Development of A Transient Analysis Code for S-CO_2 Power Conversion System

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ABSTRACT

Supercritical CO_2 Brayton cycle is a good choice of thermal-to-electric energy conversion system, which owns a high cycle efficiency and a compact cycle configuration. It can be used in many power-generation applications, such as nuclear power, concentrated solar thermal, fossil fuel boilers, shipboard propulsion system. Transient cycle analysis for S-CO_2 Brayton cycle is quite important in the area of transient analysis, control strategy study and accident analysis. In this paper, a transient analysis code SCTRAN/CO2 is developed for S-CO_2 Brayton Loop based on a homogenous model. Heat conduction model, point neutron power model(which is developed for nuclear power application), turbomachinery model for gas turbine, compressor, shaft and valve model, PCHE recuperator model are all included in this transient analysis code. The verifications and validations were performed for models like heat transfer model, friction model, compressor model. The verification of integrated system transient was also conducted through making comparison with experiment data of SCO2PE of KAIST. The comparison results show that SCTRAN/CO2 owns the ability to simulate transient process for S-CO_2 Brayton cycle. SCTRAN/CO2 will become an important tool for S-CO_2 based Bryton cycle development.

KEYWORDS

S-CO_2, Brayton cycle, Transient, Code development

1. INTRODUCTION

Transient analysis code is a necessity for study of control strategy, dynamic characteristic as well as safety analysis for S-CO_2 Brayton cycle direct or indirect cooled reactors. The transient analysis code should include reactor model, precooler model, turbomachinery model (include compressor and gas turbine), rotating shaft model.

Different transient analysis codes have been developed to satisfy the demand for control strategy and accident study for S-CO_2 Brayton cycle direct or indirect cooled reactors. A transient analysis code MMS-LMR was developed to simulate the system transient and evaluate control logics for sodium cooled fast reactor KALIMER-600[1]. The code can simulate coolant of Na and CO_2, and modules like reactor, pipe, Na-CO_2 heat exchanger, recuperator and compressor. Code MARS has been applied to carry out up-power and down-power transient simulation for the Supercritical CO_2 Integral Experimental Loop (SCIEL)[2]. A modified GAMMA+ code was developed and applied for the analysis of KAIST Micro Modular Reactor(MMR) for simulation of loss of load and loss of coolant accidents[3]. Accurate CO_2 properties near critical point and turbomachinery performance map were incorporated into the original GAMMA+ which was previously a transient analysis code for Very High Temperature Reactor (VHTR) system developed by KAERI. The performance map of turbomachinery for GAMMA+ is produced by KAIST-TMD, which is an in-house code to design the turbomachinery. GAMMA+ code simulation ability near critical point has been validated with comparing with the experiment data from SCO2PE [4]. RELAP5-3D has S-CO_2 properties and compressor and turbine models, which could help to simulate the S-CO_2 Brayton cycle. It has been used to analyze the safety performance for SCO_2 cooled fast reactors with passive safety system under loss of coolant accident and loss of generator load accident [5]. A plant dynamics computer code named Plant Dynamics Code (PDC) has been developed by ANL [6]. The PDC solves time-dependent mass, momentum and energy conservation equations for S-CO_2 fluid plus the turbomachinery shaft dynamics equation. This code has been applied to various applications, such as transient and control strategies analysis of S-CO_2 Brayton cycle coupled to lead-cooled fast reactor [7], autonomous load following for an SFR by coupling with SAS4A/SASYSYS-1 to determine the core side [8], simulation of S-CO_2 Integrated System Test[9], off-design behavior analysis for S-CO_2 Brayton cycle coupled to sodium-cooled fast reactor[10]. Validation work has been done by comparing PDC compressor model with SNL/BNI compressor test data [11]. TRACE source code was modified by adding new fluid(S-CO_2) as well as Brayton turbomachinery components to enhance its ability to simulate S-CO_2 Brayton cycle [12], [13]. Cycle design and control features during startup and operation has been carried out [14]. GAS-PASS is a dynamic simulation and control code for gas-cooled Brayton cycle reactor power conversion system. It has been modified to deal with the use of S-CO_2 Brayton cycle [15]. The control strategies has be studied [16].

As China is also launching projects into S-CO_2 Brayton cycle development, transient analysis code for S-CO_2 Brayton cycle is in urgent need to help predesign experimental facility, as well as the new Brayton cycle-based reactor concept development. In this paper, SCTRAN, which is safety analysis code for SCWR, was selected to be developed to simulate the S-CO_2 Brayton cycle through adding accurate thermal property and constitutive model for CO_2, turbomachinery model (including compressor, gas turbine, shaft). The initial verification of the developed code SCTRAN/CO2 was carried out through code-to-code comparison and experiment data validation.

