공학석사 학위논문

Development of Dynamic Simulation Model for 10 kWe Heat Pipe Micro Fission Battery using AMESIM

10 kWe 마이크로 히트파이프 핵분열 배터리의
AMESIM을 사용한 동적시뮬레이션 모델 개발

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지종성의 석사 학위논문을 인준함
2023 년 2 월

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Abstract

Development of Dynamic Simulation Model for 10 kWe Heat Pipe Micro Fission Battery using AMESIM

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Recently, demand for replacing chemical energy is increasing as most contemporary industries require stable energy sources. Chemical energy only provides the energy for several hours to days at the longest without refueling even though it has advantages in high technology maturity and being used for various industries.

The study begins with to overcome the weakness of the chemical energy and suggest replacing it as a micro heat pipe cooled reactor. Micro heat pipe cooled

reactor is also referred to as fission battery, producing less than 20 MWe. Fission batteries have in strengths in long-refueling interval, compactness of unit design with high mobility and passive safety system by self-regulation. Various studies for the fission battery's individual components have been conducted. Muller suggested new concept design of the micro reactor, Fuel-Element Heat-pipe, FEHP (Muller, 2019) with increased 17% of fuel density. Also, Ma studies materials used for the thermoelectric generator. However, there are only few studies have conducted regarding the entire system of the micro reactor. To make a micro fission battery feasible, more studies to analyze entire system is needed. Therefore, the purpose of this study is to develop a numerical model to analyze micro reactor dynamics, and to assess the system's behavioral characteristics on possible scenarios.

The reference reactor of the study is a 10 kWe micro heat pipe cooled reactor for underwater drones. The reactor consists of three main components: the core, heat pipe and thermoelectric generator (TEG) as a power conversion system. The heat is produced from the fission of the core and transferred to heat pipe. It is a very effective system to transfer the heat by its evaporation and condensation at each end of the pipe. The condensate end of the heat pipe is connected to the hot side of the TEG. It converts heat energy to electric energy by using thermoelectric effect. The produced electric energy is firstly saved in the outer battery of the reactor and rest of the energy is remained for the control drum. This reactor system ensures the safety because of its high reactivity feedback effect and outstanding cooling performance.

To develop dynamic simulation model, AMESIM software is used, made by SIEMENS. It is a simulation software specialized in modeling, analyzing, and predicting the performance of mechatronics system. For modeling the core, equivalent annulus approximation method is used. It is widely used for the concept design and analysis of the reactor. The core is divided into the sections of fuel, matrix, a gap between fuel and matrix, and a gap between matrix and heat pipe.

Thermal resistance concept is used to model the heat pipe. Each section of evaporation and condensation is divided into three areas: shell, wick, and chamber. Thermal transfer and resistance are calculated as the heat passes each area. Also, operating limits of heat pipe: capillary, sonic, viscous, boiling, and entrainment, are considered.

Thermoelectric effect, Thomson and Seebeck, is used for modeling TEG. It converts from heat energy to electric energy by using temperature differences of each end of TEG. The governing equation for TEG includes Thomson and Seebeck effects.

To analyze dynamic behavior of the reactor, reactor kinetics with feedback effect should be considered. Point kinetics equations are used, and fuel and moderator temperature coefficient are considered for feedback effect. McCARD is used for neutron physics analysis, and kinetic parameters including effective multiplication factor and temperature coefficient are calculated.

Integrated model including the core, heat pipe, TEG, reactor kinetics with feedback effect verified its accuracy with less than 1% error by comparing the result with the reference data.

With the integrated model, several dynamic simulations based on the scenarios of possible accidents on micro reactor are conducted. First scenario is about abnormal heat sink transient. The cooling performance of heat sink area is changed by -80% to +80% of normal condition, the sinusoid wave and random distribution. Second scenario is about unexpected reactivity transient. The reactivity of the core

is abruptly increased by 0.05$, 0.10$, 0.15$ and 0.20$. Each simulation is conducted to analyze dynamic behavior of the reactor. As a result, for every case of the heat sink scenario, the reactor not only behaved within the operating limit of heat pipe and fuel temperature, but also produces stable power without significant difference from the normal condition. For abruptly increase of reactivity scenario, from 1.5$, the reactor behaved beyond the operating limit of heat pipe and fuel temperature.

In conclusion, the development of dynamic simulation model for 10 kWe micro fission battery showed its stability and robustness under severe conditions. The electric power maintained within 15% for every condition, and the reactor operates without intervention of the control drums under the reactivity insertion of 1.5$. Moreover, the study proved the feasibility of the micro heat pipe fission battery system as a power source for the underwater drones

Keywords

Micro Heat Pipe Cooled Reactor, Dynamic Simulation for Micro Reactor, AMESIM Simulation, Thermoelectric Generator

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Chapter 1.

Introduction

1.1 Background and Motivation

Recently, a variety of studies for smart technology and 4^{th} industry revolution technologies such as artificial intelligence, drones, big-data, unmanned system, Internet-of-Things, and 3D printers have conducted. These technologies require stable electric energy sources in common because most of them promotes unmanned system. Chemical energy has high technology maturity and advantage in being used for various industries. However, it only provides the energy for several hours to days at the longest without refueling as shown in Figure 1.1.

This study begins with to overcome the weakness of chemical energy and suggest replacing it as a micro reactor. A micro reactor is defined as a reactor producing less than 20 Mwe and referred to as a nuclear battery or a fission battery. Fission batteries have strengths in long-refueling interval, compactness of unit design with high mobility and passive safety system by self-regulation. Due to these advantages, demand on the micro fission battery is rapidly increasing and numerous research have been conducted. Micro heat pipe fission battery is one of kinds of micro reactors that have received much attention world-widely. Kilopower project, conducted by NASA, successfully developed a micro heat pipe reactor using sterling engine in 2018, and Westinghouse Electric Company has been developing eVince micro reactor, specialized in fully factory built, fueled, and assembled, as shown in Figure 1.2 and 1.3.

1.2 Previous Studies

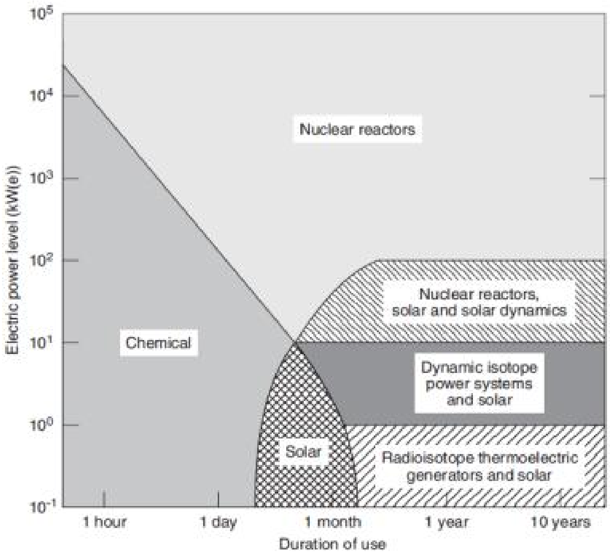
Moreover, diverse studies on the components of micro heat pipe cooled reactor have been conducted. For heat pipe, Muller suggested new concept design of the micro reactor, Fuel-Element Heat-pipe, FEHP (Muller, 2019) as shown in Figure 1.4. The main difference from traditional heat pipe design is designing a reactor system with a coolable geometry, and it increased 17% of fuel density. Ma et al. showed the stability of heat pipe system of the micro reactor. Ma simulated heat pipe failures of MegaPower Reactor model. It proved the heat pipe failures do not affect the power distribution and the reactivity of the core as shown in Figure 1.5 (Ma, 2020). For thermoelectric generator (TEG), one of power conversion systems, Liu studied materials used for the thermoelectric generator. As shown in Figure 1.6, the material's ZT values are increasing as time goes. Also, Wang suggested a concept design of thermoelectric generator with a heat pipe system as shown in Figure 1.7. For the integrated system of the micro reactor, Hu analyzed heat pipe cooled micro reactor by using the System Analysis Module (SAM), developed at Argonne National Laboratory. As shown in Figure 1. 8, SAM analyzed the steady-state solid temperature profile of the reactor. Tang studied the performance of thermoelectric generator for heat pipe cooled micro reactor experimentally as shown in Figure 1.9. Its data from the experiment verified numerical model with the maximum 5% simulation error.

However, besides the studies mentioned above for the integrated system, only few studies for micro reactor's entire system have been conducted. Therefore, to make micro reactors to be more feasible, more diverse studies for the integrated system should be conducted.

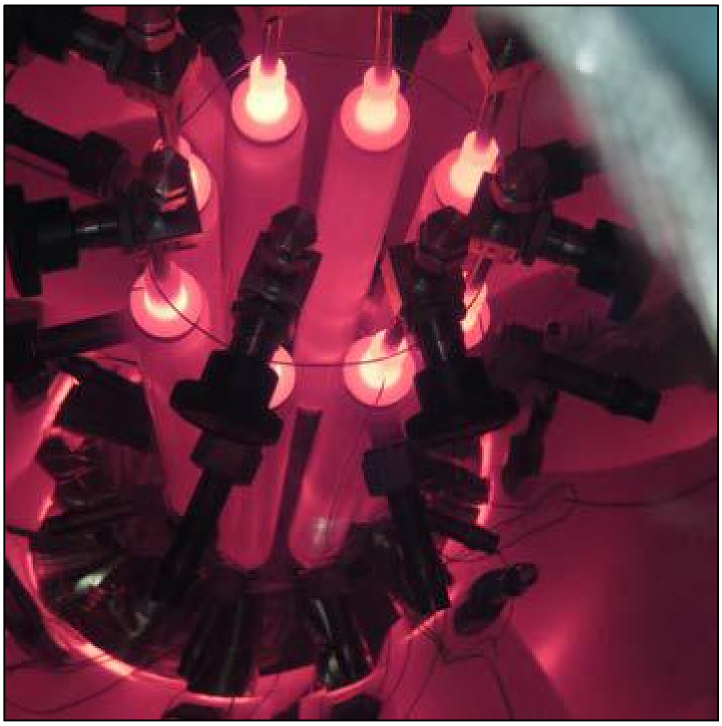
1.3 Objectives

The purpose of this study is to develop a numerical model to analyze micro reactor dynamics, and to assess the system's behavioral characteristics on possible scenarios. The specific objectives of the research are as followed:

1) The conceptual design of 10 kWe micro heat pipe fission battery for underwater drones is described. It consists of the core, heat pipe and thermoelectric generator as a power conversion system.
2) The theory on dynamic simulation for the reactor core, heat pipe, thermoelectric generator, and reactor kinetics is explained.
3) The process of modeling each part of the micro heat pipe fission battery for dynamic simulation using AMESIM software is presented
4) Dynamic simulations for the micro heat pipe fission battery is analyzed



. Figure 1.1 Properties of Energy Sources



. Figure 1.2 NASA's Kilopower reactor

Figure 1.3 Westing Electric Company’s Micro Reactor

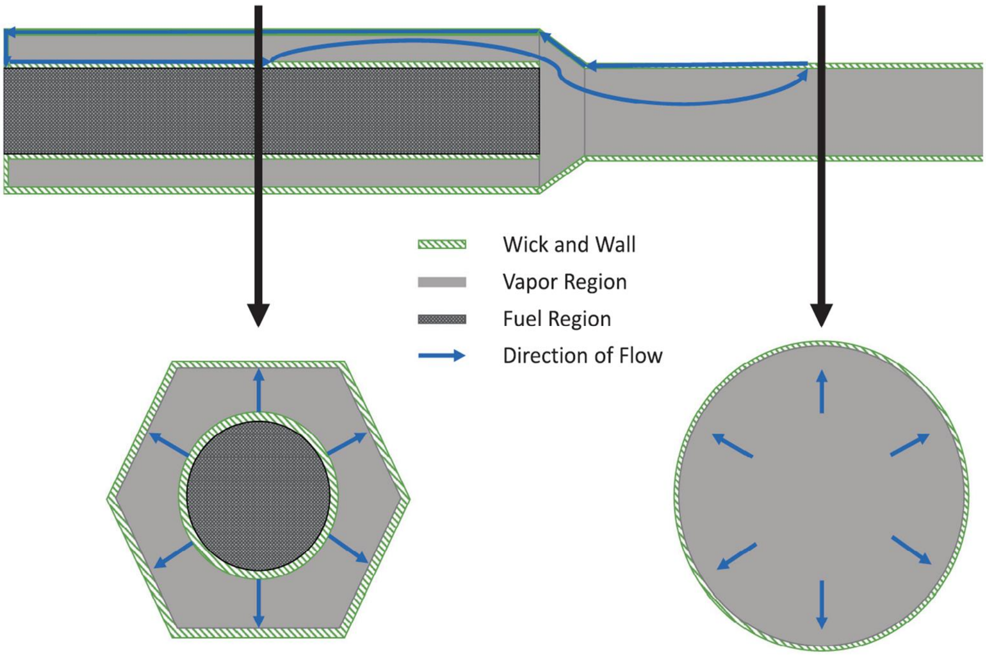


Figure 1.4 FEHP Concept Design

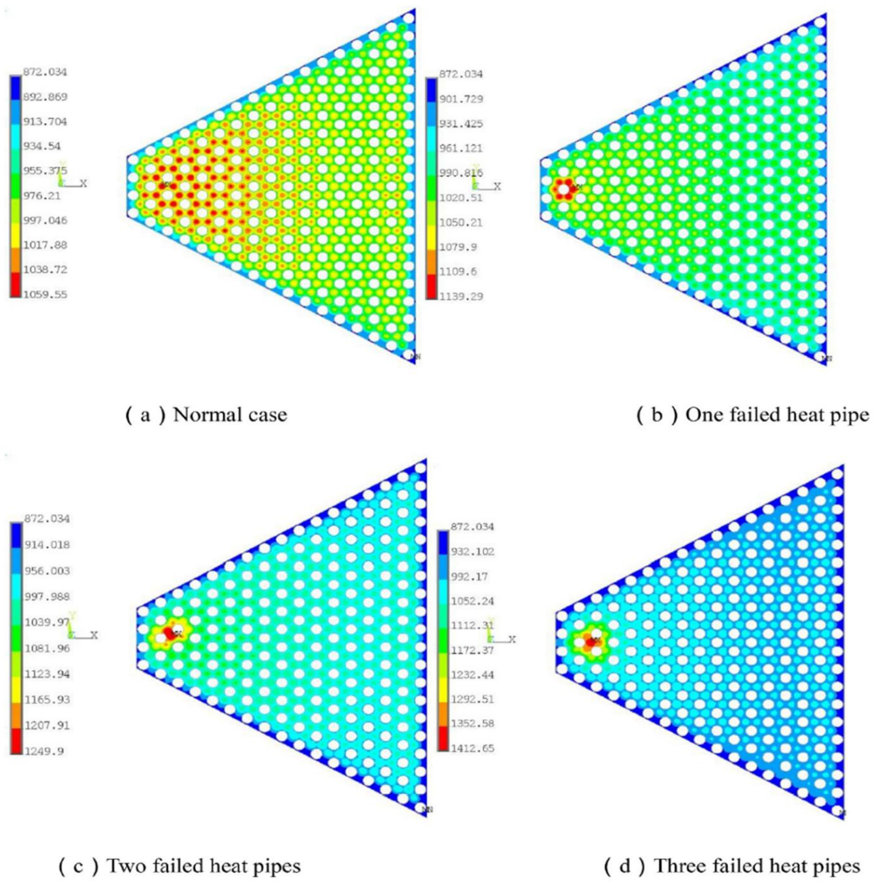


Figure 1.5 Temperature Distribution When Heat Pipe Failures Occurs

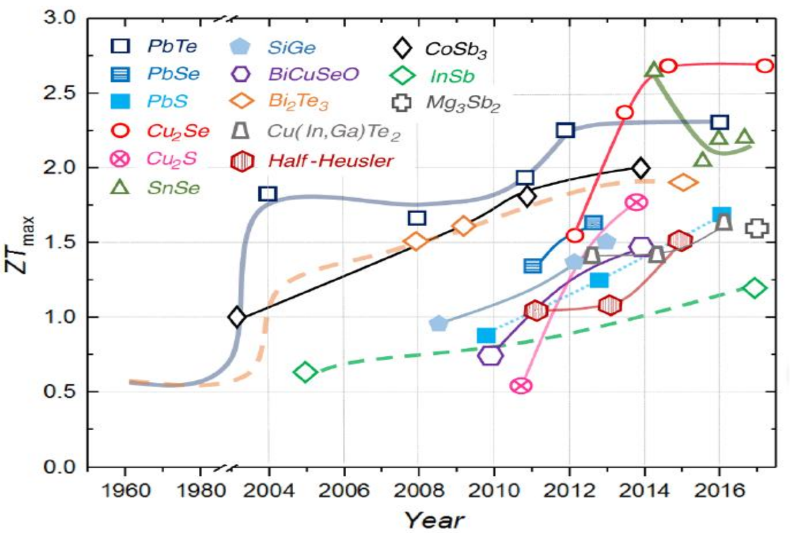


Figure 1.6 ZT Values of TEG Materials

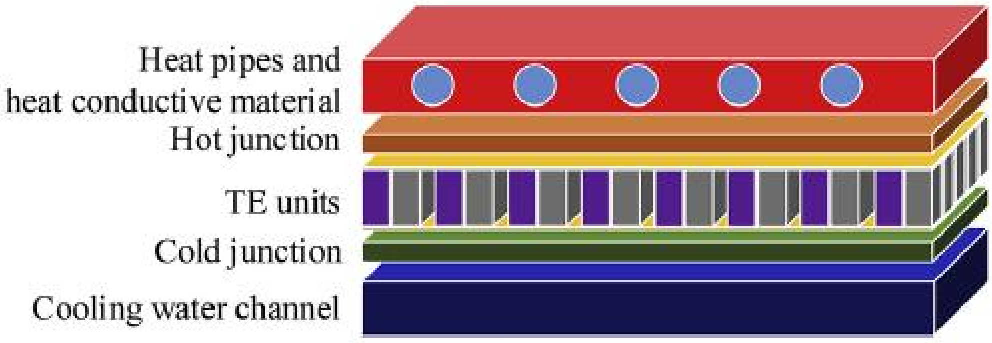
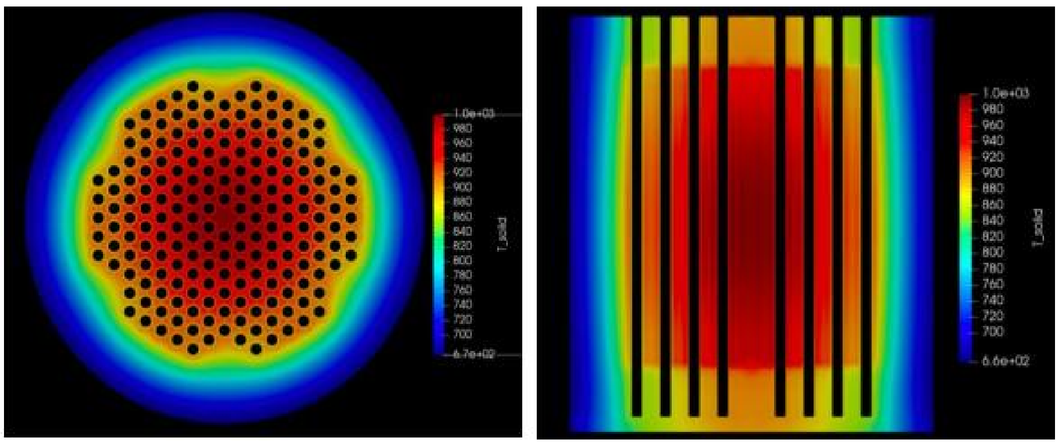


Figure 1.7 Concept Design of TEG with Heat Pipe System



. Figure 1.8 Steady state solid temperature profile of a heat-pipe-cooled micro eactor. Horizontal cut view (left) and vertical cut view (right)

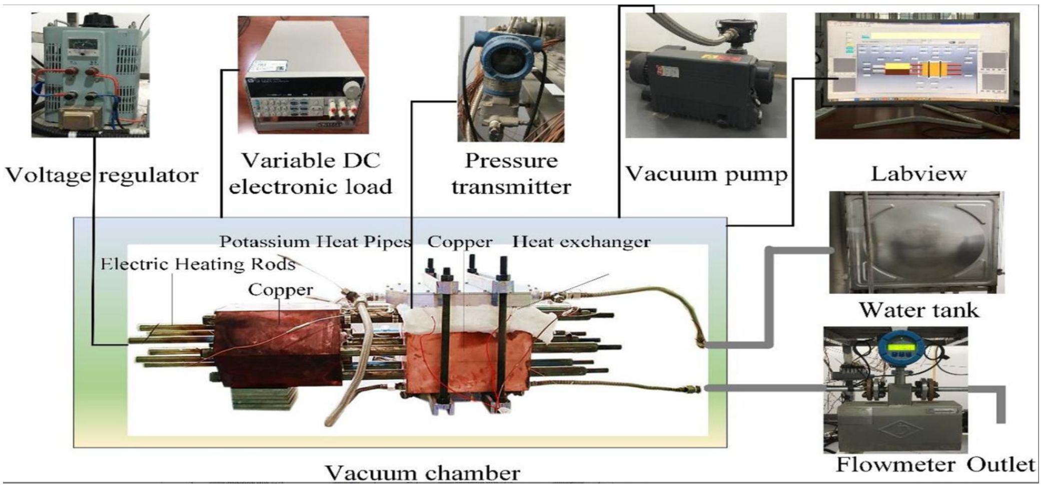


Figure 1.9 Experimental TEG Model

Chapter 2.

Micro Heat Pipe Fission Battery System

2.1 Basic System Concept

The conceptual heat pipe reactor battery is divided into three parts: core, heat pipe, and thermoelectric generator (TEG) for the power conversion system as shown in figure 2.1. It is designed to produce 74 kWt 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. In the core of the model, the point kinetic equations and the reactivity feedback effect are adopted to analyze the time-dependent behavior of the reactor and its effect on the total power of the battery.

2.1.1 Reactor Core

The reactor produces heat energy by the nuclear fission. It consists of the core, reactivity control system, and a vessel surrounding the reactor. The core is composed of fuel, reflectors, and shielding materials. Materials causing nuclear fission such as uranium is used for the fuel and formed as UO_2 or UN. Nuclear fission reaction with neutrons produces about 200 MeV of heat energy. The neutrons are formed through the fission cause chain reaction with the fissionable materials. They tend to react easily with the neutrons of lower energy, and the moderator plays a role to slow down the fast neutrons formed from the fission reaction. Water or graphite are widely used for moderator. Also, reflectors surround the reactor core and make the neutrons return back to the core.

This system enables nuclear fission reaction to be continuously maintained. The power of the core is controlled by the reactivity, and the reactivity by the total number of neutrons. The control materials are used for balancing the neutron numbers. Therefore, when the control materials are inserted in the core or taken out from it, the reactivity speed is decreased or increased.

The control materials can be classified as control rods or control drums by its mechanism. The control drum works as insertion or extraction and control drum as spinning toward the core. The heat generated from the core is transferred to heat pipe by the internal matrix. For the micro reactor, the moderator plays a role as an internal matrix.

2.1.2 Heat Pipe

To produce electricity using the heat energy, the power conversion system should transfer heat energy. Heat pipe plays a role as a coolant for the micro reactor. Heat pipe is a metal pipe filled with working fluid. It is a very effective system to transfer the heat using the phenomena of evaporation and condensation of the working fluid. Heat pipe is a unique system in that it is very conductive and no exterior energy is needed such as pumps. There have been diverse studies for heat pipe to be applied for the reactor, and sodium and lithium heat pipe are developed for the high temperature environment. In this study, sodium heat pipe is used because it is operable between 350 ~ 800℃. The heat pipe's evaporate sections is connected to the core and condensate section to the cold side of TEG.

