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Thermal Design and Dymola Modeling of the PCHE for a Thermal Energy Storage System

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1. Introduction

The importance of energy storage devices is increasing to prepare for the volatility of power production due to the expansion of renewable energy. The energy storage system can store electrical energy when generation is abundant and supplies electrical energy to the generation system when it is insufficient.

As power generation sources are diversified, the instability in power supply and demand due to uncertainty of renewable energy intensifies. Most renewable energy sources including solar, geothermal, and wind power are infinite energy sources. Despite that merits, renewable energy sources are heavily influenced by climate, seasons, and even daily weather conditions. Due to these characteristics, it is impossible for renewable energy to function as a continuous energy source that can be controlled and operated on 24 hours a year.

An energy storage system can solve this problem. A thermal energy storage system is one of the energy storage systems that can lower storage costs. Generally, molten salts are employed for thermal storage systems but Alkali metal materials can be also working fluids which is suitable because of its high heat capacity and high thermal conductivity in the operating range.

The Korea Atomic Energy Research Institute is developing an innovative heat source utilization technology cooperatively with other research institutes [1]. This research aims to secure stable power sources by developing large-capacity and high-temperature heat storage technologies and high-efficiency power generation systems in which sodium and supercritical CO_2 are employed as working fluids for storage and utilization sides, respectively. A large capacity energy module based on the safety of heat storage systems that is not fire-risky even at high temperatures above 550℃ will be developed. Additionally, an optimal operation control logic is under development using the Dymola software [2]. Therefore, each component of the system should be modeled using the Modelica language.

In this paper, PCHEs which are the key components of the system, are designed using a 1D PCHE design code, and it is implemented by using the Modelica language.

2. Methods of PCHE Design and Dymola Modeling

2.1 Heat balance

Figure 1 shows the heat balance diagram of the partially heated Brayton cycle [1]. The supercritical CO_2 Brayton cycle has two Na-CO_2 heat exchangers, two CO_2 recuperators, one compressor, and one turbine employed. The high-pressure fluid on the compressor discharge side branches in the partial heating Brayton cycle, some of which is supplied to a Na-CO_2 heat exchanger and some to the regenerator. A relatively low-temperature fluid is supplied to the Na-CO_2 heat exchanger to cope with a large temperature difference in the heat storage system. To increase efficiency through two regenerators, the energy of supercritical CO_2 through the turbine is transferred to supercritical CO_2 from the compressor.

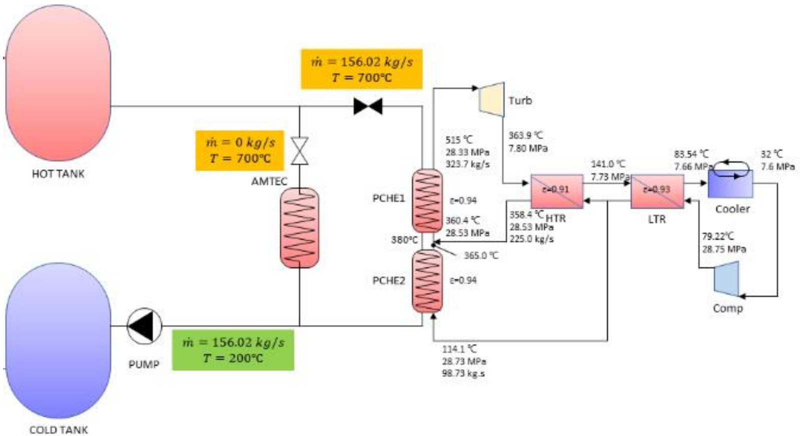

Fig. 1. Heat balance of the system [1]

2.2 PCHEs

A chemical etching technology is applied for printed circuit heat exchanger (PCHE) to create a pattern of fine flow paths with a hydraulic diameter of 1 to 2 mm on a thin plate of stainless steel. After stacking these plates vertically, the plates are attached using diffusion bonding technology to form a heat exchange block, and the head and nozzle are welded to the block.

Given the high and low-temperature side inlet/outlet temperature, pressure, and flow rate, the shape of the flow path, the length of a single flow path, and the dimension of the stacked block are determined using the PCHE design code [3].