2. CODE DEVELOPMENT

2.1. Introduction of SCTRAN

SCTRAN is a one-dimensional safety analysis code for SCWRs and applies the fission decay heat equation and point neutron kinetics equation with six groups of delayed neutron to calculate the core power. Its ability to simulate the transients and accidents of SCWR has been verified by comparing with APROS code and RELAP5-3D code, respectively [17]. It has been widely used in transient and accident analysis for supercritical water reactor [18]–[20].

In order to make SCTRAN suitable for S-CO_2 Brayton cycle based reactor system, accurate property package as well as heat transfer and friction models for carbon dioxide and turbomachinery models including gas turbine, compressor and rotating shaft should be developed.

2.2. Compressor model development

2.2.1. Basic model of compressor

The goal of compressor model is to calculate the flow condition inside the compressor and at the compressor outlet. A quasi-static status is assumed for flow inside compressor under which situation the performance map could be used to evaluate the efficiency and pressure ratio of compressor. The solution of compressor model should include pressure rise which could be used for fluid momentum conservation equation, enthalpy increase which was needed in fluid energy conservation equation and torque which is needed for shaft model to simulate rotating speed.

Figure 1 shows the fluid enthalpy and entropy variation during ideal and realistic compression process. The ideal compression process is regarded as an isentropic process and the realistic compression process need a factor of compressor adiabatic efficiency to account for the additional enthalpy increase compared to that of the ideal process. The definition of adiabatic total-to-total efficiency is as follows:

$$\eta_{ad} = \frac{\text{Isentropic work}}{\text{Actual work}} = \frac{h_{2'}^T - h_1^T}{h_2^T - h_1^T} \tag{1}$$

Therefore, the actual outlet enthalpy of compressor can be obtained with ideal outlet enthalpy and adiabatic efficiency through equation (1). The ideal enthalpy increase could be obtained through the integration of equation DH=v*DP.

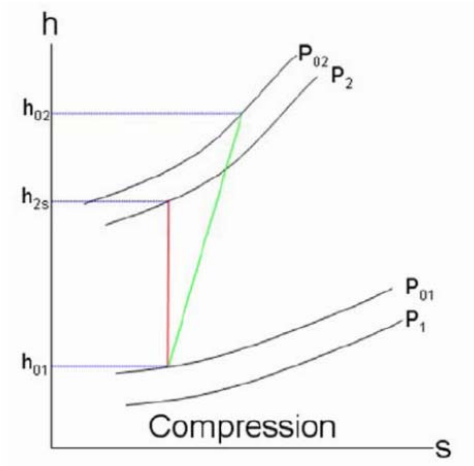

Figure 1 Ideal and realistic compression process inside compressor

A performance map could be produced by other specific code. For example, the performance map of turbomachinery for GAMMA+ is produced by KAIST-TMD, which is an in-house code to design the turbomachinery[4]. The pressure rise and adiabatic efficiency through the compressor are obtained from the performance map which is specially produced for the targeted compressor. As the compressor pressure ratio is regarded to be obtained from compressor performance map according to the rotating speed and coolant flowrate, the pressure increase through compressor can be obtained:

$$\Delta P = P_1^T\left(R_p - 1\right) \tag{2}$$

Among, R_p denotes the compressor pressure ratio and P_1^T denotes the compressor inlet total pressure. The kinetic change of the fluid is included in the item of total pressure in equation (2).

Assuming that no heat dissipated in the compression process, the compressor power acting on the fluid is:

$$\begin{aligned} W_{c.v.} &= \dot{m}\left(h_2^T - h_1^T\right) = \dot{m}\left(h_{2'}^T - h_1^T\right) + \dot{m}\left(h_2^T - h_{2'}^T\right) \\ &= \mathrm{W_s} + \mathrm{W_d} \end{aligned} \tag{3}$$

Among, h_2^T is the real enthalpy at the compressor outlet, $h_{2'}^T$ is the ideal enthalpy at the compressor outlet, W_s is the power produced by compressor during the isentropic process and W_d is the dissipated power in the compression process.