2.1.3 Power Conversion System

Power conversion system converts heat energy to electric energy. There are direct and indirect method for the power conversion system. The indirect method is selected for this study because it does not require mechanical operating parts and controlling system. The condensate section of the heat pipe passes heat to the hot side of the TEG by a heat distributor. It can be designed as various methods. Its design is significant to reduce heat transfer paths and maximize surface of TEG for the compactness of the system in size. The cold side of the TEG is connected to the heat sink areas by other heat distributor. The heat sink is a place to release the heat, and sea water is used in this study. Most electricity produced from the TEG is stored in an exterior battery, the rest is used for the control drum of the reactor.

2.2 Safety Concept

The concept of reactor's safety system is damaged when there is a loss of the reactivity control and failure of elimination of the decay heat. Micro heat pipe fission battery's safety system is shown as figure 2.2, ensuring its safety system by following reasons:

- No possibility for a loss of coolant accident (no use of coolant and pumps)
- Low possibility for the fuel melting accident (low power of the core and

high thermal capacity)

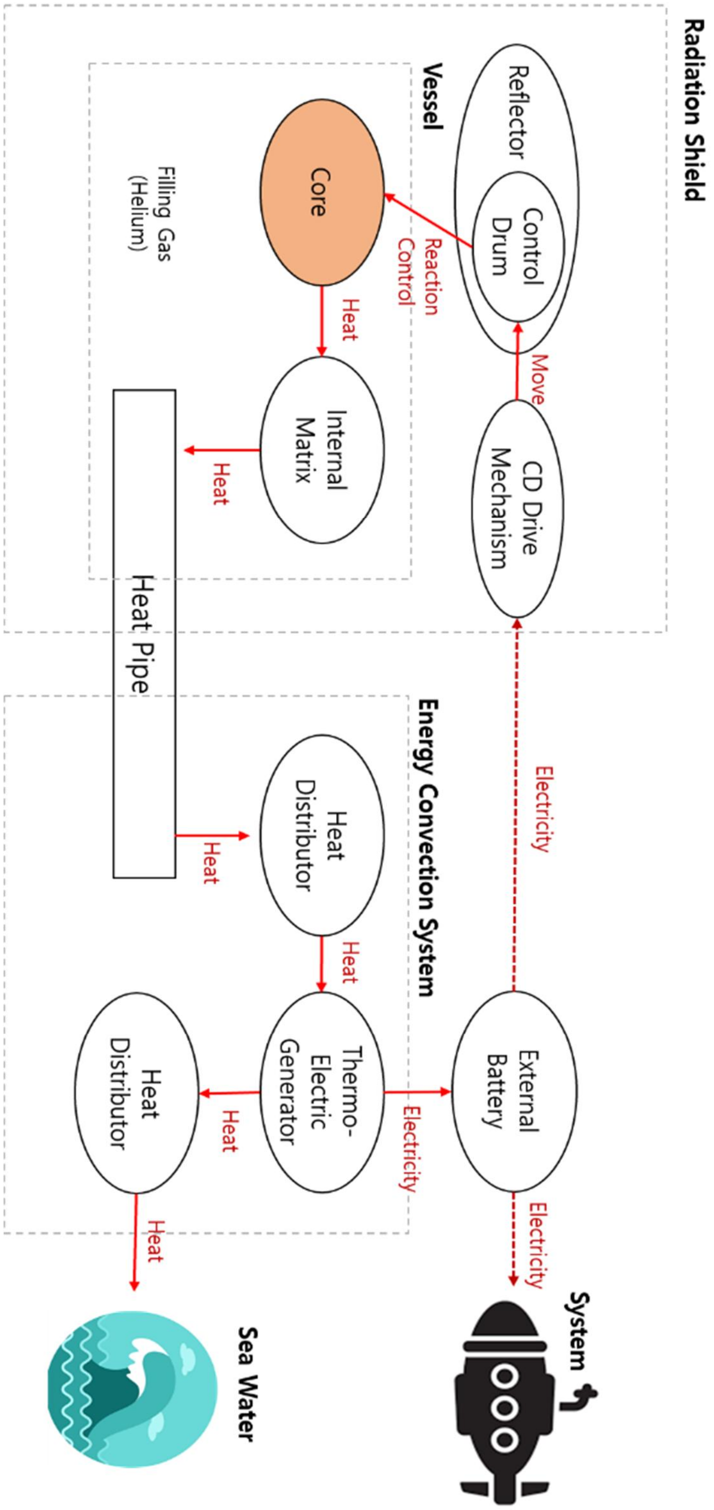
- Low possibility for the leakage of radioactive materials due to low operating pressure
- Ensured inherent safety due to the property of the solid core

2.3 Radiation Shield

The micro fission battery of the study is developed for underwater drones. Therefore, there is no need to consider radioactive effect for the people. To operate efficiently and prevent radiation hardening for the underwater drones, the thickness of the shielding materials and its installation should be considered. The main purpose of shielding for radiation is gamma ray and neutrons. As the atom number of the shielding material is bigger and its mass is smaller, the efficient for the shielding is better. The layered with tungsten and B_4C are used for the shielding materials as shown in figure 2.3 and 2.4.

2.4 Design of 10 kWe Micro Heat Pipe Fission Battery System

The basic concept of the micro heat pipe fission battery is shown as figure 2.5. The system is composed of the core, heat pipe and the TEG. The cylinder-shaped core is surrounded by the reflectors. The shielding materials are installed at the top and bottom of the core and protect the TEG and the control drum. The heat from the heat pipe is transferred to the TEG by the copper block. The TEG is a stable system to convert heat energy to electricity because there is no mechanical driving system. To cool down the reactor, sea water is mainly used at the cold side of the TEG. To increase the cooling performance of heat sink, cooling fins are adopted. The entire system is protected by a metal case, and its exterior surface is cooled down to maintain the reactor operable in emergency situation.



. Figure 2.1 Concept of the Micro Fission Battery System

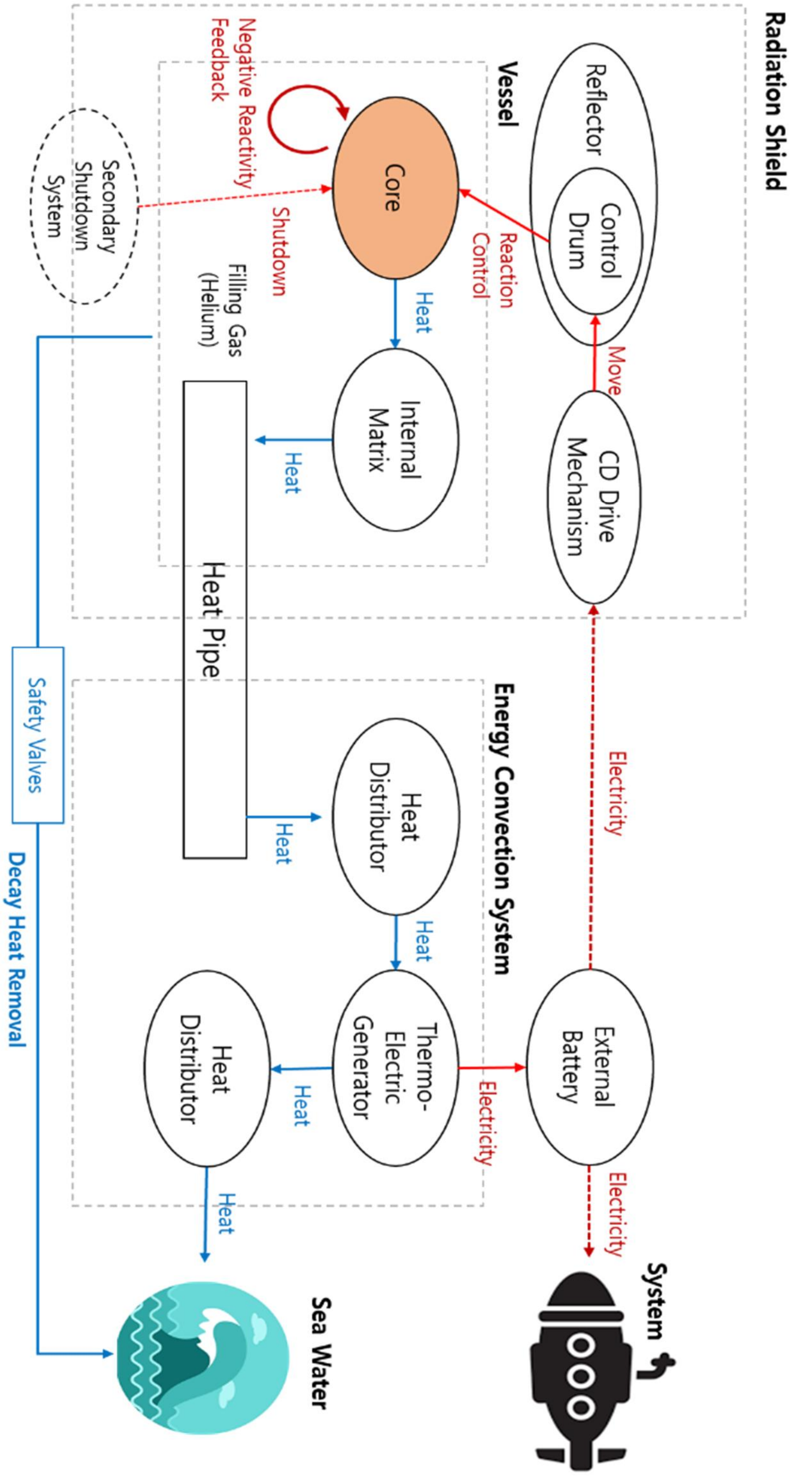


Figure 2.2 Safety Concept of the Micro Fission Battery System

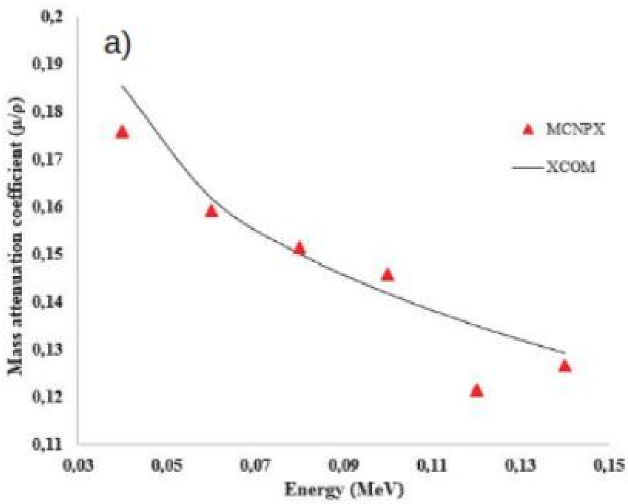


Figure 2.3 Gamma-Ray Attenuation Coefficient of B_4C

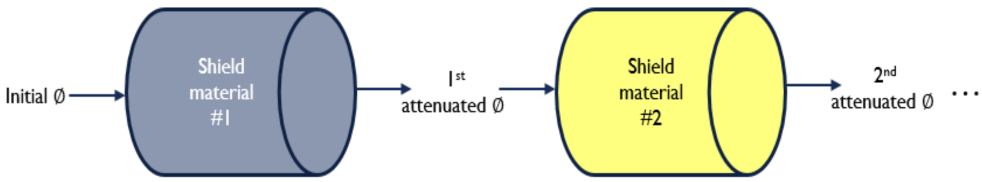


Figure 2.4 The Process of Attenuation by Multiple Layers

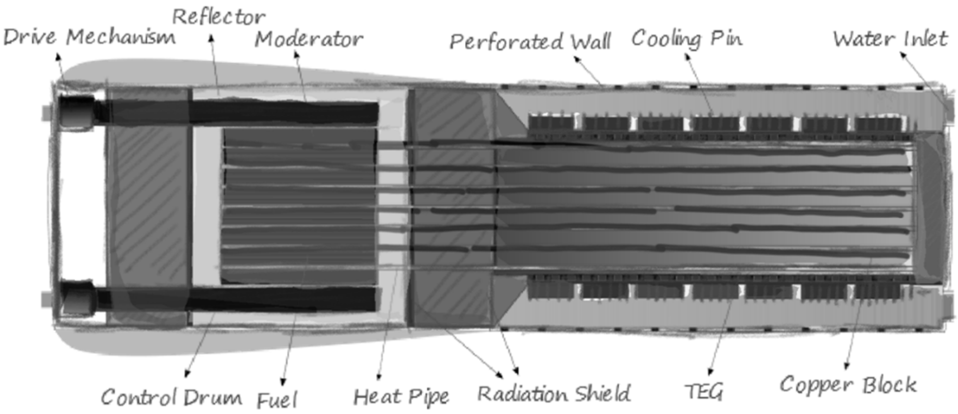


Figure 2.5 System Concept for Micro Fission Battery for Underwater Drones

Chapter 3.

Theory on Dynamic Simulation of Micro Heat Pipe Fission Battery System

3.1 Dynamic Model for Reactor Core Thermal Response

3.1.1 Equivalent Annulus Approximation

To analyze thermal response of the core, the equivalent annulus approximation method is used. This method is widely used for designing reactors because it has strength in reflecting physical properties of the complicated shapes of materials. For precise approximation, several thermal design options are considered as shown in Figure 3.2. The basic method of the equivalent annulus approximation is applied to the first option. The second and the third ones reflect the real fuel rod design. Multi-physics analysis codes are used to select the best option for the thermal analysis, and the second one is chosen for the model.

3.1.2 Equations for Reactor Core Thermal Analysis Model

The general heat transfer equation is:

$$\rho C_p \frac{dT}{dt} = \frac{1}{r}\frac{d}{dr}\left(rk\frac{dT}{dr}\right)$$

However, AMESIM provides different types of transient equations using the concept of thermal resistance. Figure 3.3 shows the general concept of thermal resistance circuit of the core. Each node of the core is connected by the thermal resistance, and governing equation is:

$$M_i C_{pi} \frac{dT_i}{dt} = \sum_j \frac{T_j - T_i}{R_{ij}} + Q_i$$

Q_i represents the heat flow rate from the fission. Each resistance of the nodes are decided by its properties. Tables 3.1 shows the resistance and heat flow rate used for the core.

3.2 Heat Pipe Model

3.2.1 Equations for Heat Pipe Model

The governing equation for the heat pipe is developed using the concept of thermal resistance. The heat pipe is divided by two parts: evaporate and condensate section. Each section includes 3 nodes meaning the wall, wick, and chamber as shown in Figure 3.4. Table 3.2 represents the resistance used for each node.

3.2.2 Heat Pipe Operational Limit

There are 5 different operating limits for the heat pipe: capillary, sonic, entrainment, boiling, and viscous limit as shown in Figure 3.5. The capillary limit occurs when the capillary effect of the wick is too weak for the working fluid to move from the condensate section to the evaporate section. The sonic limit is defined when the speed of the vapor becomes fast as the sound. The vapor at the high-speed keeps being cumulated, and results finally in slowing down the speed of the vapor. The entrainment limit happens when the path of the vapor is so narrow that the liquid is absorbed in the vapor. It results the decrease of the amount of working fluid returning from the evaporate section. The Boiling limit occurs when the evaporate section becomes too hot to cause the evaporation of the wick. The viscous limit is caused when the speed of the vapor is decreased due to the indifferent pressures between the evaporate and condensate section. The related equations of the operating heat pipe are shown in Table 3.3.

3.3 Thermoelectric Generator (TEG) Model

3.3.1 Thermoelectric Phenomena

Thermoelectric effect occurs between two different semi-conductors as shown in the Figure 3.6. They are called as ‘n-type’ and ‘p-type’ semi-conductors. The current occurs when electron carriers move from the high to the low temperature. So, ‘n-type’ semi-conductor work as an electron and ‘p-type’ as a carrier. If this phenomenon occurs in an opposite direction, there is a temperature gradient produced by a voltage gradient. These phenomena are called Seebeck, Peltier, and Thomson effects.

3.3.2 Equations for TEG Model

The equations of the thermoelectric effect and the governing equation are:

$$E_s = \alpha \Delta T \quad \text{(Seebeck Effect)}$$

$$\dot{q_p} = \pi j \quad \text{(Peltier Effect)}$$

$$\dot{q_{th}} = -\tau j \nabla T \quad \text{(Thomson Effect)}$$

$$M_i C_{pi} \frac{dT_i}{dt} = \sum_j \frac{T_j - T_i}{R_{ij}} + {j_i}^2 \rho_i V_i$$

$$(R_{ij} = \frac{|x_i - x_j|}{k_{TEG} A_{TEG}})$$

The governing equation is developed by heat transfer equation with considering the thermoelectric effects as shown in Figure 3.7.:

3.4 Reactor Kinetics Model

3.4.1 Point Kinetics

The point kinetics equations are used to approximate reactor's transient response to make it maintain stable condition. The equation is composed of several differential equations representing the neutrons' time dependent behaviors prior to their space change. The point kinetics equations are:

$$\frac{dN(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda(t)} N(t) + \sum_i \lambda_i C_i(t)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda(t)} N(t) - \lambda_i C_i(t), \ (i = 1,\ 2,\ 3,\ \cdots, 6)$$

3.4.2 Reactor with Reactivity Feedback

The reactivity feedback effect occurs when the change of the reactivity affects the power of the reactor, and it simultaneously influences the composed materials' density, and temperature, etc. The process of the reactivity feedback effect is shown in Figure 3.8. In this study, the fuel temperature coefficient (FTC) and the moderator temperature coefficient (MTC) is considered, the main factors of the feedback effect.

