# An Evaluation of Two Phase $CO_2$ homogeneous equilibrium model for Maritime Propulsion Reactor Transient Analysis

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## 1. Introduction

The northern sea route (NSR) has been considered as a valuable channel for the regional export of raw materials and has attracted substantial attention because it saves up to 40% of sailing distance between Yokohama and Rotterdam compared to the typical route through the Suez Canal [1-3]. However, the absolute distance of NSR is still enormously long as 12,700 km. It means that navigating NSR with conventional fossil fueled engine such as diesel, gas turbine, or steam power system has a few limitations in terms of refueling and greenhouse gas regulation [4, 5].

To resolve these limitations of fossil fuel engines, nuclear marine propulsion system can be a promising option. The World's first nuclear powered icebreaker '*Lenin*' went into service with the Arctic Fleet and has been reported to have journeyed more than 96,560 km, 64,374 km of them through ice fields of the NSR [6].

However, including *Lenin*, the nuclear powered fleets are usually equipped with Pressurized Water Reactor (PWR) cores and a steam Rankine cycle. Despite of many advantages of steam Rankine cycle, it has some mediocre aspects such as bulky volume of system, steam quality control at turbine, and corrosion of structure material [4]. To overcome some limitations of steam Rankine cycle, supercritical $CO_2$ cycles (S-$CO_2$ cycles) can be a good alternative because S-$CO_2$ cycles offer lots of advantages in a practical application due to high thermal efficiency, low volume to power ratio, and mild environment for keeping integrity of turbomachinery blade [7-9]. Due to its compactness and high efficiency, S-$CO_2$ cycles are potentially considered as a candidate of marine propulsion and S-$CO_2$ cycles as a fleet engine can achieve about 25% saving compared to typical diesel engine [10].

In KAIST for providing distributed power to a remote region, a fully modularized reactor called KAIST Micro Modular Reactor (MMR) has been developed. The layout of MMR is a simple recuperated cycle in order to minimize its volume and weight to be transported by ships or trailers [11]. After that, modified GAMMA+ code which was originally developed in KAERI has been used to check its autonomous load following characteristics and response of hypothetical accidents [12]. Later, MMR has been taken into account a shipboard propulsion system as well as distributed power sources [13]. However, application of S-$CO_2$ cycle to marine propulsion system is questionable especially for icebreaker. This is because it usually requires abrupt load changes, especially passing through an ice field to mill or break the ice. Thus, it is quite challenging to maintain the compressor inlet state near the critical point during the abrupt load change [14]. Moreover, average sea water temperature of NSR's major path is kept from -2 to 5$^o$C. On the other hand, the critical point of $CO_2$ is 31$^o$C and 7.38MPa so that if an S-$CO_2$ cycle that operates above the critical point is utilized for an icebreaker propulsion, a huge exergy loss can occur during voyage. To deal with these technical challenges of S-$CO_2$ cycle, a trans-critical $CO_2$ (T-$CO_2$) cycle is considered as a substitution of an S-$CO_2$ cycle. A T-$CO_2$ cycle is similar to Rankine cycle except turbine inlet state exceeds the critical point so that compression work is still reduced because compressor inlet is in the liquid state [15].

As the T-$CO_2$ cycle is applied into icebreaker propulsion that goes through abrupt and rapid change of load, dynamic modeling of T-$CO_2$ cycle should be conducted for analyzing load following operation or even under hypothetical accident conditions. One of the challenging aspects to model the T-$CO_2$ cycle is that two phase flow occurs in the cooler. Since the existing T-$CO_2$ cycle for waste heat recovery application operates with a two-phase flow near the critical point, a homogeneous equilibrium model (HEM) approach seems to be appropriate and has demonstrated good accuracy [16]. Nonetheless, a T-$CO_2$ cycle for the icebreaker propulsion has a very low bottom temperature that is far from the critical point so that HEM may need to be re-evaluated for the proposed T-$CO_2$ cycle for the icebreaker propulsion purpose. Additionally, since a micro channel T-$CO_2$ cooler has various flow patterns with respect to quality, it can also lead to a large deviation between HEM and experimental data [17]. To study this issue, a system code based on HEM and experiments data are compared for depressurization experiments where wide range of pressure variation can be observed. Thus, $CO_2$ state pass through broad range of two-phase states during depressurization.