In the ideal compression process, the power produced by compressor is as follows:

$$W_s = \dot{m} \cdot g \cdot H = \frac{\dot{m} \cdot \Delta P}{\rho_m} \tag{4}$$

The average density equals to the mean value of the density at compressor inlet and outlet. Substitute equation (2) to equation (4), the ideal torque can be obtained:

$$\tau_s = \frac{\dot{m}}{\omega}\left(h_{2'}^T - h_1^T\right) = \frac{\dot{m}}{\omega}\frac{\Delta P}{\rho_m} = \frac{\dot{m}}{\omega}\frac{P_1^T\left(R_p - 1\right)}{\rho_m} \tag{5}$$

The dissipated torque can be calculated using the following equation:

$$\tau_{\mathrm{d}}=\frac{\dot{m}}{\omega}\frac{1-\eta_{ad}}{\eta_{ad}}\left(h_{2'}^{T}-h_{1}^{T}\right)=\frac{\dot{m}}{\omega}\frac{1-\eta_{ad}}{\eta_{ad}}\frac{P_{1}^{T}\left(R_{p}-1\right)}{\rho_{m}} \tag{6}$$

Sum up equation (5) and (6), the total torque of the compressor is obtained:

$$\tau_{\mathrm{t}}=\tau_{s}+\tau_{\mathrm{d}}=\frac{\dot{m}}{\omega}\frac{1}{\eta_{ad}}\left(h_{2'}^{T}-h_{1}^{T}\right)=\frac{\dot{m}}{\omega}\frac{1}{\eta_{ad}}\frac{P_{1}^{T}\left(R_{p}-1\right)}{\rho_{m}}=\frac{\dot{m}}{\omega}\frac{1}{\eta_{ad}}\frac{\left(P_{2}-P_{1}\right)}{\rho_{m}} \tag{7}$$

Therefore, through equation (1), (2) and (7), the enthalpy increase, pressure increase of fluid through the compressor and total torque of the compressor can be obtained.

2.2.2 Incorporation of compressor model to code SCTRAN

The compressor component will be regarded as a normal junction and volume when incorporating into SCTRAN. The pressure rise calculated by compressor model will be added to the momentum conservation equation of the represented junction and the enthalpy change calculated by compressor model will be added to the energy conservation equation of the represented volume.

2.3 Gas turbine model development

Figure 2 shows the ideal and realistic expansion process inside gas turbine model. The process of turbine acting is inverse process of compressor acting. Thus the same theory was applied to gas turbine model and the below correlations is obtained:

For fluid enthalpy increase:

$$\Delta h=\frac{h_{2'}^{T}-h_{1}^{T}}{\eta_{ad}} \tag{8}$$

For pressure drop:

$$\Delta P=P_{1}\left(R_{p}-1\right) \tag{9}$$

For total torque of gas turbine:

$$\tau=\frac{\dot{m}\eta\left(P_{1}-P_{2}\right)}{\omega\rho_{m}} \tag{10}$$

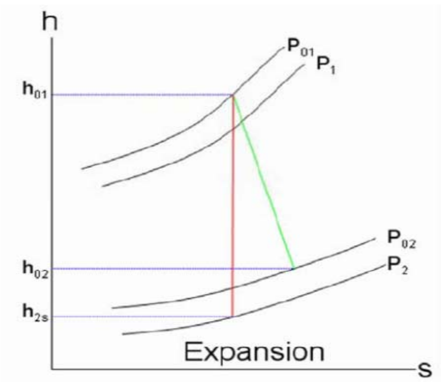

Figure 2 Ideal and realistic expansion process inside gas turbine

2.4 Shaft model development

In the Brayton cycle, there are many turbomachinery connected to the shaft, which include gas turbine, compressor, generator, control system. The shaft model for evaluation shaft rotating speed is as follows:

$$\sum_i I_i \frac{d\omega}{dt} = \sum_i \tau_i - \sum_i f_i \omega + \tau_c \tag{11}$$

The first item on right hand of equation (11) denotes the torques produced by compressor, turbine or generator. The second item denotes the torques produced by friction while the third item denotes the torque produced by control system.

2.5 Constitutive model incorporation

2.5.1 Properties of carbon dioxide

An independent and accurate thermal property model for carbon dioxide over a large parameter range is needed to be incorporated into code SCTRAN. Generally, there are three methods to calculate the fluid thermal property in thermal hydraulic analysis codes, which include property lookup tables or figures, solution of fluid state equations and direct calculation of fitting correlation. In method of property tables or figures, the fluid thermal property is plotted in figures or tabulated in tables, which is easy for users to find property for certain state. However, the calculation efficiency of this method is low, which makes it hard to be applied in large thermal analysis codes which need to calculate the fluid property repeatedly. The solution of fluid state equation is based on strict theoretical and experimental study. Thus this method can produce fluid property with high accuracy. However, these basic fluid state equations are complex and time-consuming because iterations are needed to get the final results. The method of fitting correlation is to get a mathematical correlation with certain prediction accuracy for fluid property based on the existing thermal property data. The mathematical correlation can be polynomial expression or some other type. This method with the merits of small computational effort and high prediction accuracy can be conveniently programmed into thermal analysis codes. It has been widely used in thermal analysis codes. Thus the method of fitting polynomial correlation was applied in this paper to develop the CO_2 property package. The based thermal property data which is used for fitting correlations comes from NIST REFPROP. The thermal property package covers pressure range of 0.1~20MPa and temperature range of 0~991 ºC. Parameters including saturated liquid and vapor enthalpy, temperature, specific volume, thermal conductivity and dynamic viscosity can be obtained through the pressure and enthalpy.