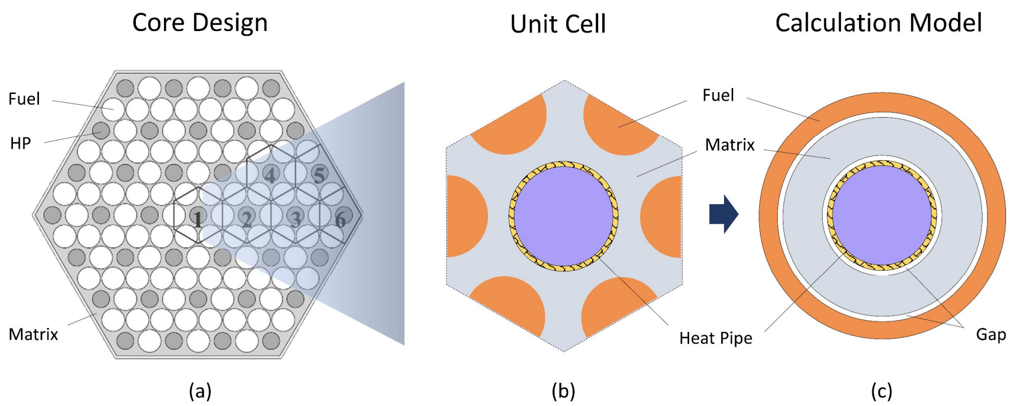


Figure 3.1 Equivalent Annulus Approximation Method

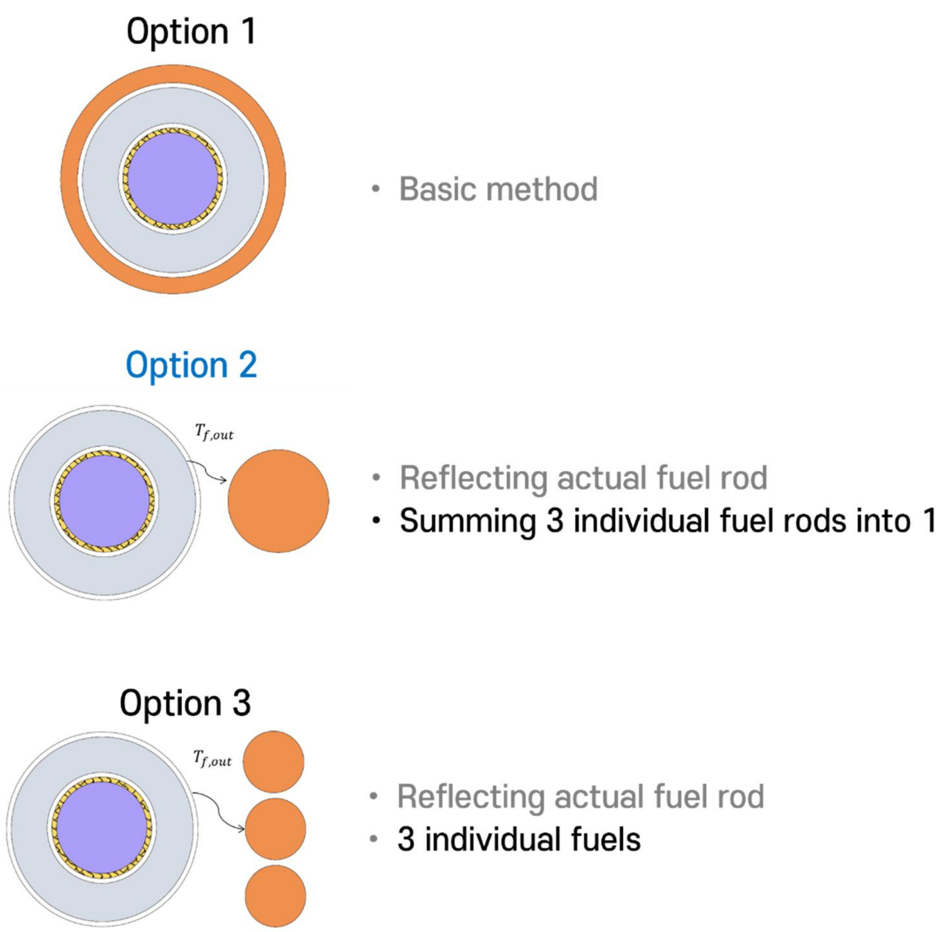


Figure 3.2 Thermal Design Options

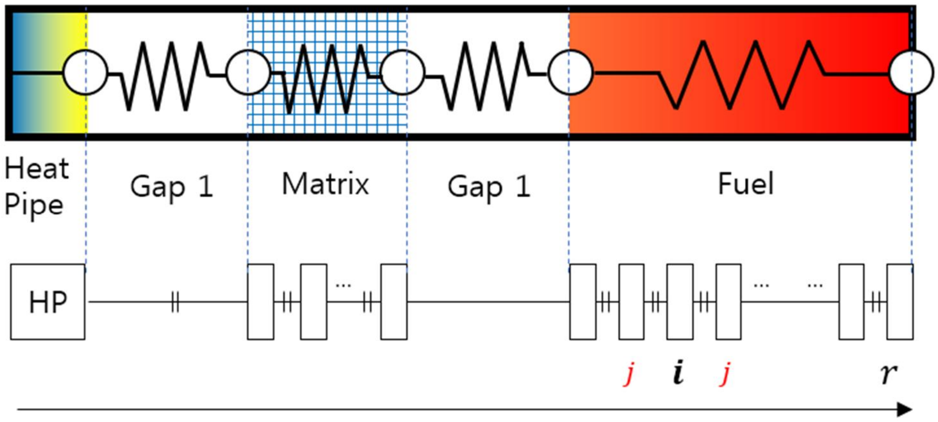


Figure 3.3 Thermal Resistance Circuit of the Core

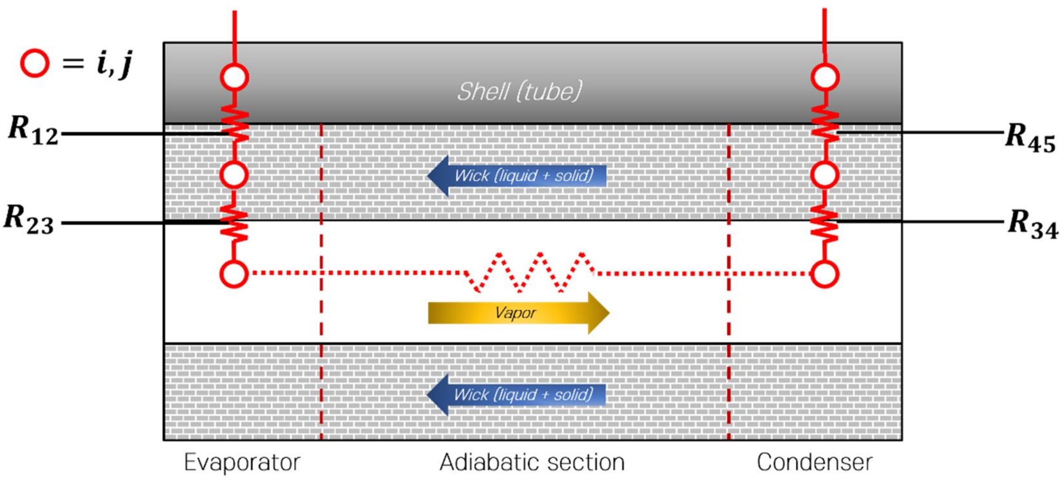


Figure 3.4 The Nodes and Resistance of the Heat Pipe

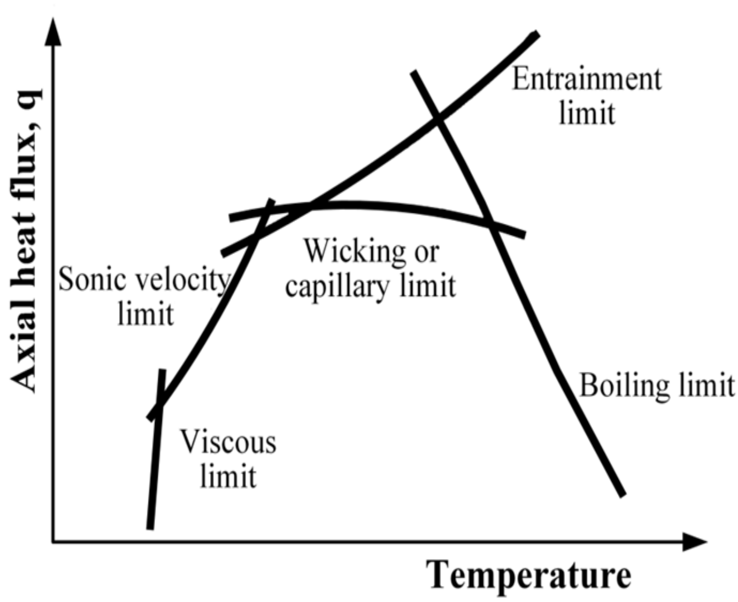


Figure 3.5 Heat Pipe Operating Limits

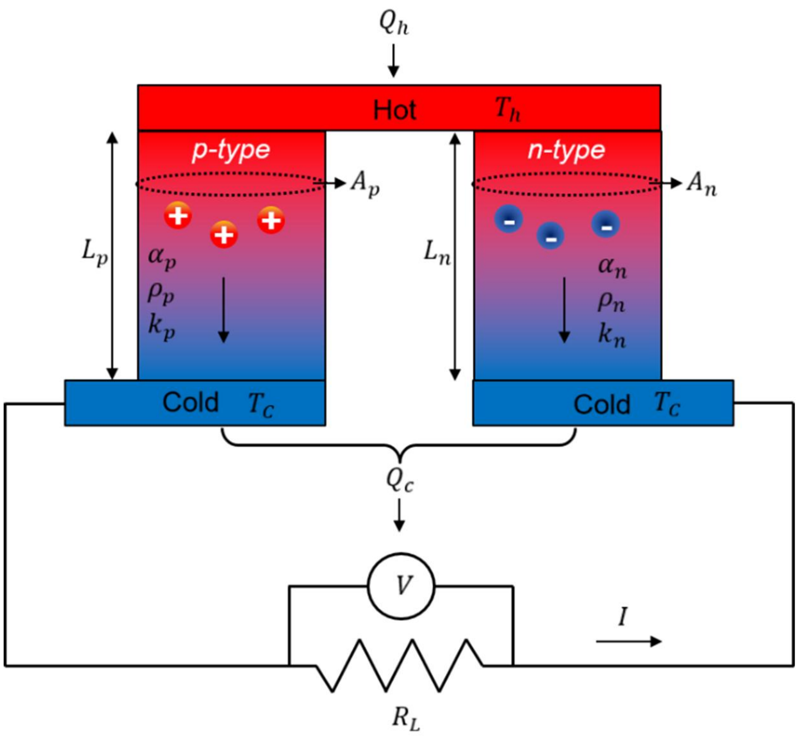


Figure 3.6 Thermoelectric Generator

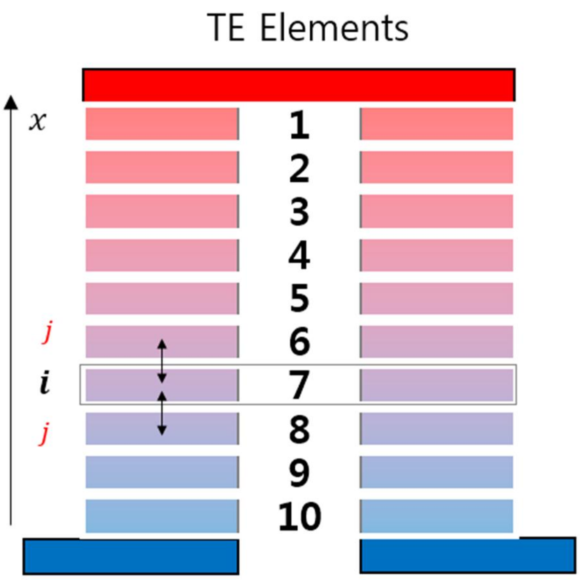


Figure 3.7 Governing Equation Diagram of the TEG

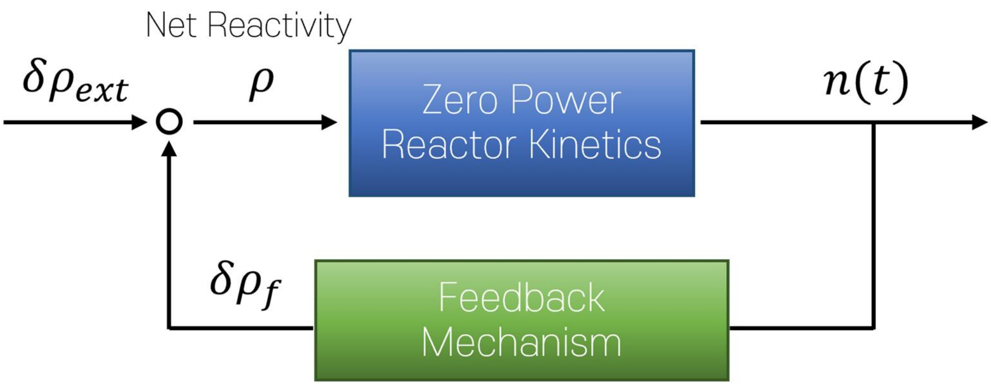


Figure 3.8 Block Diagram of the Reactor with Feedback Effect

Table 3.1 Thermal Resistance and Heat Flow rate of the Core

Component	$\boldsymbol{R_{ij}}$ $[\boldsymbol{K/W}]$	$\boldsymbol{Q_i}$ $[\boldsymbol{W}]$
Gap 2	$R_{ij}=\frac{1}{2\pi r_i L h_{gap2}}$	$Q_i=0$
Matrix	$R_{ij}=\frac{\left\lvert \ln(\frac{r_j}{r_i}) \right\rvert}{2\pi L k_m}$	$Q_i=0$
Gap 1	$R_{ij}=\frac{1}{2\pi r_i L h_{gap1}}$	$Q_i=0$
Fuel	$R_{ij}=\frac{\left\lvert \ln(\frac{r_j}{r_i}) \right\rvert}{2\pi L k_m}$	$Q_i=Q_{total}\frac{V_i}{V_{fuel}}pf_i$

Table 3.2 Thermal Resistance of the Heat Pipe

-	$\boldsymbol{R_{ij}}$ $[\boldsymbol{K/W}]$
Evap. Shell – Wick	$R_{12}=\frac{1}{2\pi r_i L_e}\left[\frac{r_o-r_i}{2k_s}+\frac{r_i-r_w}{2k_l}\right]$
Evap. Wick – Chamber	$R_{23}=\frac{1}{2\pi r_w L_e}\left[\frac{r_i-r_w}{2k_{L,eff}}\right]$
Cond. Chamber – Wick	$R_{34}=\frac{1}{2\pi r_w L_c}\left[\frac{r_i-r_w}{2k_{L,eff}}\right]$
Cond. Wick – Shell	$R_{45}=\frac{1}{2\pi r_i L_c}\left[\frac{r_o-r_i}{2k_s}+\frac{r_i-r_w}{2k_{L,eff}}\right]$

Table 3.3 Equations for the Heat Pipe Operating Limits

Type	Equation
Capillary Limit	$\Delta P_{cap} \geq \Delta P_l + \Delta P_v + \Delta P_g + \Delta P_{etc}$
Sonic Limit	$q_{s,\,max} = A_v \rho_0 h_{fg} \left[\frac{\gamma_v R_v T_0}{2(\gamma_v + 1)}\right]^{1/2}$
Entrainment Limit	$q_{e,\,max} = A_v h_{fg} \left(\frac{\sigma \rho_v}{2 r_{h,s}}\right)^{1/2}$
Boiling Limit	$q_{b,\,max} = \frac{2\pi L_{eff} k_e T_v}{h_{fg} \rho_v \ln(\frac{r_i}{r_v})} \left(\frac{2\sigma}{r_n}\right)$
Viscous Limit	$q_{b,\,max} = \frac{2\pi L_{eff} k_e T_v}{h_{fg} \rho_v \ln(\frac{r_i}{r_v})} \left(\frac{2\sigma}{r_n}\right)$

Chapter 4.

Development of Dynamic Simulation Model for 10kWe Micro Fission Battery using AMESIM

4.1 AMESIM Software

AMESIM is a simulation software developed by Siemens. It is specialized in modeling, analyzing, and predicting the performance of mechatronics system. There are various industrial libraries such as thermal, hydraulic, mechanics and electricity as shown in Figure 4.1. Each library is composed of numerous components, and time-dependent equation is installed in the components. For example, there are 'Thermal Capacity' and 'Thermal Resistance' components in a thermal library as shown in Figure 4.2. 'Thermal Capacity' component calculates heat flux between two different points, and their temperatures are used as input data. 'Thermal Resistance' component receives temperature as an input data from 'Thermal Capacity' component and calculates the heat flux as an output data. A variety of mechatronic system can be modelled by using the combination of numerous components.

4.2 Reactor Core Model

The core is divided in to 5 parts radially, and 11 parts axially as shown in Figure 4.3. By splitting the core, more precise temperature profile data can be simulated. Each divided point of the fuel, the heat from the fission is added. The end of the core model is connected to the evaporate section of the heat pipe to transfer the heat of the core.

4.3 Heat Pipe Model

The heat pipe is divided by six parts; 3 parts for evaporate section and others for condensate section as shown in Figure 4.4. Each section consists of a wall, wick and chamber. The heat from the core is transferred to the condensate section, and it is connected to the hot side of the TEG. There is a 'Temperature Sensor' attached to the component of the evaporate section, sending the temperature of the heat pipe to the operating limit model. There are 5 operating limits for heat pipe. Each limit is modelled based on its related equation as shown in Figure 4.5. The operating limit model calculates the individual unit power of the heat pipe and compare it with the limit to analyze the reactor's stability.

4.4 TEG Model

The TEG model is developed using the method same as the core model. TE elements are divided in to 10 parts for better analysis as shown in Figure 4.6. Each point of the TEG includes the joule heat from thermoelectric effect. The hot side of the TEG is connected to the condensate section of the heat pipe and the cold side to the heat sink of the reactor. The heat sink is modelled using a component to generate cooling effect.

4.5 Point Kinetics Model

There is a component ‘Integrator Solver’ to solve differential equations. There are 7 differential equations for the point kinetics: one for the total number of neutrons, the others for the total number of delayed neutron precursors. The point kinetics equations are solved by using the component mentioned above as shown in Figure 4.7. The calculated reactivity is connected to the reactivity feedback effect model.

4.6 Reactivity Feedback Model

The reactivity is calculated as a sum of the reactivity from the fuel and moderator, initial reactivity, and external reactivity as shown in Figure 4.8.. The average temperature of the fuel and moderator of the core is connected to the reactivity feedback model, and its reactivity, calculated output of the model, is sent to the variable of the point kinetics model.

4.7 Model Integration

The integrated model is shown as Figure 4.9. The core model, affected by the point kinetics and reactivity feedback model, is connected to the heat pipe model. The heat pip model includes the operating limit model. There is a ‘Thermal Capacity’ component between the heat pipe and the TEG, representing a copper block for the distribution from the heat pipe. The integrated model uses a function called ‘Super Component’. It puts all the complicated models together into a simple single component.

4.8 Verification

To verify the dynamic simulation model of the micro fission battery, Engineering Equation Solver (EES) program is used as a reference data. It solves all the equations related to the micro fission battery and calculates values of the steady state. In Figure 4.10, and 4.11, the significant parts of the micro fission battery are demonstrated. As a result of the simulation, there are only negligible errors from the AMESIM simulation compared to the reference data, and it proves the appropriateness of the dynamic model.

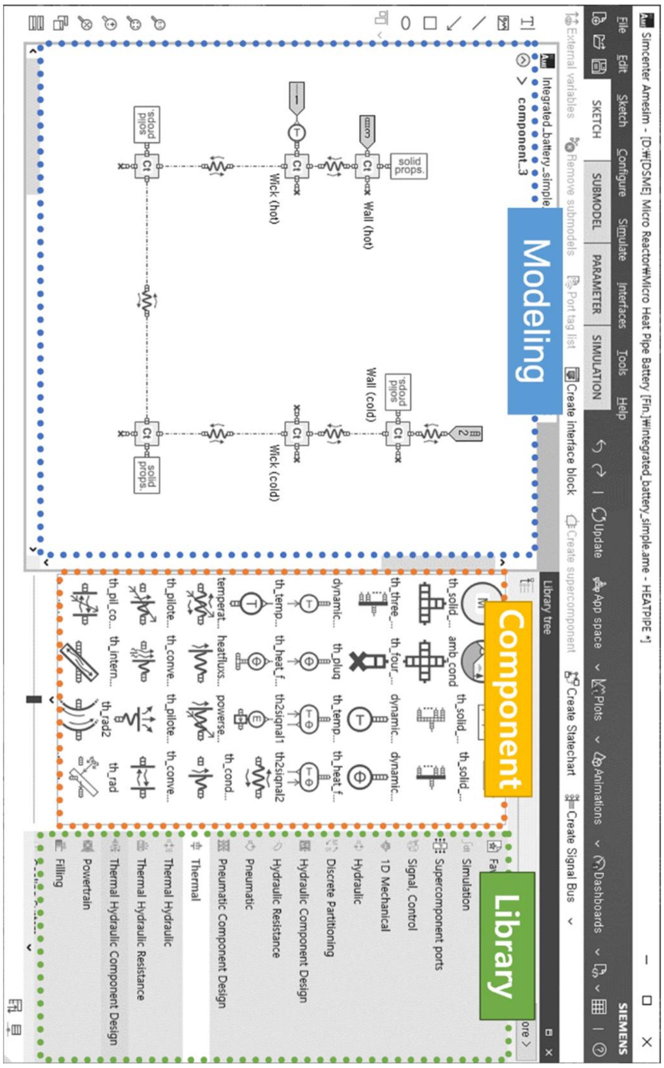


Figure 4.1 Display of AMESIM Software

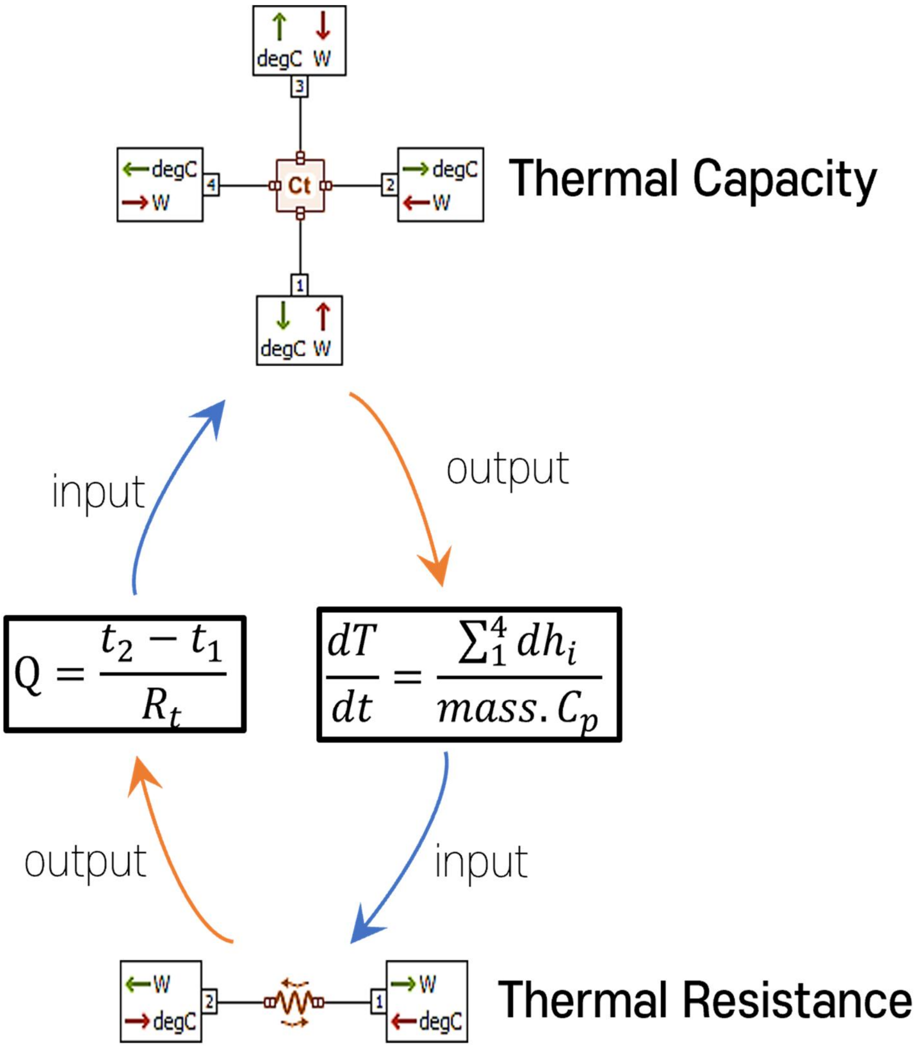


Figure 4.2 An Example of AMESIM Component

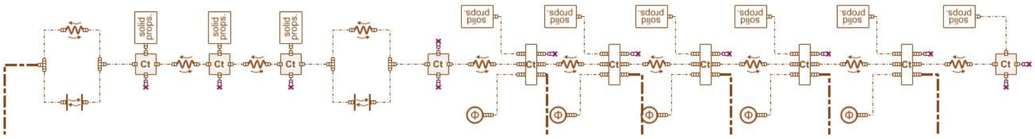


Figure 4.3 The Core Model

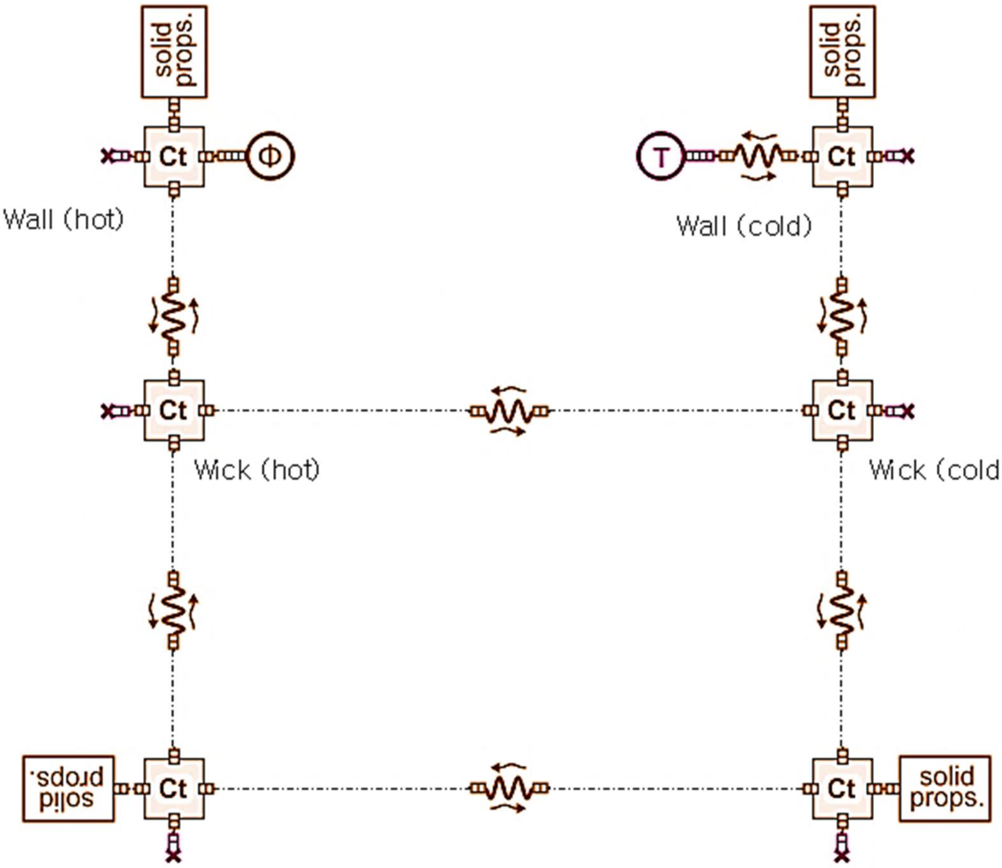


Figure 4.4 The Heat Pipe Model

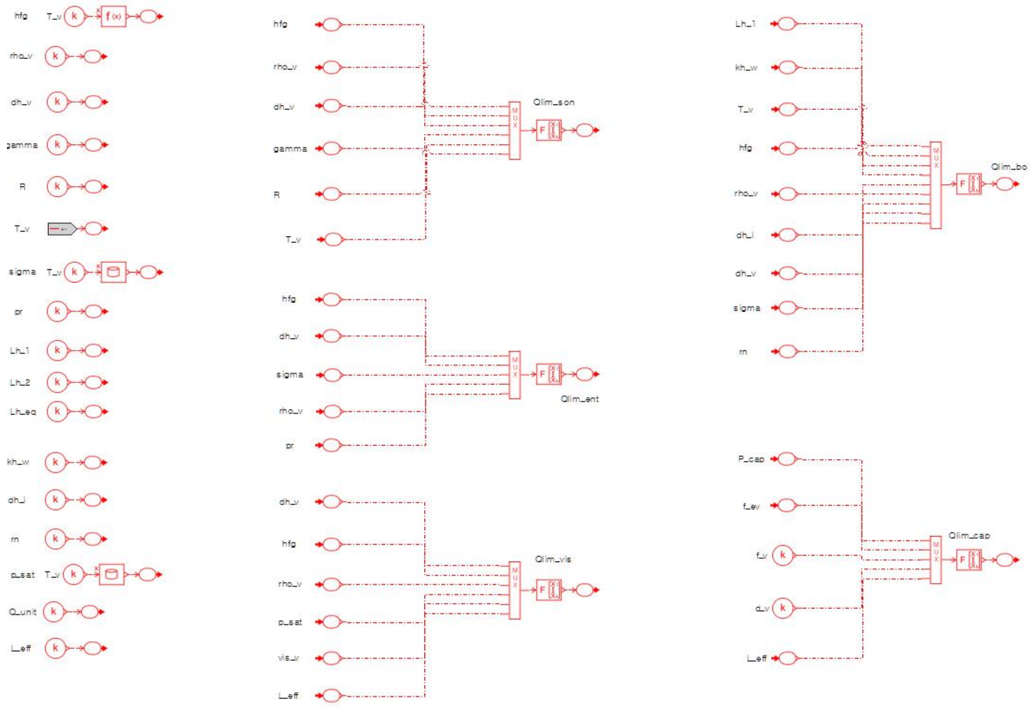


Figure 4.5 The Operating Limit Model for the Heat Pipe

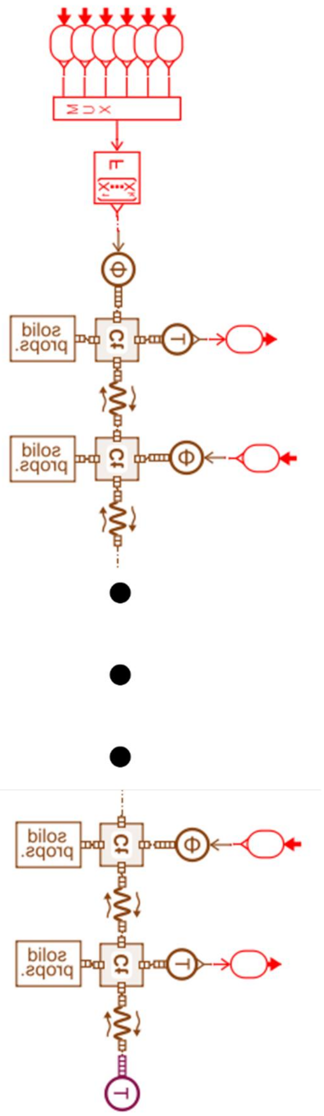
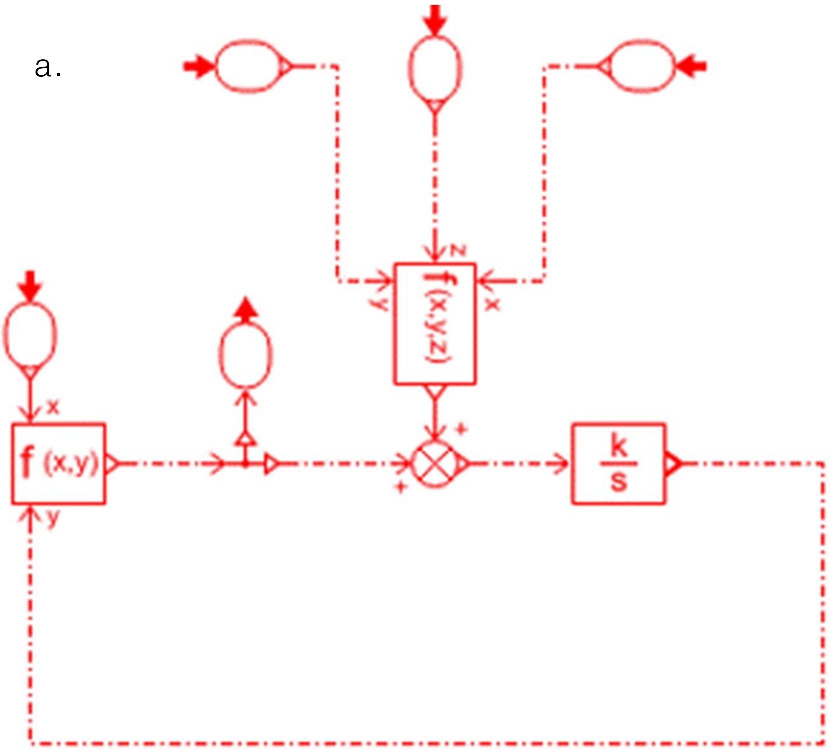


Figure 4.6 The TEG Model

a.



b.

