Development of A Transient Analysis Code for S-CO2 Power Conversion System

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CONTENTS

◆ Introduction

◆ SCTRAN/CO2 development

◆ Initial verification for component model

◆ Initial verification for loop simulation

◆ Conclusion & expectation

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PART 1 INTRODUCTION

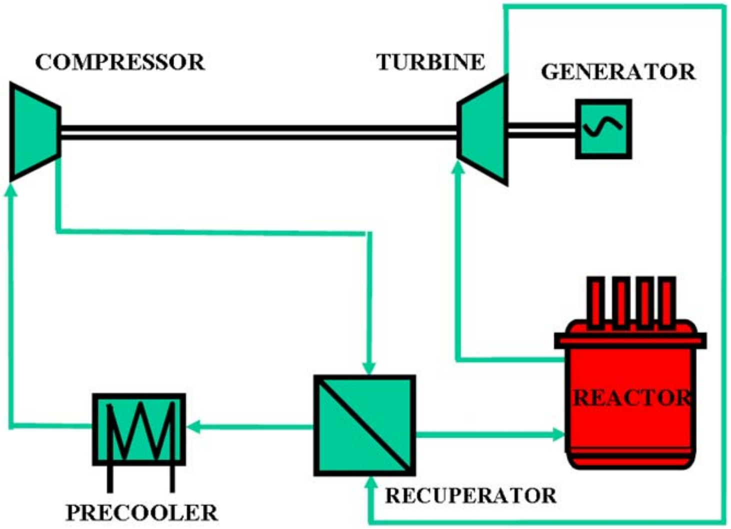
■S-CO2 Brayton Cycle

S-CO2 Brayton Cycle Advantage:

✓High thermal efficiency

✓Simple configuration

✓Compact turbomachinery



A Simple Brayton Cycle Layout

Transient analysis code used in S-CO2 Brayton Cycle

Built up method	Analysis code	Applied in
Developed with an exist Transient analysis code	TRACE	S-CO2 Brayton cycle
	GAMMA+	KAIST Micro Modular Reactor(MMR)
	MARS	Supercritical CO2 Integral Experimental Loop (SCIEL)
	RELAP5-3D	SCO2 cooled fast reactors
	MMS-LMR	Sodium cooled fast reactor KALIMER-600
	GAS-PASS	
Developed with nothing	Plant Dynamics Code (PDC)	S-CO2 Brayton cycle coupled to lead-cooled fast reactor

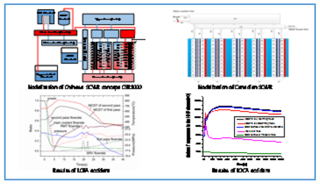
PART 2 SCTRAN/CO2 Development

- SCTRAN introduction
- Component model needed for SCTRAN/CO2
  - ✓Constitutive model
  - ✓Compressor model
  - ✓ Gas turbine model
  - ✓ Shaft model

2.1 SCTRAN Introduction

SCTRAN

A safety analysis code for SCWR



Thermal Property for CO_2

Heat Transfer & Friction Correlation

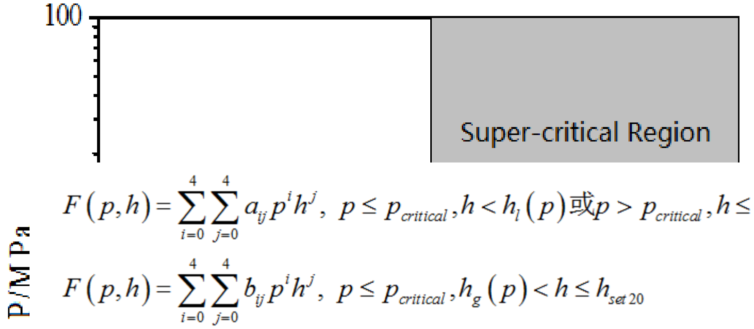
Compressor model & Gas Turbine model

SCTRAN/CO2

Transient Analysis Code for S-CO2 Brayton Loop

2.2 Constitutive Model

- ☐ Property of carbon dioxide



$$F(p,h)=\sum_{i=0}^{4}\sum_{j=0}^{4}a_{ij}p^ih^j,\ p\le p_{critical},h<h_l(p)\text{或}p>p_{critical},h\le h_{set10}$$

$$F(p,h)=\sum_{i=0}^{4}\sum_{j=0}^{4}b_{ij}p^ih^j,\ p\le p_{critical},h_g(p)<h\le h_{set20}$$

$$\text{或}p>p_{critical},h_{set11}<h\le h_{set20}$$

$$F(p,h)=\sum_{i=0}^{4}\sum^{4}c_{ij}p^ih^j,\ h>h_{set21}$$

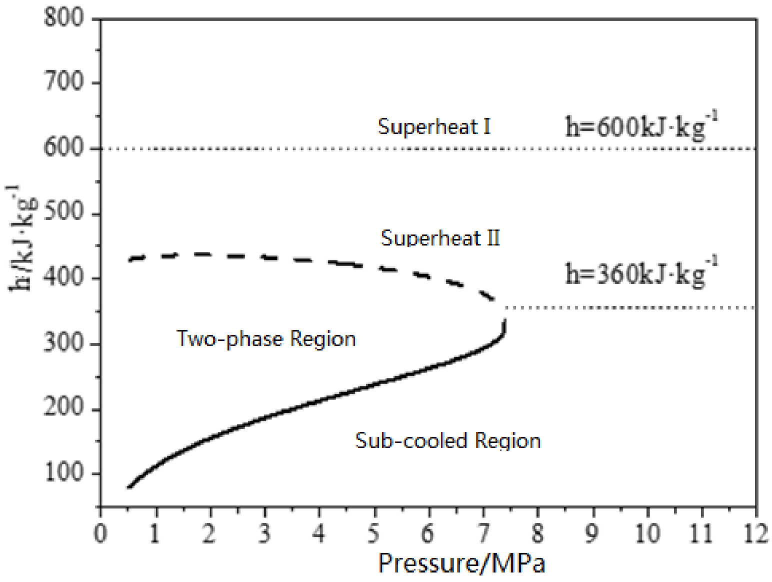
$$F(p,h)=F(\quad F=\sum_{i=0}^{4}\sum_{j=0}^{4}a_{ij}T^i\rho^j \quad -F(p,h_{set10})]$$