2.5.2 Heat transfer correlation

For the straight semi-circular flow channels in PCHE, correlation Gnielinski is applied([21]). This correlation is suitable for application range of Re between 2300 and 5×10^6 and Pr between 0.5 and 2000.

$$N_u = \frac{hD_e}{\lambda} = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\sqrt{(f/8)}\left(\mathrm{Pr}^{2/3}-1\right)} \tag{12}$$

Among,

$$f = \frac{1}{\left(1.8\log(\mathrm{Re})-1.5\right)^2} \tag{13}$$

The correlations for other Reynold number and other structure of flow channel are not included in code. Further study should be carried out in this area to expand the code application range.

2.5.3 Friction correlation

The friction is evaluated by correlation Zigrang-Sylvester, which is an approximate explicit correlation of Colebrook-White correlation[21]. The Zigrang-Sylvester is suitable for situation whose Re number is larger than 3400. The correlation is listed as:

$$\frac{1}{\sqrt{f}} = -2\log\left\{\frac{\varepsilon}{3.7D_e} + \frac{2.51}{\mathrm{Re}}\left[1.14 - 2\log\left(\frac{\varepsilon}{D_e} + \frac{21.25}{\mathrm{Re}^{0.9}}\right)\right]\right\} \tag{14}$$

When the Re is lower than 2300, the friction model for laminar flow is used:

$$f = \frac{64}{\mathrm{Re}} \tag{15}$$

When the Re number is between 2300 and 3400, an linear interpolation is needed. The surface roughness is set to 0.15mm as a default value.

3. INITIAL VERIFICATION FOR COMPONENT MODEL IN SCTRAN/CO2

3.1 Friction model verification

Wang et al. [22] has attained friction coefficients of supercritical carbon dioxide with various pressures and temperatures in pipes through experiments. The temperature range is 30-150ºC, the pressure range is 3.5-40 MPa, the Reynolds number range is 200-2.0×10^6, and surface relative roughness (ratio of roughness over tube diameter) is 0.005, 0.015 and 0.025. The experiment data in [22] is applied to verified the friction model in code SCTRAN/CO2. Figure 3 illustrate the friction coefficient comparison between the experiment data and SCTRAN/CO2 predicted result. The Reynold number varies from 200 to 2.0×10^6. You can see the prediction results in laminar flow area and turbulent flow area fit well with the experiment data.

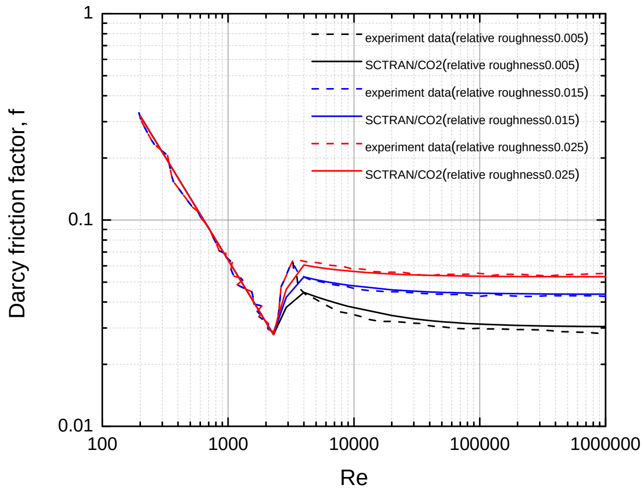

Figure 3 Comparison for friction coefficient of various roughness between experimental data and SCTRAN/CO2 prediction

3.2 Heat transfer model verification

The heat transfer model for S-CO_2 has been introduced in the previous chapters. The verification of heat transfer model need help from heat transfer experiment conducted by [23]. In his work, experiments on turbulent heat transfer by S-CO_2 in a vertical upward flow tube were conducted. The experiments were performed at bulk fluid temperatures varying from 29 to 115ºC, pressure ranging from 74.6 to 102.6 bar, local wall heat fluxes ranging from 38 to 234kW/m^2, and mass fluxes ranging from 208 to 874 kg/m^2s.In this experiment, the maximum errors of the measured temperature, heat transfer rate, and mass flow rate were ±0.2ºC, ±5% and ±4.2%,respectively. The effect of fluid acceleration and buoyancy on S-CO_2 heat transfer was analyzed. The schematic diagram of the experiment loop and test section are illustrated in Figure 4. One of the experiment condition, which owns pressure of 84.19bar, mass flux of 230kg/m^2s, and heat flux of 83kW/m^2, was simulated by SCTRAN/CO2.