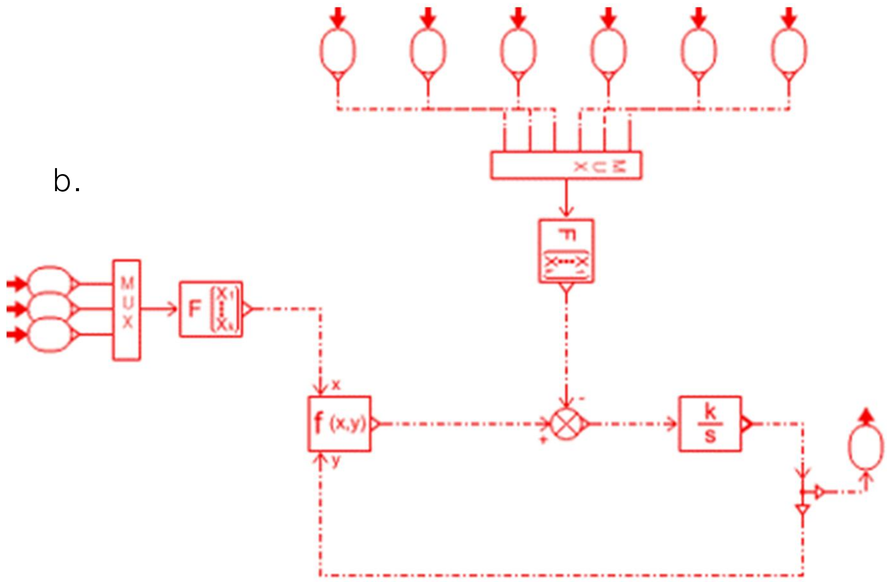


Figure 4.7 The Point Kinetics Model; (a) The Total Number of Delayed Neutrons Precursors; (b) The Total Number of Neutrons

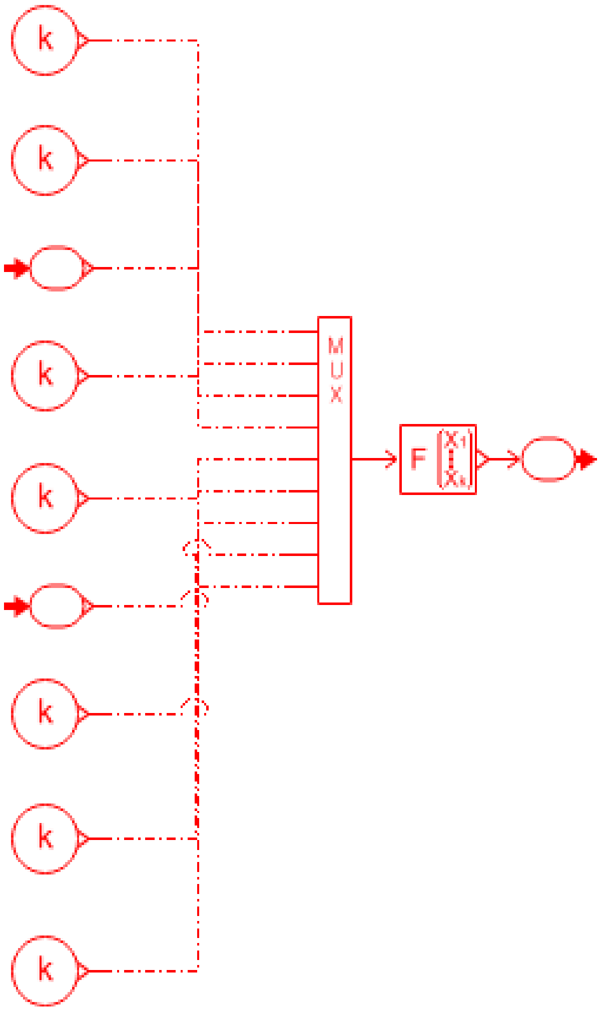


Figure 4.8 The Reactivity Feedback Model

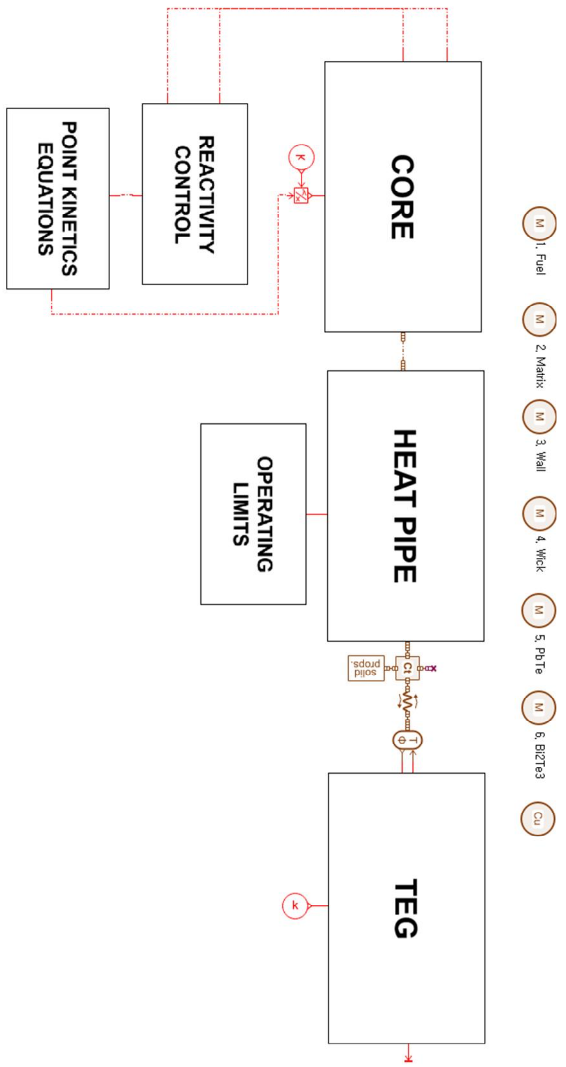


Figure 4.9 The Integrated Model for the Micro Fission Battery

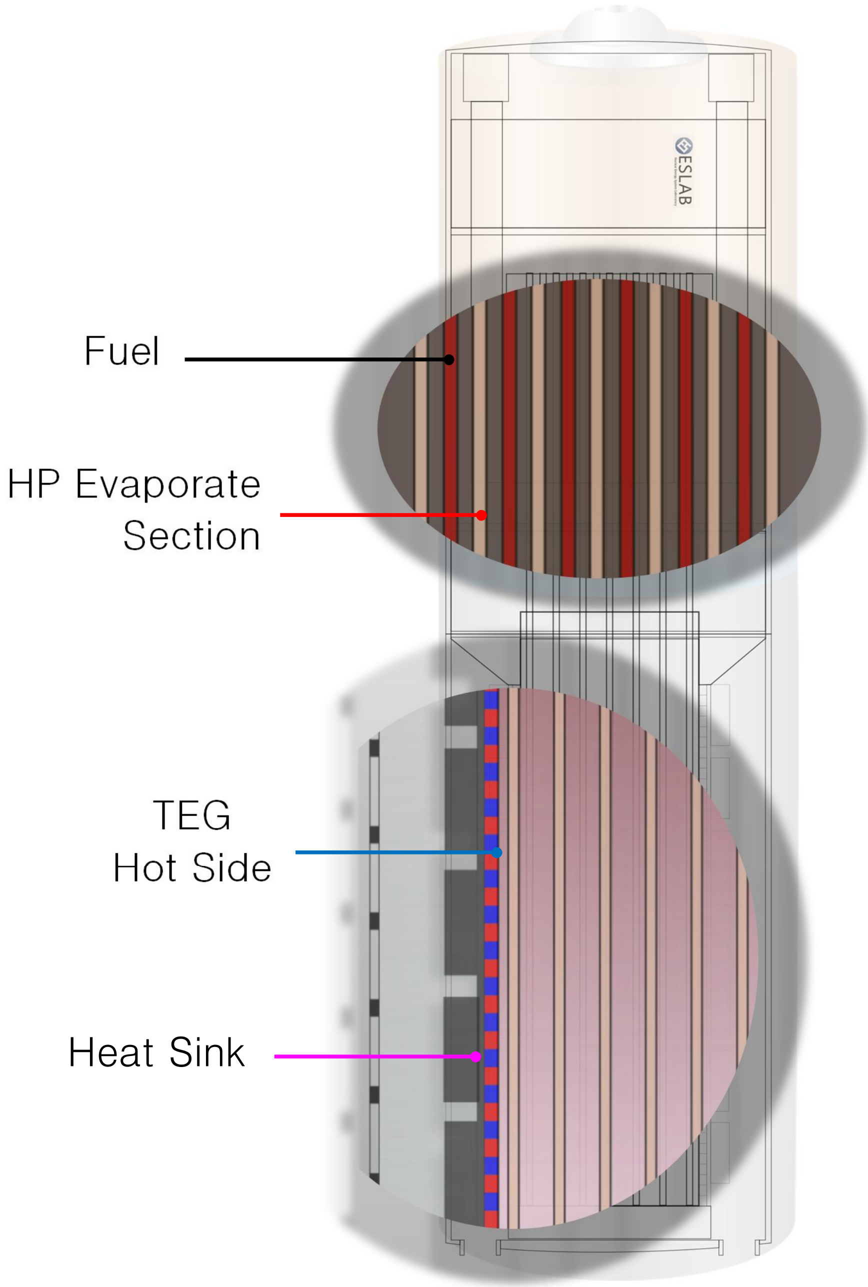


Figure 4.10 The Significant Parts Used as Reference of the Micro Fission Battery

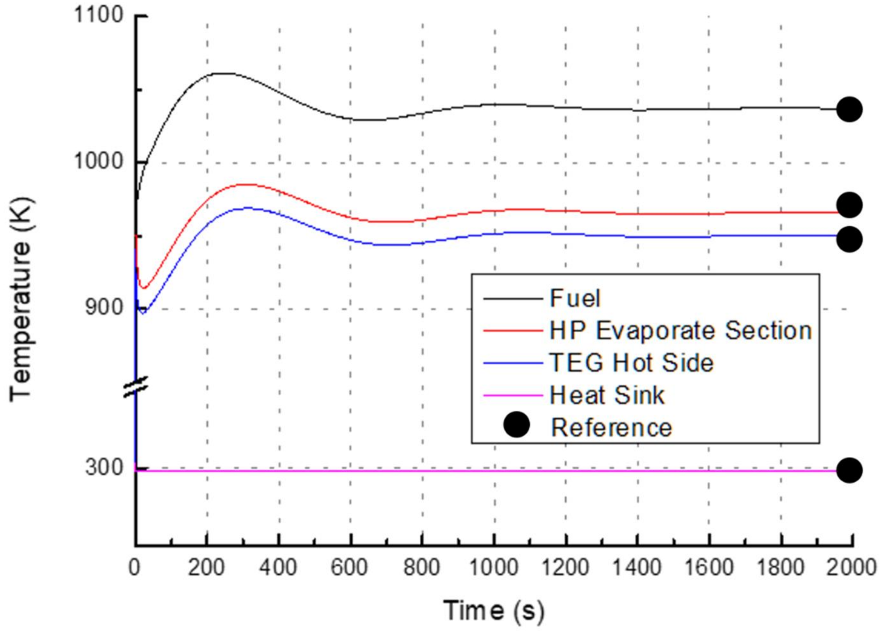


Figure 4.11 The Significant Parts Used as Reference of the Micro Fission Battery

Table 4.1 The Temperature Profile of the Micro Fission Battery

Region	**Reference Design (K)**	**AMESIM Temperature (K)**	**Error (%)**
Fuel	1030.04	1036.80	0.65
Heat Pipe Evaporate Section	964.50	965.67	0.12
TEG Hot Side	950.04	950.06	0.11
Heat Sink	298.08	298.05	0.01

Chapter 5.

Dynamic Simulation for 10kW Micro Heat Pipe Fission Battery

5.1 Abnormal Heat Sink Transient

This scenario represents abnormal change of cooling performance at heat sink of the TEG as shown in Figure 5.1. Since the micro fission battery is developed for underwater drones, there are various scenarios for changing the cooling performance such as some foreign matters stock in the heat sink area or increase of water speed. The purpose of this simulation is to analyze the reactor's stability under abnormal heat sink transient. The simulation begins with the heat sink transient after maintaining steady state for 2,500 seconds. The transient simulation is continued for 2,500 seconds. The time step for the simulation is 10 seconds.

5.1.1 Abrupt Undercooling

The cooling performance of TEG is decreased by -20%, -40%, -60% and -80% of its normal condition. Figure 5.2 shows results of the simulation. As the cooling performance is decreased, heat flux of the heat sink is gradually increased. The temperature of the cold side of TEG is slightly increased proportionally, but the whole system's temperature is not affected. The maximum temperature of the core slightly increased and the unit power of the heat pipe is decreased. Their changes are under the operating limits. The reactivity feedback effect becomes more significantly observed as the cooling performance decreased, but there is only slight change in thermal and electric power. The efficiency of the power changed from 14.9% to 13.8%.

5.1.2 Abrupt Overcooling

Overcooling can be observed when the speed of the water is increased, or underwater drones accelerates its speed. The cooling performance of TEG is increased by +20%, +40%, +60%, and 80% of the normal condition. The results are shown in Figure 5.3. As the cooling performance is increased, heat flux of the heat sink is decreased proportionally, but temperature profile of the system does not show significant change. There are slight changes in maximum core temperature and heat pipe unit power under the operating limits. As the change of the reactivity, thermal and electric power increased negligibly.

5.1.3 Oscillated Cooling

The cooling performance changes with sinusoidal wave. The maximum and minimum value for the oscillation is +80% and -80% of the normal condition. The periods of 100 seconds, 500 seconds and 1,000 seconds are observed. As shown in Figure 5.4, heat flux of the heat sink and system temperature profiles fluctuation with the change of sinusoidal wave. Thermal and electric power shows same phenomenon, but the reactor behaves under the operating limits of both fuel temperature and heat pipe.

5.1.4 Random Cooling

The cooling performance of TEG is abnormally changed with uniformly generated random distribution. The range of the random distributions is between -80% and +80% of the normal condition. Figure 5.5 shows the result of the simulation. Heat flux of the heat sink changes randomly. The system temperature profile shows only slight change in the cold side of TEG. The reactor operates under the limits of fuel temperature and heat pipe. Thermal and electric power shows negligible changes.

5.2 Unexpected Reactivity Transient

This scenario represents a situation when there is an unexpected reactivity insertion of the core. The purpose of the simulation is to observe the robustness of the reactor regarding the reactivity changes without the intervention of the control drums as shown in Figure 5.6. The simulation condition is same as the heat sink transient, and the reactivity is inserted by 0.05$, 0.10$, 0.15$, and 0.20$.

As a result of the simulation in Figure 5.7, the reactivity is abruptly increased. The reactor maintains is stability before 0.10$ but when there is reactivity insertion of 0.15$ and 0.20$, its maximum core temperature reaches beyond the operating limit. The heat pipe unit power is increased beyond the operating limit by the reactivity insertion of 0.20$.

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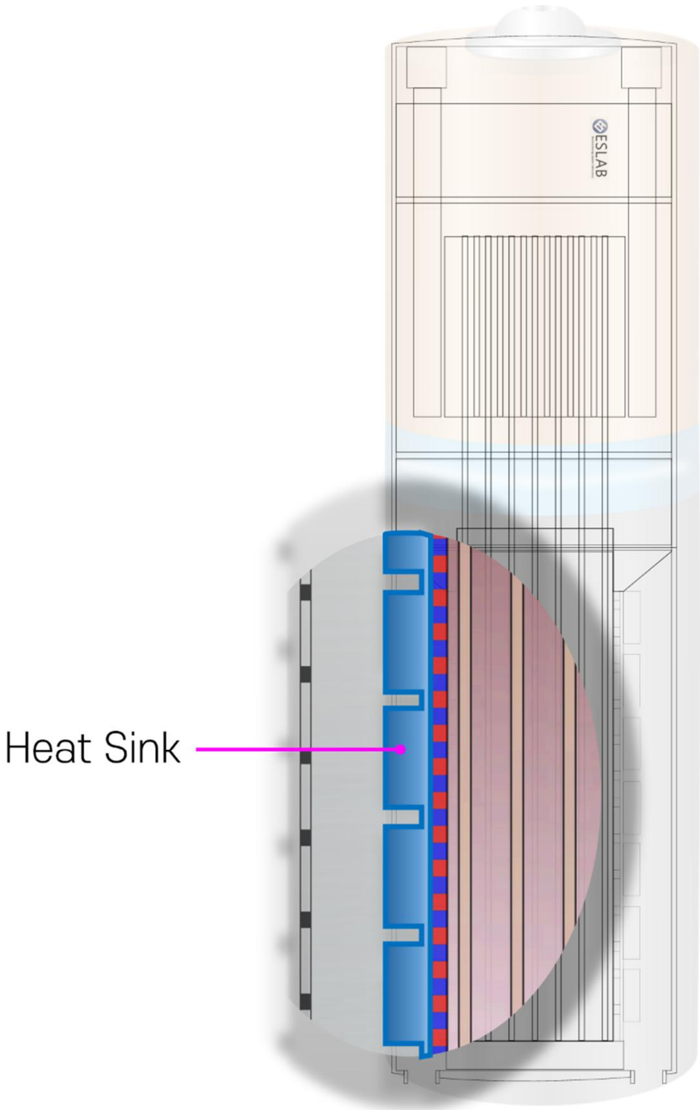
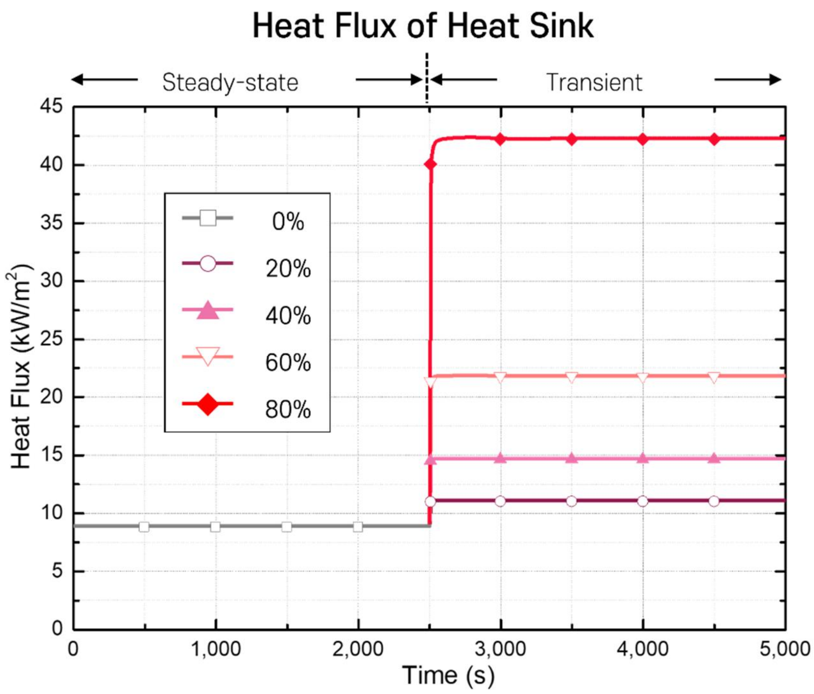


Figure 5.3 Heat Sink of the Micro Fission Battery



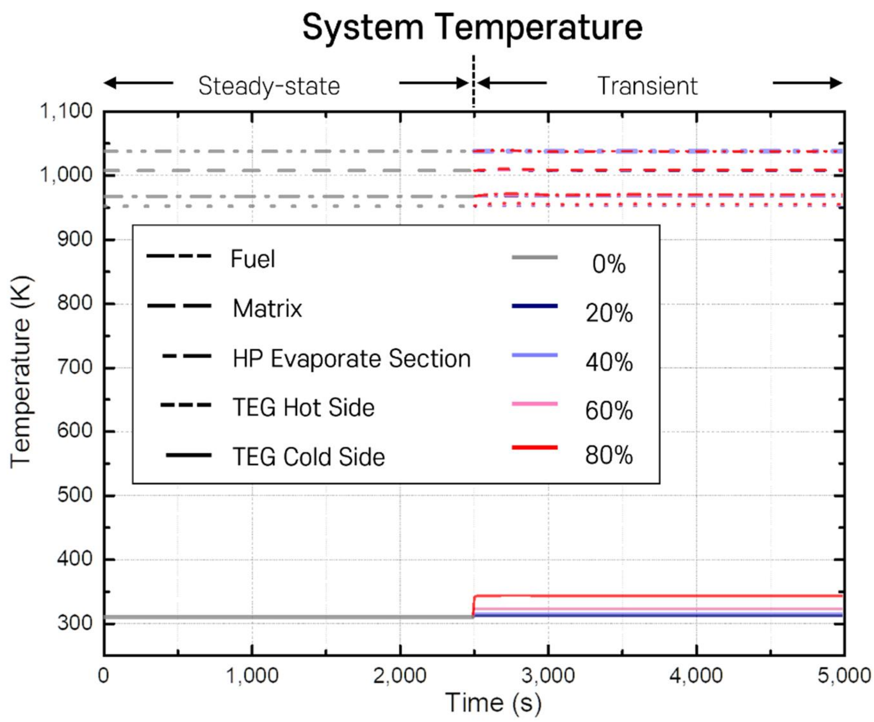


Figure 5.4 Simulation of Abrupt Undercooling (1)