## 2. Methods and Results

### *2.1 HEM addition to GAMMA+ code*

GAMMA+ code has been developed in Korea Atomic Energy Research Institute (KAERI) to model dynamics of a gas-cooled system. Basically, an original GAMMA+ code utilized Newton method to linearized dependent scalar variables that governs mass continuity, momentum conservation and energy conservation by using temperature and pressure as independent variables as shown in equation (1)-(3).

$$\rho^{n+1} \to \rho^k + \left(\frac{\partial \rho}{\partial P}\right)^k \Bigg|_T \delta P + \left(\frac{\partial \rho}{\partial T}\right)^k \Bigg|_P \delta T \qquad (1)$$

$$\begin{aligned}(\rho H)^{n+1} \to (\rho H)^k &+ \left[\rho\left(\frac{\partial H}{\partial P}\right)^k + H\left(\frac{\partial \rho}{\partial P}\right)^k\right]\Bigg|_T \delta P \\ &+ \left[\rho\left(\frac{\partial H}{\partial T}\right)^k + H\left(\frac{\partial \rho}{\partial T}\right)^k\right]\Bigg|_P \delta T\end{aligned} \qquad (2)$$

$$\begin{aligned}q_w^{'''n+1} &\to q_w^{'''k} + \left(\frac{\partial q_w^{'''}}{\partial P}\right)^k \Bigg|_T \delta P + \left(\frac{\partial q_w^{'''}}{\partial T}\right)^k \Bigg|_P \delta T \\ &q_w^{'''k} + htc\left(\frac{\partial T}{\partial P}\right)^k \Bigg| \delta P + htc^k\Big|_P \delta T\end{aligned} \qquad (3)$$

HEM is very similar to single-phase gas governing equation except using mixture fluid properties of vapor and liquid. It is assumed that HEM is well mixed between phases so that vapor and liquid phases reach thermal and mechanical equilibria. Thus, the quality of current state can be calculated from equilibrium quality. Due to thermal and mechanical equilibria, various parameters that represent two-phase state such as void fraction, flow quality and static quality can be directly obtained from the equilibrium quality.

As a result, to incorporate GAMMA+ code with HEM, previous independent variables, i.e. temperature and pressure, should be modified to enthalpy and pressure as new independent variables as shown in the following equations. With these independent parameters, governing equation should be linearized differently [18].

$$\rho^{n+1} \to \rho^k + \left(\frac{\partial \rho}{\partial P}\right)^k \Bigg|_H \delta P + \left(\frac{\partial \rho}{\partial H}\right)^k \Bigg|_P \delta H \qquad (4)$$

$$\begin{aligned}(\rho H)^{n+1} \to (\rho H)^k &+ \left[H\left(\frac{\partial \rho}{\partial P}\right)^k\right]\Bigg|_H \delta P \\ &+ \left[\rho + H\left(\frac{\partial \rho}{\partial H}\right)^k\right]\Bigg|_P \delta H\end{aligned} \qquad (5)$$

$$q_w^{'''n+1} \to q_w^{'''k} + \left(\frac{\partial q_w^{'''}}{\partial P}\right)^k \Bigg|_H \delta P + \left(\frac{\partial q_w^{'''}}{\partial H}\right)^k \Bigg|_P \delta H \qquad (6)$$

When $CO_2$ cycles are analyzed by GAMMA+ code, NIST database is used to reflect exact $CO_2$ properties but NIST database cannot provide derivative properties at constant enthalpy. Thus, derivative properties at constant enthalpy should be converted into derivatives at constant density, temperature or pressure. By cyclic relation, the first derivative term in right hand side of equation (4) can be converted in equation (7) [19].

$$\begin{aligned}&\left(\frac{\partial \rho}{\partial P}\right)\Bigg|_H \left(\frac{\partial H}{\partial \rho}\right)\Bigg|_P \left(\frac{\partial \rho}{\partial P}\right)\Bigg|_\rho = -1 \\ &\left(\frac{\partial \rho}{\partial P}\right)\Bigg|_H = -\left(\frac{\partial \rho}{\partial H}\right)\Bigg|_P \left(\frac{\partial P}{\partial \rho}\right)\Bigg|_\rho = -\left(\frac{\partial \rho / \partial T}{\partial H / \partial T}\right)\Bigg|_P \left(\frac{\partial P}{\partial \rho}\right)\Bigg|_\rho \\ &\left(\frac{\partial \rho}{\partial P}\right)\Bigg|_H = -\frac{(\partial \rho / \partial T)|_P}{C_p}\left(\frac{\partial P}{\partial \rho}\right)\Bigg|_\rho\end{aligned} \qquad (7)$$

