Development of the System Dynamics Code using Homogeneous Equilibrium Model for S-CO_2 Brayton cycle Transient Analyses

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1. Introduction

A Supercritical CO_2 (S-CO_2) Brayton cycle has gained a lot of attention as one of the promising power conversion systems for numerous applications, including the next generation nuclear system due to its many advantages [1]. The features of the S-CO_2 Brayton cycle come from a small compressing work by designing the compressor inlet close the critical point of CO_2 [1]. This means the system condition can be operating under two-phase or sub-critical phase during transient situations such as changes of cooling system performance, load variations, etc.

Since there is no operating MW scale S-CO_2 Brayton cycle system in the world yet, using an analytical code is the only way to predict the system behavior and develop operating strategies of the S-CO_2 Brayton cycles. Therefore, the development of a credible system code is an important part for the practical S-CO_2 system research.

A few studies on the S-CO_2 system transient analysis with analytical codes have been conducted previously [2-4]. However, the analysis for the CO_2 two-phase analysis is still in its early stage.

Previously, the modeling of the S-CO_2 cycle transient with GAMMA+ code (Gas Multidimensional Multicomponent mixture Analysis plus code) was performed, originally developed as a gas system transient analysis code for analyzing a high temperature gas-cooled reactor in KAERI (Korea Atomic Energy Research Institute). The GAMMA+ code conducted the validation and verification for a helium system [5, 6], but there was no additional validation or verification with other fluid system. Regarding the S-CO_2 systems, a GAMMA+ code validation results can be found in [7, 8]. From these studies, it was found that using the GAMMA+ code has some limitations for the S-CO_2 system analysis when the system is going through phase change. The reason was because the current version of GAMMA+ code can just deal with two-phase problem of a water-cooled system. Several attempts to modify the GAMMA+ code to conduct the CO_2 two-phase analysis were made as the first step for the S-CO_2 system phase change scenario analysis. However, the revised GAMMA+ code has shown some errors related with convergences of the code. There are two main reasons why the errors occur in the modified GAMMA+ code. First, the absence of constitutive relations for CO_2 two phase flow in GAMMA+ code. As mentioned above, the current version of GAMMA+ code has correlations for two-phase flow calculations of a water-cooled system. The most representative cases are the models related to dynamic slip of momentum, vapor generation and condensation, etc. near the critical point. Most of errors of GAMMA+ code during the phase change calculation occur for all working fluids including water and CO_2. The second reason is related to the dependent scalar variables being solved. GAMMA+ code adopts the linearized dependent scalar variables by the Newton method, so the partial derivatives with respect to the independent scalar variables, pressure and temperature, are used in GAMMA+ code. However, because of the rapidly changing properties of CO_2 near the critical point, using the partial derivatives of enthalpy with respect to pressure and temperature can cause significant numerical instability in the code.

To avoid these issues, a new system dynamic analysis code using Homogeneous Equilibrium Model (HEM) is decided to develop. The main reason why the HEM is chosen for the S-CO_2 transient analysis is because homogeneous flow conditions are good assumptions when the liquid and gas properties are similar like the two-phase flow near the critical point of fluid. The backbone of the code is the GAMMA+1.0 code's 1-D single phase flow, but considering the quality of fluid by treating a system enthalpy gradient at every time step. This in-house code is based on MATLAB and REFPROP of NIST.

This paper shows the first verification result of the in-house system analysis code to the GAMMA+ code.

2. The in-house transient analysis code review

The same field equations of GAMMA+ code for continuity, momentum conservation, and energy conservation are used for the in-house code except for the diffusion, chemical reaction, and gas mixture terms.

1. Continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho V)=0 \quad (1)$$

2. Energy conservation equation

$$\frac{\partial}{\partial t}(\rho H)+\frac{\partial}{\partial x}(\rho HV)=\frac{\partial P}{\partial t}+V\frac{\partial P}{\partial x}-\frac{\partial q''}{\partial x}+q'''_w \quad (2)$$

3. Momentum conservation equation

$$\frac{\partial}{\partial t}(\rho V)+\frac{\partial}{\partial x}(\rho VV)=-\frac{\partial P}{\partial x}-\rho g-\rho\left(\frac{f}{d}+K\right)V^2 \quad (3)$$

The dependent scalar variable is linearized by the Newton method. In GAMMA+ code, the property derivatives are the partial derivatives with respect to the independent scalar variables, pressure, temperature and species mass fractions. However, in the in-house code, pressure and enthalpy are adopted as the independent scalar variables to track the enthalpy of the system for updating the quality of the system every time step. This is one of the major differences between the GAMMA+ code and the in-house code.

