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Preliminary modeling and analysis of thermal energy storage system using Modelica

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1. Introduction

Human technology and civilization are growing rapidly, leading to an increase in daily electricity demand. This has resulted in a greater focus on the economics of energy sources, particularly those that are carbon-free due to the impact of climate change. While using these energy sources is the current answer for humanity, controlling the power output of each energy source is challenging. Limiting all energy sources to meet this demand without economic loss is impossible. To address this, the Integrated Energy System (IES) was developed, which involves storing energy produced for later use. As one kind, Thermal Energy Storage (TES) has been identified as an efficient way to store energy produced as heat rather than converting it to electricity [1].

A significant amount of research is currently focused on improving the efficiency of Thermal Energy Storage (TES). There are various ideas proposed to achieve this goal, but the majority of research is centered on the use of phase change materials and latent heat storage. One such study by Shabgard et al. [2] examined the quantitative results of heat transfer in a system that utilized Latent Heat - Thermal Energy Storage (LH-TES). They used Phase Change Material (PCM) for latent heat storage and heat pipe for improving heat transfer, and both the charging and discharging modes of the system were considered using MATLAB. They also evaluated the heat pipe in LH-TES by the code. As a conclusion, the researchers found that using heat pipes improved thermal efficiency in both modes.

In their research paper, Jose et al [3] have summarized the studies conducted on LH-TES (low-temperature thermal energy storage) across the world. They listed keywords, associated researchers, and countries to map the related research globally. The paper concludes that there are many models and experiments on this concept, but numerical analysis on the same topic is still lacking. Additionally, the paper notes that while low-temperature models are well-validated, high-temperature models should also be studied as they exhibit different behaviors.

Yong et al. [4] initiated a numerical analysis of sodium TES before using the sodium TES verification test facility. They created their own Modelica library to interpret the system with model verification. By benchmarking the basic Modelica library, they were able to obtain more detailed simulation results, including specific cover gas pressure for precise calculation. Additionally, they successfully simulated their test facility using Modelica code.

In photovoltaic research, low-temperature conditions have been extensively validated. Papadimitratos et al [5] have demonstrated the efficiency of a solar connector that combines heat pipes with PCMs with low melting temperatures, such as paraffin, tritriacontane, and erythritol, and have shown the system's effectiveness. Diao et al [6] have also used paraffin as a PCM in a novel type of planar micro-heat pipe thermal storage device.

There is a need for validation of high-temperature Thermal Energy Storage (TES) in full systems, especially by numerical methods. TES has many models that vary depending on the conditions and purpose. In this study, we will use INL's TES model [7] as the reference model for the optimization and validation of a TES model for nuclear engineering. To simulate the entire system including the reactor, we will use Modelica language, an object-oriented language that can find the optimal point of the combined system with TES in terms of reliability and efficiency. In this paper, we will focus on the charging mode, using heat pipes and PCMs for better heat transfer. We have set up several layers of models and physical properties to maximize the thermal performance of the system. The simulation results will be used to analyze each component's thermal behavior and characteristics.

2. Numerical Methodology

This section will introduce the Modelica language and the steps done for developing the TES model.

2.1 Language introduction

Modelica is a high-level, open-source, equation-based language based on C/C++. The language is particularly strong in solving equations and parameters quickly compared to other similar computer codes [8]. It is important to note that Modelica can solve Differential Algebraic Equations (DAE). When solving problems with Modelica, some of the equations in the model become flat hybrid DAEs. Modelica is an object-oriented language, so a model can easily be incorporated into larger models by drag and drop. During simulation, the Modelica solver converts object-oriented code structure into simple several equations, which are flat. The equations then define a DAE, which may have discontinuities and include variables controlled by a discrete-event system. The equation is then referred to as a hybrid (discrete) DAE. The solver makes the DAE into an ODE by matching, index reducing, casualization, and optimization of the DAE. This process means that the solver itself can distinguish and organize variables and equations to solve. In other words, the language does not require the user to have a deep understanding of computational science. This feature greatly reduces calculation and modeling time for the user [9].