The second derivative term on the right hand side of equation (4) can be simplified as in equation (8)

$$\left(\frac{\partial \rho}{\partial H}\right)\Bigg|_P = \left(\frac{\partial \rho / \partial T}{\partial H / \partial T}\right)\Bigg|_P = \frac{(\partial \rho / \partial T)|_P}{C_p} \qquad (8)$$

Equation (6) can be expressed in terms of heat transfer coefficient as shown in (9)

$$\begin{aligned}q_w^{'''n+1} &\to q_w^{'''k} + \left(\frac{\partial q_w^{'''}}{\partial T}\right)\left(\frac{\partial T}{\partial P}\right)^k \Bigg|_H \delta P + \left(\frac{\partial q_w^{'''}}{\partial T}\right)\left(\frac{\partial T}{\partial H}\right)^k \Bigg|_P \delta H \\ &q_w^{'''k} + htc\left(\frac{\partial T}{\partial P}\right)^k \Bigg|_H \delta P + \frac{htc}{C_p}\delta H \\ &q_w^{'''k} - htc\frac{(\partial H / \partial P)^k\big|_T}{C_p}\delta P + \frac{htc}{C_p}\delta H\end{aligned}$$

(9)

By adopting altered equations, GAMMA+ can model two-phase flow of $CO_2$ with thermal and mechanical equilibria assumptions.

### *2.2 Comparison between HEM and experimental data*

The target experimental test loop is $SCO_2PE$ that is a $CO_2$ compressing experimental loop for testing the S-$CO_2$ compressor and heat exchanger near the critical point as shown in Fig. 1.

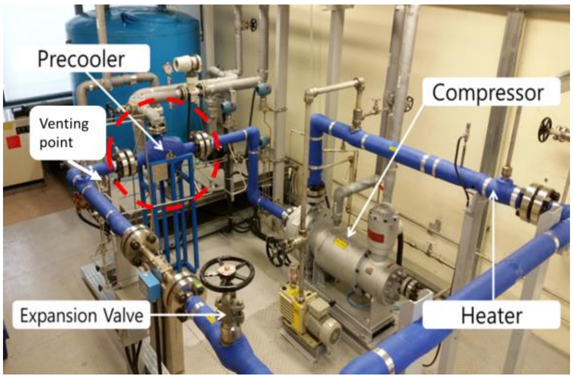


Fig. 1. Picture of $SCO_2PE$

In the previous work, transient two-phase flow of $CO_2$ can be observed by abruptly increased water mass flow rate but it is hard to detect the broad range of two-phase flow during the transient [20]. Thus, by venting the system to quickly approach saturation pressure, a wide range of two-phase flow state can be obtained in this work. Venting was implemented at the precooler inlet and three different experimental cases were conducted: the first case started at the liquid state as the initial state, the second case started at the supercritical state near the critical point and the third case started at the supercritical state far from the critical point.

Table I: Initial condition of PCHE cooler

| | $T_{in}$ (°C) | $P_{in}$ (MPa) | $T_{out}$ (°C) | $P_{out}$ (MPa) |
|---|---|---|---|---|
| Case 1 | 28.9 | 8.52 | 27.8 | 8.4 |
| Case 2 | 31.7 | 7.48 | 31.1 | 7.39 |
| Case 3 | 33.4 | 7.88 | 32.8 | 7.77 |

Heat transfer coefficient and friction factor correlations were selected from Baik's work [21]. These correlations were validated in two-phase flow even though it was originally developed in single phase environment [22]. Therefore, these correlations also used to model printed circuit heat exchanger (PCHE) type cooler in this paper. In this work, only the PCHE section is modeled to confirm HEM characteristics with respect to various conditions. Therefore, the inlet information of PCHE such as pressure, temperature, mass flow rate and quality is prescribed as boundary conditions and outlet information is calculated from HEM. Fig. 2 to Fig. 4 shows the PCHE outlet parameters: Pressure, Temperature, and Quality. Similar to Bae's results, HEM is capable of modeling two-phase flow near the critical point and high quality region accurately, which implies that near gas state is well modeled by HEM as shown in Figs. 3 and 4 as well. However, when quality becomes lower HEM results starts to deviate from the observation.