The PCHE design code includes four types of heat transfer coefficient correlation and three types of pressure loss correlation. In the zig-zag flow path, the Ishizuka, Hesselgreaves, Dittus-Boelter, and Lockart-Martinelli correlations are available for the heat transfer coefficients. For the pressure loss models, the Ishizuka, Idelchik, and Hesselgreaves models can be used.

For design, fundamental geometry information such as channel bending angle of hot channel (θ_{hot}), half length of bent channel segment (L_{seg}), pitch between cold flow channels (P_{cold}), width of single plate (Y) are given and then other geometrical information including channel bending angle of cold channel (θ_{cold}), number of bend in single hot and cold channels ($N_{bend,hot}, N_{bend,cold}$), length of single plate (X) is calculated during design process. Channel configuration is shown in Figure 2. [3]

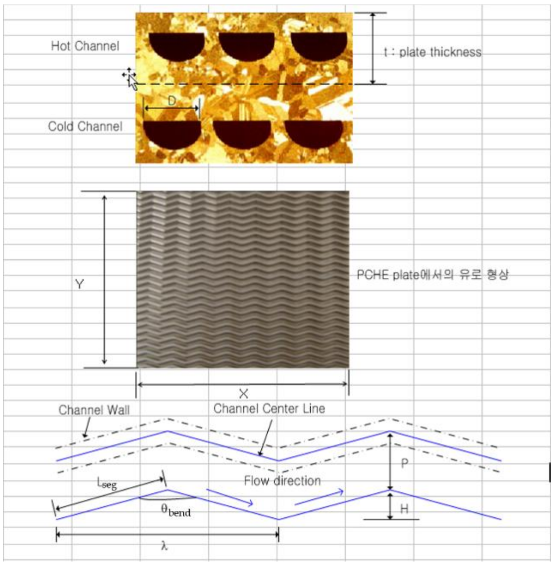

Fig. 2. Channel configuration and geometrical parameters [3]

Table I summarizes the design conditions of PCHE1 and PCHE2 according to the heat balance conditions in Figure 1.

Table I: Design input parameters for PCHEs

Parameter	PCHE1	PCHE2
D_{ch} [mm]	2.0	2.0
θ_{hot} [deg]	180	180
P_{cold} [mm]	4.0	4.0
t [mm]	2.0	2.0
L_{seg} [mm]	5.0	5.0
Y [m]	0.6	0.6
Hot channel path	Straight	Straight
Cold channel path	Zig-Zag	Zig-Zag
Hot fluid	Sodium	Sodium
Cold fluid	CO_2	CO_2
$T_{hot,in}$ [℃]	700.0	380.0
$T_{hot,out}$ [℃]	380.0	200.0
$T_{cold,in}$ [℃]	360.4	114.1
$T_{cold,out}$ [℃]	515.0	360.4
$P_{hot,in}$ [MPa]	0.1174	0.1094
$P_{hot,out}$ [MPa]	0.1094	0.1014
$P_{cold,in}$ [MPa]	28.53	28.73
$P_{cold,out}$ [MPa]	28.33	28.53
$\dot{m}_{hot}$ [kg/s]	156.02	156.02
$\dot{m}_{cold}$ [kg/s]	323.70	98.73

2.3 Dymola

Dymola is a commercial modeling and simulation environment based on the open Modelica language developed by Dassault Systems [2]. Dymola constructs the system as a device model, and each device is simulated by a mathematical equation that simulates the dynamic behavior of each system. The Modelica language itself is a free, non-commercial language, particularly object-oriented, and has a good property to extend and apply to complex systems [4].

Modelica has been applied to various physical systems such as machinery, electricity, fluids, heat, control, and power production. Dassault Systems developed a commercial simulator called Dymola by adding the developed library and improving numerical algorithms and interfaces.

A heat exchanger of the heat storage system can be modeled using the vapor-liquid equilibrium (VLE) model provided by ClaPlus Library v1.3.0 of the Dymola.

The VLE provides information including physical properties for the coolant of CO2 to the extent required by the supercritical CO2 power conversion system. However, the heat exchanger model of the basic pipe cannot model detailed geometric information about the semi-circle, zig-zag, and spacing of the PCHE. The heat exchanger can be simulated with basic information such as the number, diameter, and length of pipes so that approximate performance can be evaluated.

