Modification of GAMMA$^+$ code for MicroURANUS transient analysis

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1. Introduction

MicroURANUS is a 60 MW_{th} Lead-Bismuth cooled micro modular reactor, which could be used for the propulsion of ships sailing in Norther Sea Route. For the power conversion system of MicroURANUS, the transcritical-CO_2 (TC-CO_2) Rankine cycle has been selected due to its small sized components with suitable thermal efficiency [1]. To simulate the steady state and transient conditions, GAMMA$^+$ code was used. GAMMA$^+$, General Analyzer for Multi-component and Multi-dimensional Transient Application, is a code developed by Korea Atomic Energy Research Institute to analyze Very High Temperature Reactor. Previously, MARS-LBE code, modified by Seoul National University, was used to analyze the lead-bismuth cooled reactors because the thermophysical property of lead-bismuth was updated [2]. When the thermodynamic properties of lead-bismuth implemented in the GAMMA$^+$ code and those in the MARS-LBE were compared, there were discrepancies between the properties in two codes.

In this paper, the modification process of GAMMA$^+$ code, especially the modification in the lead-bismuth thermodynamic properties, is explained. Also, the steady state result of the MicroURANUS and its power conversion system is calculated using GAMMA$^+$ code.

2. Methods and Results

In this section, six properties of lead-bismuth applied in the GAMMA$^+$ code and their modification are examined. Additionally, the steady state result of the MicroURANUS from GAMMA$^+$ code is calculated

2.1 Comparison of Lead-Bismuth properties

Saturation pressure, density, enthalpy, thermal expansion, compressibility, and specific heat are compared. Table 1 shows the thermophysical property correlations that were implemented in GAMMA$^+$ code to calculate the values as functions of temperature.

For MARS-LBE code, the properties are calculated by interpolating the values in the table implemented in the code. Figure 1 shows the comparison of the properties in the GAMMA$^+$ code and MARS-LBE code.

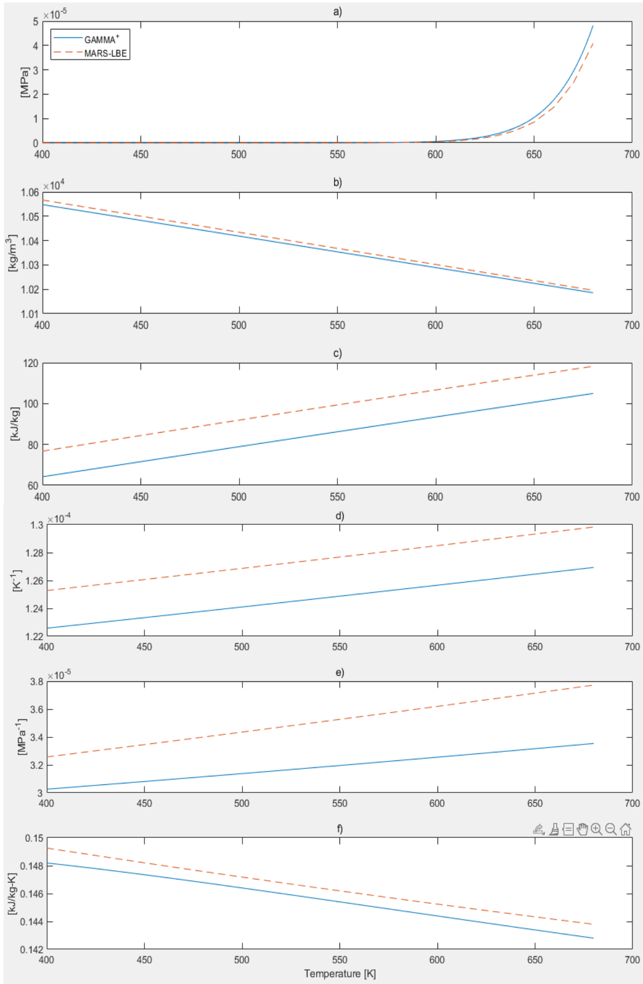
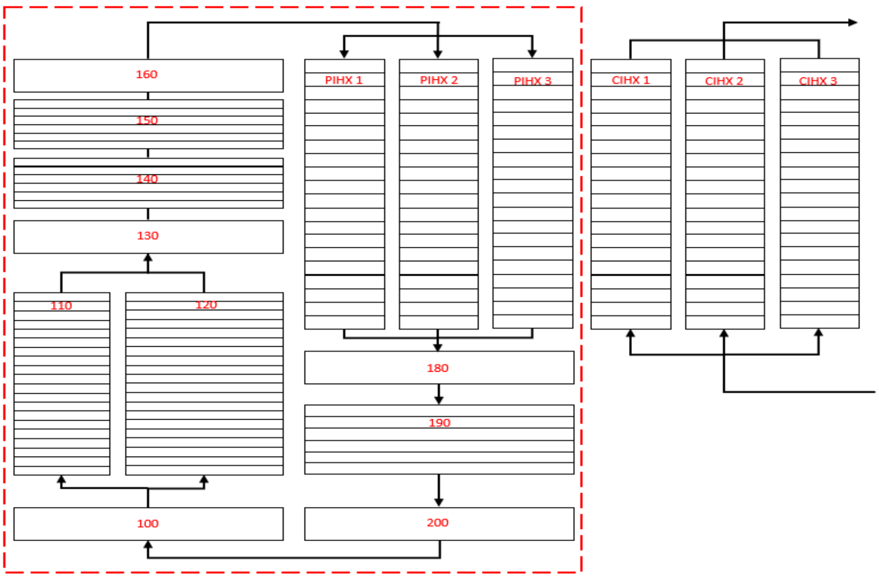