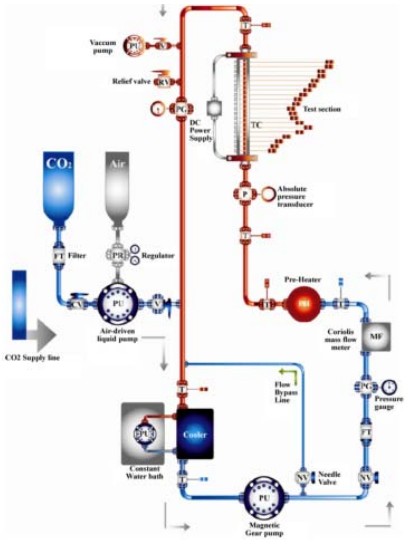

Figure 4 schematic diagram of the experiment loop

Figure 5 depicts the wall temperature and bulk temperature predicted by SCTRAN/CO2 and observed in the experiments. For the bulk temperature prediction, SCTRAN/CO2 accurately predicted the bulk temperature variation trend. However, the prediction error at the test section outlet is larger than that at the test section inlet. This is mainly due to the excluding of energy dissipation in the SCTRAN/CO2 model. For the wall temperature prediction, at the test height above 0.4m, SCTRAN/CO2 accurately predicted the overall wall temperature variation trend. At the test height of 0.1-0.4m, when the coolant temperature is close to critical temperature, the experimental wall temperature has a peak value while the SCTRAN/CO2 result shows a heat transfer enhancement. Therefore, the Gnielinski correltion in code SCTRAN/CO2 is not able to predict the heat transfer deterioration near the critical temperature area for S-CO_2. The application of Gnielinski correlation for recuperator heat exchange simulation should be studied in more details.

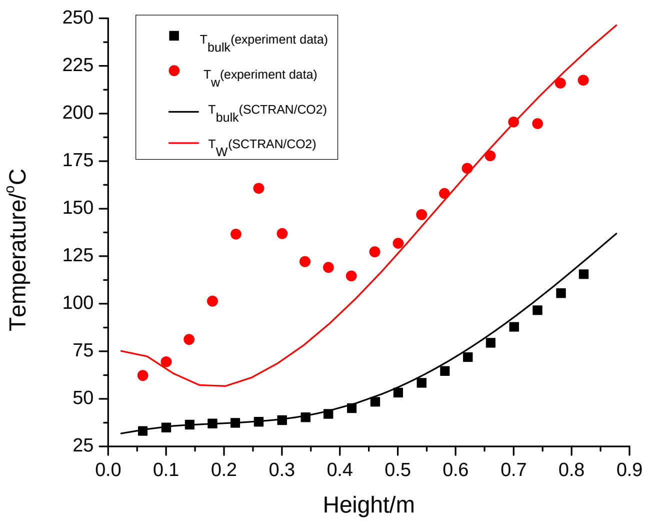

Figure 5 Comparison of bulk temperature and wall temperature of SCTRAN/CO2 result and observed experiment data

3.3 Compressor model verification

Due to lack of design and experiment data on compressor performance, the verification of compressor model is carried out through code to code compressor with RELAP5-3D code on compressor consuming power and GAMMA+ on the outlet temperature prediction in the open literature.

3.3.1 Comparison with code RELAP5-3D on compressor consuming power

Fisher and Davis[24] presented a detailed information of compressor model in RELAP5-3D and carried out a comparison between RELAP5-3D and the operation result of recompressing compressor designed by MIT. The same operation condition will be simulated by SCTRAN/CO2 in this part to verify its ability to calculate the consuming power needed for compressor operation.

Figure 6 depicts the nodalization of the recompressing compressor simulation. Control volume 341 and 382 are the inlet and outlet boundaries of this simple model, which are simulated by time dependent volume in SCTRAN/CO2 and RELAP5-3D. The pressure of control volume 341 is 9.08MPa and the temperature is 363K,which will keep constant in the simulation. Control volume 350 represents the compressor. A series of steady state calculation were carried out to study the performance of the compressor under relative compressor rotating speed of 0.5, 0.8 and 1.0, as well as relative S-CO_2 flowrate between 0.4 and 1.0. The performance map of the compressor in [24] was adopted for SCTRAN/CO2 simulation.

