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Simulation of 10kWe Heat Pipe Reactor Battery using AMESim

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1. Introduction

The rapid development of information technology such as IoT, A.I., and big data, etc., has changed people's lifestyle dramatically. It also boosts the advancement in unmanned vehicle technology. Flying a variety kind of drones is easily found anywhere in the world, and the autonomous driving technology has been adopted to most brand-new cars. With the development of unmanned system, providing stable electrical power has become very significant because most unmanned vehicles require high specification of the power system. As the miniaturizing of nuclear reactor technology has been advanced, nuclear power source became one of promising solutions for their power system. Especially, much attention has been drawn to heat pipe cooled nuclear reactors [1]. They can provide not only stable electrical energy without refueling for years, but also the advantages of low decay heat emission, inherent reactivity control, and no additional pressurized system. These strengths are expected to meet the requirements of unmanned vehicles used for various purposes such as to provide electricity in military bases, offshore platform, and the space. In particular, the heat pipe reactor has high potential to be used in underwater drones because the ocean itself plays a pivotal role as great heat sink and radiation shielding materials.

In this study, a 10 kWe miniature heat pipe reactor battery system is conceptually designed using Advanced Modeling Environment for Simulation (AMESim) and Engineering Equation Solver (EES) programs. These programs are used to improve reliability of the model. AMESim is a simulation program which has strength in analyzing models with transient response. It consists of diverse components solving engineering equations. Simply connecting those components and making different combination of them are able to design numerous engineering models and simulate them in short period of time. In this article, the heat pipe reactor battery is divided into three parts: core, heat pipe and thermoelectric generator (TEG).

The heat energy, produced from the core, is cooled down by the heat pipe system and then transferred to the TEG. Fig. 1 shows the conceptual design of the heat pipe reactor battery. The analysis of the temperature changes through the heat pipe reactor battery is performed to give reliability and validity of the simulation model.

2. Heat Pipe Reactor Battery Design

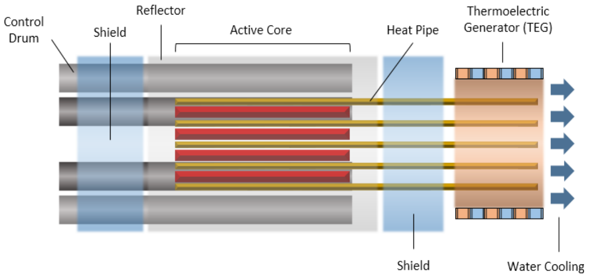

Fig. 1. Conceptual Design of Heat Pipe Reactor Battery

The concept heat pipe reactor battery is designed to produce 74kWt thermal power and 11% of enriched UN fuel is used. The sodium heat pipe system is used because of its operable temperature range. The total of 37 sodium heat pipes and 90 fuel rods are installed in a triangle array into moderators [2]. The heat from the heat pipe is transferred to the TEG, the power conversion system. The cold junction of the TEG is designed to be cooled by flowing coolant. Table I shows the conceptual design of the battery and its detailed specification.

Table 1. Design Parameters of Heat Pipe Reactor Battery

Design Parameter	**Value**
Core Thermal Power (kW_t)	74
Electric Power (kW_e)	11.3
Efficiency (%)	15.3
Core Diameter (m)	0.4
Height of Active Core (m)	0.4
Fuel Diameter (m)	0.0165
Heat Pipe Working Fluid	Na
Heat Pipe Diameter (m)	0.02
Heat Pipe Length (m)	1.8
TEG Material	PbTe + Bi_2Te_3
TE Element Length (m)	0.0123
Number of TE Elements	12,347

2.1 Core

To design the core, equivalent annuls approximation method which has a strength in accurately reflecting physical properties. This method enables AMESim to make a model using several simple components.