$$,p>$$

$$F(p,h)=F(p,h_{set20})+\frac{(h-h_{set20})}{(h_{set21}-h_{set20})}\left[F(p,h_{set21})-F(p,h_{set20})\right]$$

$$,\ h_{set20}<h\le h_{set21}$$

$$5<p<5.5$$



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2.2 Constitutive Model

☐ Heat transfer correlation

Gnielinski Correlation:

$$N_u = \frac{hD_e}{\lambda} = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\sqrt{(f/8)}\left(\mathrm{Pr}^{2/3}-1\right)} \quad ,2300 < \mathrm{Re} < 5\times10^6 \quad ,0.5 < \mathrm{Pr} < 200$$

☐ Friction correlation

$$\frac{1}{\sqrt{f}} = -2\log\left\{\frac{\varepsilon}{3.7D_e} + \frac{2.51}{\mathrm{Re}}\left[1.14 - 2\log\left(\frac{\varepsilon}{D_e} + \frac{21.25}{\mathrm{Re}^{0.9}}\right)\right]\right\} \quad ,\mathrm{Re} > 3400$$

$$f = \frac{64}{\mathrm{Re}} \quad ,\mathrm{Re} < 2300$$

2.3 Compressor Model

☐ Compressor model : Solution

- ✓ Compressor torque

$$\tau_t = \tau_s + \tau_d = \frac{\dot{m}}{\omega}\left(h_{2s} - h_{01}\right) + \frac{\dot{m}}{\omega}\left(h_{02} - h_{2s}\right)$$

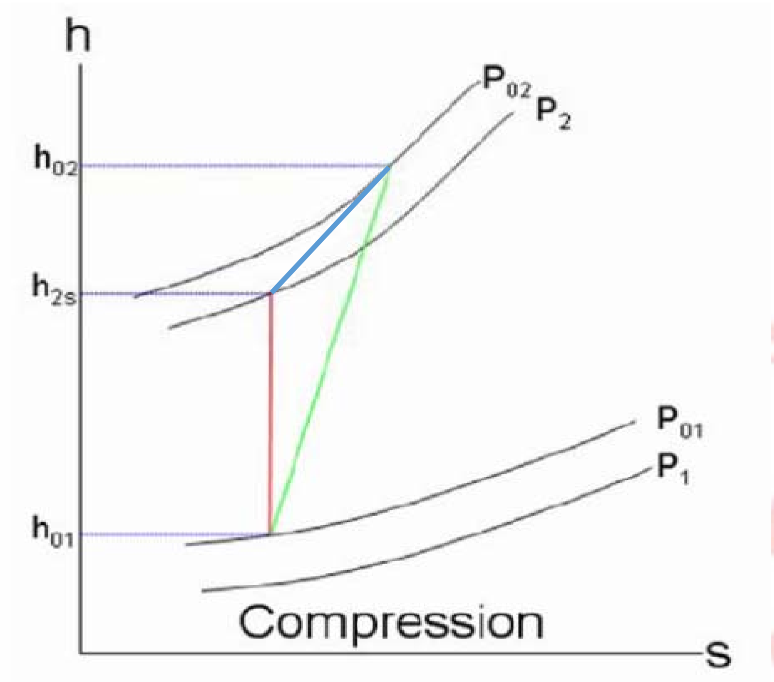
- ✓ Ideal outlet fluid enthalpy

$$h_{2s} = h_{01} + \int_{P_1}^{P_2} v_m * dp$$

among, $P_2 = P_1 * R_P$

- ✓ Realistic outlet fluid enthalpy

$$\eta_{ad} = \frac{h_{2s} - h_{01}}{h_{02} - h_{01}}$$



Ideal and realistic compression process inside compressor

2.3 Compressor Model

☐ Compressor model : Intergrated in SCTRAN

✓Total torque of compressor

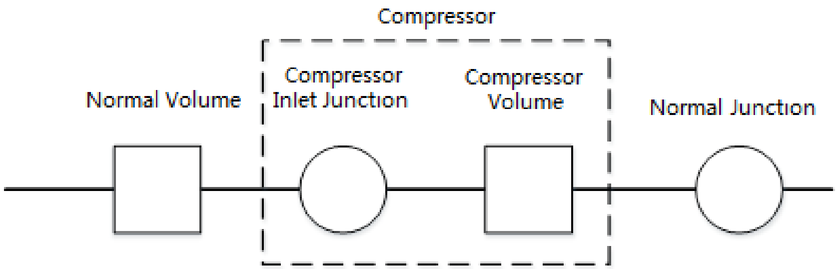
$$\tau_t = \tau_s + \tau_d = \frac{\dot{m}}{\omega}\left(h_{2s} - h_{01}\right) + \frac{\dot{m}}{\omega}\left(h_{02} - h_{2s}\right) = \frac{\dot{m}}{\omega}\frac{1}{\eta_{ad}}\left(h_{2s} - h_{01}\right) = \frac{\dot{m}}{\omega}\frac{1}{\eta_{ad}}\frac{P_1^T\left(R_p - 1\right)}{\rho_m} = \frac{\dot{m}}{\omega}\frac{1}{\eta_{ad}}\frac{\left(P_2 - P_1\right)}{\rho_m}$$