4. Linearized dependent scalar variables

$$\rho^{n+1} \rightarrow \rho^{k} + \left(\frac{\partial \rho}{\partial P}\right)^{k} \delta P + \left(\frac{\partial \rho}{\partial H}\right)^{k} \delta H \qquad (4)$$

$$T^{n+1} \rightarrow T^{k} + \left(\frac{\partial T}{\partial P}\right)^{k} \delta P + \left(\frac{\partial T}{\partial H}\right)^{k} \delta H \qquad (5)$$

Therefore, in the in-house code, the primary dependent variables are pressure (P), velocity (V), enthalpy (H). The independent variables are time (t) and distance (x). The remaining state variables are defined as a function of primary dependent scalar variables: temperature (T) density (ρ). These thermodynamic properties (temperature, density, etc.) and physical transport properties (viscosity, thermal conductivity, etc.) are referred from REFPROP database.

The heat conduction equations are integrated for the finite volume with respect to distance and for the time scheme the Crank-Nicolson method is applied which is the same as the GAMMA+ code.

The heat transfer correlation and frictional losses on the pipe are referred from the GAMMA+ code.

3. Verification of the code

To verify the in-house system transient analysis code, a simple heat transfer problem between 2 types of fluid channel, hot channels and cold channels, is solved and compared as shown in Fig. 1.

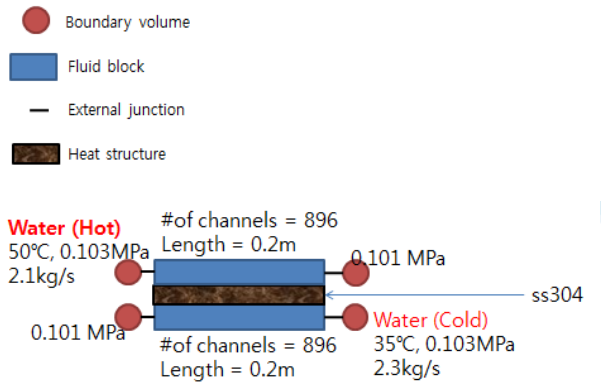

Fig. 1. The example for verifying the in-house code.

Each fluid block has 896 channels and 0.2m, and the material of the heat structure is assumed as ss304. The hot channel inlet condition is 50℃, 0.103MPa, 2.1kg/s water and the cold channel inlet is 35℃, 0.103MPa, 2.3kg/s water.

The below figures show the verification results between the in-house code and GAMMA+ code.

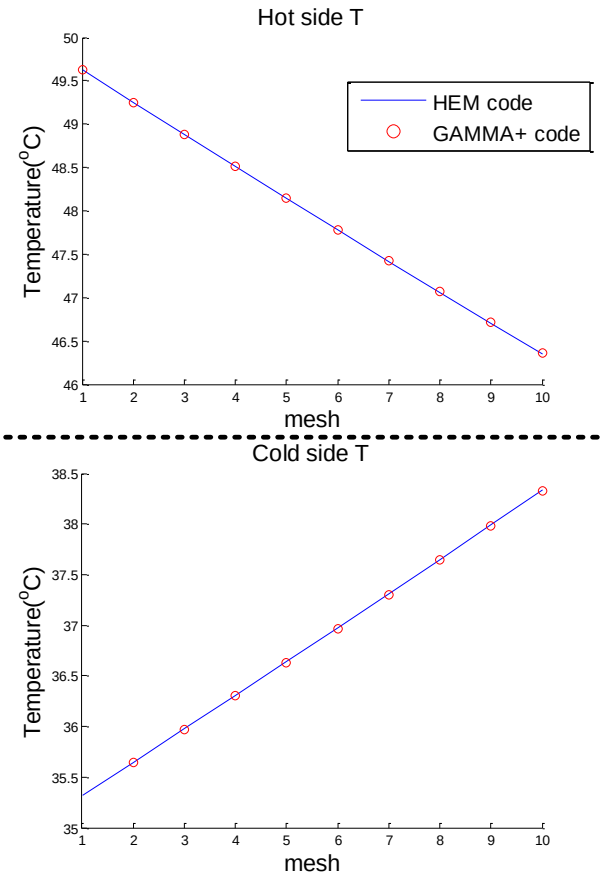

Fig. 2. Verification results: Temperature comparisons of the hot channel (Top) and the cold channel (Bottom)

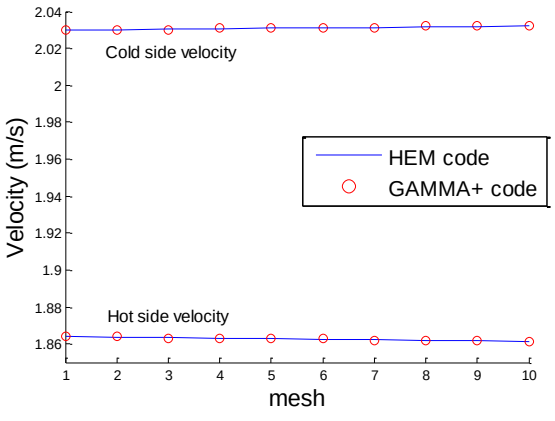

Fig. 3. Verification results: Velocity comparisons of the hot channel (the bottom part of the figure) and the cold channel (the top part of the figure)

