KAIST-Micro Modular Reactor Steady State Modeling with GAMMA+ Code

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1. Introduction

A Supercritical CO_2 Brayton cycle is receiving attention as a power conversion system for various heat sources because of its high thermal efficiency, compact turbomachinery and briefness of the cycle layout. From the characteristic of S-CO_2 Brayton cycle, KAIST research team has developed a SMR by targeting portable and perfectly modular reactor which is the KAIST Micro Modular Reactor (MMR). Some safety and transient analyses of the MMR should be carried out whether the designed reactor exceeds safety margin when a major accident occurs. The GAMMA+ code which is developed by KAERI is one of the transient analysis codes to simulate S-CO_2 system. However, existing GAMMA+ code was coupled with NIST database to employ CO_2 properties directly. This coupling method requires long time to simulate the whole S-CO_2 power cycle. Therefore, the authors attempted to implement CO_2 thermal and transport properties into GAMMA+ code by using CO_2 property equations directly, rather than connecting NIST database externally. After the modification, CPU time was improved by 16 times compared to the previous coupling. To test the implementation a benchmark problem was selected and solved. The results of the benchmark problem calculation results as well as nodalization of the KAIST-MMR are presented in this paper.

2. Methods and Results

In this section thermal and transport property equations are introduced. After successfully modeling properties, CPU time and numerical difference between former GAMMA+ code connected with NIST and modified GAMMA+ code with CO_2 properties equations are presented.

2.1 Thermal Properties Modeling

Helmholtz Function is the basic equation to model the real gas thermal properties like CO_2.

$$\emptyset(\delta,\tau) = \emptyset^o(\delta,\tau) + \emptyset^{\mathrm{r}}(\delta,\tau) \quad (1)$$

Where $\delta = \rho/\rho_c$ the reduced density and $\tau = T_C/\mathrm{T}$ are the inverse of reduced temperature. ρ_c,T_c are critical pressure and temperature respectively. First term represents ideal gas state and second term means residual state of real gas in RHS of equation (1). From the equation, thermal properties can be calculated by differentiating Helmholtz terms. Below table contains essential thermal properties which were inserted in GAMMA+ code.

Table. 1. Thermal property equations as function of Helmholtz equation.

Property		Equation
$\frac{P(\delta,\tau)}{\rho RT}$	Pressure	$1+\emptyset^r_\delta$
$\frac{s(\delta,\tau)}{RT}$	Entropy	$\tau(\emptyset^o_\tau+\emptyset^r_\tau)$- $\emptyset^o-\emptyset^r$
$\frac{C_v(\delta,\tau)}{R}$	Isochoric Capacity	$-\tau^2(\emptyset^o_{\tau\tau}+\emptyset^r_{\tau\tau})$
$\frac{h(\delta,\tau)}{RT}$	Enthalpy	$1+\tau(\emptyset^o_\tau+\emptyset^r_\tau)+\delta\emptyset^r_\delta$
$\frac{C_p(\delta,\tau)}{R}$	Isobaric Capacity	$-\tau^2(\emptyset^o_{\tau\tau}+\emptyset^r_{\tau\tau})+\frac{(1+\delta\emptyset^r_\delta-\delta\tau\emptyset^r_{\delta\tau})^2}{1+2\delta\emptyset^r_\delta+\delta^2\emptyset^r_{\delta\delta}}$
$\frac{w^2(\delta,\tau)}{RT}$	Speed of Sound	$1+2\delta\emptyset^r_\delta+\delta^2\emptyset^r_{\delta\delta}-\frac{(1+\delta\emptyset^r_\delta-\delta\tau\emptyset^r_{\delta\tau})^2}{\tau^2(\emptyset^o_{\tau\tau}+\emptyset^r_{\tau\tau})}$

$\emptyset_\delta = \left[\frac{\partial\emptyset}{\partial\delta}\right]_\tau$, $\emptyset_{\delta\delta} = \left[\frac{\partial^2\emptyset}{\partial\delta^2}\right]_\tau$, $\emptyset_\tau = \left[\frac{\partial\emptyset}{\partial\tau}\right]_\delta$, $\emptyset_{\tau\tau} = \left[\frac{\partial^2\emptyset}{\partial\tau^2}\right]_\delta$

In 1994, R. Span and W. Wagner proposed more specific equations and parameters. [1], [2]

Thermal properties can be calculated by inserting density and temperature as independent variables. However, pressure and temperature should be entered as independent variables in GAMMA+ code. Therefore, numerical method is needed to get final density in equation (1) from given pressure. The Newton-Raphson method is one of the fastest methods and requires one initial point to solve equation. Thus, Newton-Raphson method was implemented.

$$P_\delta(\delta_i) = \frac{P(\delta_i)-0}{\delta_i-\delta_{i+1}} \quad (2)$$

$$\delta_{i+1} = \delta_i - \frac{P(\delta_i)}{P_\delta(\delta_i)} \quad (3)$$

δ_{i+1} can be obtained from δ_i by equation (3) in the same temperature. The specific algorithm is shown in below figure.