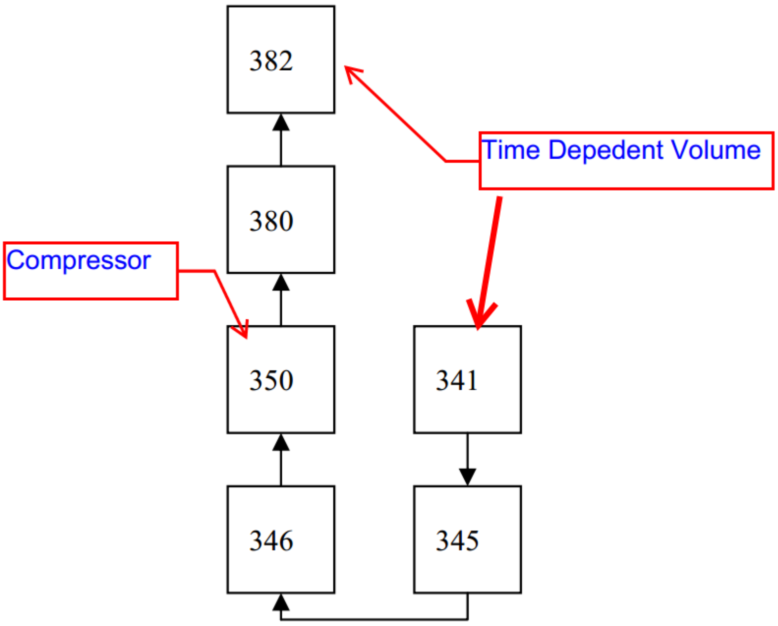

Figure 6 Nodalization of the recompressing compressor

Figure 7 showed the result comparison between SCTRAN/CO2 and RELAP5-3D. As shown in Figure 7, the results predicted by SCTRAN/CO2 were in excellent agreement with the RELAP5-3D predicted result. At relative speed ratio of 1.0, the largest relative error the consuming power is 1.2% while at relative speed ratio of 0.8, the largest relative error the consuming power is 1.47%. When the relative speed ratio comes to 0.5, the largest relative error is 8.1%, which is much higher than those. This larger error may be produced in the process of assembling data from the paper, not due to the compressor model. The performance of SCTRAN/CO2 compressor model verified its ability to predict the compressor consuming power.

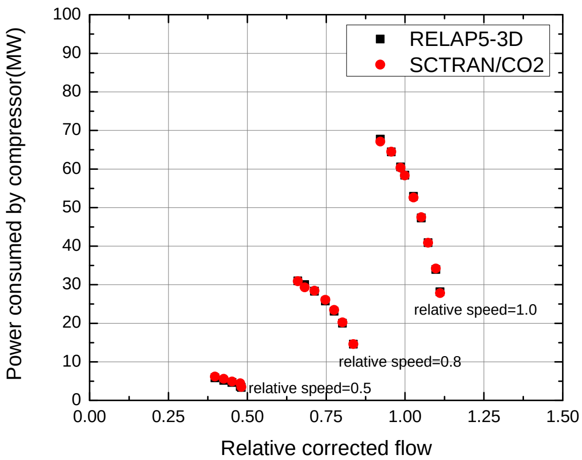

Figure 7 Predicted compressor consuming power by SCTRAN/CO2 and RELAP5-3D

3.3.2. Comparison with code GAMMA+ on temperature prediction

Bae et al. [25] carried out experimental and numerical investigation of S-CO_2 test loop(SCO2PE) near critical point operation. Two different operation conditions near the critical point were designed to verify the GAMMA+ predicted result with experiment data. **Figure 8** shows the nodalization of code GAMMA+ for the compressor part of SCO2PE. Control volume 15, 20, 25 denote the compressor part, control volume 100 is a time dependent junction, which can adjust the inlet flowrate and temperature for the compressor. Control volume 30 is the outlet boundary, which is also simulated by time dependent volume. A same model was built by SCTRAN/CO2. Two different operation conditions are simulated. In case 1, the compressor flowrate is 2.86kg/s and the fluid temperature is 32.5ºC, compressor inlet pressure 7.44MPa. In Case 2, the compressor flowrate is 2.00kg/s and the fluid temperature is 39.9ºC, compressor inlet pressure 8.29MPa. Table 1 shows the experiment data from SCO2PE and predicted result from SCTRAN/CO2 and GAMMA+ on the compressor outlet temperature. In case 1, the compressor operation condition is more close to the critical point, the prediction value of both codes are larger than those in case 2. In case 1, SCTRAN/CO2 predicted a smaller outlet temperature bias 2.25ºC, compared to temperature bias 3.9 ºC which is predicted by GAMMA+. In case 2, these outlet temperature predicted by these two codes are close to each other, which are also close to the experiment data. However, large experiment data uncertainty exists when the operation condition is close to critical point.