One of the key aspects of language is the use of connectors. Connectors act as a gateway for models to share information. Once the connectors are connected, Kirchhoff's law (1) applies to all the connected models. Initially, $\widetilde{\iota_k}$ denotes the current at node k, but in Modelica, $\widetilde{\iota_k}$ can represent any flow variable that moves through the connected models, not just the current. In this particular model, the flow variable is the rate of heat flow, q.

$$\sum_{k}^{n} \widetilde{\iota_k} = 0 \tag{1}$$

All the information of the model is gathered and exchanged through connectors. The sum of the values in linked connectors must be zero; in other words, the sign of the values is determined based on the amount of input and output. This keeps all variables to maintain their total amount and requires modeling of all losses. By using this feature, assessing the thermal performance of the TES model will be done. Connectors are examined and the tendency of variables will be observed.

2.2 problem definition

The main issue in the system is solving the radial and axial conduction with thermal capacitance, as shown in Figure 1. The working temperature is 475°C on the left and upper sides. Table I provides the set conditions for the system. The guide tube and interface region can convey heat both radially and axially. The heat pipe is assumed to be lumped with constant thermal conductivity and only simulated in the axial direction due to the complicity of the model. The guide tube wall and interface region have half the total length of themselves. The heat pipe is a lumped axial conduction model but simulated in full-scale volume. The PCM tank is a simple thermal capacitance model in this simulation, as further study is required to determine the material and effective thermal conductivity values.

2.3 IES package

Modelica has a keyword package that serves as an envelope for smaller models, much like libraries in other programming languages. Within the IES package, there are several smaller packages for simulation, such as Base model and Component. Base model is a package that contains unit models for every system component, including the Conduction model, which will be explained further in Section 2.3. On the other hand, Component is designed to specify objects that will be organized, limited, and simulated with certain initial conditions. Component includes various models such as the guide tube, interface region, heat pipe, and PCM tank model.

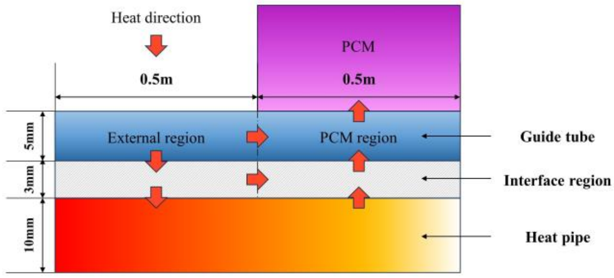

Fig. 1. Schematic representation of the problem situation: guide tube half-wall, interface region half-wall, and full heat pipe model.

Table I: Physical properties of the model.

Category	Guide Tube	Interface region	Heat Pipe	PCM
Material	Copper	SS316	Haynes 230	$MgCl_2$-NaCl
Density [kg/m^3]	8,679.59	8,000	9,050	1,847.5
Specific heat capacity [J/g·K]	0.444	0.5	0.471	0.91
Thermal conductivity [W/m·K]	369	5.437	40,000	-
Mass [kg]	2.864	0.984	0.226	8,000

2.3 Conduction model

The purpose of this study is to examine the behavior of a TES (Thermal Energy Storage) system in both axial and radial directions. However, Modelica, the software used for simulation, does not have a discrete, multidirectional thermodynamic model, so a new model was required. To accurately simulate the system's thermodynamic behavior, it's essential to consider not only the direction of conduction but also thermal capacitance. Therefore, Conduction was developed as a Base model to capture the impact of boundary conditions and heat transfer to and from other components. Conduction includes several thermo-dynamic features, as shown in Figure 2, and is utilized to simulate the overall thermal performance of the larger model. The main governing equations used in the model are as follows:

$$\sum_{i=1}^{n} q_i = \sum_{i=1}^{n} -kA\frac{dT}{dx} \tag{2}$$

$$q = -kA\frac{dT}{L/2} \qquad (3)$$

$$q = mc_p\frac{dT}{dt} \qquad (4)$$

Equation (2) is used for radial conduction models, (3) for axial conduction models, and (4) for capacitance models. Each model is also governed by (1), which conserves heat flux rate.