Figure 1. The Comparison of a) Saturation Pressure, b) Density, c) Enthalpy, d) Thermal Expansion, e) Compressibility, and f) specific heat of GAMMA$^+$ and MARS-LBE code at temperature 400K to 680K and Pressure at 0.968 MPa

Table 1. Lead-bismuth thermophysical property correlations, temperature ranges and estimated error [3,4]

Parameter	Correlation	Temperature Range [K]	Estimated Error
Saturation Pressure [Pa]	$P_{sat} = (1.22 \times 10^{10}) \cdot e^{\left(\frac{-22552}{T}\right)}$	670 – 1927	60%
Density [kg m^{-3}]	$\rho = 11065 - (1.293 \cdot T)$	400 – 1300	0.8%
Enthalpy [J kg^{-1}]	$h = 164.8 \cdot T - (1.97 \times 10^{-2}) \cdot T^2 + (4.167 \times 10^{-6}) \cdot T^3 + (4.56 \times 10^5) T^{-1}$	400 – 1100	7%
Thermal Expansion [K^{-1}]	$\alpha = \frac{1}{8558 - T}$	400 – 1300	0.8%
Compressibility [Pa^{-1}]	$\beta = \frac{1}{(38.02 - 1.296 \times 10^{-2} \cdot T + 1.320 \times 10^{-6} \cdot T^2)}$	400 – 1000	3%
Specific heat [J kg^{-1} K^{-1}]	$c_p = 164.8 - (3.94 \times 10^{-2}) \cdot T + (1.25 \times 10^{-5}) \cdot T^2 - (4.56 \times 10^5) T^{-2}$	400 - 1100	7%



Lower Plenum	100
Core Average. Channel	110
Core Hot Channel	120
Upper Nozzle	130
Middle Plenum	140
Upper Plenum	150
Weir	160
Intermediate Heat Exchanger	PIHX1-3
Concourse	180
Downcomer	190
Coldwell	200

Figure 2. Nodalization of MicroURANUS Primary side. Red dotted box represents the primary side of the system

As shown in Figure 1, the properties, especially the enthalpy, calculated in GAMMA$^+$ code differs from those calculated in the MARS-LBE code. Thus, the table used in the MARS-LBE code were implemented in the GAMMA$^+$ source code, so that at a given temperature and pressure, the thermodynamic properties of lead-bismuth calculated using GAMMA$^+$ is equal to the those calculated using MARS-LBE.

2.2 Steady State Result of Primary side

After the modification of GAMMA$^+$ code, the steady state condition of MicroURANUS was calculated. Figure 2 represents the nodalization of MicroURANUS primary side. The design condition of MicroURANUS is that the core inlet and outlet temperatures are about 250 °C and 350 °C, respectively, with 60 MW_{th} generated in the core. Table 2 shows the result of GAMMA$^+$ for steady state calculation of MicroURANUS primary side.