✓Compressor work added on fluid

$$\mathrm{W} = \tau_t * \omega$$

✓Pressure rise

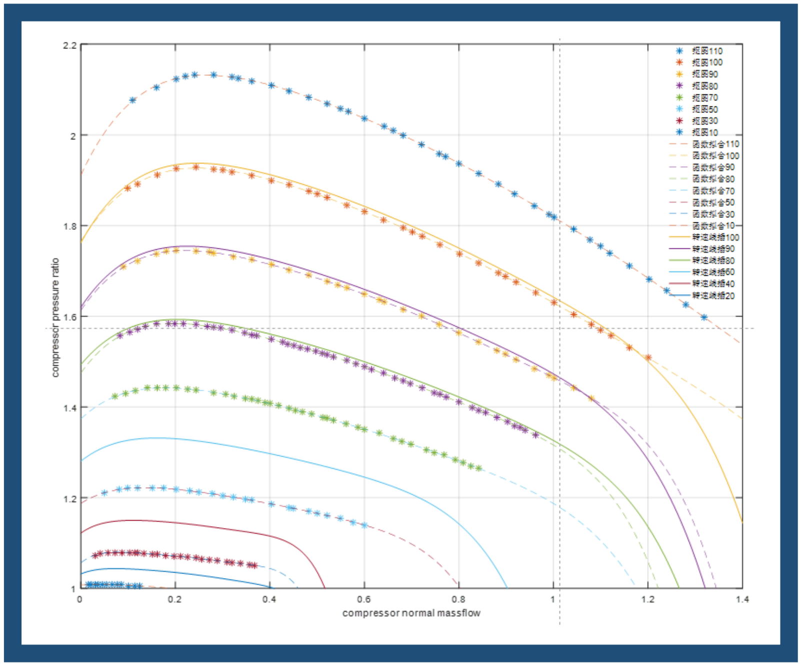
$$\Delta P = P_1\left(R_p - 1\right)$$



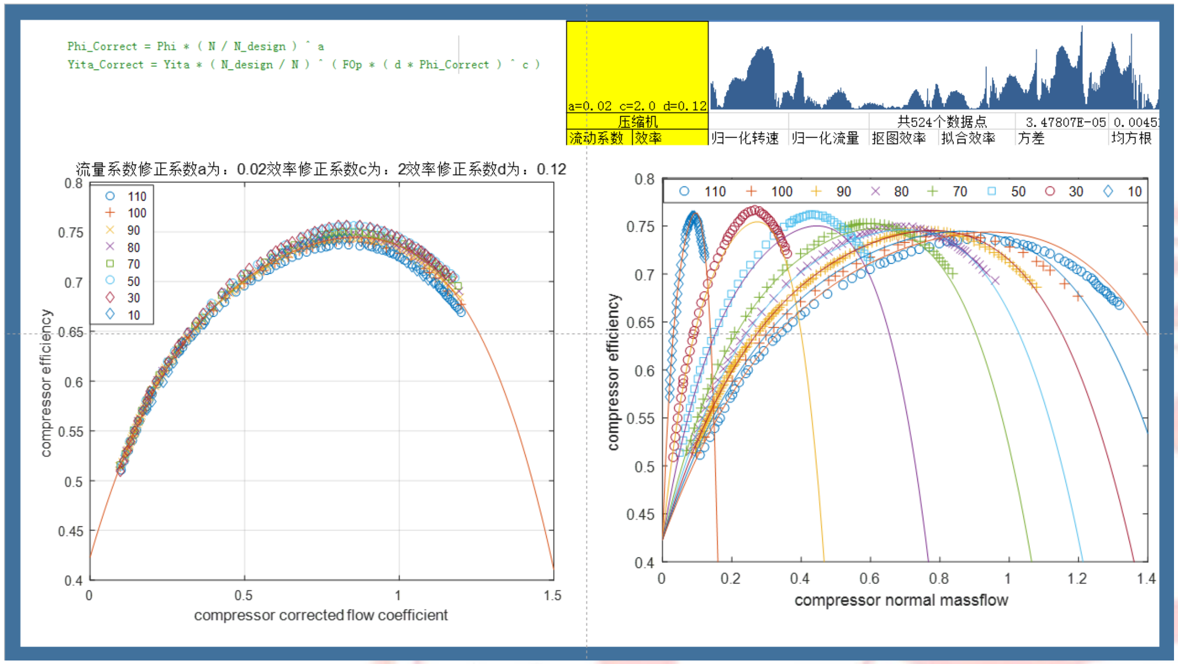
The compressor incorporated in SCTRAN/CO2

2.3 Compressor Model

☐ Compressor model : Performance Map



Compressor Pressure Ratio



```
Phi_Correct = Phi * ( N / N_design ) ^ a
Yita_Correct = Yita * ( N_design / N ) ^ ( F0p * ( d * Phi_Correct ) ^ c )
```

a=0.02 c=2.0 d=0.12				共524个数据点		3.47807E-05	0.0045
压缩机							
流动系数	效率	归一化转速	归一化流量	抠图效率	拟合效率	方差	均方根