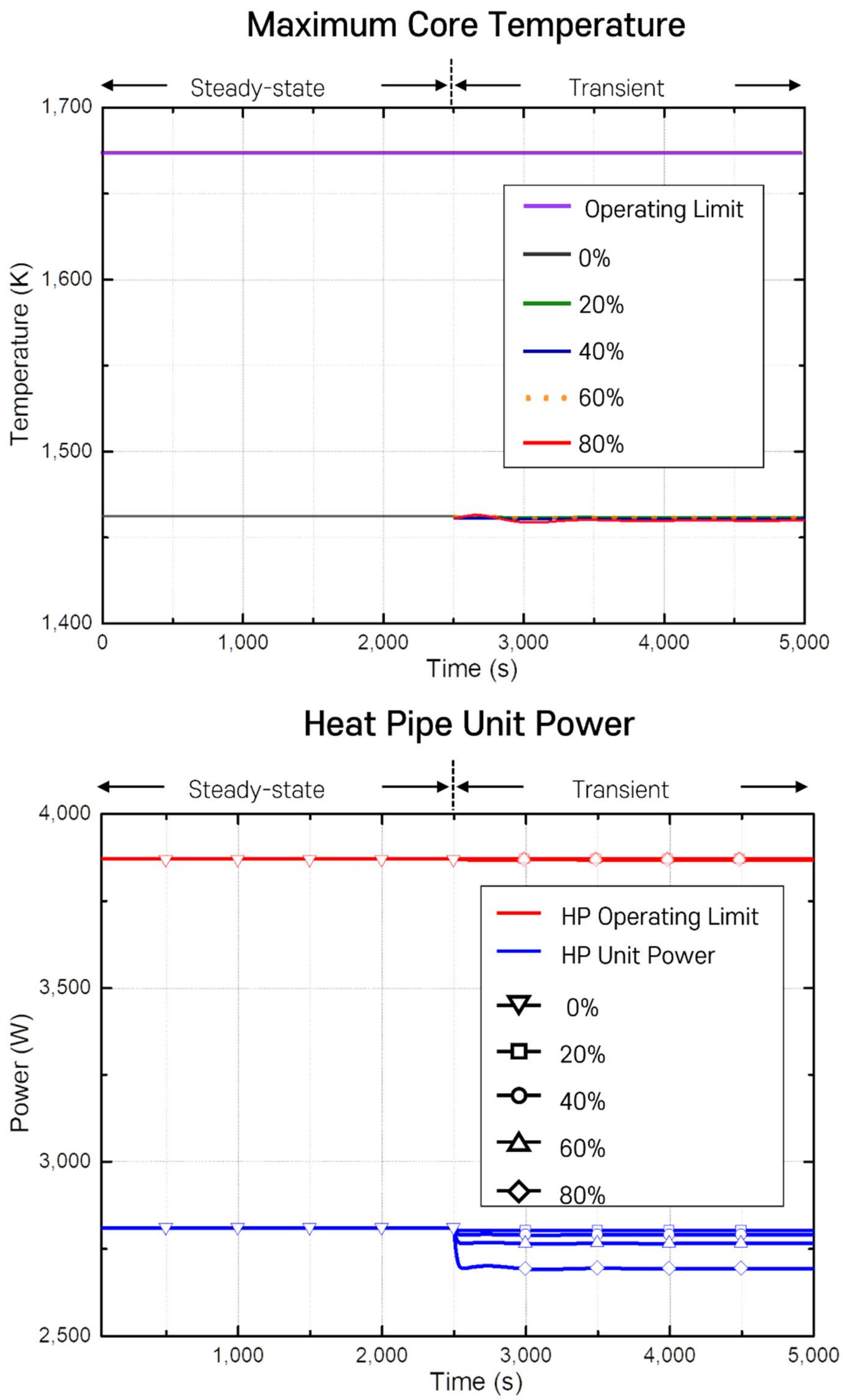


Figure 5.5 Simulation of Abrupt Undercooling (2)

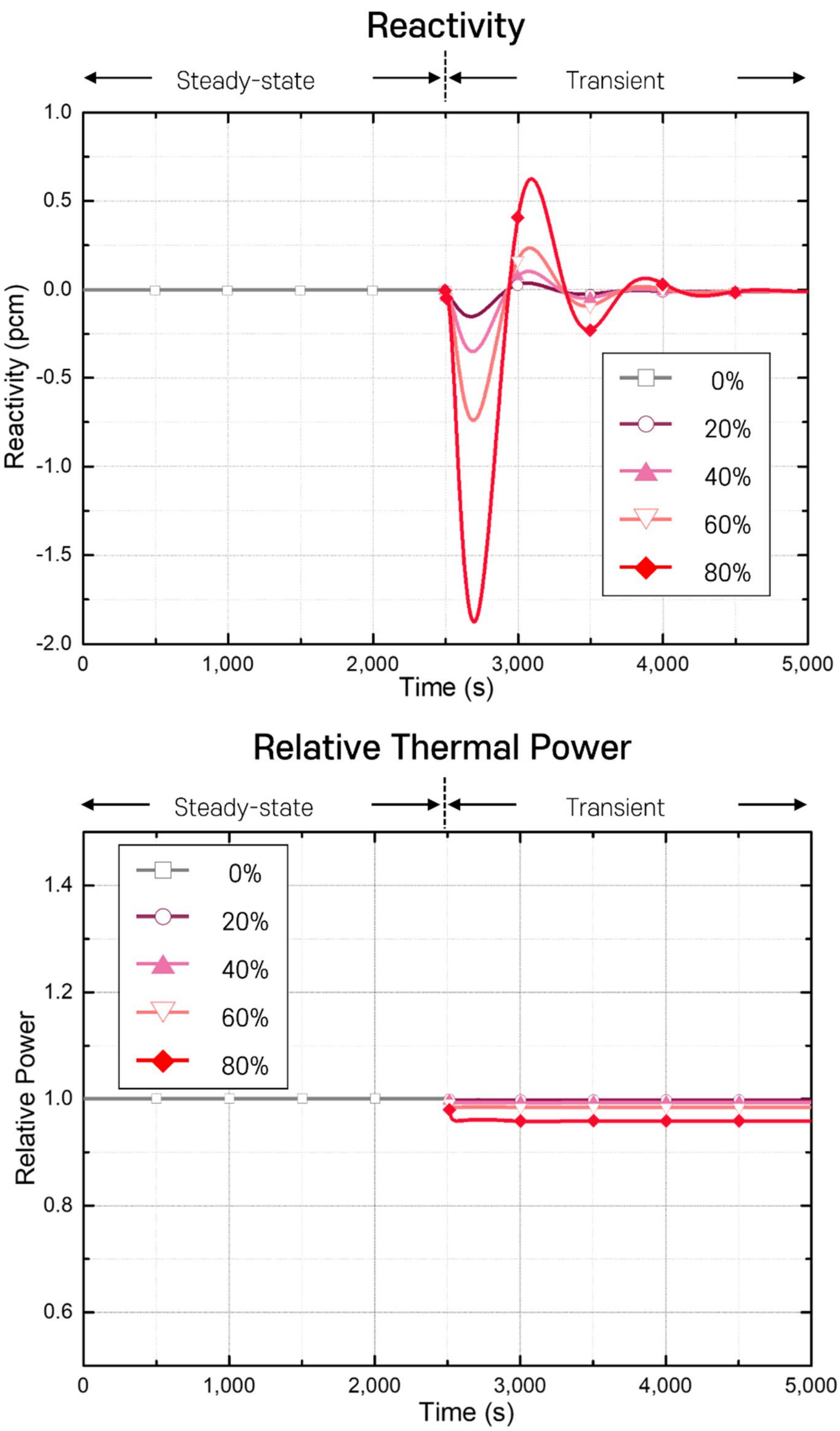


Figure 5.6 Simulation of Abrupt Undercooling (3)

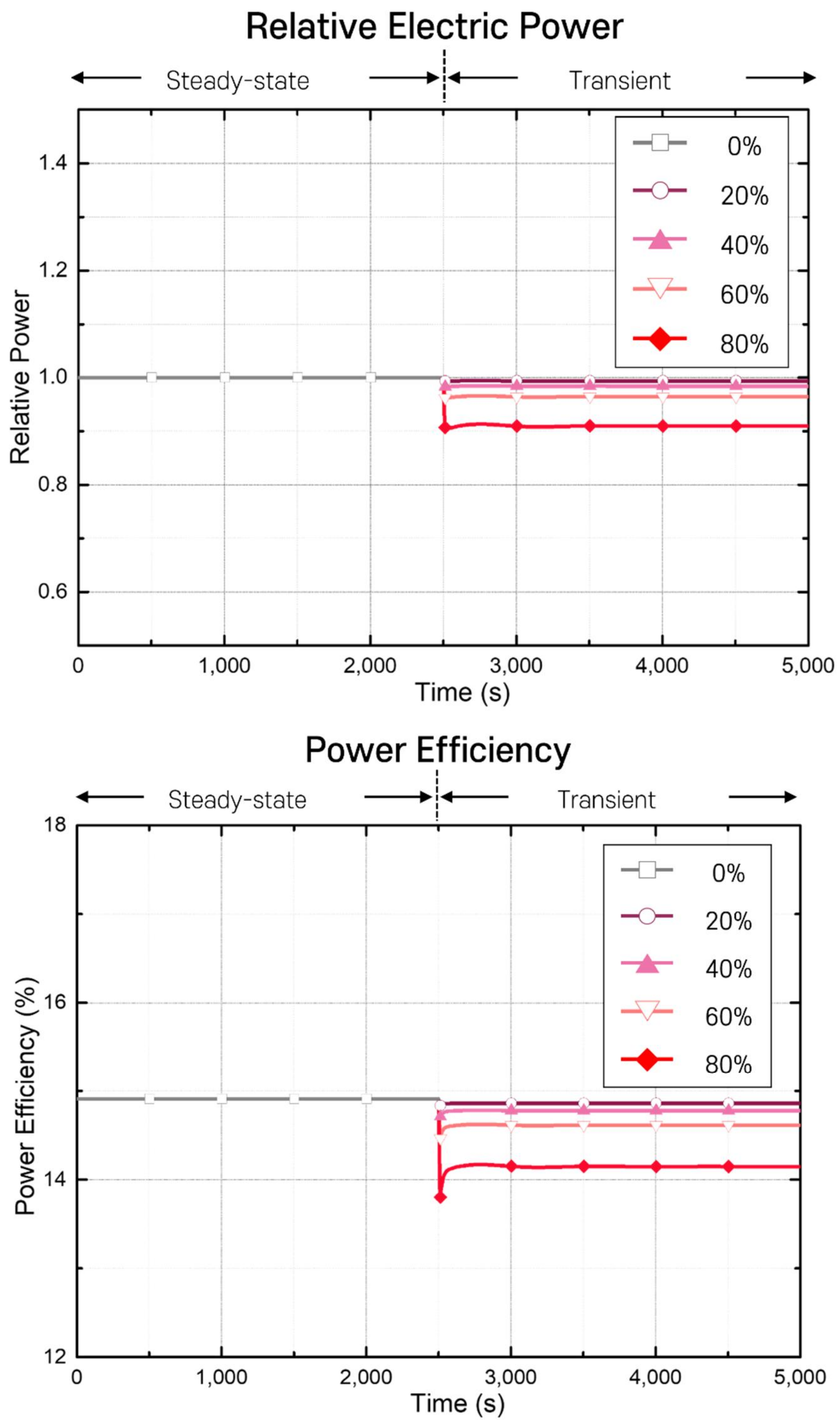


Figure 5.7 Simulation of Abrupt Undercooling (4)

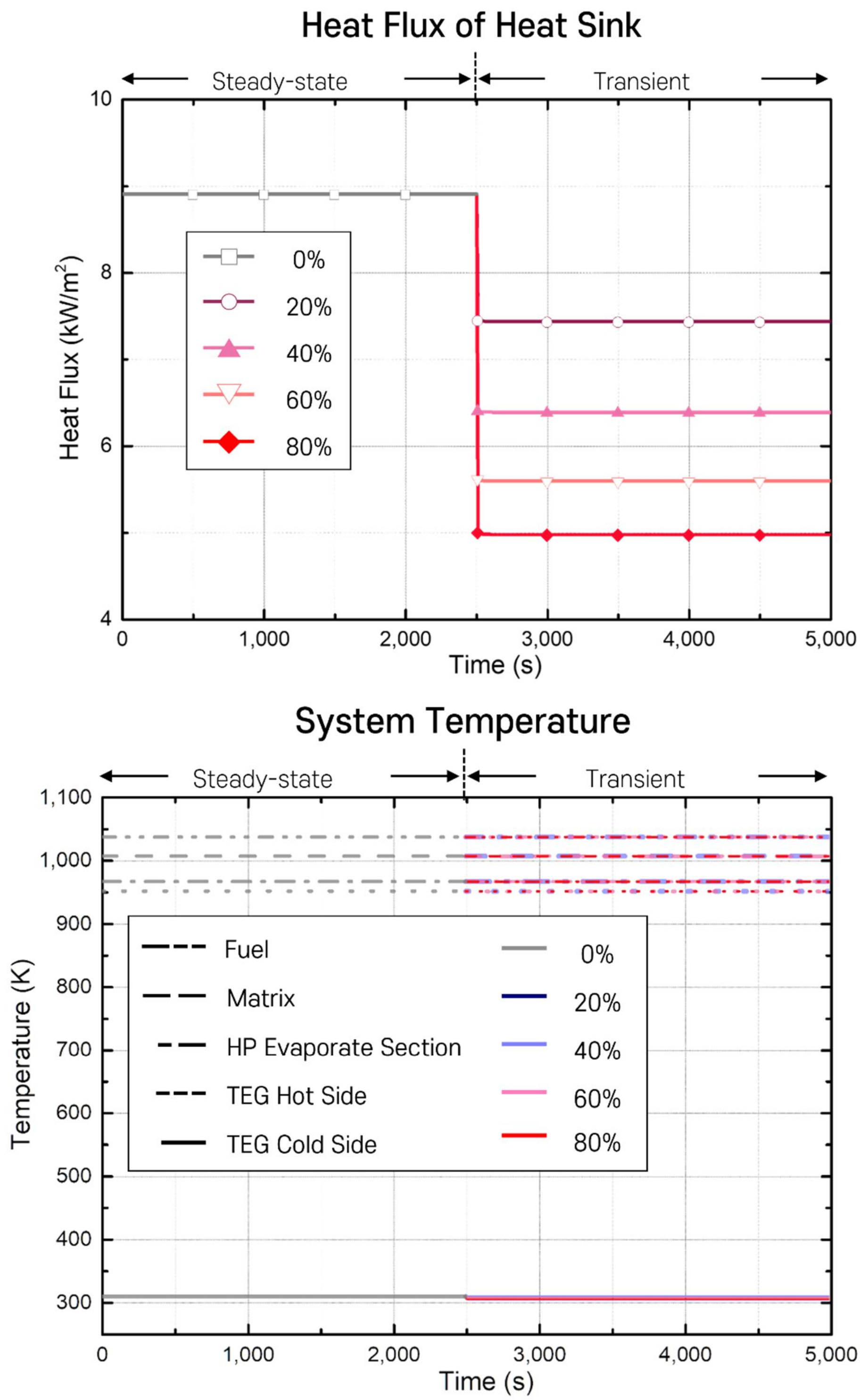


Figure 5.3 Simulation of Abrupt Overcooling (1)

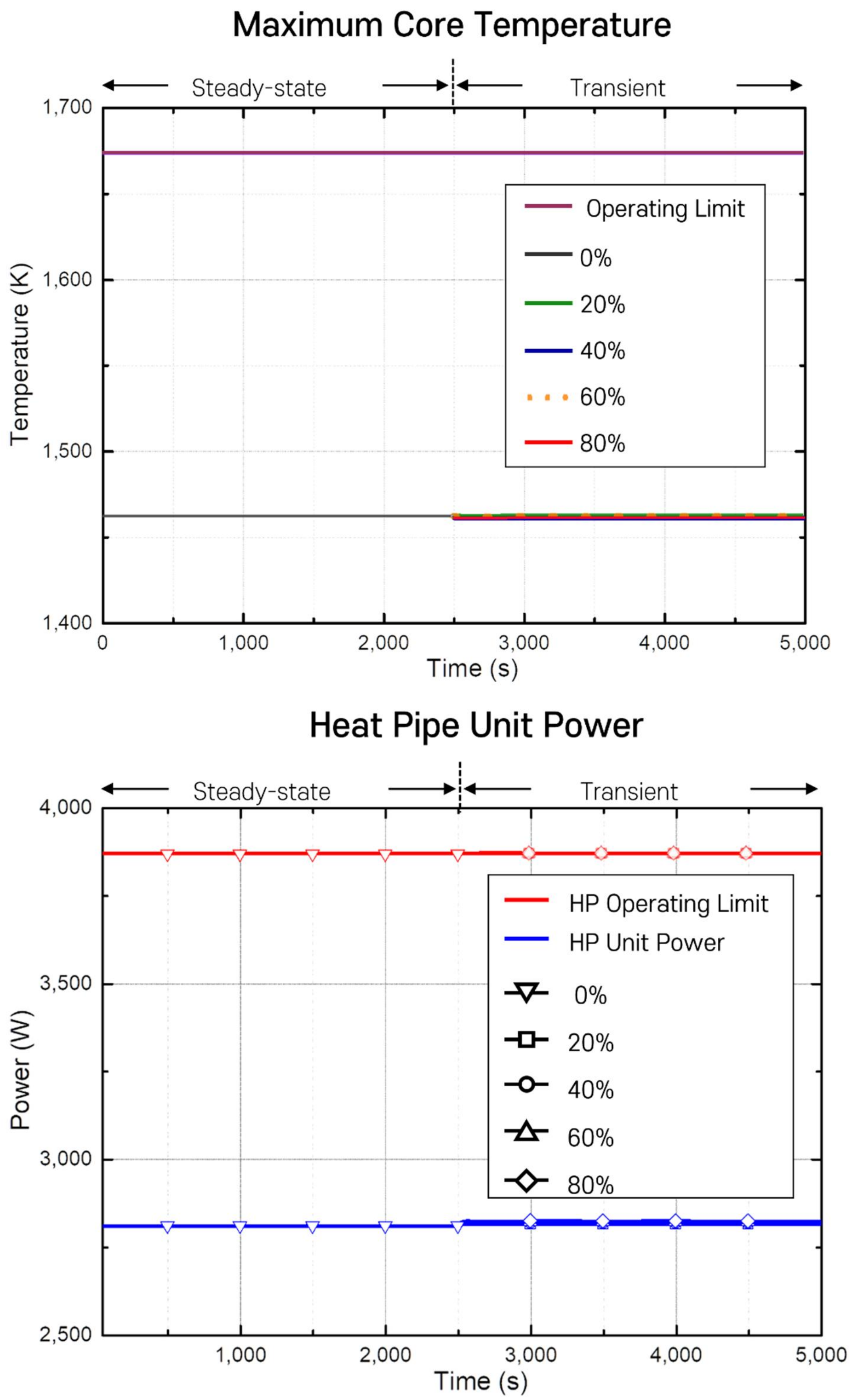


Figure 5.3 Simulation of Abrupt Overcooling (2)

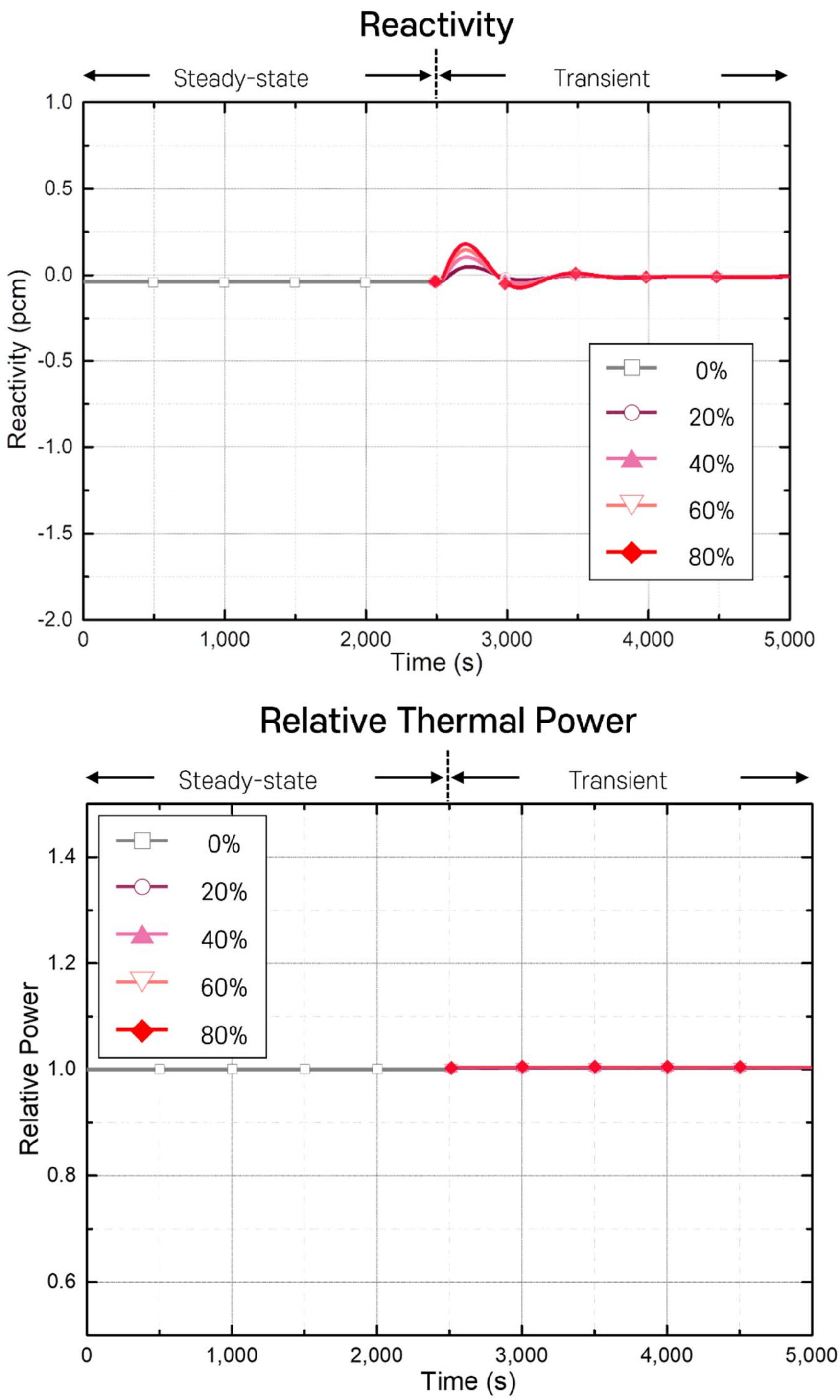


Figure 5.3 Simulation of Abrupt Overcooling (3)

