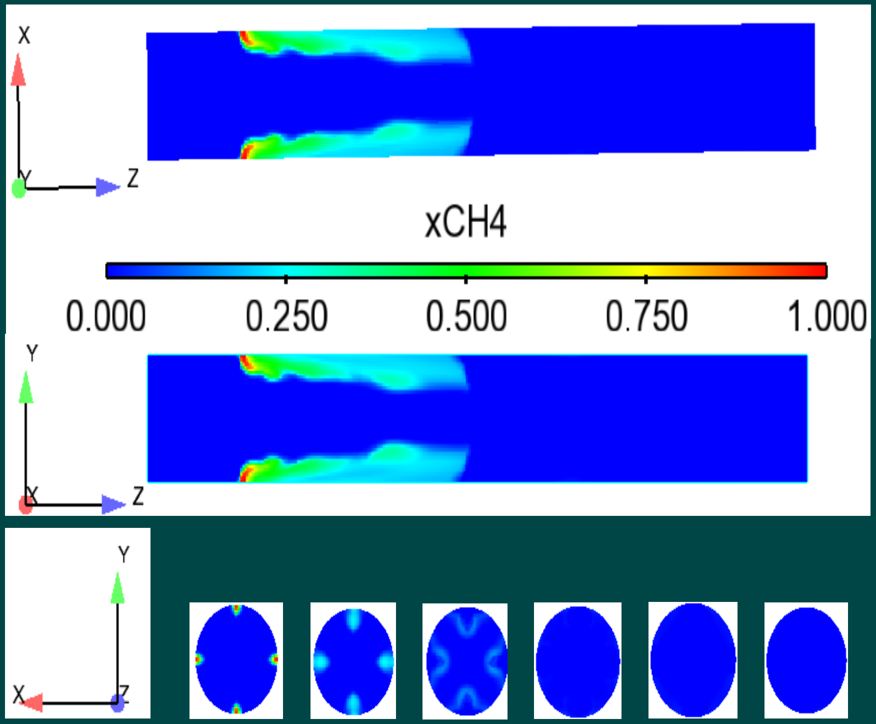
Task 2 Results: Pressure (Pa)