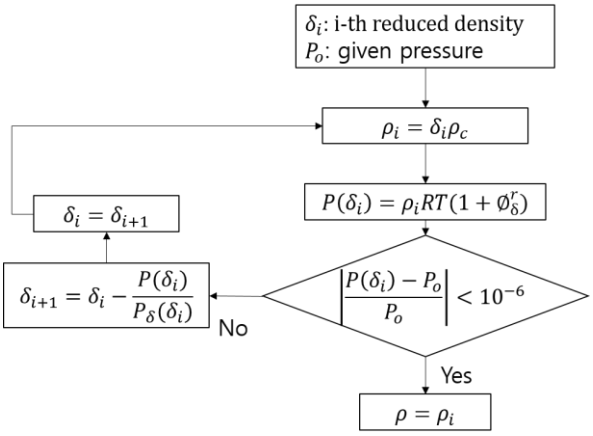

Fig. 1. Density calculation from given pressure.

2.2 Transport Properties Modeling

Transport properties used in GAMMA+ code are only thermal conductivity,λ and viscosity,μ. These properties consist of 3 terms.

$$X(\rho, T) = X^o(T) + \Delta X(\rho, T) + \Delta_c X(\rho, T) \quad (4)$$

The first term is the transport property in the limit of zero density, assuming only two-body molecular collision occur. The second term represents all other effects like many-body interaction, molecular-velocity correlations. The final term represents the critical enhancements near the critical point. However, critical term of viscosity is too complicated to model. Moreover, even though critical term $\Delta_c \mu(\rho, T)$ is not included in equation (4), difference between viscosity with and without critical term is very minor. Thus, only two terms, $\mu^o(T) + \Delta\mu(\rho, T)$, can represent viscosity without critical term. On the other hand, thermal conductivity near the critical point is very different when $\Delta_c \lambda(\rho, T)$ term isn't included. Unfortunately, $\Delta_c \lambda(\rho, T)$ term is also complicated to model. Thus, thermal conductivity near the critical point is used from NIST in the temperature and density range, 240k< T <450K and 25 kg/m^3 < ρ< 1000kg/m^3. The method is simple and hardly affect CPU time.

V. Vesovic and W.A. Wakeham proposed specific coefficient and equations in 1989. [3]

2.3 Simulation results of modified GAMMA+ Code

Below table contains CPU time depending on how the CO_2 properties are modelled.

Table. 2. CPU time depending on properties inputting method.

Category	CPU time
NIST connection	29180 sec
Modified	1791 sec

After the properties are modeled with equations (1) and (4), CPU time became shorter than former one by 16 times.
Below figure represents a benchmark problem to check the difference between previous and modified GAMMA+ Code.

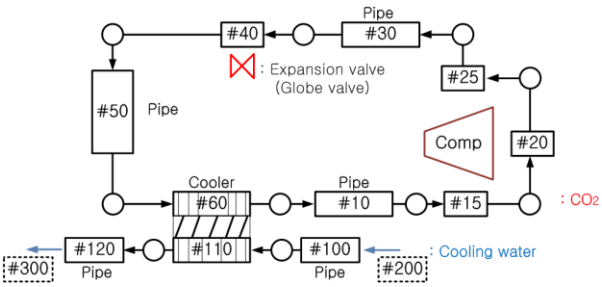

Fig. 2. SCO_2PE device as a benchmark problem.

The benchmark problem input was prepared by Bae *et al* [4] and it was selected to guarantee that modified GAMMA+ code accuracty.

Consequently, the GAMMA+ Code results should be the same regardless of which methods are used. Below figures indicate temperature and pressure at number 20 because thermal properties is most unstable in the compressor.

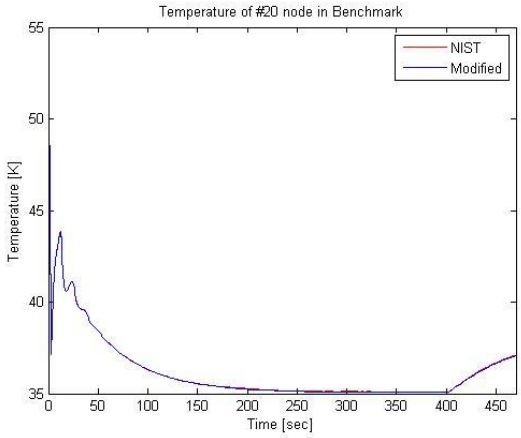

Fig. 3. Temperature trend of the benchmark in number 20 node.

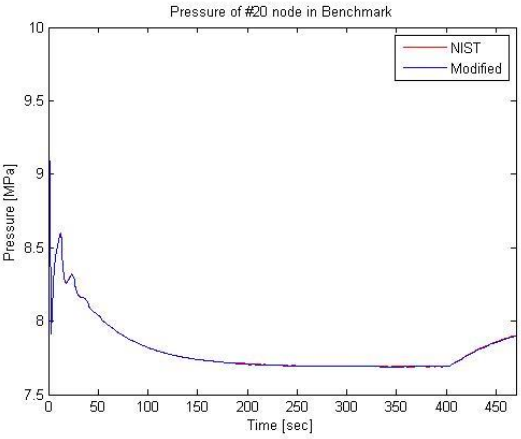

Fig. 4. Pressure trend of the benchmark in number 20 node.

