Investigation of accurate physical representation of sCO_2 Heat Exchanger for System Transient Analysis

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1. Introduction

A supercritical carbon dioxide (sCO_2) power cycle is considered as the next generation of power cycle due to their compact volume and competitive thermal efficiency in the moderate temperature range (400-600°C) [1, 2]. The reason for these advantages is that the CO_2 in the supercritical phase has properties similar to the density of the liquid phase and the viscosity of the gas phase. The dramatic change in properties of CO_2 near the critical point also contributes to these benefits as shown in Fig.1.

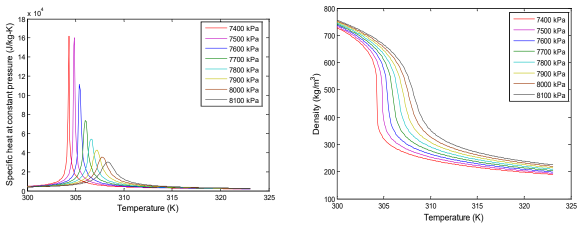

Fig 1. Property variation of sCO_2 (Specific heat, Density)

However, the abrupt changes in properties near the critical point can affect system operational reliability if not properly controlled. This is because the surge margin of the compressor can deviate substantially if the inlet conditions are not maintained. Therefore, to ensure sufficient safety margin while operating the sCO_2 power cycle, it is necessary to accurately analyze the transient performance of the precooler which determines the inlet condition of the compressor. From this point of view, a method for the calculation of the effective thermal inertia for the accurate estimation of the transient performance of heat exchangers has been proposed in the previous study [3]. In the previous study, the steady state was simulated and compared to the data from Autonomous Brayton Cycle (ABC) loop constructed at KAIST. The steady state was simulated using the modified GAMMA+ code, which was tailored to the sCO_2 environment with REFPROP [4, 5, 6]. Therefore, in this study, the transient experiment of the ABC loop precooler is carried out and the transient is simulated using the GAMMA+ code.

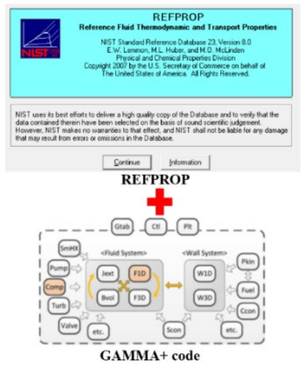

Fig. 2. Modified GAMMA+ code with REFPROP

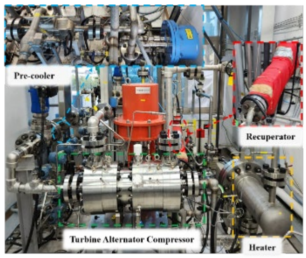

Fig 3. ABC Test Loop at KAIST

2. Experiment value

In this study, a change in water cooling experiment was performed in the ABC loop and the experiment is simulated using a modified GAMMA+ code. An undercooling scenario as shown in Figure 4 was performed. In this scenario, the water mass flow rate is reduced from 20 kg/min to 5 kg/min in 300 seconds, held for 1 minute, and then increased back to 20 kg/min with the same rate.

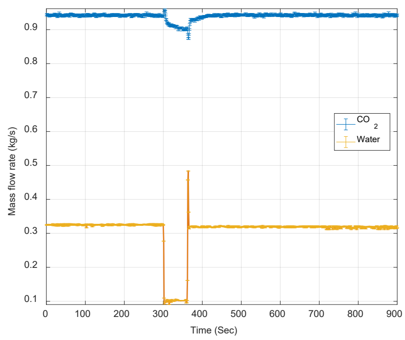

Fig 4. CO_2 and water mass flow rate graph during undercooling scenario

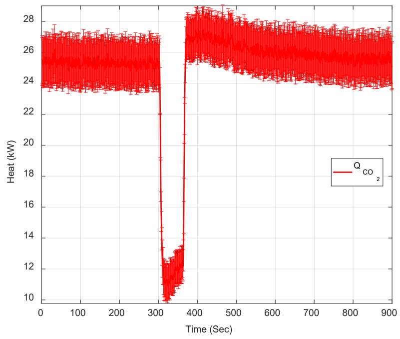

Fig 5. CO_2 heat graph during undercooling scenario

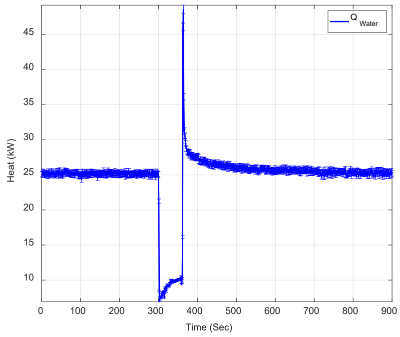

Fig 6. Water heat graph during undercooling scenario

2.1 GAs Multi-component Mixture Analysis (GAMMA)+ code input for transient analysis

The GAMMA+ code input for transient analysis is prepared by referencing the design specification of the PCHE type pre-cooler in the ABC loop as shown in Table 1.