流量系数修正系数a为：0.02效率修正系数c为：2效率修正系数d为：0.12

Compressor Efficiency

2.4 Turbine Model

- ✓ fluid enthalpy increase

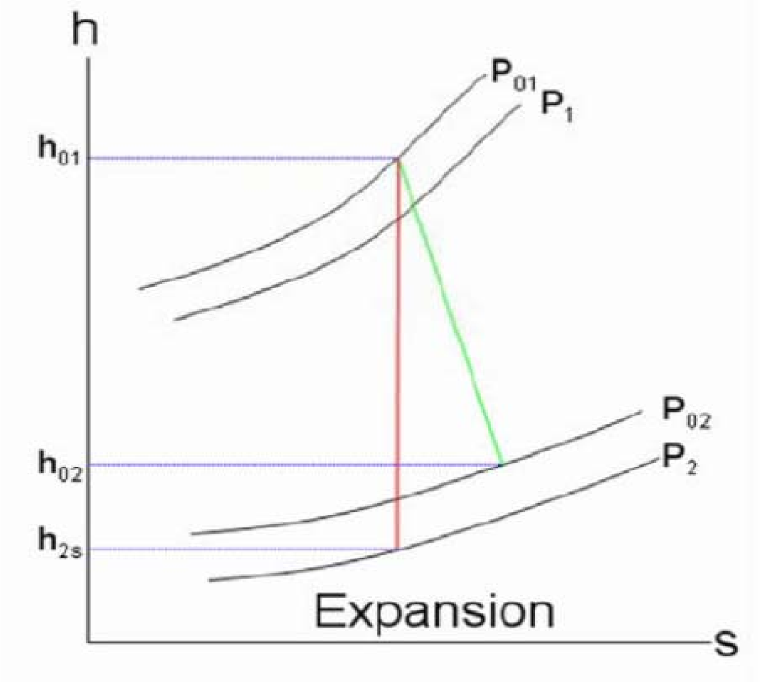
$$\Delta h = \frac{h_2^T - h_1^T}{\eta_{ad}}$$

- ✓ pressure drop

$$\Delta P = P_1\left(R_p - 1\right)$$

- ✓ total torque of gas turbine

$$\tau = \frac{m\eta\left(P_1 - P_2\right)}{\omega\rho_m}$$



Ideal and realistic expansion process inside gas turbine

2.5 Shaft Model

✓ Mode 1(without control system)

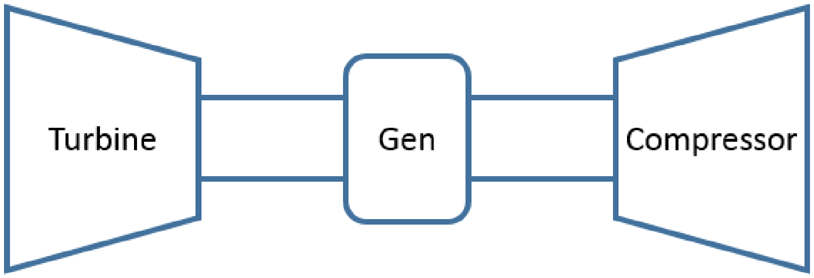
$$\omega_{T,i} = \omega_{C,k} = \omega_{Shaft} = User\ difined$$

✓ Mode 2(with control system)

$$\sum_i I_I \frac{d\omega}{dt} = \sum_m \tau_{T,m} - \sum_n \tau_{C,n} + \tau_g$$

Among:

$$\tau_g = C * \tau_{g,i}$$



PART 3 COMPONENT MODEL VERIFICATION

- Thermal property verification
- PCHE model verification
- Compressor model verification

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3.1 Thermal Property Package Verification

Relative prediction error of the developed CO2 property package compared to NIST REFPROP 9.0

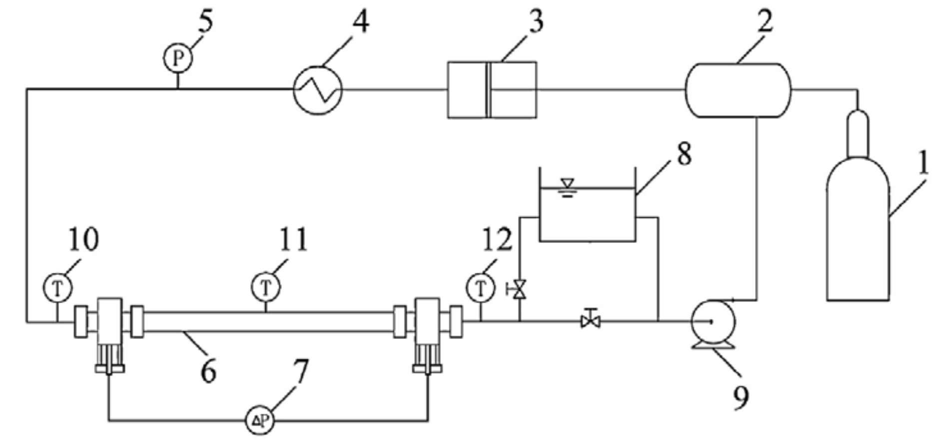
CO_2 Property	Symbol	Regions	Relative Error
Saturated Liquid Enthalpy	h_f	-	±0.015%
Saturated Vapor Enthalpy	h_g	-	±0.009%
Temperature	T	Subcooled area	(-0.05% ,0.1%), 99% of which is within relative errors of ±0.05%
		Superheated region 1	(-0.2%, +0.2%) , 99% of which is within relative errors of ±0.1%
		Superheated region 2	(-0.1%,0.25%), 99% of which is within relative errors of ±0.05%
Specific Volume	v	Subcooled area	(-0.5%,1%) , 99% of which is within relative errors of ±0.5%
		Superheated region 1	(-1%,4%) , 99% of which is within relative errors of ±1.0%
		Superheated region 2	(-0.5%,0.1%) , 99% of which is within relative errors of ±0.1%
Thermal Condutivity	λ	-	(-30%, 40%) near the critical region , (-2%,+2%) at other regions
Dynamic Viscosity	μ	-	(-1.5%,0.5%) , 99% of which is within relative errors of ±0.5%