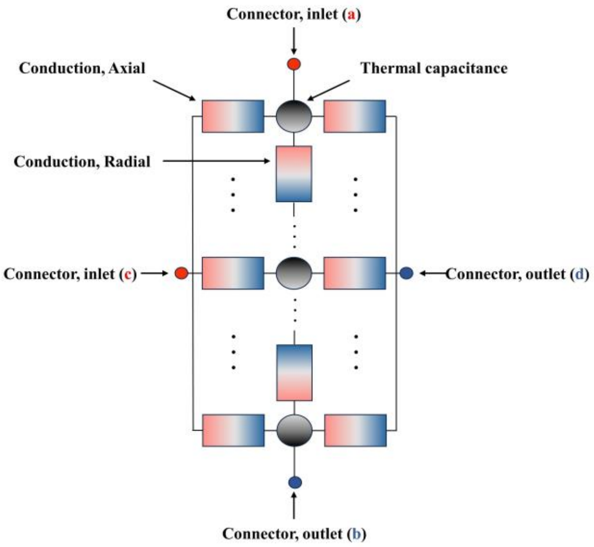

Fig. 2. Simplified scheme for explanation of Conduction model

2.4 Verification of TES Conduction

The development of Conduction began by analyzing and enhancing Thermal Conductor, which is a model included in the Modelica base library. While Thermal Conductor is a basic model that only considers Fourier's law of conduction, Conduction modified several parameters and created an upgraded version of the model that includes axial and radial conduction, thermal capacitance, and more. In contrast, BasicConductor is a validation model constructed from the Modelica base library and has the same configuration as Conduction.

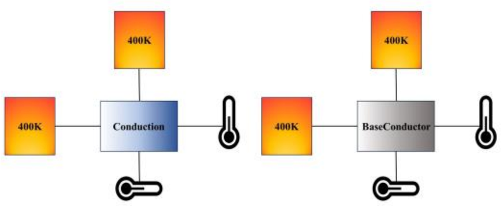

Fig. 3. Verification setup scheme using Conduction (left) and BasicConductor (right).

To summarize, validation works by comparing the simulation results of two models: BasicConductor, created with the Modelica base library, and Conduction, our own enhanced model. Figure 3 shows a model composition that validates Conduction and BasicConductor.

During this validation process, we maintained a constant temperature of 400K on both the top and left sides as boundary conditions while running simulations for Conduction and BasicConductor simultaneously. The analysis results of the validation simulation are shown in Figure 4. The results indicate that Conduction validates proper heat transfer. The temperature evolution of Conduction is stable enough to say that its overall thermodynamic behavior is quite similar to the lumped model, BasicConductor. However, there are some temperature discrepancies in the plots, caused by differences in the assumptions of the two models. BasicConductor only sets thermal capacitance’s initial temperature. In contrast, Conduction can set the initial temperature of connectors, conduction models, and capacitance models.

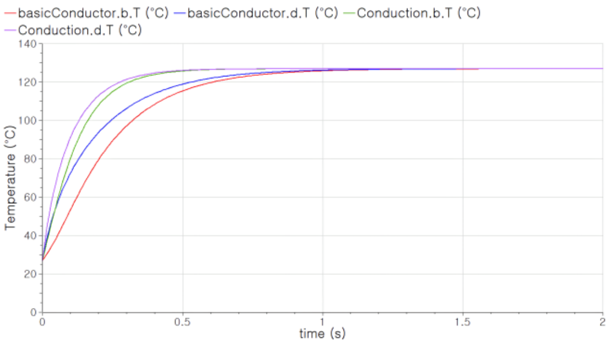

Fig. 4. Verification results for outlet temperature of the right side (connector d) and the bottom side (connector b) for BasicConductor and Conduction.