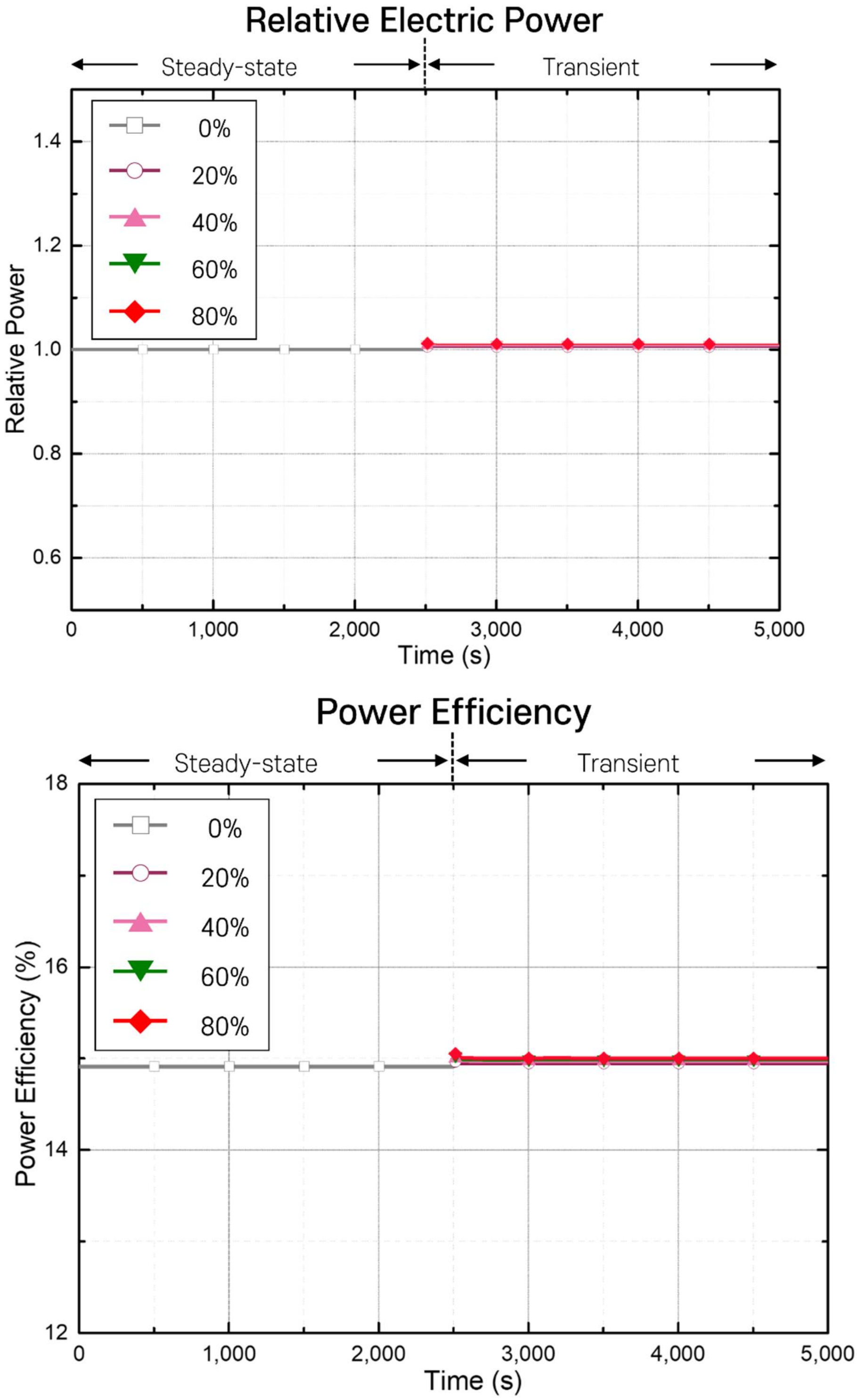


Figure 5.3 Simulation of Abrupt Overcooling (4)

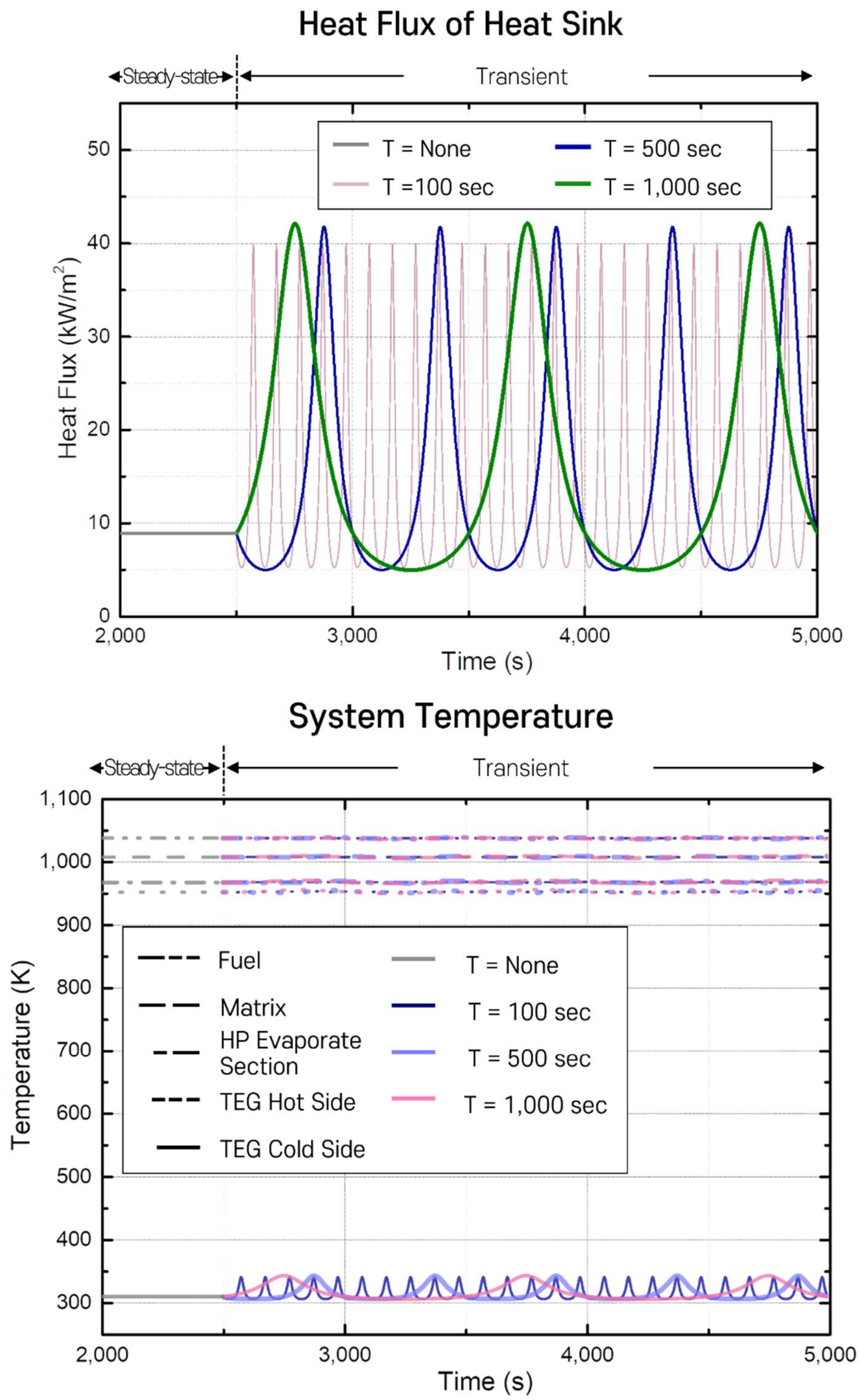


Figure 5.4 Simulation of Oscillated Cooling (1)

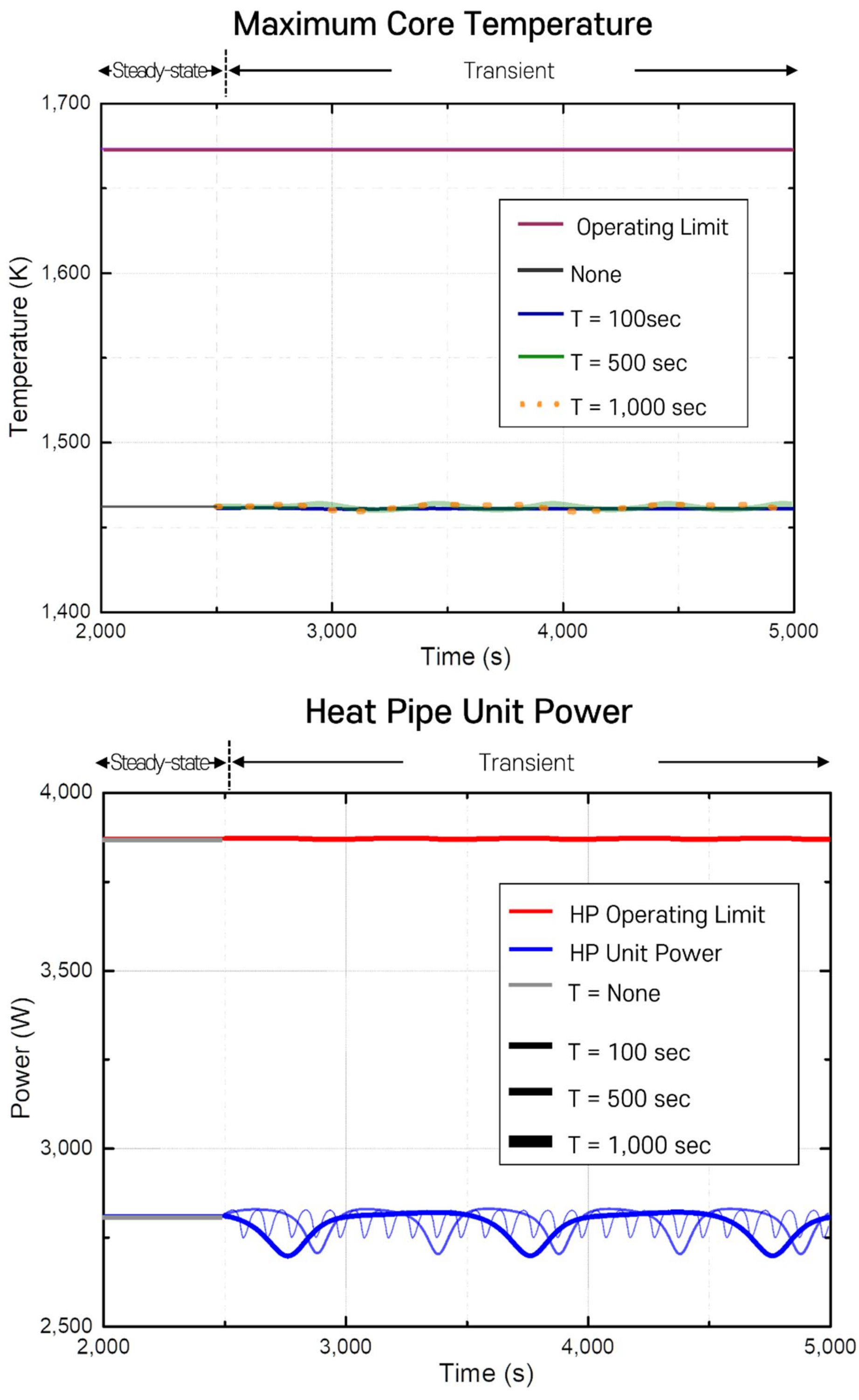


Figure 5.4 Simulation of Oscillated Cooling (2)

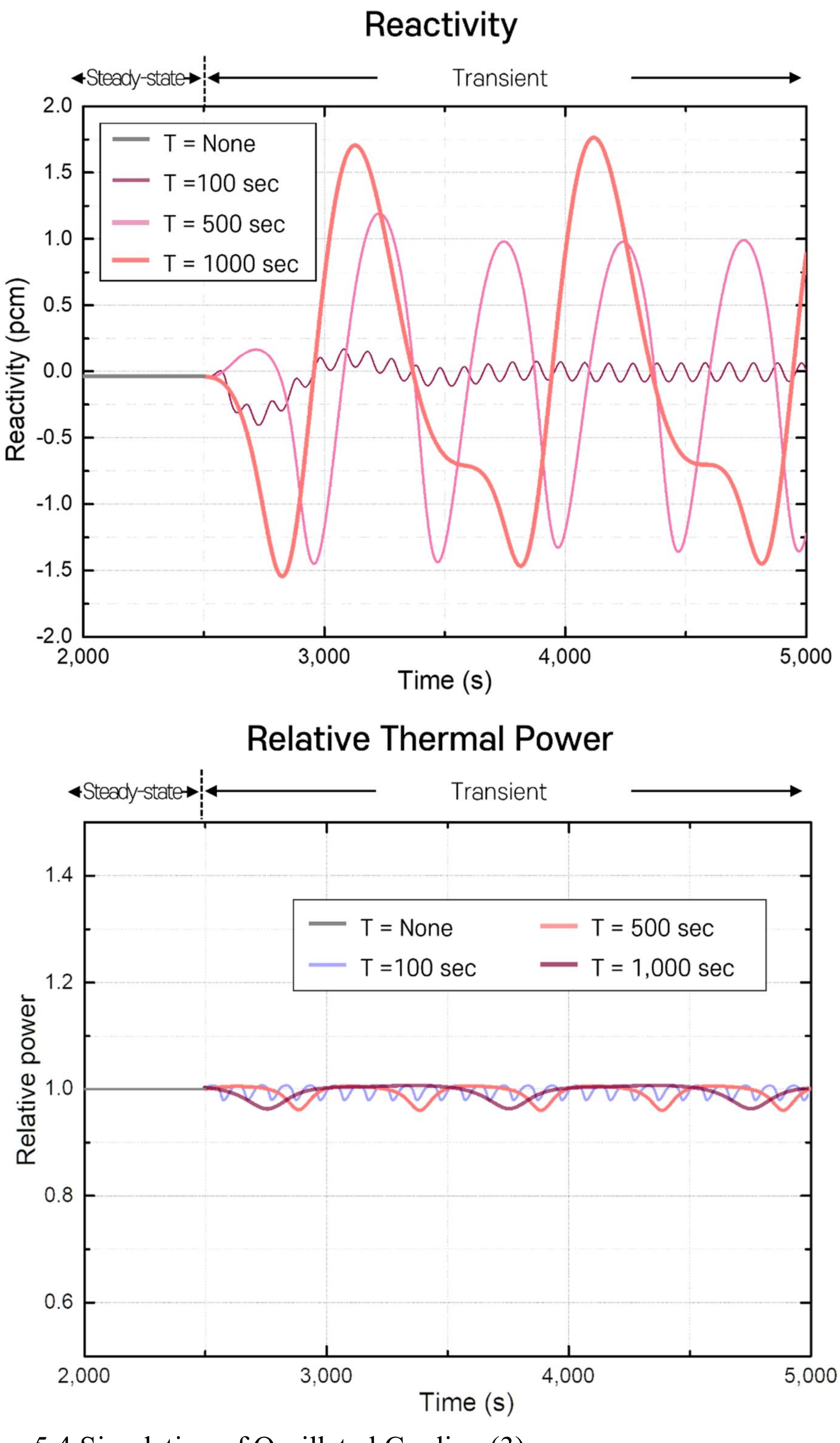
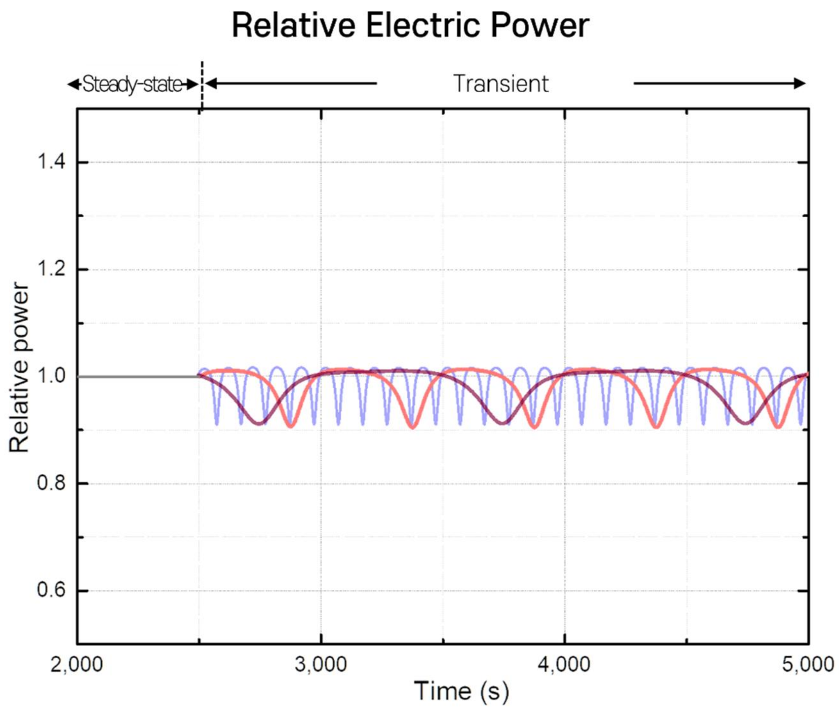


Figure 5.4 Simulation of Oscillated Cooling (3)



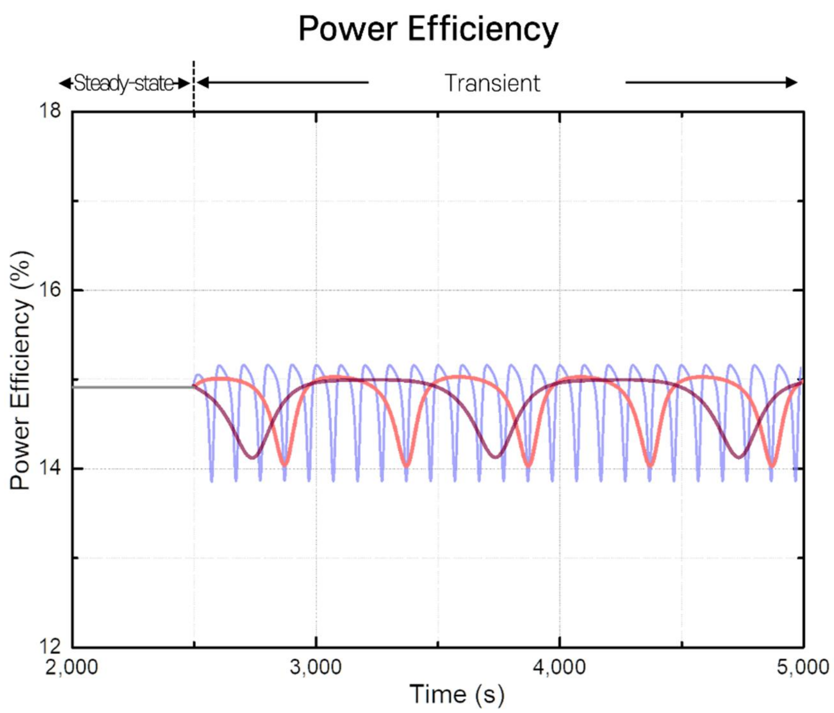


Figure 5.4 Simulation of Oscillated Cooling (4)

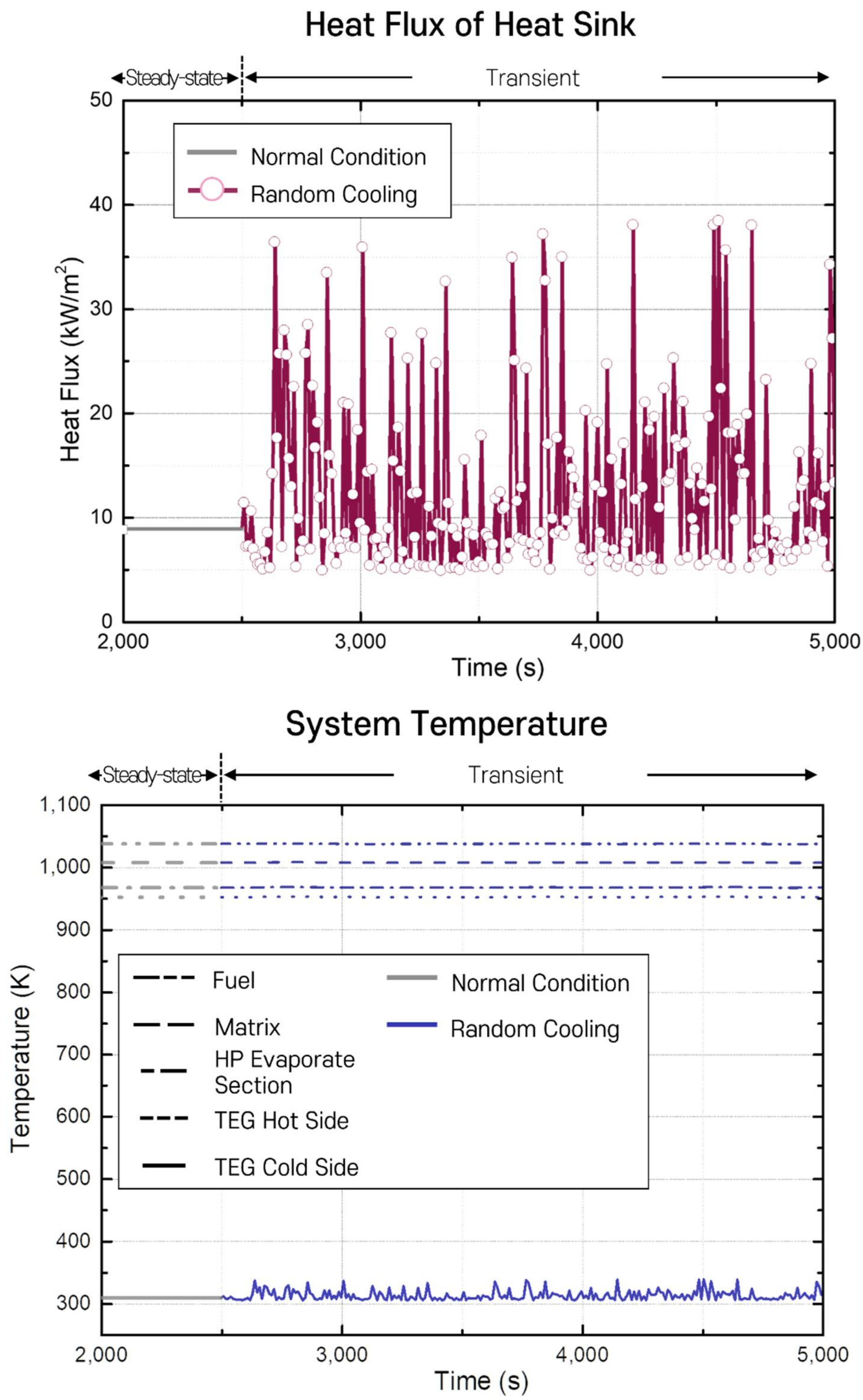
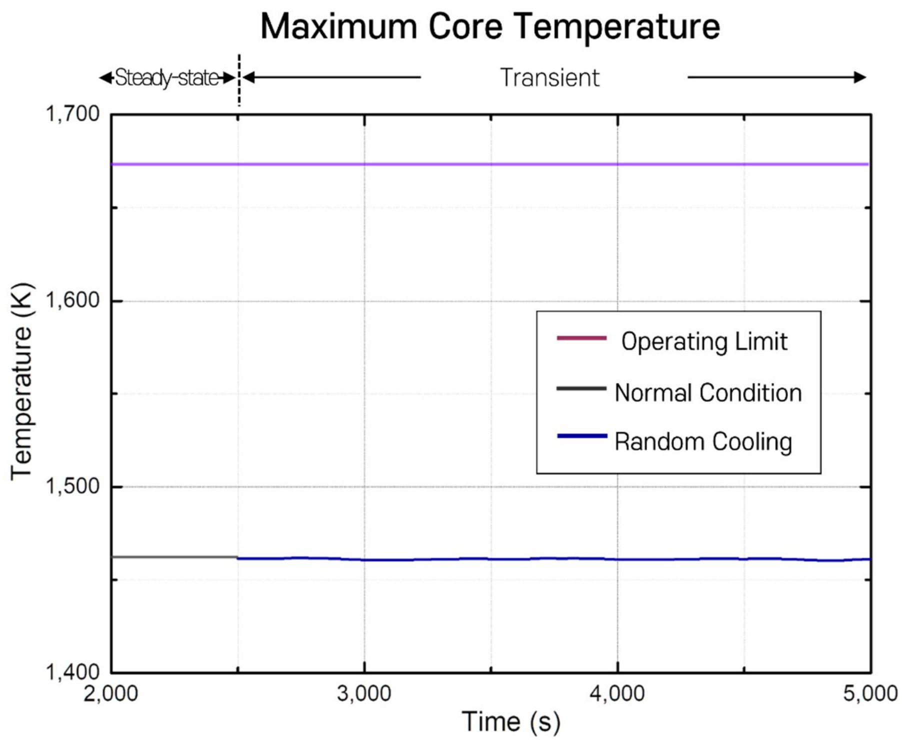