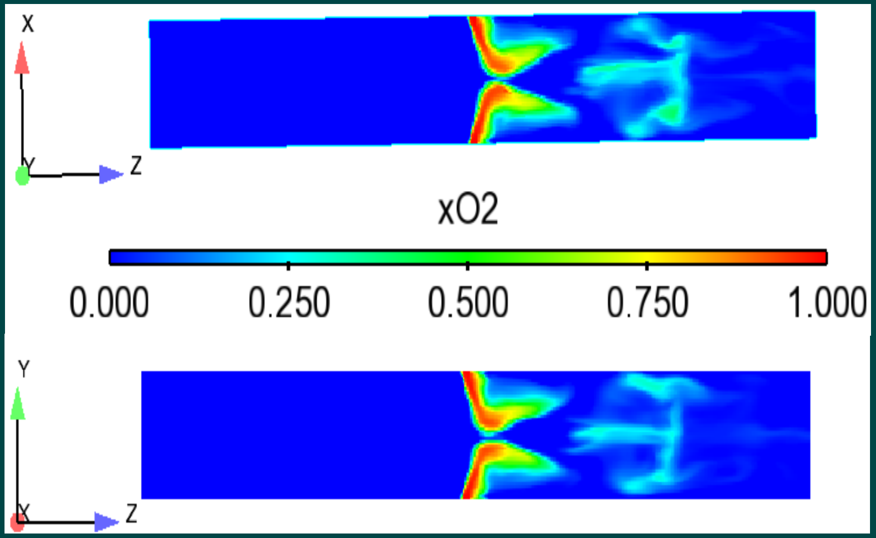


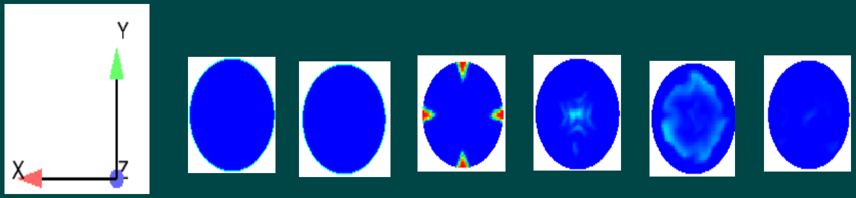


Task 2 Results: Mole fraction of CH_4

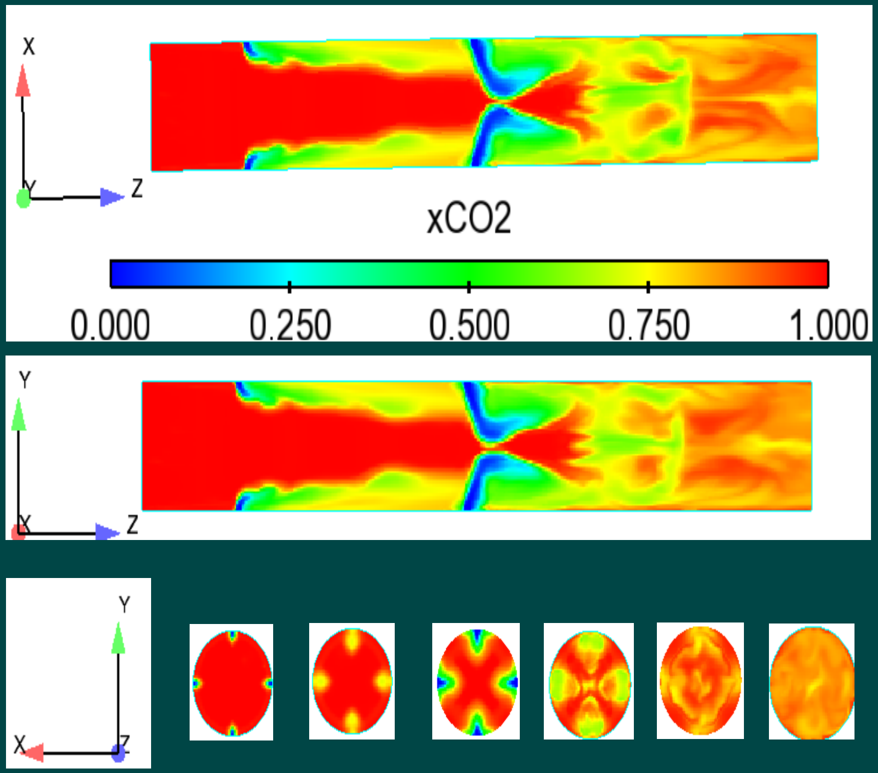


Task 2 Results: Mole fraction of O_2

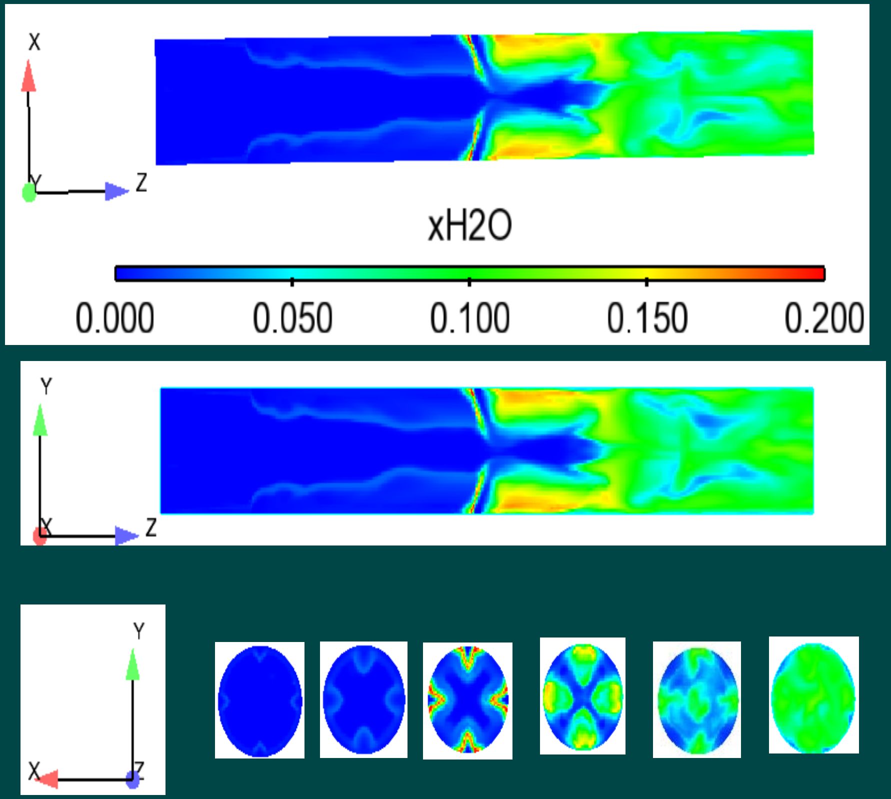




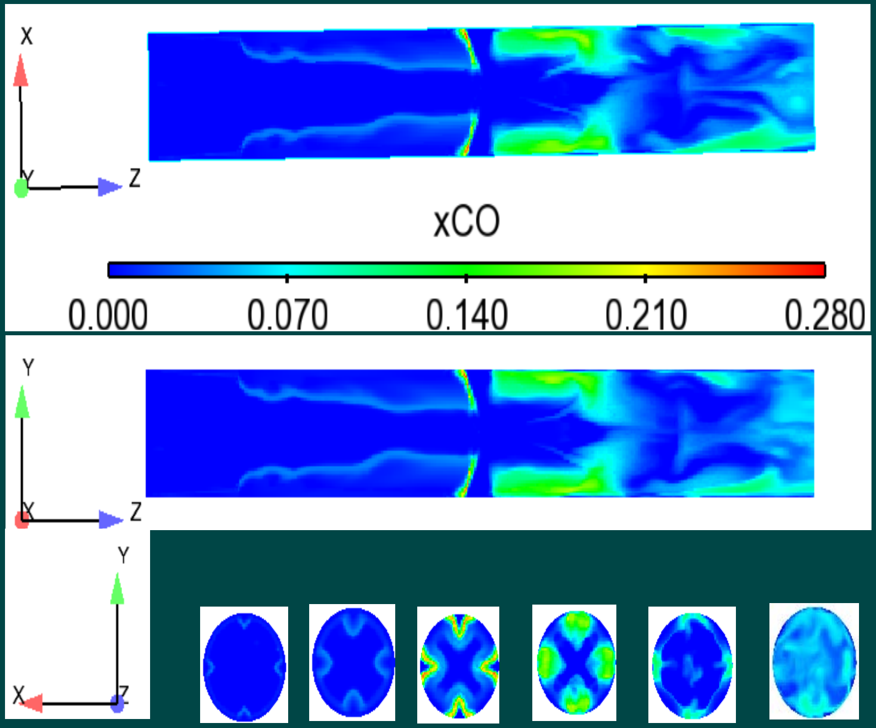
Task 2 Results: [Mole fraction of CO_2]



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.