3. TES Simulation setup and results

3.1 Setup conditions for the TES model

The TES model is comprised of various components, such as boundary conditions, several conduction models, a sensor, and a PCM tank. These can be seen in Figure 5. The TES is subjected to constant operating temperatures of 748.15 K for 800 seconds, with the top and left sides of the TES receiving this constant temperature. Heat is transferred from the guide tube wall to the interface region and heat pipe in the radial direction. From there, it is then transferred back to the PCM tank. In the axial direction, heat is transferred from the left side of each part and, finally, reaches each temperature sensor to ensure proper axial conduction in the model. The boundary condition is 475°C (=748.15K). As a result, several physical properties of the material, such as density, specific heat capacity, and thermal conductivity, assumed to be made of copper, while the interface region between the guide tube and the heat pipe is filled with porous SS316 for better thermal conductivity [5]. In this simulation, the heat pipe is set as a lumped model due to its complex thermodynamic behavior and properties. The physical properties of the components are set as shown in Table I.

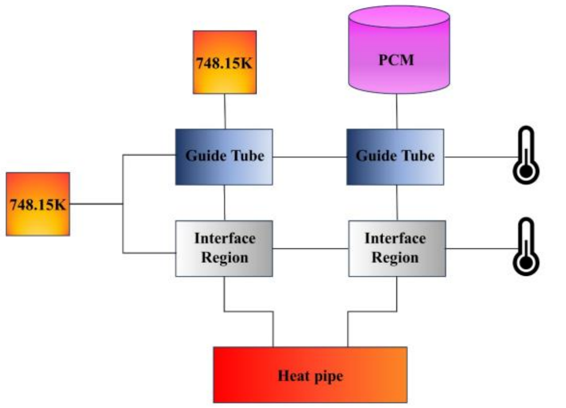

Fig. 5. Overall Modelica scheme for TES model with detailed setup applied, to simulate charging mode.

3.2 Simulation results from TES

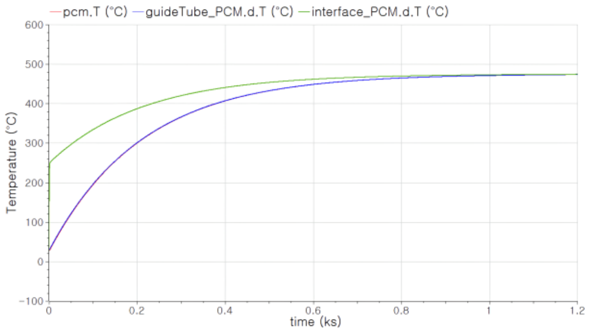

Fig. 6. Axial outlet (d) temperature of the guide tube and interface region with PCM tank temperature.

Based on the simulation results, it was observed that in Figure 6, the outlet temperature of each component displayed an interesting behavior. Despite having different characteristics, the temperature of the axial outlet of the guide tube and the radial inlet of the PCM tank were found to be identical. This is due to the copper guide tube's characteristics where the temperature difference within the system is relatively small. The guide tube's temperature steadily increases at the outlet towards boundary conditions, starting from the initial temperature of 26.85°C. However, the interface region showed a rapid temperature increase in the first 2 seconds, where the temperature jumped from 26.85°C to 247.565°C. After that, the interface region's temperature steadily increases towards boundary conditions. It was observed that the use of a heat pipe significantly influenced the behavior of the interface region as it was more deeply influenced by the heat pipe's high thermal conductivity and rapid temperature increase, particularly during start-up conditions.

It is noteworthy that time plays a significant role in the results obtained. Figure 7 shows that different parts of each component have varying initial temperatures, however, they eventually converge to the same boundary conditions. It takes around 1000 seconds for the simulation to reach this state. Before this time, some parts of the system may experience a sudden increase in temperature within a short period. For instance, the interface region experiences a dramatic temperature increase in the middle of itself within 2.4 seconds and reaches 438.109°C. On the other hand, the axial outlet of the interface region also experiences a rapid temperature increase, but it lasts until it reaches 250.192°C within 2.4 seconds. Due to the different temperature gradients in these regions, the chosen material and working conditions can induce thermal instability.