Figure 5.5 Simulation of Random Cooling (1)



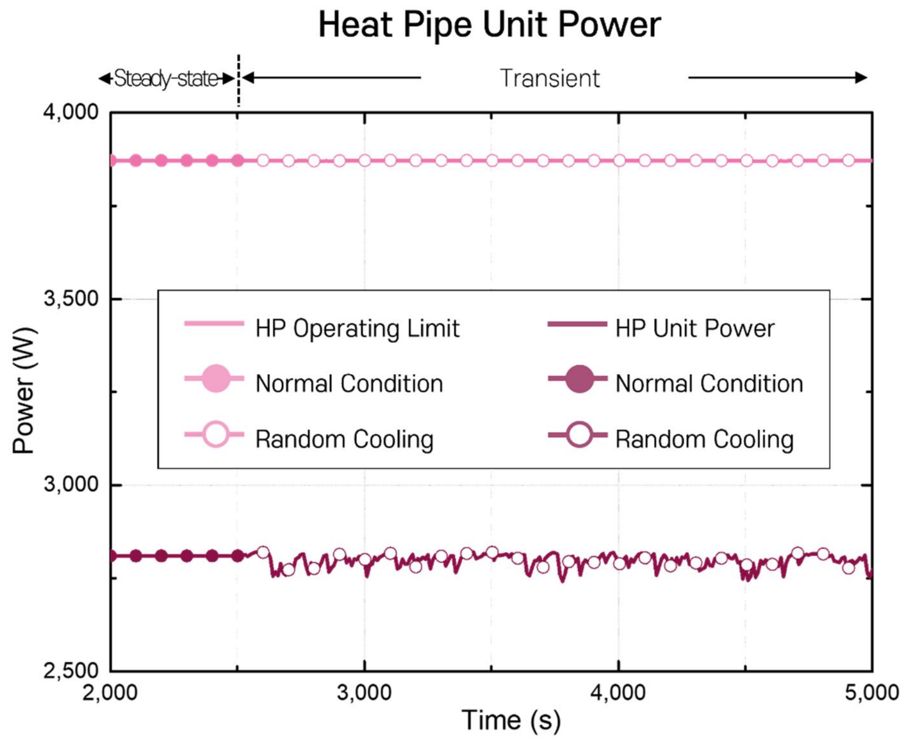


Figure 5.5 Simulation of Random Cooling (2)

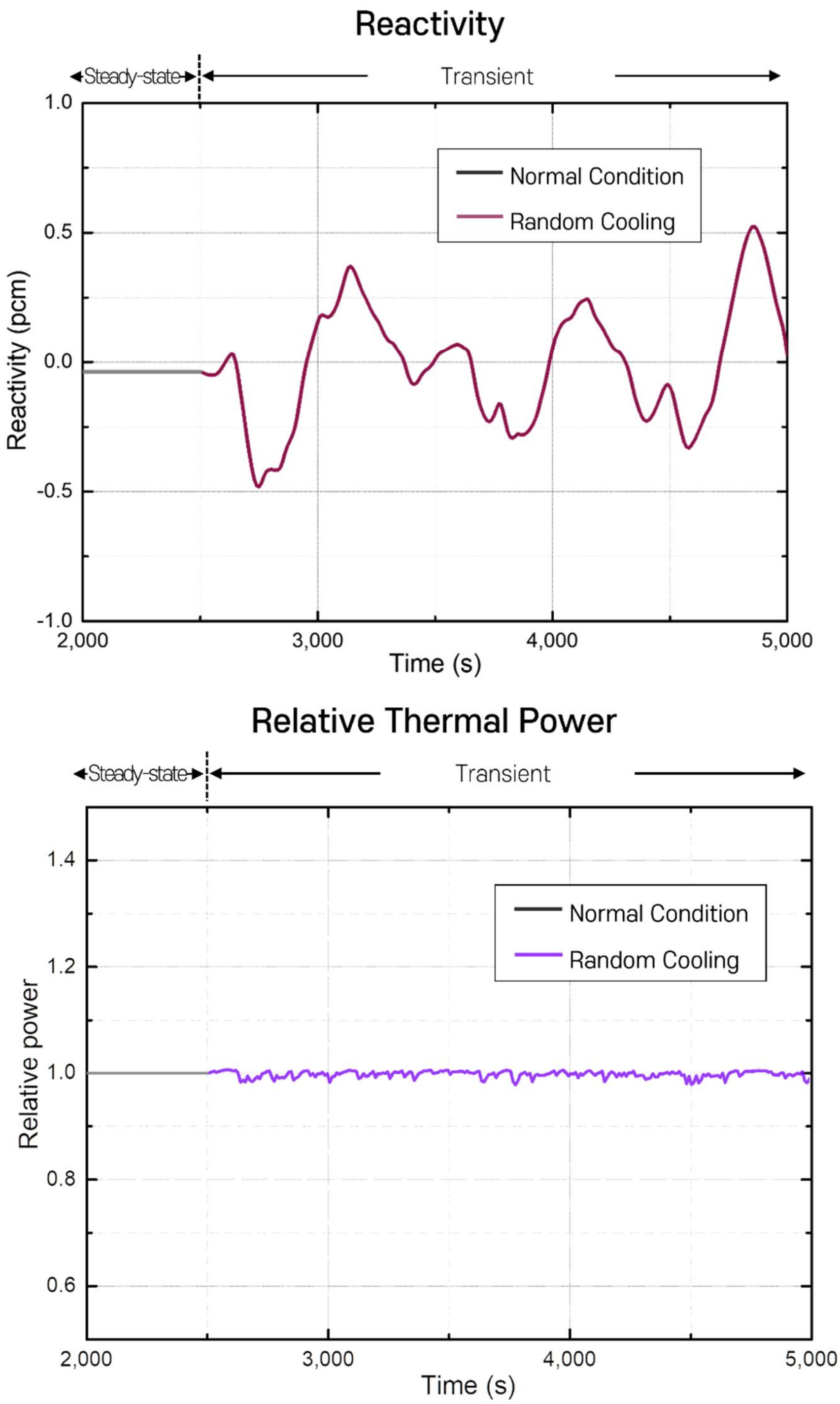
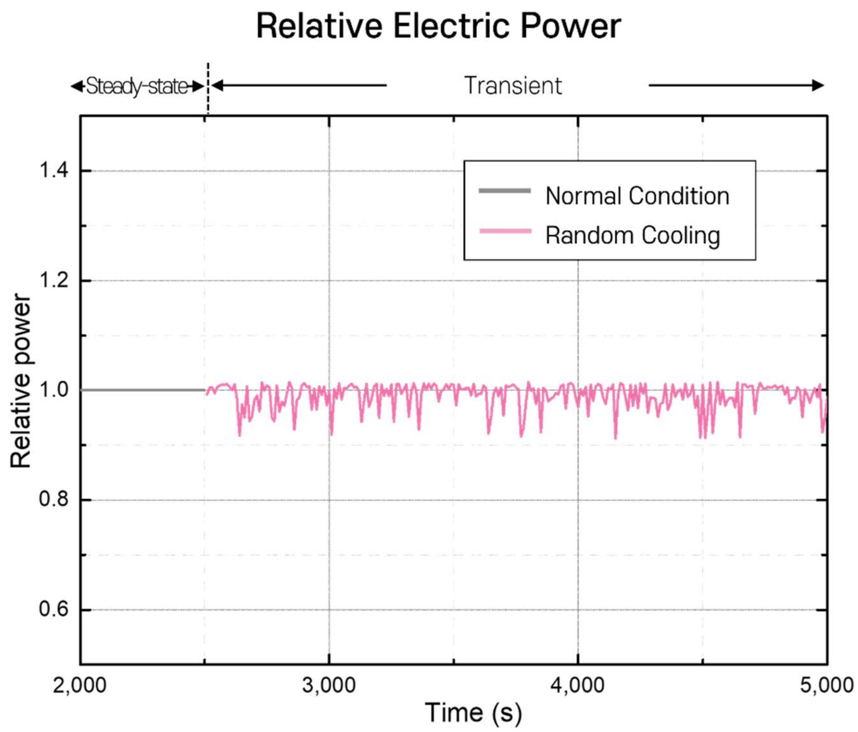


Figure 5.5 Simulation of Random Cooling (3)



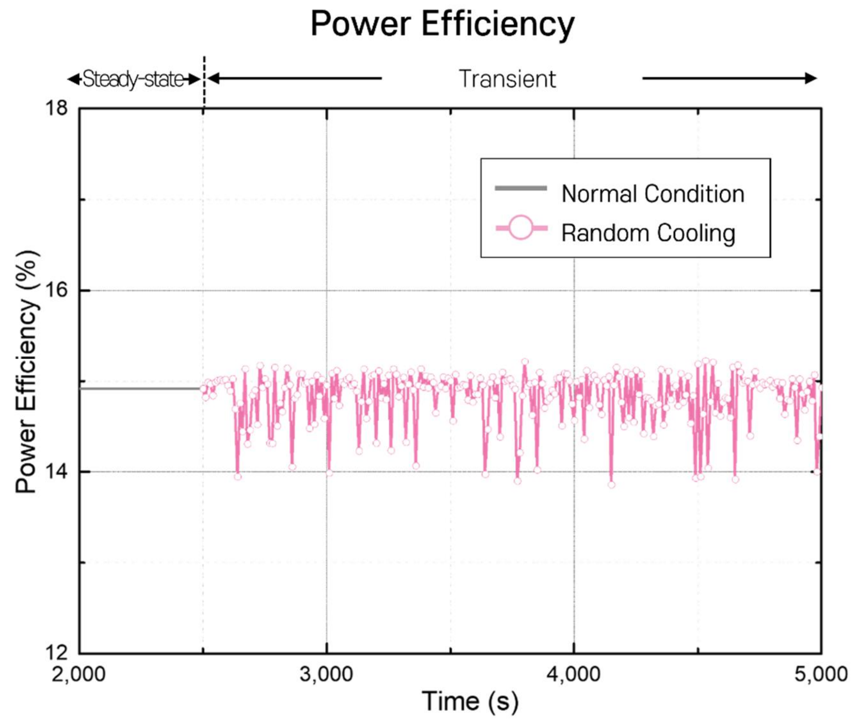


Figure 5.5 Simulation of Random Cooling (4)

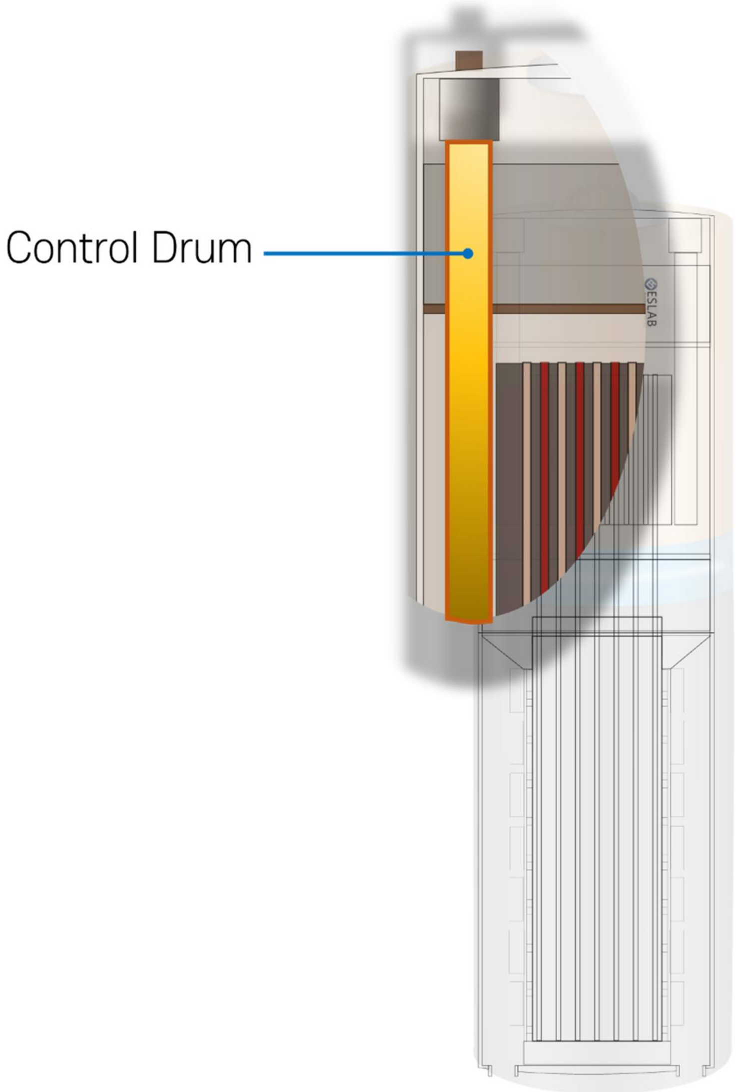


Figure 5.6 The Control Drums of the Micro Fission Battery

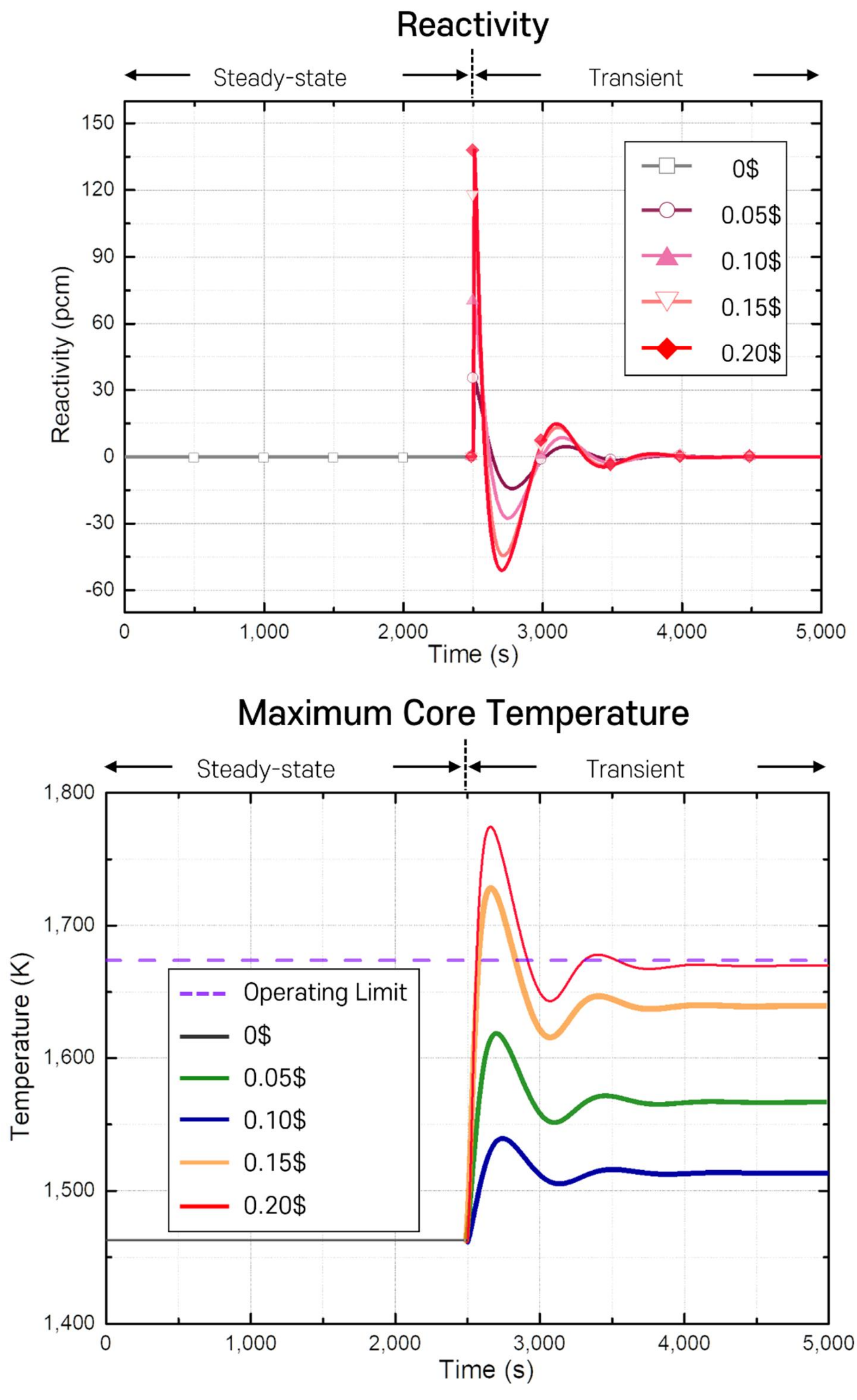
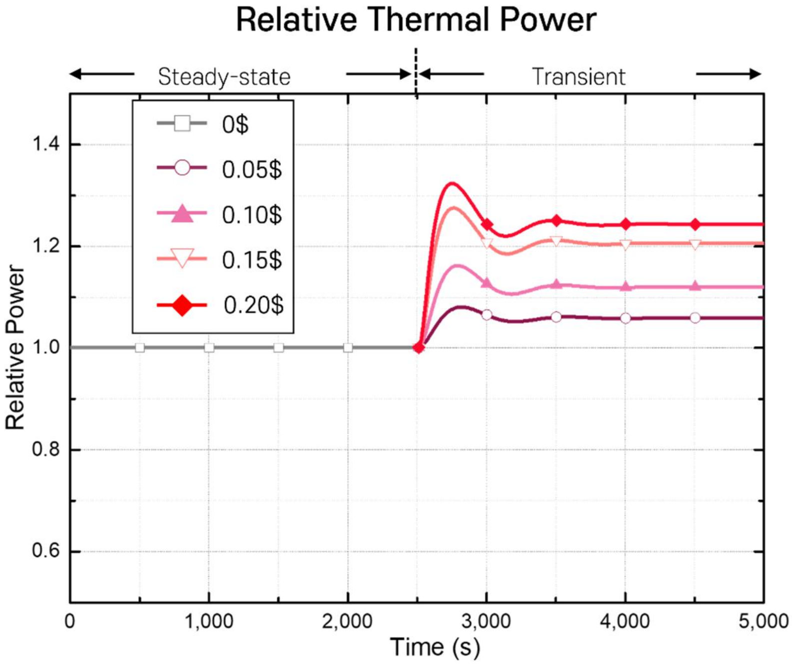


Figure 5.7 Simulation of Unexpected Reactivity Insertion (1)



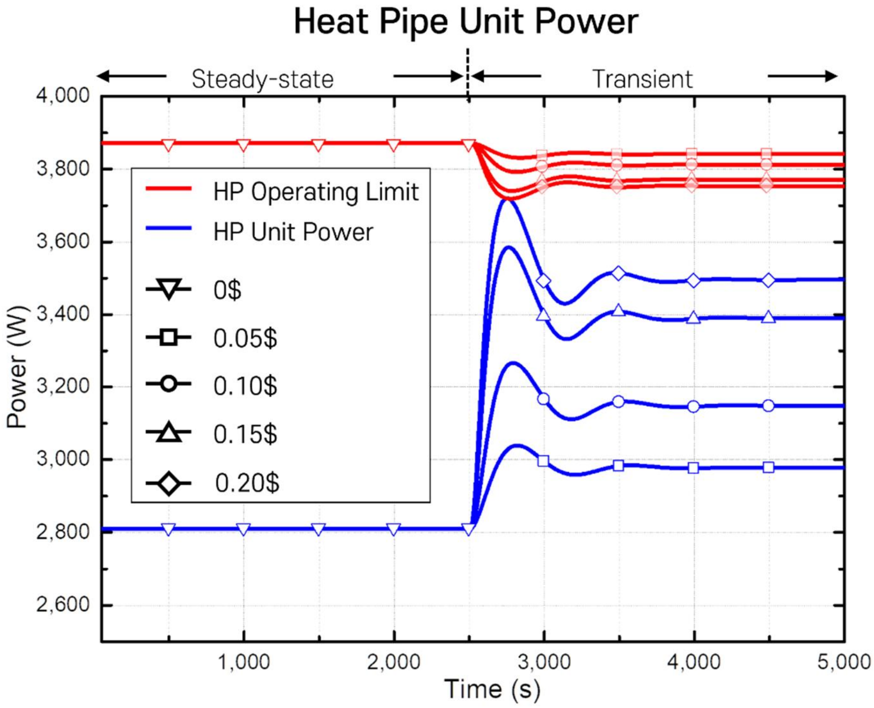


Figure 5.7 Simulation of Unexpected Reactivity Insertion (2)

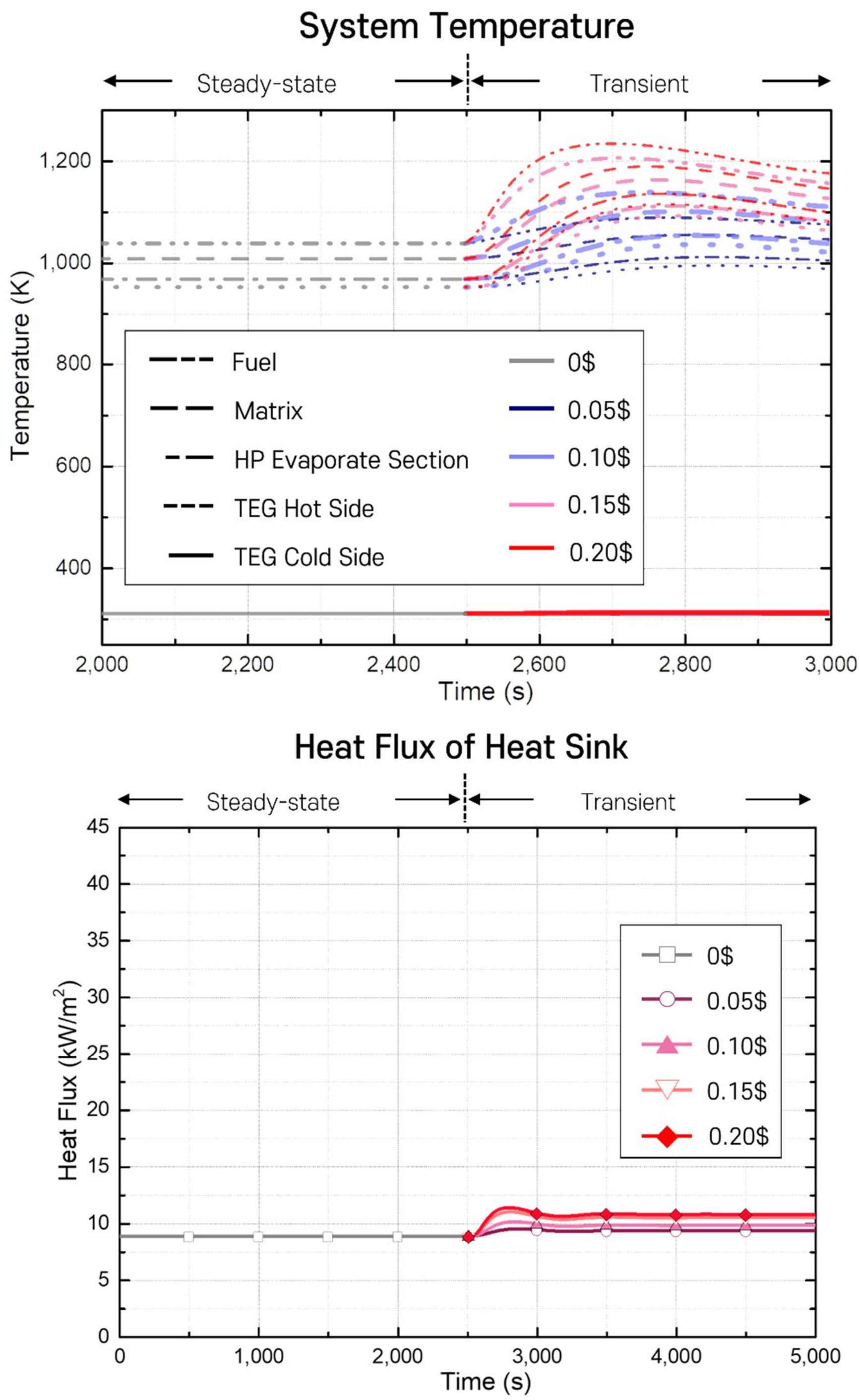


Figure 5.7 Simulation of Unexpected Reactivity Insertion (3)