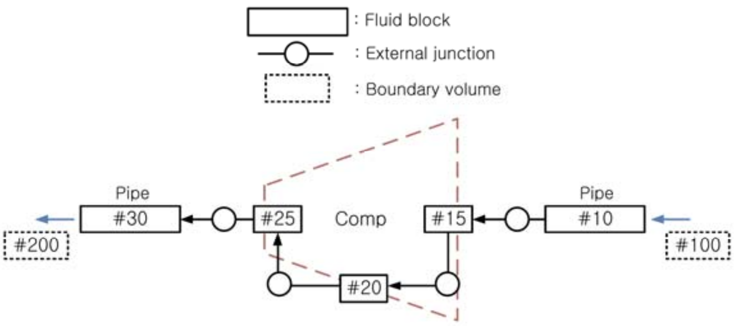

Figure 8 Nodalization of GAMMA code[25]

Table 1 Experiment data from SCO2PE and predicted result from SCTRAN/CO2 and GAMMA+ on the compressor outlet temperature

		Experiment(SCO2PE data)	GAMMA	SCTRAN/CO2
Compressor outlet temperature/ºC	case 1	38.3	42.2(+3.9)	40.55(+2.25)
	case 2	45.8	46.5(+0.7)	46.67(+0.87)
Compressor outlet pressure/MPa	case 1	8.65	8.65	8.65
	case 2	9.12	9.12	9.15
compressor efficient	case 1	58.6	58.6	58.6
	case 2	36.1	36.1	36.1

3.3.3 Summary

According to the two verifications for compressor model, the compressor model in code SCTRAN/CO2 can predict reasonable compressor consuming power and outlet temperature. The prediction accuracy of code SCTRAN/CO2 is close to those of RELAP5-3D and GAMMA+.

4. INITIAL VERIFICATION FOR CYCLE SIMULATION WITH SCTRAN/CO2

4.1. SCO2PE loop simulation

The SCO2PE loop is simulated by code SCTRAN/CO2. The nodalization of SCTRAN/CO2 model is shown in **Figure 9**. Compared to the GAMMA+ model described in (Bae et al., 2016a), SCTRAN/CO2 made some minor modification in its model. SCTRAN/CO2 applies a heat flux boundary to simulate the heat exchanger. The gas turbine model with no heat adding to the fluid is used to simulate the expansion valve. The pressure ratio and efficiency are kept constant in the steady and transient simulation. **Figure 9** shows the nodalization of SCTRAN/CO2 model and the predicted steady state result at each node. The steady state fluid temperature and pressure is very close to the experiment data and the result of GAMMA+.

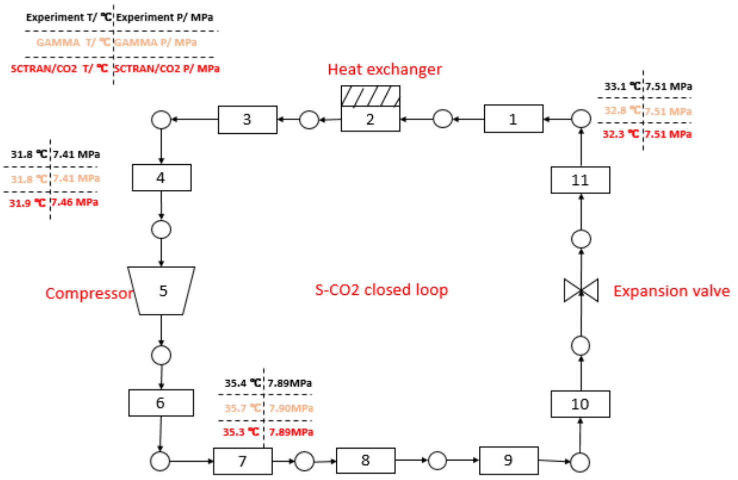

Figure 9 Nodalization of SCTRAN/CO2 model and steady state result at each node

A reduction in water cooling transient is initialed by reducing the water flowrate from 0.25 kg/s to 0.17 kg/s in 50 second. The transient simulation by SCTRAN is illustrated in Figure 10. In the comparison, code SCTRAN/CO2 predicted the right parameter variation and the results are very close to the experiment data and GAMMA+ result. Compared to the experiment data, the relative error of compressor inlet and outlet pressure is within 1% while the absolute error of the compressor inlet and outlet temperature is within 2 ºC.

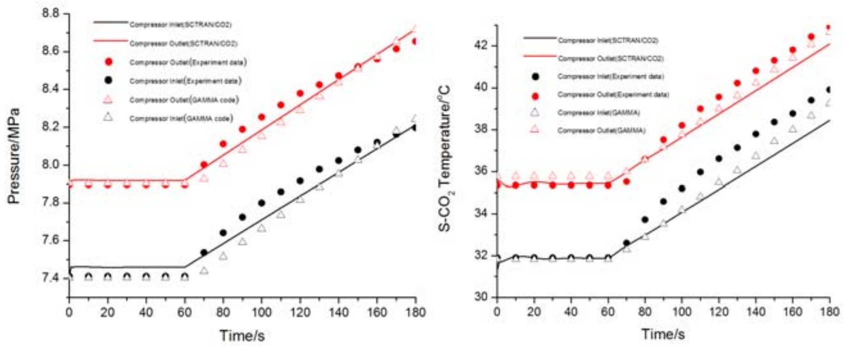

Figure 10 Pressure and temperature variation during the cooling reduction transient