As shown in Table 2, the calculated core inlet temperature and outlet temperature are 254.28 °C and 351.94°C, respectively. Similarly, the calculated inlet and outlet temperatures of intermediate heat exchanger are 348.79 °C and 254.72 °C, respectively. The calculated temperatures are close to the design temperature. The mass flow rate of the primary side is 4196.0 kg/sec, and the heat generated in the core and heat released through the intermediate heat exchanger are 59.999 MWth. The calculated temperatures and pressures for the power conversion system is given in the following section.

2.3 Steady State Result of Secondary side

For the power conversion system, transcritical-CO_2 Rankine cycle is used. From the previous study, the steady state conditions of the power conversion system were compared with the KAIST-CCD code, which is an in-house MATLAB code for the cycle optimization, for fixed inlet and outlet temperatures of intermediate heat exchanger from the primary side [1].

Table 2. Steady State result of primary side

Component	Temp [°C]		Pres [MPa]	
	Inlet	Outlet	Inlet	Outlet
100	254.28		1.133	
110	254.34	351.93	1.045	0.778
120	254.34	352.24	1.045	0.778
130	351.94		0.768	
140	351.96	352.09	0.745	0.539
150	352.12	352.27	0.489	0.242
160	352.34		0.126	
PIHX1-3	348.79	254.72	0.106	0.382
180	254.69		0.414	
190	254.66	254.53	0.470	0.684
200	254.44		0.832	

The secondary side of the MicroURANUS uses the recompression cycle layout, because it is compact and efficient. The layout and the design parameter check points for the cycle are given in Figure 3, and the steady state temperatures and the pressures of the secondary side are calculated using modified GAMMA$^+$ code are reported in Table 3.

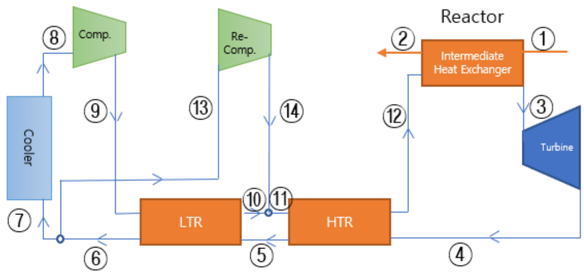


Figure 3. Layout of the TC-CO_2 recompression cycle

Table 3. Result from KAIST CCD and GAMMA$^+$

Code / Point	KAIST CCD		GAMMA$^+$	
	Temp (°C)	Pres (MPa)	Temp (°C)	Pres (MPa)
1	350.0	-	348.79	0.106
2	250.0	-	254.72	0.382
3	327.0	14.7	329.60	14.45
4	243.6	6.5	246.14	6.33
5	114.5	6.33	117.27	6.25
6	35.4	6.2	35.93	6.19
7	35.4	6.2	35.92	6.19
8	15.0	6.15	14.97	6.18
9	25.4	14.85	25.38	15.02
10	107.4	14.85	110.45	14.99
11	109.0	14.85	111.51	14.99
12	207.3	14.72	210.53	14.94
13	35.4	6.2	35.93	6.19
14	110.3	14.9	112.53	14.99

As shown in Table 3, the results from GAMMA$^+$ code are similar to those of KAIST-CCD code. The mass flow rate is 411.6 kg/sec with split ratio of 0.4846.

3. Summary and Future Work

To analyze the MicroURANUS, the GAMMA$^+$ code is used. However, the fluid properties of lead-bismuth in GAMMA$^+$ code differed from those in MARS-LBE. Therefore, the fluid property table for lead-bismuth implemented in MARS-LBE code was applied to the GAMMA$^+$ source code. After the modification of GAMMA$^+$ code, the steady state calculation of MicroURANUS was performed. As shown in the tables earlier in this paper, the results of the primary side were close to the design point. Additionally, the results of the secondary side were similar to KAIST-CCD code. For future work, GAMMA$^+$ code will be used to analyze various transient conditions of MicroURANUS.

Acknowledgement

This research was supported by the National Nuclear R&D program funded by Ministry of Science and ICT and by the National Nuclear R&D program (NRF-2019M2D1A1067204) organized by the National Research Foundation (NRF) of South Korea in support of the Ministry of Science and ICT.

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