3.2 PCHE Model Verification

■ Friction model code programming verification

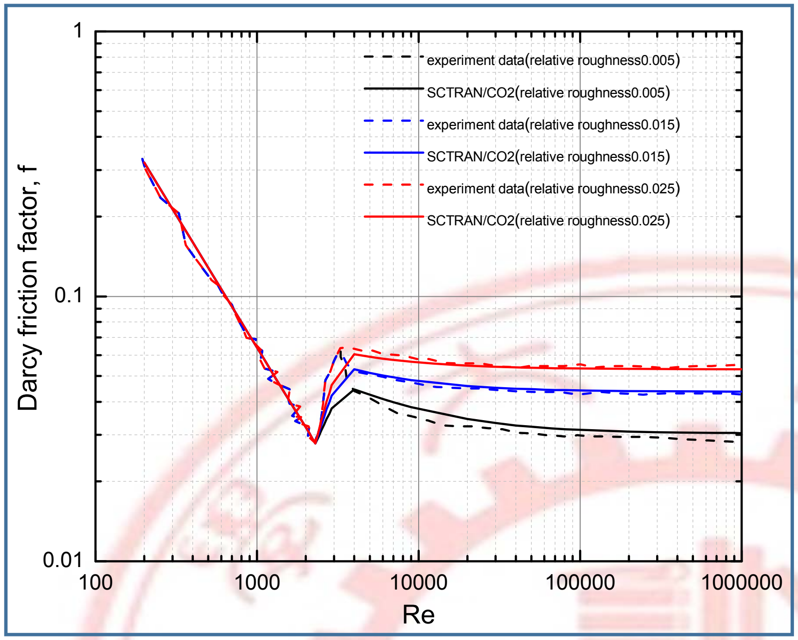
Experimental Conditions:

The temperature range : 30-150°C;
The pressure range : 3.5-40 MPa;
The Reynolds number range : 200-2.0×10^6;
The surface relative roughness (ratio of roughness over tube diameter) : 0.005, 0.015 and 0.025.



1. Carbon dioxide gas source; 2. Circulation tank; 3. Gas booster pump; 4. Heating system;
5. Pressure sensors; 6. Measuring pipeline; 7. Differential pressure sensors; 8. cooling unit;
9. Gas circulation pump; 10, 11, 12. temperature sensors