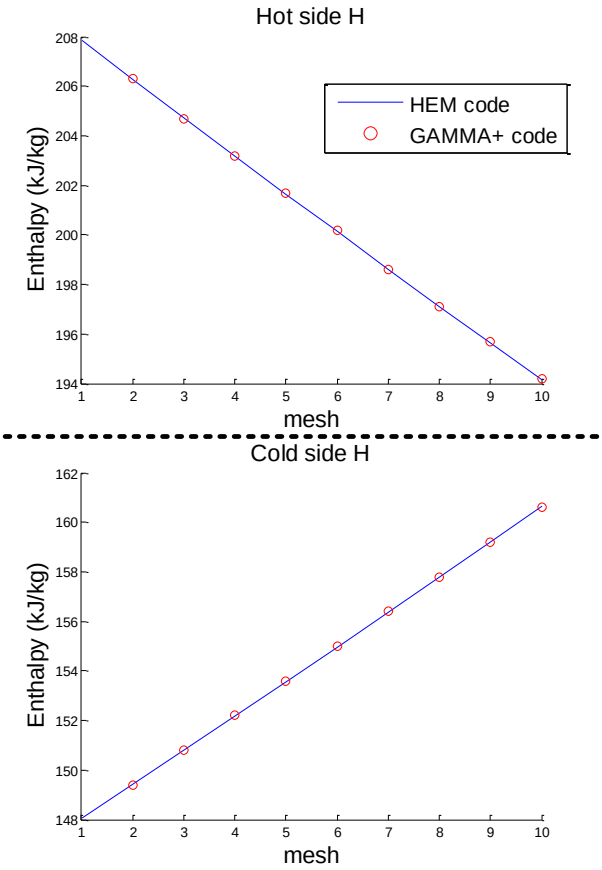

Fig. 4. Verification results: Enthalpy comparisons of the hot channel (Top) and the cold channel (Bottom)

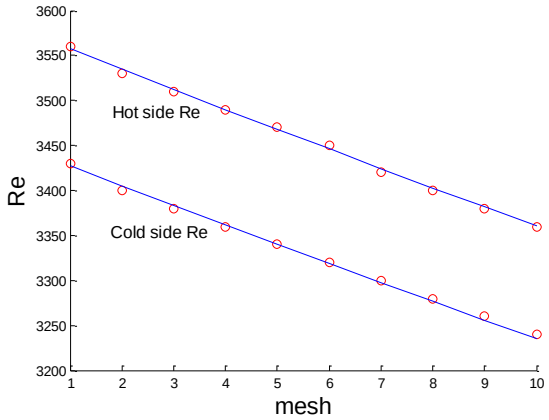

Fig. 5. Verification results: Reynolds number comparisons of the hot channel (the top part of the figure) and the cold channel (the bottom part of the figure)

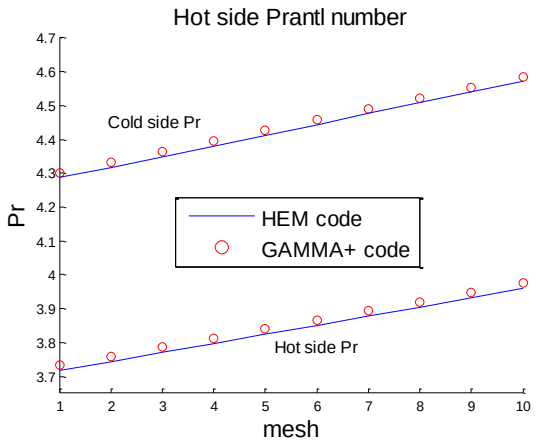

Fig. 6. Verification results: Prandtl number comparisons of the hot channel (the bottom part of the figure) and the cold channel (the top part of the figure)

4. Conclusions

The current status of the developed system analysis code for S-CO_2 Brayton cycle transient analyses in KAIST and verification results are presented in this paper.

To avoid errors related with convergences of the code during the phase changing flow calculation in GAMMA+ code, the authors have developed a system analysis code using Homogeneous Equilibrium Model (HEM) for the S-CO_2 Brayton cycle transient analysis.

The backbone of the in-house code is the GAMMA+1.0 code, but treating the quality of fluid by tracking system enthalpy gradient every time step. Thus, the code adopts pressure and enthalpy as the independent scalar variables to track the system enthalpy for updating the quality of the system every time step. The heat conduction solving method, heat transfer correlation and frictional losses on the pipe are referred from the GAMMA+ code.

The in-house code is based on MATLAB and REFPROP database is used for fluid properties.

A simple heat exchanging example was solved for the verification of the in-house code with the GAMMA+ code.

The verification results are satisfactory. However, the Reynolds number and the Prandtl number comparisons show some gaps between the codes. The differences are caused by the transport property difference between the codes or geometry errors from the input file, etc. The output file of GAMMA+ code does not provide the transport properties directly, so the comparing of transport property of each code is going to be conducted as the next step to find out the reason.

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