4.2 IST loop simulation

The Integrated Systems Test S-CO_2 Brayton loop provides a test bed to evaluate a wide range of control strategies which could be used for S-CO_2 Brayton power plant[12]. The system includes a two shaft design for the turbomachinery, which allows the turbine generator to operate at constant speed while the compressor speed varies. Simulation of the IST loop was used to prove SCTRAN/CO2's ability in simulating closed Brayton cycle. Due to lack of accurate performance map, the steady state of IST loop at full power operation was simulated instead of simulating transients or accidents.

Simulation of precooler, recuperator, heater, gas turbine and compressor were carried out separately with defining corresponding inlet and outlet boundary. Then the precooler model was connected to the compressor model with eliminating the outlet boundary of the precooler model and inlet boundary of compressor model. Then the combined precooler and compressor model will be connected to the recuperator model at the same way. All the separated models can be combined into a closed Brayton cycle through this way. However in the combining process, the boundary condition of the original model keep changing due to the effects from neighbor models, which make the final state of the Brayton cycle different from the original design one.

Figure 11 shows the steady state result comparison between SCTRAN/CO2 prediction and the original IST design. The S-CO_2 cycle flowrate was predicted as 10.99 lbm/s while in the original design it was 11.1 lbm/s. The biggest fluid temperature error was kept within 1^{o}C and biggest relative pressure error was kept within 0.5%. SCTRAN/CO2 predict pretty close cycle operation result compared to the IST design value.

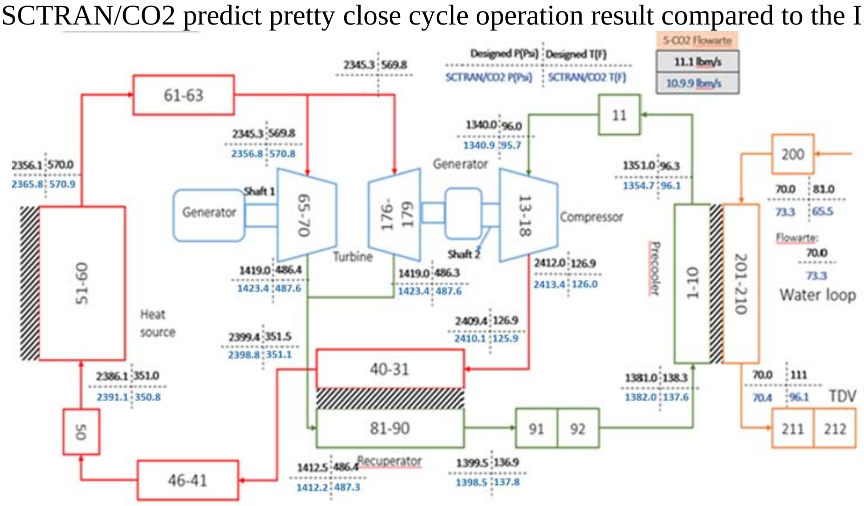

Figure 11 Comparison of SCTRAN/CO2 predicted and the IST designed steady state result

5. CONCLUSION

A transient analysis code SCTRAN/CO2 was developed through incorporating accurate thermal property, heat transfer model and friction model for CO_2, turbomachinery model including compressor, gas turbine and rotating shaft. The initial verification work on friction model with tube experimental data and compressor model with results of RELAP5-3D was carried out to testify the code programing. The validation work on heat transfer correlation and compressor model with experimental data is to validate their applicability on S-CO_2 applications. The results of cycle simulation indicate that SCTRAN/CO2 owns the ability to simulate steady and transient conditions for closed S-CO_2 Brayton cycle. The following conclusions can be made:

1) The friction model in SCTRAN/CO2 was able to predict the right friction coefficient in a wide Reynold number of 200-10^6.

2) The Gnielinski correlation in code SCTRAN/CO2 could predict a reasonable wall temperature variation away from the pseudo critical point while it can't predict the heat transfer deterioration near the critical temperature.
3) The compressor model of SCTRAN/CO2 can predict accurate compressor consuming power and outlet temperature, which indicate it can be used for Brayton cycle simulation.
4) Transient simulation of SCO2PE and steady state simulation of IST with a transient method indicate that SCTRAN/CO2 owns the ability to conduct transient simulations for S-CO_2 Brayton cycle. However, accurate turbomachinery performance map should be developed and incorporated into the code in the future.

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