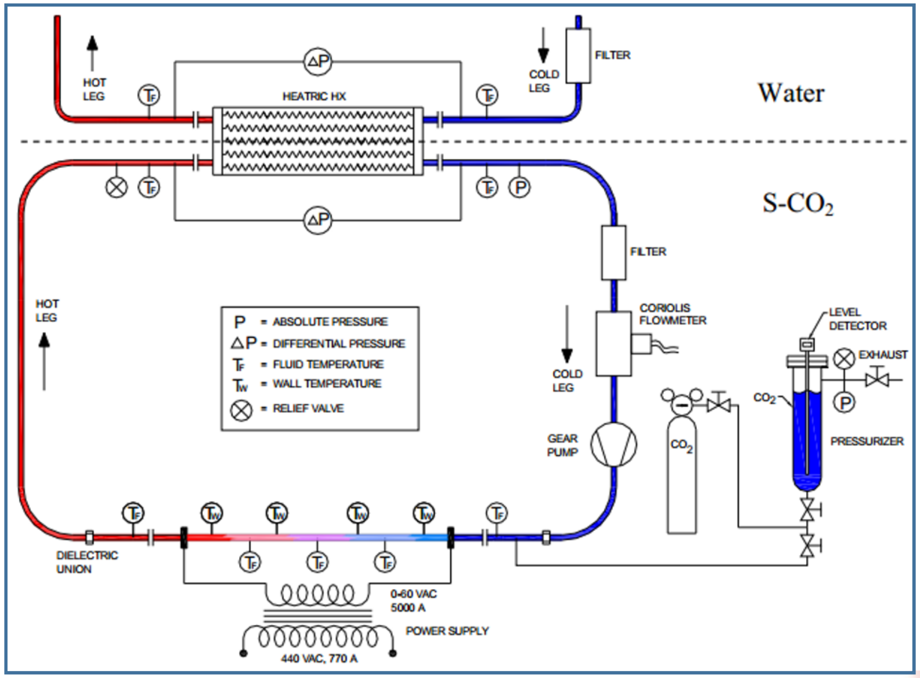
Wang et al. Experimental Loop



Comparison with experimental data
for friction coefficient of various roughness

3.2 PCHE Model Verification

■ PCHE model verification



JOSH VAN METER PCHE Experimental Loop

Built in:
ANL

Composed of:
Cooling water system
CO_2 Circle System
Pressure Stabilizing System

Focused on:
Water and CO_2 heat transfer characteristic in PCHE

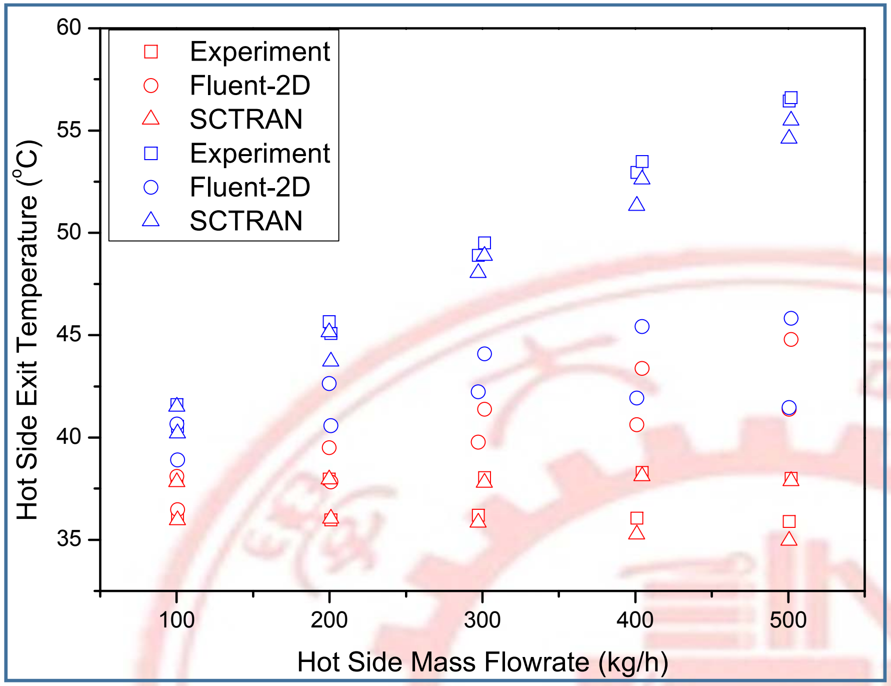
3.2 PCHE Model Verification

■ PCHE model verification

TEST_NO.	CO_2 Side			H_2O Side	
	Pressure	Flowrate	Temp_In	Flowrate	Temp_In
B6	8.003	100.53	88.63	701.59	35.63
B7	8.001	200.77	88.1	699.78	35.11
B8	7.972	297.14	89.36	701.8	35.05
B9	8.003	401.01	87.92	701.77	33.28
B10	7.995	500.61	87.93	700.09	31.28
B11	8.003	100.03	87.68	697.8	37.68
B12	8.005	199.73	88.85	697.8	37.53
B13	7.998	301.31	88.17	699.86	37.48
B14	8.02	404.29	88.97	701.62	37.58
B15	7.998	501.79	88.09	702.25	36.83

Test Conditions :

PCHE fluid inlet temperatures and Mass flowrate

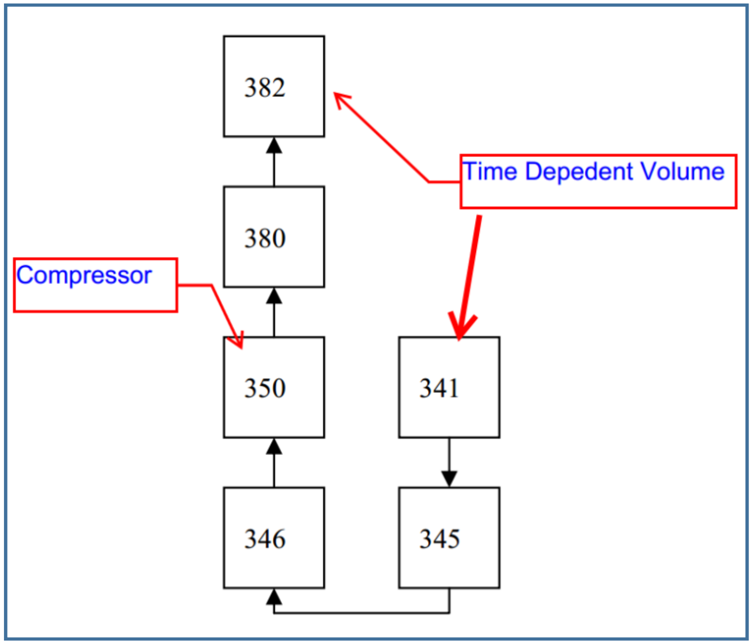


PCHE modeling results : PCHE fluid outlet temperatures

3.3 Compressor Model Verification

- ■ Compressor model verification

$$W_{c,v} = \dot{m}\frac{1}{\eta_{ad}}\frac{P_1\left(R_p - 1\right)}{\rho_m}$$

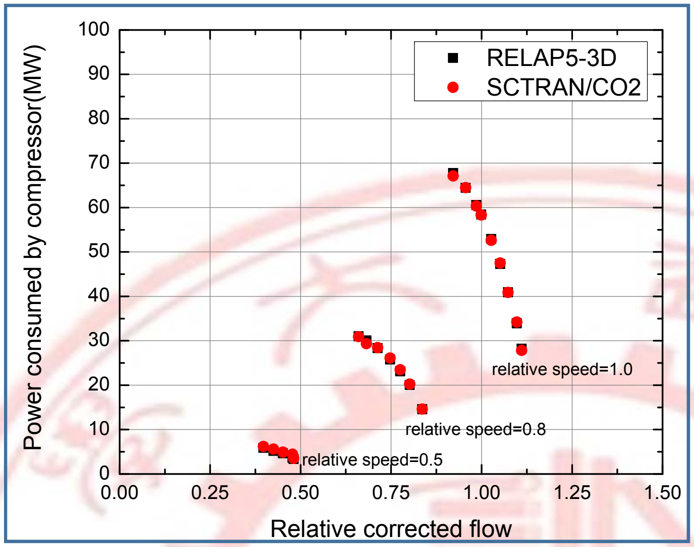


Nodalization of the recompressing compressor

Boundary conditions:
TDV 341:9.08MPa, 363K

Operation parameters:
Relative flowrate: 0.4-1.0
Relative speed:0.5,0.8,1.0

Result:
The compressor model in SCTRAN/CO2 is able to predict the compressor consuming power.