Therefore, the PCHE heat exchanger was modeled by connecting pipe, solid, and pipe. When using VLE working fluid, all connected ports must be VLE ports, which are not compatible with the default Modelica Standard Library (MSL) port. Therefore, with the solid between pipes as a boundary, MSL models was used for the sodium side and VLE models for the supercritical CO_2 side. Both flows are counter-current and thus the calculation directions of the control volume must be opposite to each other in the Modelica code.

3. Results

3.1 Design of PCHEs

Preliminary design of the heat exchanger of the heat storage system was carried out using heat balance-based heat fluid conditions.

The combination of the Hesselgraves heat transfer coefficient correlation and the Idelchik pressure loss correlation was applied to the CO_2 side and the Lockart-Martinelli heat transfer coefficient correlation equation was used for the sodium side. The design was carried out using the 1D option which uses control volumes. The design results are shown in Table 2.

Table II: Designed data of PCHEs

		PCHE1	PCHE2
Heat transfer area [m^2]		208.8	278.6
	Hot	159	250

N_{ch} [-]	Cold	150	149
$N_{ch,total}$ [-]	Hot	103434	114413
	Cold	97523	68266
L_s [mm]	Hot	392.58	473.63
	Cold	419.32	793.71
Unit [m]	Length	0.39	0.47
	Width	0.6	0.6
	Height	2.60	1.83
θ_{cold} [deg]		139.04	73.30
P_{hot} [mm]		3.7810	2.3960
$\dot{m}_{ch}$[g/s]	Hot	1.5084	1.3637
	Cold	3.3192	1.4462
Q_{total} [MW]		62.9285	36.8457

3.2 Dymola model of PCHE

Figure 3 shows the connection diagram of basic models for PCHE modeling.

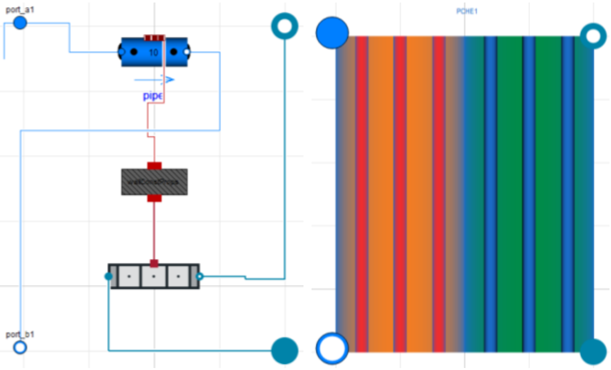

Fig 3. PCHE model(left) and PCHE icon(right)

As for the physical properties of sodium, the model provided by SolarTherm [5], an open Modelica package, was used. For the sodium side, "FluidPort_a" and "FluidPort_b" are extended and connected on the "DynamicPipe." The reason for connecting the inlet/outlet port from the pipe is that these ports are required to represent the heat exchanger as an icon. The icon is used to hide the detailed configuration. For the CO_2 side, "FluidPortIn" and "FluidPortOut" are extended and connected on the "PipeFlowVLE_L4_Simple." The working fluid for the CO_2 side can be selected from the "simCenter" and for the sodium side, a basic environment can be set through "system."

Based on the design results (Table 2), the total number of flow paths (nParallel), the length of flow paths (length), the cross-sectional area of the flow paths (crossArea), the length of wetted diameter (perimeter) are entered for "DynamicPipe" model. The heat transfer coefficient on the sodium side is different for each control volume for the design code, but the average of all control volumes was entered.

Heat conduction in the solid between the flow paths uses the "wallConstProps" model, the number of controlled volumes (n), thickness (s), total heat transfer area (area_h), the coefficient of thermal conductivity (k_wall) were entered. The "wallConstProps" model models heat transfer for pipe walls, so heat conduction and geometries of the PCHE do not match. Therefore, the thermal conductivity coefficient was adjusted to match the result of the design code.

Based on the design results, the overall flow rate of CO_2 (m_flow_nom), pressure loss (Delta_p_nom), length of the flow path, the diameter of water, the total number of the flow path (N_tubes), the number of control bodies (N_cv) are entered for the "PipeFlowVLE_L4_Simple" model.