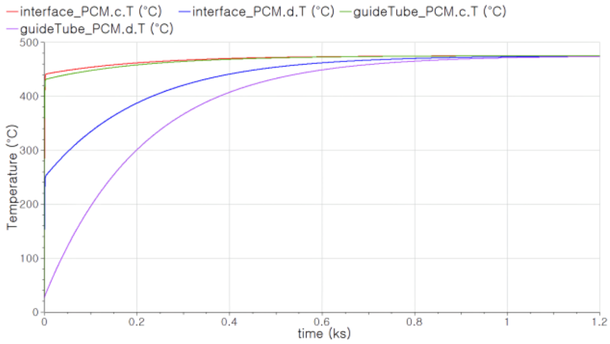

Fig. 7. Inlet (c) and outlet (d) temperature differences from guide tube and interface region models in axial direction.

Upon analyzing Figure 8&9, it is evident that the temperature distribution of the interface region, which is located close to PCM, is based on various geometrical features. In contrast to the external system part, the interface region near PCM undergoes various temperature gradients. This suggests that enhancing the overall heat transfer efficiency of the interface region can lead to an increase in the entire system. However, it is important to find a consensus between improving heat transfer efficiency and maintaining system stability.

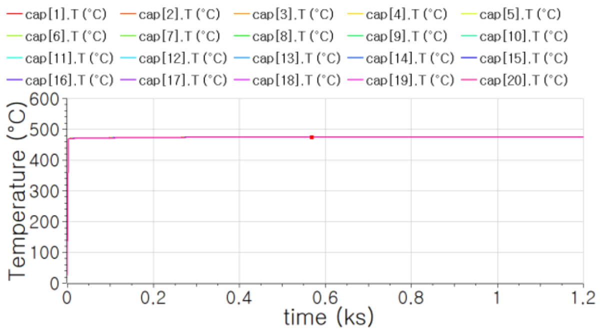

Fig. 8. Temperature of each capacitance model of the interface region close to the external system.

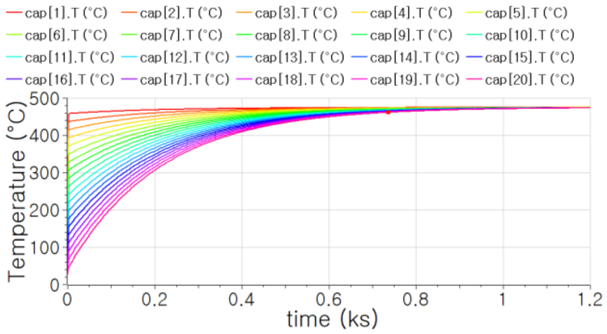

Fig. 9. Temperature of each capacitance model of the interface region close to the interface region close to the PCM.

4. Conclusion

A study was conducted to model the LH-TES (latent heat thermal energy storage) system with heat pipe's charging mode using the Modelica language. An improved model was created and verified by comparing it with the Modelica basic library. The entire LH-TES system was then built, simulated, and analyzed in terms of the thermodynamic behaviors of each component.

The results showed that most of the parts experienced a sharp temperature increase within 2.4 seconds, but the amount of increase and subsequent behaviors varied by the component's characteristics. The interface region showed distinct temperature distribution through simulation depending on the position. These features can induce thermodynamic instabilities, which can lower the thermal efficiency of the total system or invoke safety issues.

The behavior of the heat pipe, which is very complex, can also influence this situation. In this study, the heat pipe was assumed to be a simple solid model with high thermal conductivity, so future work must simulate the heat pipe in detail to accurately predict such a system's behavior. Considering the discharging mode with a more detailed simulation model can also provide insight into understanding the overall system, which will be required in future work.

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