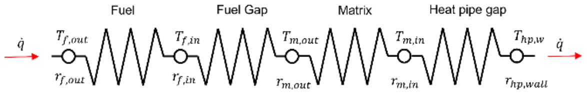

Fig. 2. Thermal Resistance Circuit of the Core

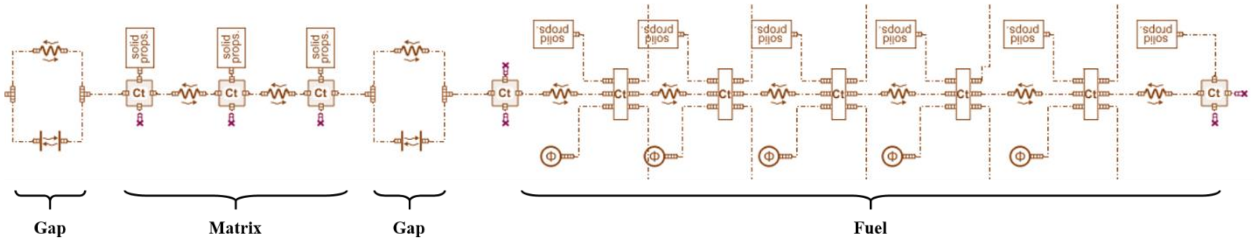

Fig. 3. AMESim Model of the core

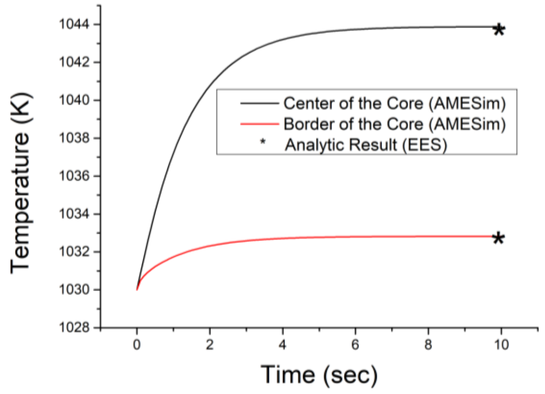

Fig. 4. Temperature Changes in the Core

The model is made based on thermal resistance of each sector of the core. The model represents the core by dividing it into 11 parts both radially and axially to see clear heat distribution of the core in detail. Fig. 3 represents one of the axial parts of the core. To compare the simulation result of AMESim, EES calculates the response at the steady state at each part of the core.

As a result of the simulation, the temperatures, calculated by AMESim, of the center and the border of core shows the same those of EES as shown in Figure 3. In particular, the temperature distribution from the border to the center shows gradual increase as it closes to the center both axially and radially.

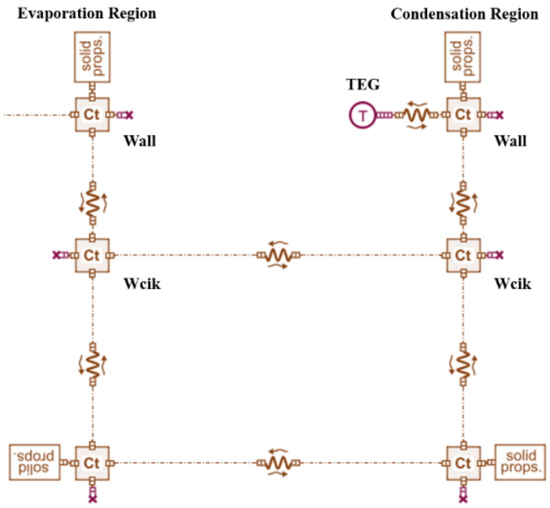

Fig. 5. AMESim Model of the Heat Pipe

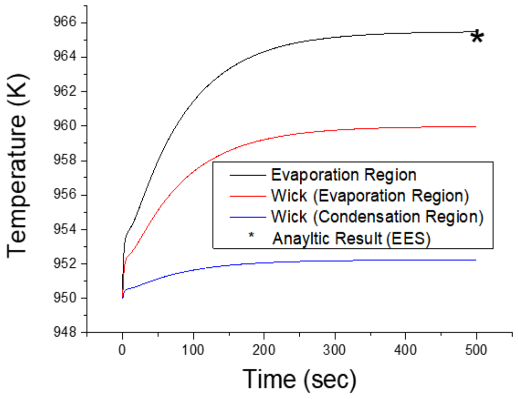

Fig. 6. Temperature Changes in the Heat Pipe

2.2 Heat Pipe

The heat from the core evaporates working fluid filled in the heat pipe and it is condensed at the other end. Regarding this process going under high temperature, sodium heat pipe is used because of its significantly high creep strength. As the heat from core is transferred through the wall, the evaporated working fluid moves to the end and condensed. AMESim models the heat pipe using thermal resistances between its wall and wick. Fig. 5 shows the evaporation is connected to the core, and the condensation region is to a components giving constant low temperature acting as TEG. Also, the operation limits such as capillary, viscous, entrainment, boiling, and sonic are adopted in the model [3]. The simulation shows a warning sign when the temperature of the heat pipe rises above the operation limits.

As a result of the simulation, the temperature of the heat pipe calculated by AMESim shows gradual decrease from the core as shown in Fig 6. Its temperature in response to steady state meets the ones calculated by EES.