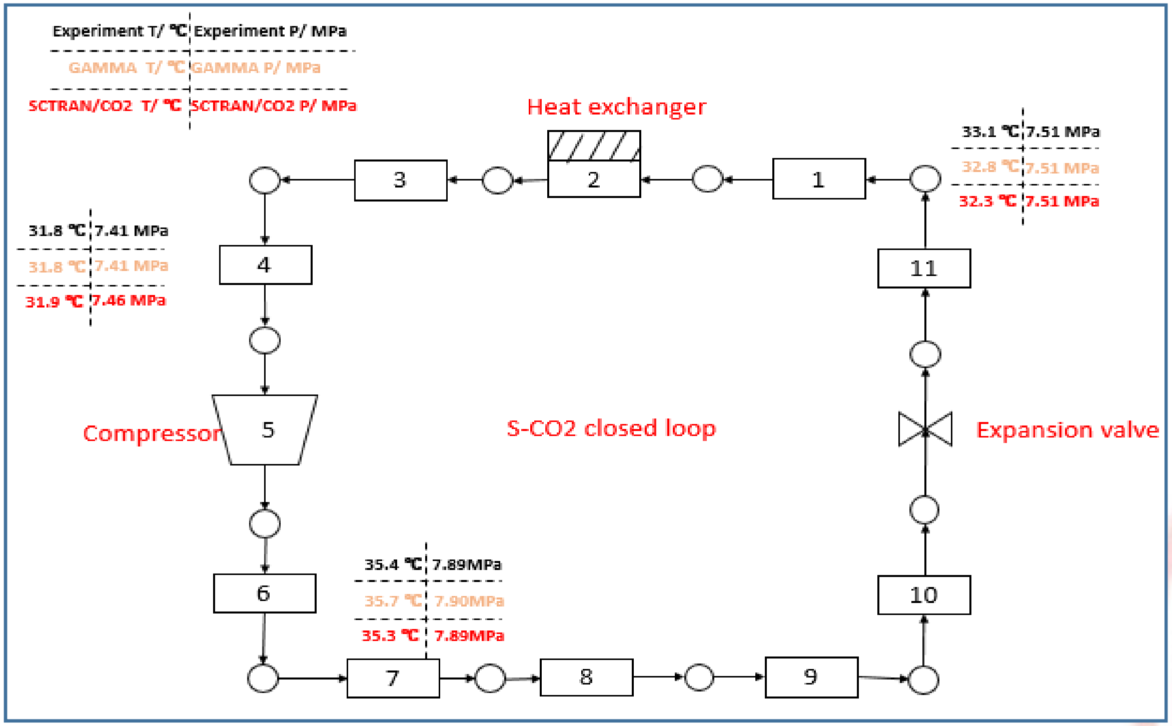
Predicted compressor consuming power by SCTRAN/CO2 and RELAP5-3D

PART 4 LOOP SIMULATION VERIFICATION

- S-CO_2 PE Loop
- IST Loop

4.1 S-CO2 PE Loop Simulation Verification

■ S-CO2 PE Loop Steady State Simulation



SCO2PE loop simulation nodalization and steady result

Simplification:

1. SCTRAN/CO2 applies a heat flux boundary to simulate the heat exchanger in the steady
2. The pressure ratio and efficiency keeps constant in the steady and transient simulation

Steady Result:

1. The Temp Error is within 0.2 ^{o}C
2. The Pressure Error is within 0.1 MPa

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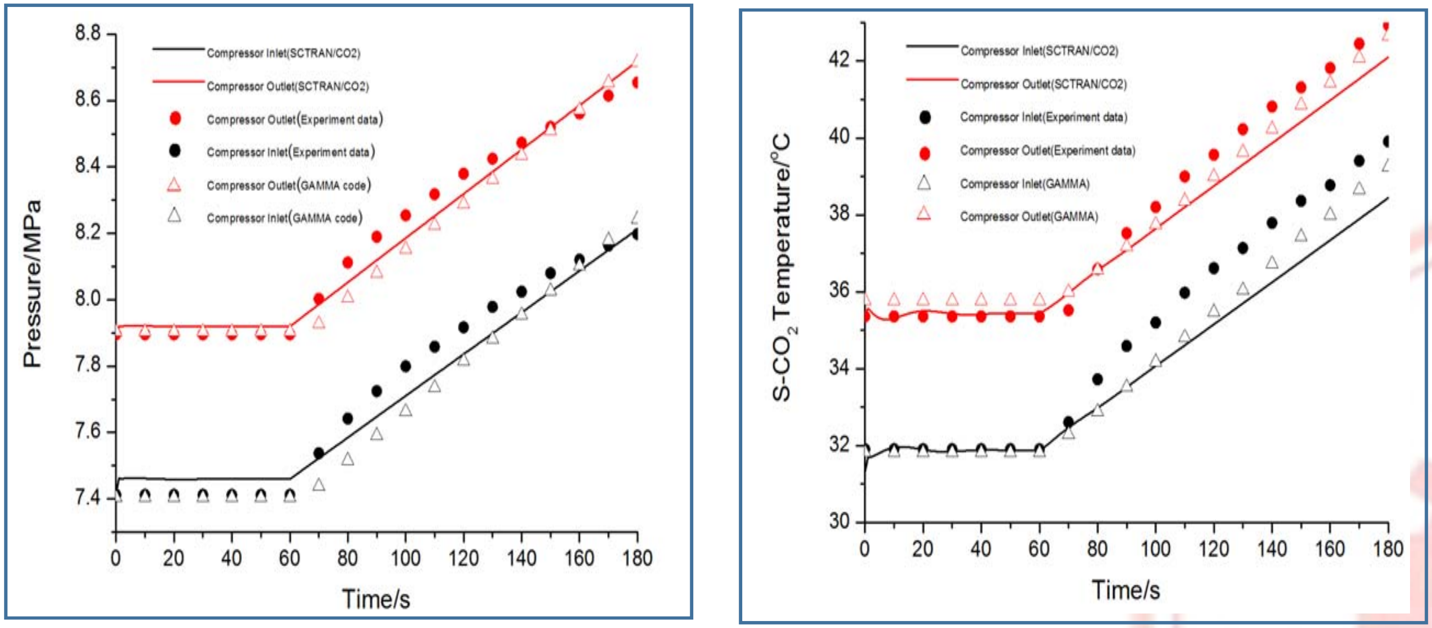
4.1 S-CO2 PE Loop Simulation Verification