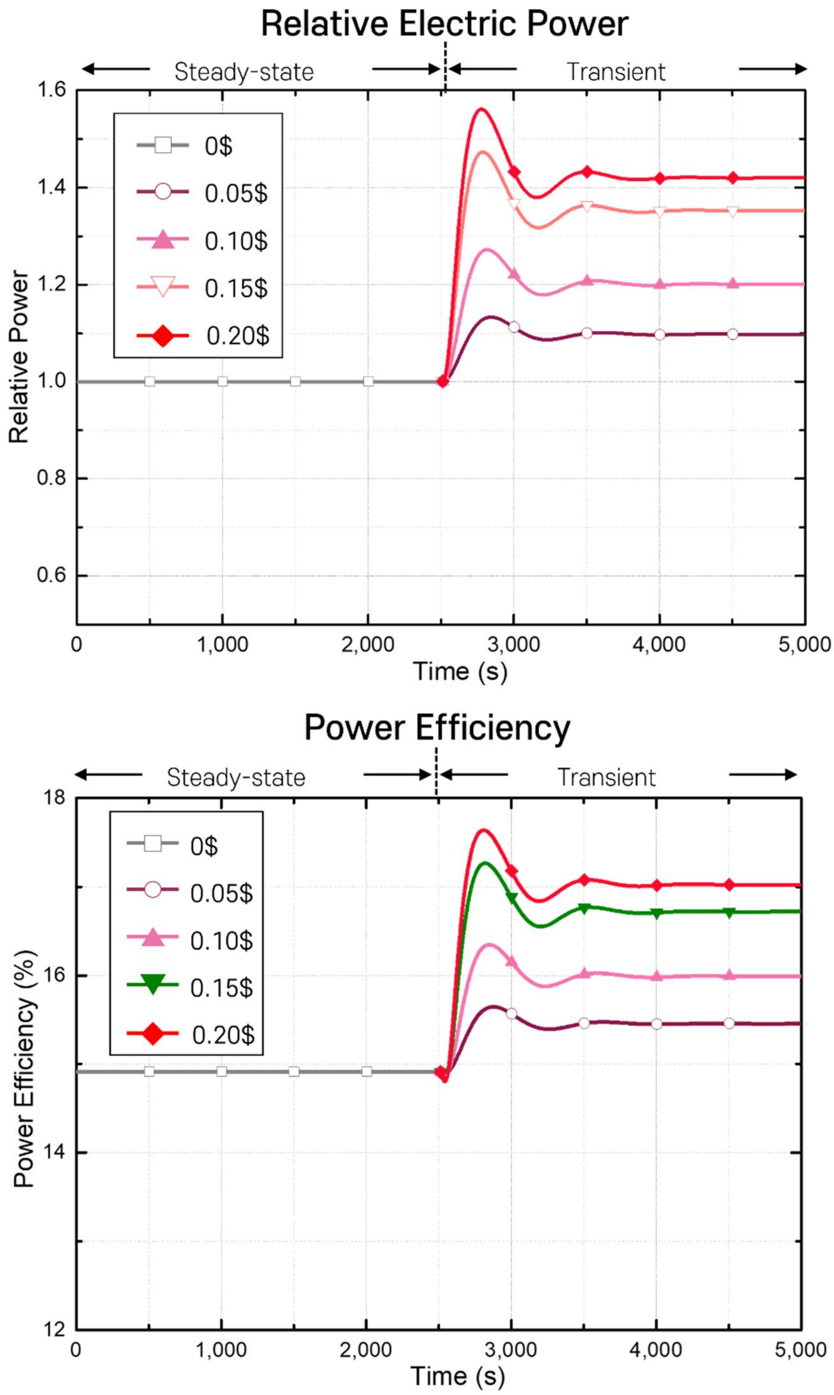


Figure 5.7 Simulation of Unexpected Reactivity Insertion (4)

Chapter 6.
Conclusion

6.1 Summary

The dynamic simulation model is developed using AMESIM for the micro heat pipe fission battery. The system of the fission battery consists of the core, heat pipe and TEG as a power conversion system. The core is modelled using transient heat balance equations with equivalent annulus approximation, the heat pipe model is developed using thermal resistance concepts with considering various heat pipe operational limits. Also, for the TEG model, transient heat balance equations with considering Seebeck & Thomson effects are used. Neutronics and thermal response using point kinetics model is analyzed.

With the developed mode, dynamic behaviors of 10kWe micro heat pipe fission battery for underwater drones are analyzed for various anticipated scenarios. As a simulation result, the system conditions and its power outputs are stably maintained with 15%, even under very serious abnormal heat sink scenarios without any external controls. Also, the simulation proved that the reactor system is operable for a sudden reactivity insertion up to 0.15\$ ~ 0.20\$ without any external controls.

6.2 Significance of the Study

The study shows the provision of a simple and fast analysis tool for transient fission battery behaviors. The developed model can be a useful tool for evaluating dynamic system performance and transient behaviors given fission battery design. It also can be utilized for optimization and improvement of a fission battery system design.

Moreover, the study demonstrates the feasibility of the micro fission battery concept. Its system configuration consisting of a solid core, heat pipe, and thermoelectric generators can be a very stable and robust concept for anonymous underwater drones. Even under serious heat sink and reactivity changes, the system power outputs, temperature, efficiencies can be stably maintained with a little deviation from the nominal conditions.

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Appendix A. Kinetic Parameters

Division	Value	RSD	SD
Prompt Neutron Generation Time from Fission to Next Fission	7.2837E-06	6.5483E-04	4.7696E-09
Prompt Neutron Generation Time Weighted by Adjoint Flux	2.1678E-05	1.9227E-03	4.1680E-08
Prompt Neutron Lifetime Time	2.7366E-05	5.4350E-04	1.4874E-08
The Number of Delayed Neutrons	104,235	-	-
The Number of Total Neutrons	15,000,000	-	-

Group	β_i	RSD	SD
1	2.6053E-04	5.92E-02	1.5432E-05
2	1.2867E-03	2.63E-02	3.3794E-05
3	1.2334E-03	2.99E-02	3.6855E-05
4	2.9511E-03	1.71E-02	5.0489E-05
5	1.2057E-03	2.68E-02	3.2323E-05
6	5.0847E-04	3.78E-02	1.9238E-05
β_{eff}	7.4458E-03	1.06E-02	7.9280E-05

Group	λ_i	RSD	SD
1	1.3351E-02	1.37E-06	1.8259E-08
2	3.2666E-02	2.67E-06	8.7258E-08
3	1.2091E-01	1.31E-06	1.5899E-07
4	3.0386E-01	4.28E-06	1.3011E-06
5	8.5241E-01	4.12E-06	3.5077E-06
6	2.8631E+00	4.25E-06	1.2154E-05

Appendix B. The Burn-Up Calculation

McCARD Burn-Up (Depletion) Calculation Options	
The Number of Neutrons	50,000
Active Cycle	300
Inactive Cycle	150
Cross-Section Data	ENDF-B VIII.0

Multiplication Factor		
EFPD (day)	k_{eff}	SD
0	1.02392	0.00030
0.1	1.02425	0.00028
5	1.02338	0.00030
10	1.02329	0.00029
20	1.02339	0.00029
30	1.02279	0.00027
40	1.02297	0.00030
50	1.02292	0.00028
100	1.02191	0.00029
200	1.02058	0.00030
365	1.01959	0.00028
730	1.01600	0.00030
1,095	1.01360	0.00029
1,460	1.01183	0.00029
1,825	1.00984	0.00027
2,190	1.00820	0.00030
2,555	1.00689	0.00028
2,920	1.00608	0.00029
3,285	1.00373	0.00028
3,650	1.00256	0.00028

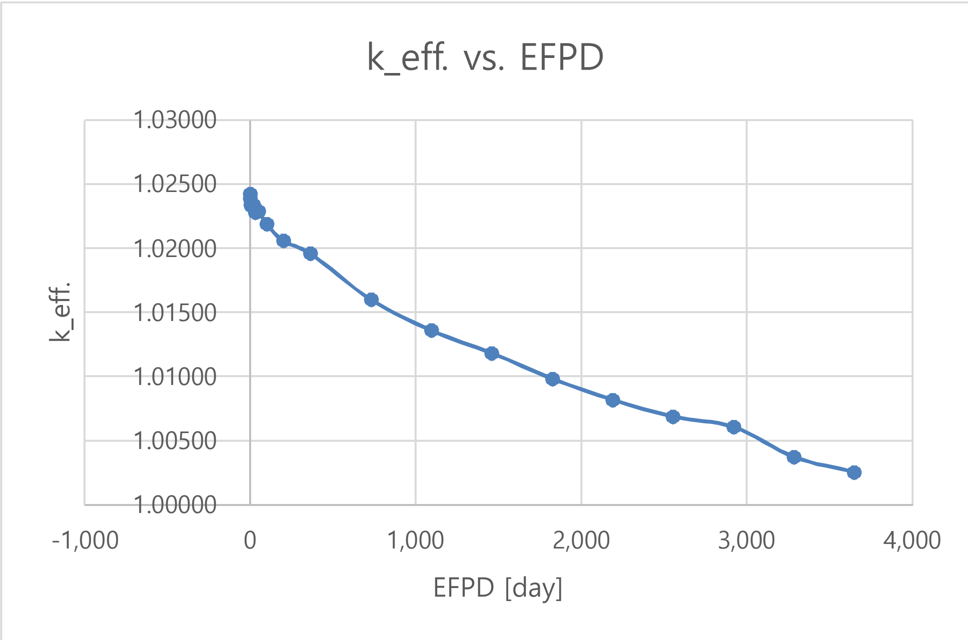

Figure B.1 Burn-Up Calculation of the Fission Battery

Appendix C. Temperature Coefficient of Reactivity Feedback

-	-	Material	Density [g/cc]	Enrichment [wt%]	Thickness [cm]
Fuel Temp. [K]	1200	UN	13.60	9	-
Moderator Temp. [K]	900	Zr2H3	5.60	-	-
Ref. Temp. [K]	900	BeO	3.01	-	8
Cladding. Temp. [K]	900	Zr4	6.56	-	-

-	[pcm / K]
FTC	-0.9341
MTC	-0.0922

국문 초록

최근 세계적으로 마이크로 원자로의 수요가 증가하고 있다. 마이크로 원자로의 특징은 연료 재공급 없이 오랫동안 사용이 가능하며, 크기가 작아 전력이 필요한 곳으로의 이동이 자유롭고 음의 반응도 궤환효과로 인한 높은 안정성 등이 있다. 마이크로의 원자로 관련 선행연구들은 주로 전력변환장치 및 히트파이프 등 원자로의 구성요소에 대한 심층적인 연구들로 활발히 진행되고 있다. 하지만, 개별 구성요소들에 대한 연구에 비해 마이크로 원자로의 통합적 시스템에 대한 연구는 상대적으로 부족한 상태이며, 마이크로 원자로의 상용화를 위해서는 전체 시스템에 대한 연구가 더욱 필요하다.

따라서, 본 연구에서는 기존에 개념 설계된 10kW 수중 드론의 마이크로 히트파이프 핵분열 배터리를 기반으로 아메심 소프트웨어를 사용한 동적 시뮬레이션 모델을 개발하였다. 마이크로 히트파이프의 주 구성요소인 노심 및 원자로 동특성, 히트파이프, 그리고 전력변화체계인 열전소자발전기를 모델링하여 과도상태의 마이크로 원자로를 해석하였다. 이 동적 시뮬레이션 모델을 통해 마이크로 원자로에 발생할 수 있는 열침원 성능 증가 및 감소, 반응도 삽입 등 여러 시나리오에 대한 시뮬레이션을 수행하였다. 이를 통해 마이크로 원자로의 건전성 및 안전성을 확인하였다.

본 원자로 시스템은 수중 드론을 위한 마이크로 히트파이프 핵분열 배터리로 3개의 주요 구성요소 (노심, 히트파이프, 에너지 변환계통)로 나타낼 수 있다. 열전소자발전기는 원자로의 열을 통해 전기에너지를 생산하고, 이 에너지는 집전 장치를 통해 외부로 보내진다. 전체 시스템은 금속케이스로 둘러 쌓여 보호되며, 사고 및 비상 시 케이스 외부를 냉각함으로써 원자로를 안전한 상태로 유지할 수 있다.

노심에서는 열해석을 위해 마이크로 원자로 노심을 단위 셀 (Unit

Cell) 단위로 분리한 후 등가환형근사법을 적용하여 해석하였으며, 히트파이프는 각 노드로 특정하여 노드 간의 열전달을 계산하였다. 또한, 히트파이프의 작동한계를 고려하여 마이크로 원자로가 한계내에서 거동할 수 있도록 설계에 반영하였다. 열전발전기는 열전현상을 반영한 열전달방정식을 사용하여 설계하였다. 또한, 원자로의 과도현상을 분석하기 위해 일점방정식 및 반응도 궤도효과를 반영하여 설계하였다.

이러한 설계를 바탕으로 아메심 소프트웨어를 사용한 동적시뮬레이션 모델을 개발하였다. 아메심(Advanced Modeling Environment for Simulation, AMESIM)은 과도 계산에 특화된 1-D 시스템 시뮬레이션 프로그램으로서 시스템 성능을 가상으로 평가하고 최적화할 수 있다. 노심 모델링에는 노심의 온도분포를 더 세밀하게 확인할 수 있도록 핵연료 부분을 5등분, 축방향으로 11등분하여 모델링 하였다. 또한, 핵연료 부분의 컴포넌트에는 핵반응을 통한 열속을 반영하였으며, 모델의 끝부분이 히트파이프의 증발부와 연결되도록 모델링 하였다. 히트파이프는 총 6개 부분으로 나누어 모델링 하였다. 증발부 및 응축부의 쉘, 윅, 그리고 챔버로 나누어 열전달 모델을 개발하였으며, 히트파이프 증발부는 노심으로부터의 열이 전달되도록 연결이 되 있으며, 응축부는 열전발전기의 고온부와 연결이 되어있다. 또한, 히트파이프 성능한계의 관련 식을 모델링하여 연동하였다. 열전발전기 모델링은 노심과 동일한 방법으로 개발하였다. 열전소자를 총 10등분하여 각 부분에는 열용량 컴포넌트를 사용하고, 저항 컴포넌트를 사용하여 연결하였으며, 각 열용량 컴포넌트에는 줄열에 의한 열속을 반영하여 개발하였다. 열전발전기의 저온단은 열침원의 냉각효과를 모사할 수 있는 컴포넌트를 사용하였다. 일점방정식과 반응도 궤도효과는 미분방정식의 해를 구하는 컴포넌트를 사용하여 모델링하였으며, 결과값으로 계산된 반응도 및 중성자수가 노심부분과 연결되어 출력과 중성자 거동이 서로 연관되어 계산되도록 설계하였다. 완성된 모델은 Engineering Equation Solver(EES)를

사용한 정상상태의 주요부분의 값과 비교하여 성공적으로 검증하였다.
개발된 모델로 마이크로 히트파이프 원자로 동적 시뮬레이션을 실시하였으며, 총 2가지의 경우(열침원 과도현상 및 반응도 삽입현상)를 고려하였다. 시뮬레이션 결과 열침원의 냉각 성능이 극한으로 변화되는 상황에서도 출력이 효율이 15% 내로 유지되고, 급작스런 반응도 변화에도 제어드럼 없이도 $0.15 ~ $0.20까지 배터리의 운용이 가능한 것을 확인하였다.

본 연구를 통해 핵분열 배터리의 과도현상 해석에 아메심 프로그램을 적용이 가능한 것을 확인하였다. 아메심을 사용한 모델링은 동적 시스템 성능 평가 및 과도현상 해석에 유용한 방법으로 쓰일 수 있으며, 배터리의 성능 최적화 및 개선에 또한 사용될 수 있음을 확인하였다. 또한, 마이크로 핵분열 배터리 개념 설계의 타당성을 본 연구에서 보여주었다. 본 연구의 고체 노심, 히트파이프와 열전발전기로 구성된 시스템은 수중 드론에 사용되기에 적합하며, 다양한 냉각성능 및 반응도 변화에도 정상상태의 성능을 크게 벗어나지 않고 유지하는 안정성을 보여주었다는데 큰 의의가 있다.

주요어 마이크로 히트파이프 원자로, 열전발전기, 마이크로 히트파이프 원자로 동적시뮬레이션, 아메심 시뮬레이션

학번 : 2021-29347

감사의 글

연구실로 부푼 마음과 설렘을 가지고 처음으로 출근한 지 벌써 약 2년의 세월이 흘렀음을 지금 학위논문의 ‘감사의 글’을 쓰면서 실감하게 됩니다. 다시 생각해보면, 새로운 환경에서 군복이 아니라 사복을 입고 출근한다는 막연한 기대보다는 제가 학부 때 전공하지 않았던 학문을 배운다는 것이 더 큰 부담감이 더 컸었으며, 10년 가까이 연필을 놔서 대학원 수업을 잘 따라갈 수 있을까에 대한 걱정도 많이 했었던 것 같습니다. 그래도 이렇게 ‘감사의 글’을 쓸 수 있는 순간까지 온 과정을 돌이켜보면 저의 노력과 힘만으로는 올 수 없었던 것 같습니다. 교수님을 비롯하여 연구실 동생들, 그리고 우리 가족들의 응원 덕분에 이렇게 무사히 학위를 마무리할 수 있었습니다. 이 글을 통해서라도 그 분들께 감사의 말씀을 드리고 싶습니다.

먼저, 저를 받아 주시고 열정으로 지도해주신 김응수 교수님께 감사드리고 싶습니다. 군 위탁생을 처음으로 받으셔서 많이 부담도 되셨을 것 같습니다. 수영을 전혀 할 줄 모르는 어른에게 영법을 가르치는 것이 매우 어려운 것처럼, 원자핵공학과 관련이 전혀 없는 삶을 살았던 저에게 기본부터 가르쳐 주시고, 지도해 주셔서 감사드립니다. 몇 주 동안 끙끙대며 고민하던 연구에도 핵심을 관통하는 교수님의 지도로 어려움을 해결할 때마다 “와!” 하는 탄성이 나올 때가 여러 번 있었던 기억이 생생합니다. 군으로 복귀해서도 교수님의 가르침을 잊지 않고, 항상 성실하게 근무하겠습니다.

또한, 연말에 바쁘신 와중에도 학위심사를 해 주신 최성열 교수님께도 감사의 말씀을 전합니다. 저의 연구주제가 더 발전할 수 있도록 많은 조언과 의견을 아낌없이 주셔서 다시 한번 감사드립니다.

대학원에서 얻은 것 중 가장 큰 것은 석사 학위에 따른 전문지식과 더불어 ESLAB 동생들과의 인연입니다. 우리나라 최고의 대학원에서 수학하고 있는 동생들과 같은 공간에서 연구했다는 것만으로도 저의 자랑이 되었고, 자부심이 되었습니다. 올 초부터 연구실의 최고 연장자 자리를 기쁨으로 내어드릴 수 있게 해주시고, 아기 아빠로서 강한 동지애를 공유할 수 있었던 시호 선배님. 사랑스러운 막내의 자리를 1년만 해서 아쉬울 수도 있겠지만, 후배보다는 선배의 모습이 더 잘 어울리는 경준이. 연구실의 군기를 책임지며(?), 사람들에게 신뢰감을 주는 태수. 연구뿐만 아니라 구기종목은 다 잘하는 연구실의 멀티플레이어 영범이. 연구 성과에 놀라고, 야구 실력에 두 번 놀라게 한 수산이. 조용하지만 입학 처음부터 잘 챙겨준 진현이. 주변 사람들을 세심하게 배려해주고, 엄청난 센스로 점심 메뉴를 추천해주는 예린이. 성난 근육을 감추고 있는 친절한 희상이. 랩장으로 큰 행사를 여러 번 성공적으로 임무 완수한 책임감 있는 태훈이. 부러워할 정도의 대단한 도전 정신을 가진 훈이. 조용하지만 가위바위보에는 가장 진심인 진우. 석사과정 경험자로서 모든 부분을 물심양면 도와준 꼼꼼한 준성이. 대학원 수업부터 축구 활동까지 같이 함께하며 도와준 도현이. 대화할수록 남을 매우 기분 좋게 해주는 주룡이. 몬스터에 진심이며, 에너지가 가장 넘치는 태환이. 20대의 패기를 느끼게 해준 다경이. 학업과 직장 생활을 같이 너끈히 해내는 규병이. 이제 연구실에는 없지만 의젓하고 다부진 어깨가 멋진

해윤이와 연구실의 달콤한 티타임을 주관해주었던 소현이. 모두의 미래가 너무나 기대가 되고, 소중한 시간을 만들어준 연구실 동생들께 감사하다는 말씀을 드리고 싶습니다.

또한, 대학원에 입학하기 전부터 저의 정신적 지주 역할을 해 주신 도균 선배님. 자신과 관련이 없는 저의 졸업 연구에도 불구하고, 자신의 시간을 아끼지 않고 도와주시며, 귀찮다고 느껴지실 만큼 많은 질문을 하였음에도 항상 친절하게 가르쳐 주셨던 선배님께 정말 감사의 말씀을 드립니다. 선배님과 같이 지낸 시간동안 군인으로서, 한 가정의 가장으로서, 또한 인생의 선배로서 많은 것을 느끼고 배울 수 있었습니다.

마지막으로, 지난 2년동안 임신부터, 출산까지, 그리고 육아까지 하면서 대학원 생활을 도와준 사랑하는 아내, 예랑이에게 가장 큰 고마움을 전하고 싶습니다(존재만으로도 너무 사랑스러운 서율이 역시 건강하게 자라주고 있어서 너무 고마워). 지금까지 한 가정의 가장으로 올바르게 성장할 수 있게 무한한 사랑으로 아들을 위해 기도해주시고 아껴주신 부모님과, 대학원 생활하면서 자주 찾아 뵙지 못하였지만 부산에 갈 때마다 반겨주시며, 항상 넘치는 사랑으로 기도해주시는 저의 두번째 부모님께 감사의 말씀을 드립니다. 또한, 새벽기도로 날마다 손자를 위해 기도해주시는 할아버지와 할머니, 남아공에서 항상 철부지 동생을 기억하고 챙겨주는 형과 형수님, 서희까지 감사합니다. 마지막으로, 지금까지 저의 길을 인도해주시고, 앞으로의 길도 계획하시는 하나님께 감사드립니다.