Comparing modified GAMMA+ Code with GAMMA+ Code connected with NIST, pressure and temperature deviation is about 0.0261% and 0.0538% respectively.

2.4 KAIST-MMR steady-state input.

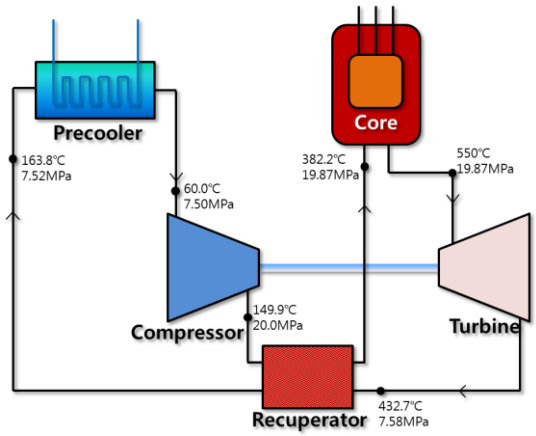

Fig. 5. MMR cycle configuration on the design poin

The KAIST-MMR design was developed from previous research, Kim *et al* [5]. Below table shows the design parameters of the MMR in steady state

Table. 3. Design parameters of the MMR.

Category	Design Parameter
Reactor Power	36.2 MWth
Compressor inlet pressure	7.5 MPa
Compressor inlet temperature	60 ℃
Turbine inlet pressure	20 MPa
Turbine inlet temperature	550 ℃
Mass flow rate	175.34 kg/sec

Based on the design, MMR is nodalized for system safety analysis and transient performance in the GAMMA+ code. Nodalization of the MMR is proposed in the below figure.

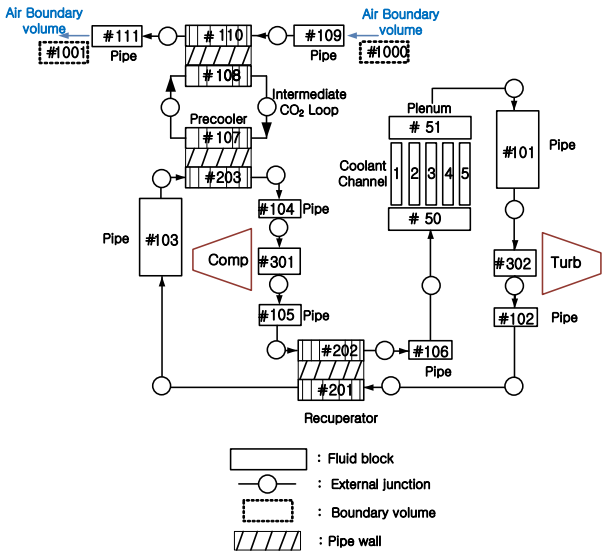

Fig. 6. MMR nodalization.

The ultimate heat sink of MMR is air. Thus, intermediate loop can remain pure CO_2 even precooler is breached. The precooler is PCHE type which has small channel diameter and recuperator as well. Below figure is the configuration of recuperator.

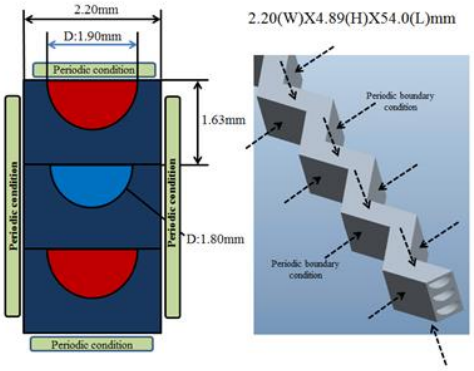

Fig. 7. PCHE of recuperator configuration.

PCHE correlations developed by KIM *et al* [6] is used for modeling recuperator and precooler in the modified GAMMA+ code.

2000<Re<58000, Diameter=1.9mm, Fin angle=32.5°

$$Nu = 0.0293Re^{0.814} \quad (5)$$

$$f = 0.2515Re^{-0.203} \quad (6)$$

Compressor modeling is also modified by KAIST research team. Compressor performance map in the GAMMA+ code is modeled as a function of cycle mass flow rate. The map is developed by KAIST-TMD which is in-house code.

3. Conclusions

Previous GAMMA+ Code connected with NIST was too slow when modeling a fully integrated system. Thus, each property equation should be coded in the GAMMA+ code to reduce calculation time. The modified GAMMA+ code reduces CPU time and has a negligible difference about 0.02~0.06%. Moreover, PCHE correlation and compressor performance map were also modeled in the modified GAMMA+ code. Consequently, on-design point of the MMR can be modeled with the modified GAMMA+ code. Furthermore, transient simulation of the MMR can be analyzed quickly than before.

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