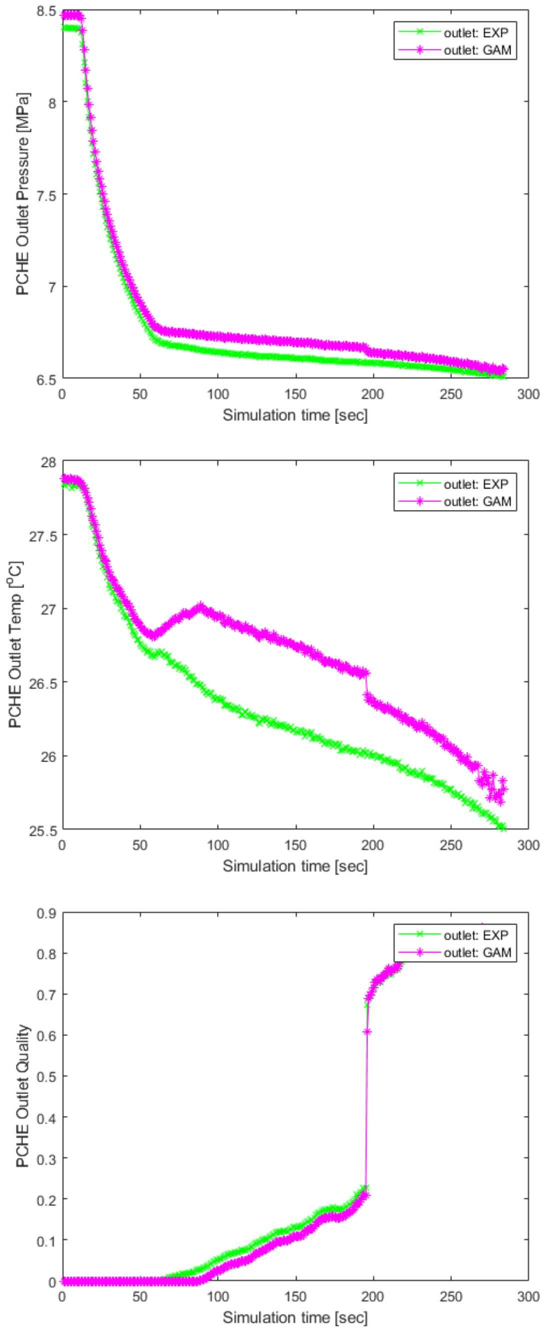


Fig. 2. Case 1 PCHE outlet comparison between GAMMA+ HEM and Experiment (Top: Pressure, Middle: Temperature, Bottom: Quality)