Table 1. PCHE design specification for GAMMA+ model

PCHE width (mm)	99.2
PCHE length (mm)	200
PCHE height (mm)	84
Plate thickness (mm)	1.5
Total channel # on each side	896
Modified hydraulic diameter (mm)	1.17
One channel area (mm^2)	1.07
Wetted perimeter (mm)	3.66
Equivalent thickness between hot and cold side in 1-D model (mm)	1.56

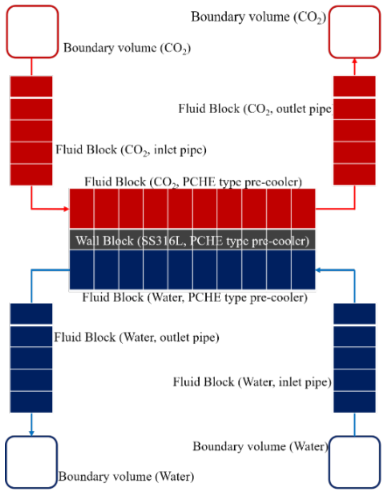

Fig. 7. Pre-cooler nodalization of GAMMA+ code

In addition, Baik's correlations developed from the same heat exchanger testing are used as heat transfer and pressure drop correlations in the GAMMA+ code [7].

Water side (50 < Re < 200):

$$f = 6.9982\ Re^{-0.766}$$
$$Nu = 0.2829\ Re^{0.6686}$$

CO_2 side (15,000 < Re < 85,000):

$$f = 0.0748\ Re^{-0.19}$$
$$Nu = 0.8405\ Re^{0.5704} Pr^{1.08}$$

The comparison of the steady state of the GAMMA+ code and the experimental values shows that the GAMMA+ code matches very well with the experimental values as shown in Table 2.

Table 2. Comparison of experimental results and GAMMA+ simulated results

	Experiment value	GAMMA+ code results	Relative error (%)
Heat load (kW)	25.24	25.20	0.16
ΔP_{CO_2}	31.25	31.63	1.22
ΔP_{Water}	16.58	16.69	0.66

2.2 Comparison of GAMMA+ code results to experimental data

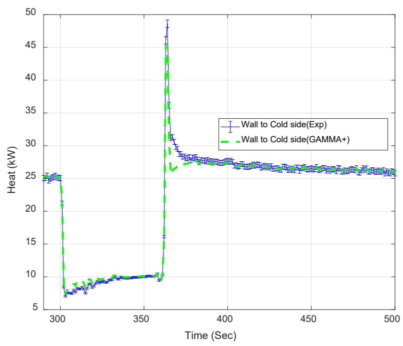

Fig 8. Comparison of GAMMA+ and experimental results graph (CO_2

heat)

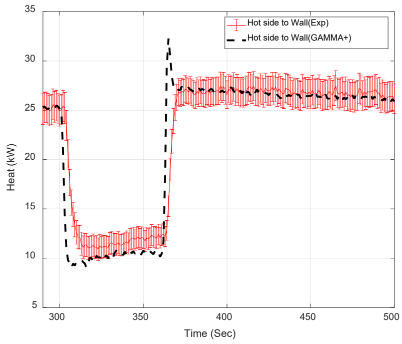

Fig 9. Comparison of GAMMA+ and experimental results graph (Water heat)

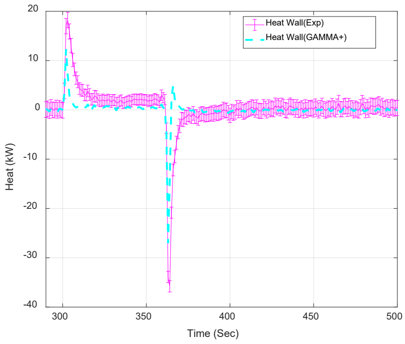

Fig 10. Comparison of GAMMA+ and experimental results graph (CO_2 heat – Water heat)

When the GAMMA+ code results are compared to the experimental data, the code results show a substantial error during the transient experiment. The main cause of this error seems to be the time lag phenomena of the CO_2 heat curve. To reduce this error, it is necessary to analyze different effect during transient.

The reason for the time lag is that there is a higher thermal resistance than the resistance of the heat exchanger core modeled in the GAMMA+ code. This increased thermal resistance is assumed to be due to transient heat conduction to the header, pipe and flange around the heat exchanger core. In addition, there are results in the literature that the heat transfer coefficient changes as the fluid in the developed region transitions to the developing region during transient [7]. Therefore, the GAMMA+ code is modified to obtain results for two cases:

1. Heat exchanger wall inertia is multiplied (from 1 to 4 times) to evaluate the effect of heat conduction to surrounding and increasing the effective thermal inertia
2. Water side convective heat transfer coefficient is multiplied (from 0.5 to 4 times) to evaluate the effect of change in transient convective heat transfer coefficient.