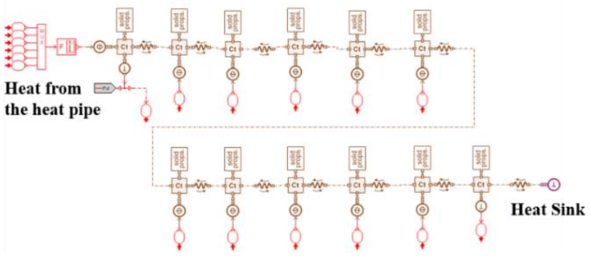

Fig. 7. AMESim Model of TEG

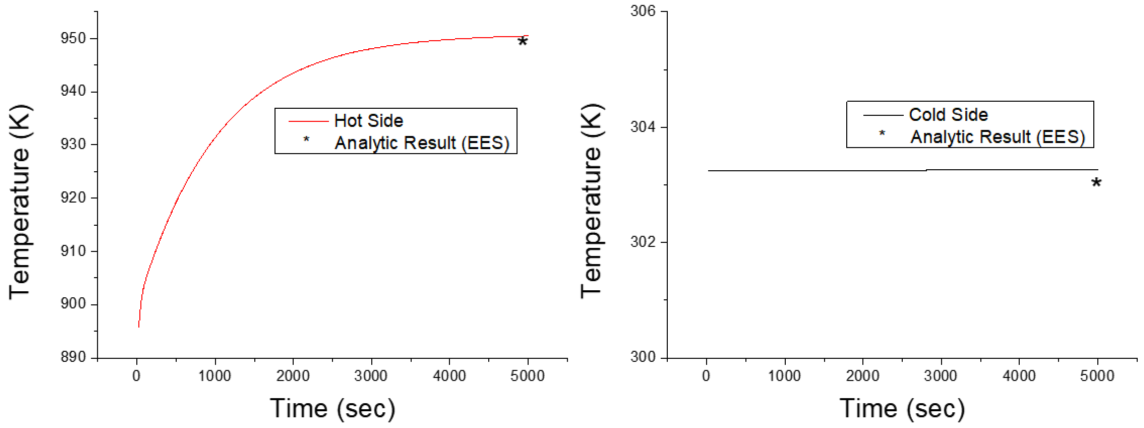

Fig. 8. Temperature Changes in TEG

2.3 Thermoelectric Generator (TEG)

TEG system is used as a power conversion system that transforms the heat energy produced from the core to electric power using Seebeck effect [4]. In the AMESim model, the hot side of TEG is connected to the heat pipe to receive the heat from it. On the other end, the heat sink, the comparably low temperature about 300 (K) is applied to simulate flowing coolant. The two semi-conductors, n-type and p-type, are assumed to be combined as a single conductor to calculate its thermal resistance. The Semi-conductor is divided into 10 equivalent parts to analyze the temperature changes in detail as shown in Fig 7.

The simulation result shows that the temperatures of the hot and cold junction correspond to the ones calculated analytically by EES as shown in Fig 8.

2.4 Integrated simulation

The integrated simulation is performed among the core, heat pipe and TEG. Each part is connected by a component which transfers heat flow and temperature. As a result of the simulation, the temperature changes of the whole system regarding the time is well calculated. In particular, the analytic result calculated by EES proves the correspondence to the steady state simulated by AMESim as shown in Table 2.

Table 2. Integrated Simulation by AMESim and EES

System	AMESim (K)	EES (K)
Core Center	1043	1047
Heat Pipe		
Evaporation Region	965.4	964.5
Condensation Region	952.2	950.0
TEG		
Hot Side	950.4	950.0
Cold Side (Heat Sink)	303.3	303.2

3. Summary

In this paper, the simulation of the heat pipe reactor battery is performed using AMESim in response to transient state. The reliability of the model is gained by comparing the analytic result calculated by EES. In conclusion, the result of the simulation shows the temperature distribution through the whole system is well calculated and its changes regarding the time clearly observed. In possible future work, point kinetics equations will be modeled and combined with the current model to analyze time-dependent behavior of the reactor. It will be expected to simulate various scenarios such as single and double heat pipe failures to give meaningful data for the safer reactor battery.

REFERENCES

[1] S. Park, J. W. Kim, Y. I. Kim, J. H. Kim, H Chae, J. S. Chi & E. S. Kim (2021). 10kWe Heat Pipe Reactor Battery Design for Underwater Vehicles, Transaction of the Korean Nuclear Society Virtual Autumn Meeting, Oct.21-22, 2021.
[2] Ibid.
[3] Patrik Nemec, et al., “Mathematical model for heat transfer limitations of heat pipe”, Mathematical and Computer Modelling 57 (2013): 126-136.
[4] W. Thomson, “Account of researches in thermo-electricity” Proceedings of the Royal Society of London (1854): 49-58.