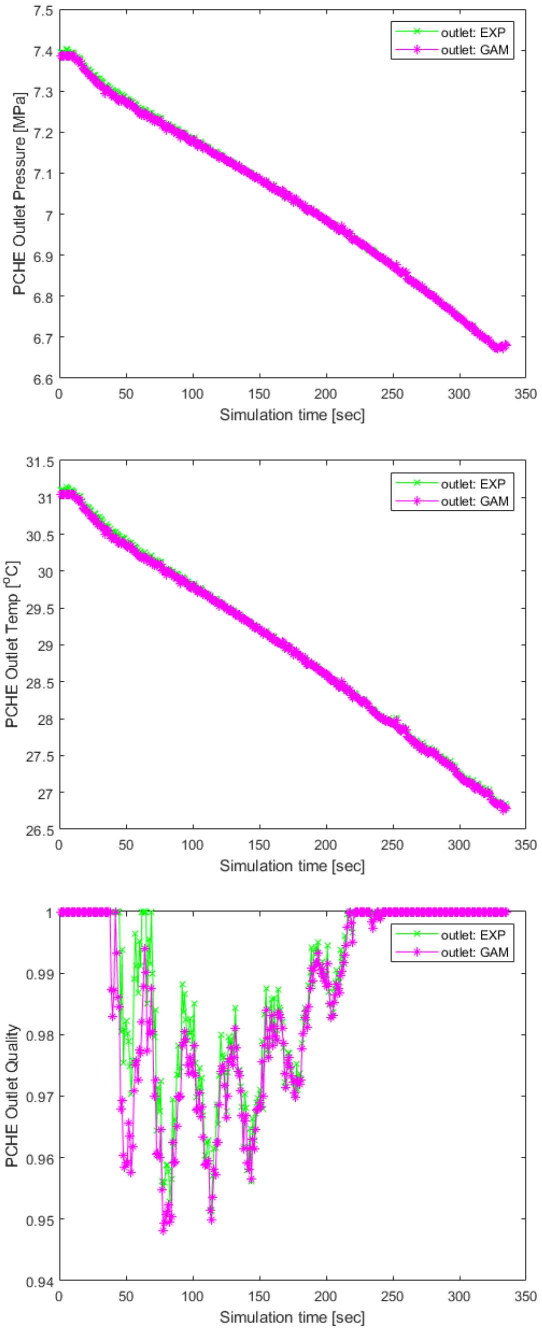


Fig. 3. Case 2 PCHE outlet comparison between GAMMA+ HEM and Experiment (Top: Pressure, Middle: Temperature, Bottom: Quality)

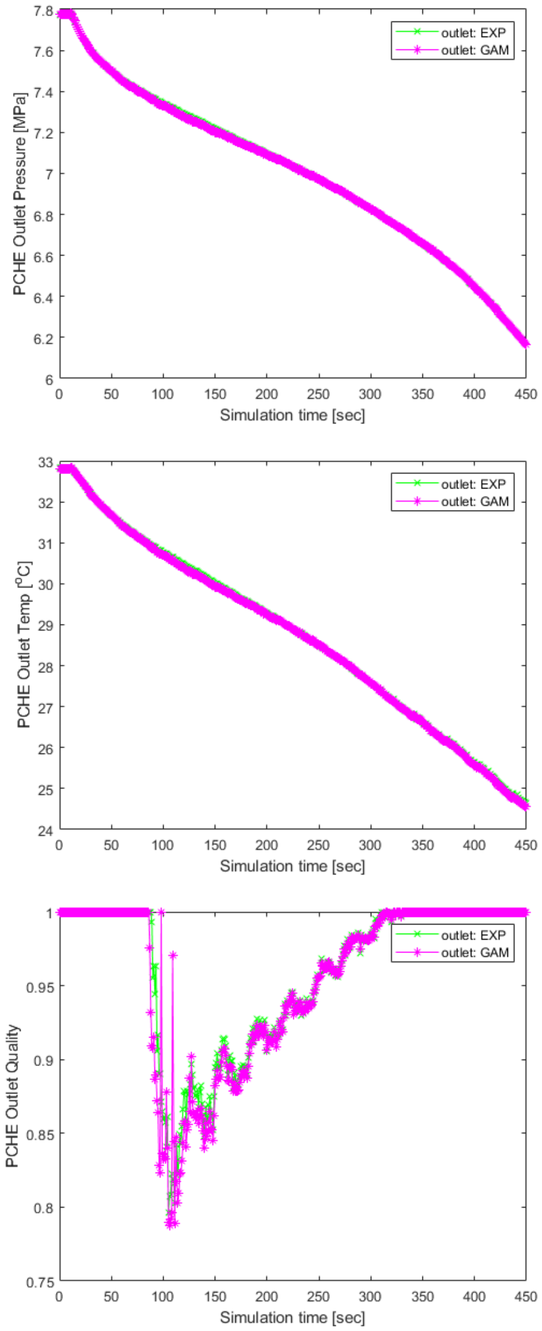


Fig. 4. Case 3 PCHE outlet comparison between GAMMA+ HEM and Experiment (Top: Pressure, Middle: Temperature, Bottom: Quality)

## 3. Conclusions

For an application for the icebreaker nuclear propulsion, trans-critical $CO_2$ cycle is considered in this work. However, to model the control logic or accident conditions of a trans-critical $CO_2$ cycle, a system code capable of modeling $CO_2$ two-phase flow is required. Previously, homogeneous equilibrium model was demonstrated that the model has good ability to simulate two-phase flow of $CO_2$ near the critical point. In this paper, three different initial conditions were tested to re-evaluate homogeneous equilibrium model with respect to quality. The result is consistent with the previous research at the near the critical point or high quality i.e. near gas state. On the other hand, case 1 whose initial state is liquid shows significant deviation of homogeneous equilibrium model results from experiment data. In the future, different two phase flow models will be tested to have better predicting capability under wide range of operational conditions of a propulsion system.

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