2.3 Heat exchanger wall inertia effect (1 to 4 times)

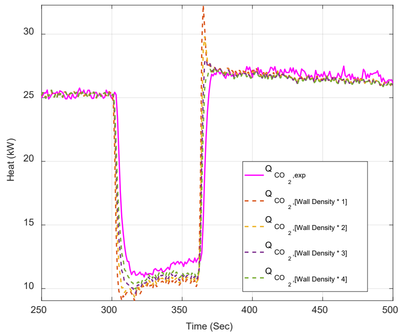

Fig 11. CO_2 heat graph for the wall thermal inertia multiplier

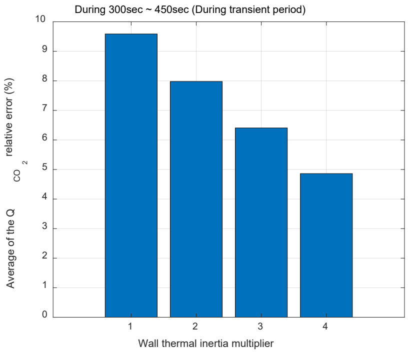

Fig 12. CO_2 heat relative error vs. a multiplier of the wall thermal inertia

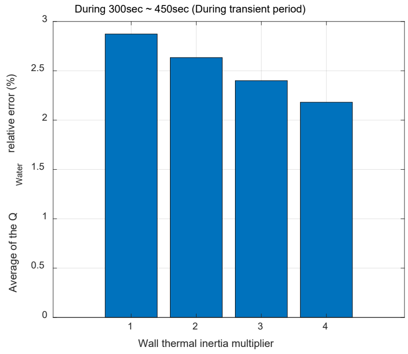

Fig 13. Water heat relative error vs. a multiplier of the wall thermal inertia

It can be seen from Figures 12 and 13 that the relative error of the heat on each side is reduced when the wall thermal inertia is increased. In particular, the reduction in the relative error of the CO_2 heat is greater than that of water side heat. Therefore, the time lag on the hot side appears to be largely due to effective thermal inertia of the heat exchanger which owes to the conduction to surrounding structure.

2.4 Convective heat transfer coefficient effect (0.5 to 4 times)

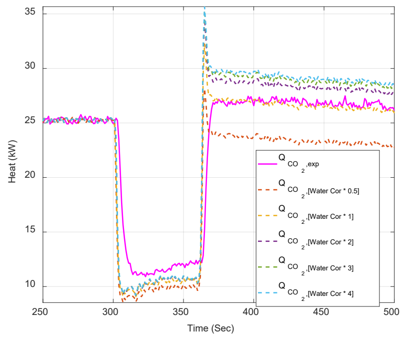

Fig 14 CO_2 heat graph for the water heat transfer coefficient multiplier

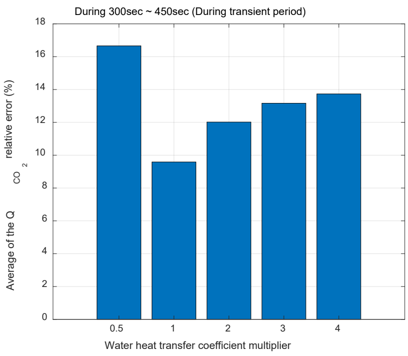

Fig 15. CO_2 heat relative error vs. multiplier of the water side convective HTC

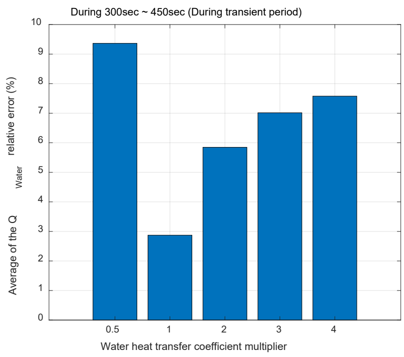

Fig 16. Water heat relative error vs. multiplier of the water side convective HTC

Figures 15 and 16 show that the relative errors of both CO_2 heat and water heat increase as the water side convective heat transfer coefficient multiplier changes. These results show that the change in convective heat transfer coefficient does not affect the time delay on the hot side, and therefore the relevance to the transient modeling is less than the effective thermal inertia.

3. Conclusions

In this study, transient experiments were performed with the PCHE type precooler in the ABC loop at KAIST. The results are compared with those simulated by the GAMMA+ code. The comparison shows that the GAMMA+ code predicts the steady state very well. However, it shows a non-negligible error for the transient case. In particular, the error on the hot CO_2 side is relatively large. The hot CO_2 side heat of the experimental value changes more slowly than that of the GAMMA+ code. These results suggest that to accurately evaluate heat exchanger transient performance with a 1-D model, it is necessary to consider other variables to better represent the heat exchanger physically in the numerical model. These variables include the transient heat conduction which increases effective thermal inertia and the effect of the transient convective heat transfer coefficient.

To evaluate each variable, a sensitivity analysis is performed by multiplying a number to wall density to artificially increase the thermal inertia and to the water side convective heat transfer coefficient in the GAMMA+ code. The sensitivity analysis results showed that transient heat conduction increasing the effective thermal inertia has more significant effect on the hot CO_2 side prediction and reduces errors significantly. Therefore, the results suggest that this effective thermal inertia should be considered more seriously to accurately predict the transient performance of the sCO_2 heat exchanger with 1-D system analysis code.

ACKNOWLEDGEMENTS

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