The models of PCHE1 and PCHE2 were applied to the basic loop to calculate the performance under steady-state conditions and compared with the design results using the 1D design code.

Figure 4 shows a test loop constructed using only PCHE model implemented by the Modelica language and Figure 5 and 6 show the performance test of PCHE models in which steady state simulations were carried out. Table 3 summarizes the results. The CO_2 side produces almost the same results, and the sodium side produces a slight error. This is because the PCHE models were modeled thoroughly to meet the conditions of the CO_2 side in which side the fluid properties are more sensitive to temperature than the sodium side.

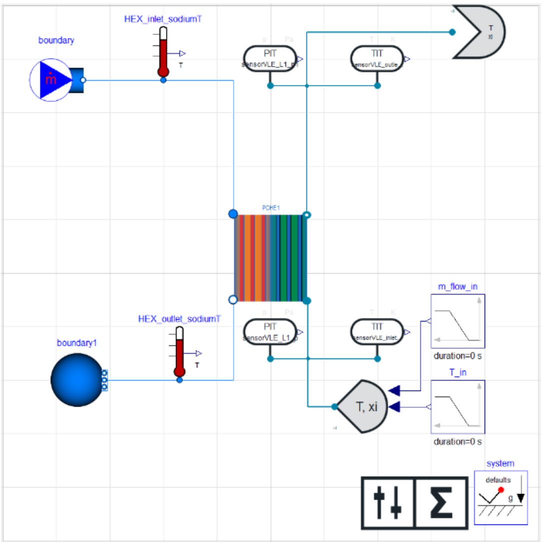

Fig. 4. Test loop for performance analysis of PCHE model

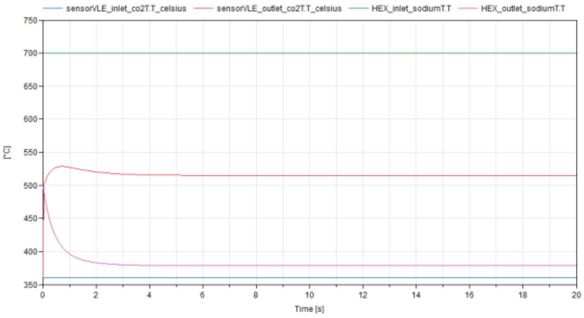

Fig. 5. Performance analysis of PCHE1 model

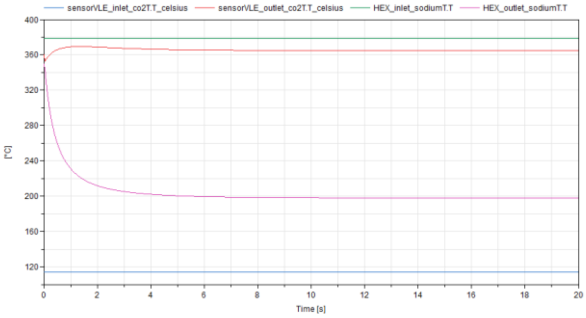

Fig. 6. Performance analysis of PCHE2 model

Table III: Comparison of code and Dymola

	PCHE1		PCHE2	
	Code	Dymola	Code	Dymola
Sodium In [℃]	700	700	380	378.3
Sodium Out [℃]	380	378.3	200	198.1
CO_2 In [℃]	360.4	360.4	114.1	114.1
CO_2 Out [℃]	515	515	365	364.9

4. Conclusion

PCHEs are key components of heat storage and heat utilization system in which sodium is used for storing heat as well as for transporting the stored heat to heat utilization system and a supercritical CO_2 Brayton cycle is employed as a power conversion system of the heat utilization system.

Dymola modeling of the heat exchanger is important for simulator development. The PCHEs were designed and the design specifications of Na-CO_2 PCHE were implemented for the Dymola before developing operational control logic for the entire system. The PCHE heat exchanger was modeled with a pipe-solid-pipe configuration and it was evaluated whether the temperature at the exit was consistent with the design result given the inlet temperature and the flow rate of the design conditions.

As a result of the evaluation, it was confirmed that the result of the Dymola PCHE model and the result using the 1D design code were well matched. The developed Dymola PCHE component model will be utilized for development of operational control logic for the heat storage and heat utilization system.

ACKNOWLEDGEMENT

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