■ S-CO2 PE Loop Transient Simulation



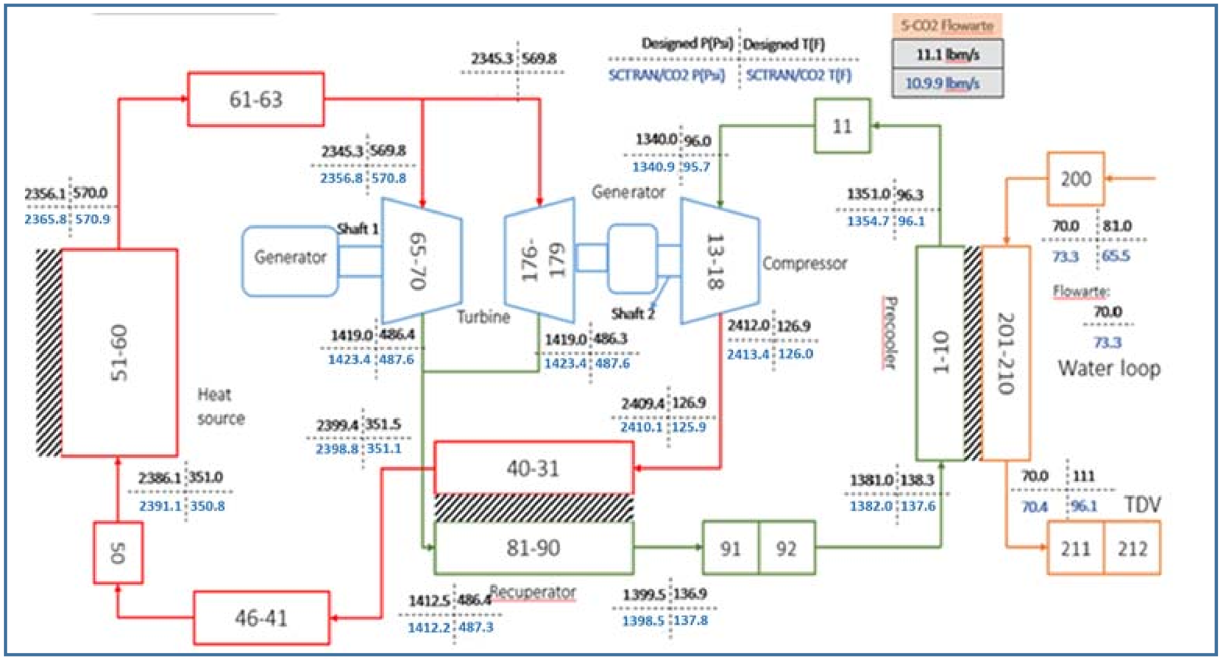
Pressure and temperature variation during the cooling reduction transient

Transient:
water flowrate from 0.25 kg/s to 0.17 kg/s in 60 second

Result:
the relative error of pressure is within 1% ;
the error of temp is within 2 ^{o}C.

4.2 IST Loop Simulation Verification

■ IST Loop Full Power Heat Balance Simulation



Comparison of SCTRAN/CO2 predicted and the IST designed steady state result

Designed	SCTRAN/CO2	Error
CO2 Loop Flowrate(lbm/s)		
11.1	10.99	-0.99%
Max Temperature Difference(F)		
486.4	487.6	1.2
Max Pressure Difference(psi)		
2345.3	2356.8	1.2%

Conclusion:

1. The SCTRAN/CO2 is able to simulate S-CO2 Brayton cycle
2. Transient process isn't presented

PART 5 CONCLUSION & EXPECTATION

■ Conclusion

- ✓ The PCHE model can predict the fluid outlet temperature at steady state.
- ✓ The compressor model of SCTRAN/CO2 can predict accurate compressor consuming power, which indicate it can be used for Brayton cycle simulation.
- ✓ Transient simulation of SCO2PE and steady state simulation of IST indicate that SCTRAN/CO2 owns the ability to conduct transient simulations for S-CO2 Brayton cycle.

■ Expectation

- ✓ The firction model for PCHE model should be validated
- ✓ The transient validation for PCHE model is wanted
- ✓ To do some control strategy analysis for brayton cycle with our newly developed code

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THANK YOU

Welcom your suggestions!

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A Team for **NU**clear's **SOL**ution