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Development of Thermal Design Code on Micro Heat Pipe Reactor Using Engineering Equation Solver (EES)

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1. Introduction

It is important to have a system that can reliably supply power to special-purpose unmanned underwater vehicles. Although widely used chemical energy-based technologies are highly mature and are used in many areas, they have limited capacity to charge at once. A nuclear reactor battery technology that can overcome these limitations, which have good mobility, and can be powered continuously for years without additional charging, can be an alternative.

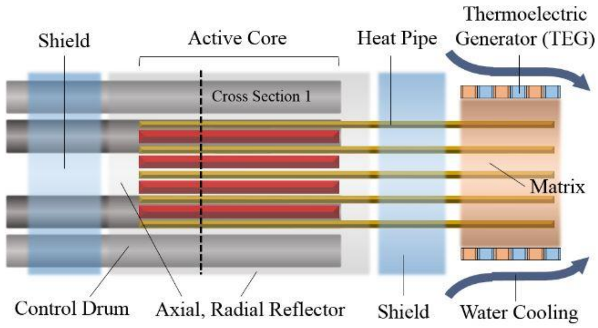
In this respect, this study suggested a micro reactor system that transfers heat through a heat-pipe without coolant flow and converts the transferred heat into electric power through a thermo-electric generator (TEG). In order to demonstrate feasibility of proposed reactor design, a system-level thermal design code, which solves thermal model and related equations for each component (Core, Heat-Pipe, TEG, etc.), was developed using Engineering Equation Solver (EES).

This paper summarizes the overall implementation of the system code for heat pipe reactor analysis. Section 2 describes the conceptual design of the proposed reactor system, and Section 3 describes the thermal design methodology in each region. Section 4 describes the design limitation guidance of the code. Section 5 presents the conceptual design results for the 100kWe reactor system as an example.

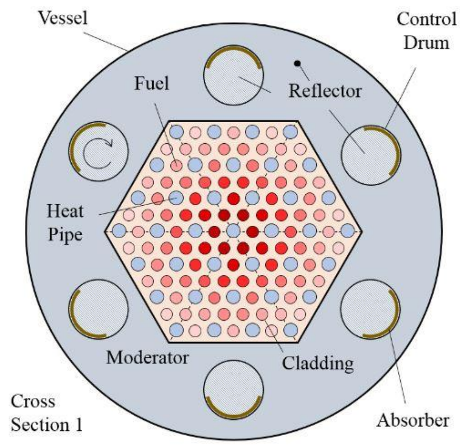
2. Design of Micro Heat Pipe Reactor

The conceptual design of the micro heat-pipe reactor system proposed in this study is shown in Figure 1. As shown in Figure 1 (a), the heat generated by fission in the core region is transferred to the power conversion system through heat-pipes without coolant flow. Thermo-electric generator (TEG) is adopted as an electricity generation system, considering the advantages for special-purpose usage such as its intrinsic modularity and mechanical characteristics having no driving parts.

Figure 1 (b) shows a cross section of the core region. The proposed micro reactor takes thermal neutron type in which fuel pins and heat-pies are plugged into a hexagonal moderator block. A reflector surrounds the core region to prevent neutron leakage, and six control drums that can control the criticality of reactor are installed in the reflector area, as shown in Figure 1 (b). The heat generated by the fission is transferred to the heat pipe evaporation side in core region. In the power conversion part, the heat transferred is distributed to the thermo-electric module through the hexagonal metal matrix, and the residual heat is removed by the convection of water flowing through the cold junction of TE module.



(a)



(b)

Figure 1. Design of Micro Heat-Pipe Reactor

The materials of each component (fuel, moderator, heat-pipe, thermo-electric element, etc.) in Figure 1 can be flexibly selected according to the operating power, temperature, etc. Thermal analysis of the current reactor design was performed by dividing it into 1) core region, 2) heat-pipe region, and 3) thermo-electric generator & heat sink region. The thermal model and related equations are summarized in the following section.

3. Thermal Design Methodology

3.1 Reactor Core

The core consists of nuclear fuel, heat pipes, and a moderator matrix between them, as shown in Figure 2(a), where heat from the fuel passes through the matrix to the heat pipes. The core is divided into unit cells as shown in

Figure 2(b) for heat calculation and the unit cells are approximated into an equivalent annulus as shown in Figure 2(c) for simplifying heat transfer calculation. Equivalent annular approximation is simple, but it is widely used in reactor conceptual design and analysis as it reflects actual physics well.[1]

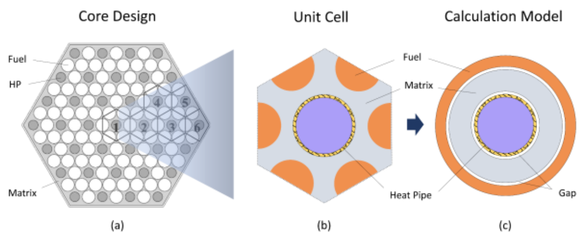


Figure 2. Reactor Core Cross Section, Calculation Model

The calculated area consists of fuel rod, fuel-matrix gap, matrix, matrix-heat pipe gap and heat pipe. The code calculates the temperature distribution and heat flux through radial thermal resistance calculations. The fuel rods were calculated in a cylindrical shape rather than an annular shape, as shown in Figure 3. Figure 3(b) approximates the three fuel rods as a single fuel rod, and Figure 3(c) calculated as three individual fuel rods.

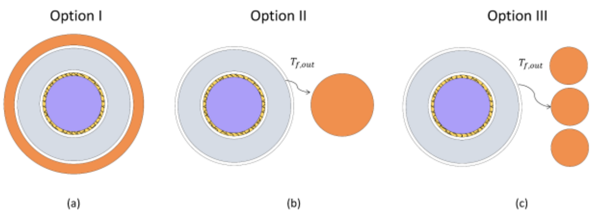


Figure 3. Equivalent Annulus Approximation, Modification

The thermal resistance at each part is as follows:

- Matrix - Heat pipe gap

$$(T_{m,in} - T_{hp,w}) = \frac{q'}{h_{gap,m-hp}\pi D_{hp,w}} \quad (1)$$

- Inside the Matrix

$$(T_{m,out} - T_{m,in}) = \frac{q'}{2\pi k_m} ln\left(\frac{r_{m,out}}{r_{m,in}}\right) \quad (2)$$

- Fuel - Matrix gap

$$(T_{f,in} - T_{m,out}) = \frac{q'}{h_{gap,f-m}\pi D_{m,out}} \quad (3)$$

- Fuel rods

(a) $$(T_{f,out} - T_{f,in}) = \frac{\dot{q}}{16k_f}(D_{f,out}^2 - D_{f,in}^2) + \frac{\dot{q}D_{f,out}^2}{8k_f}\ln\left(\frac{D_{f,out}}{D_{f,in}}\right) \quad (4)$$

(b) $$(T_{f,out} - T_{f,in}) = \frac{\dot{q}}{16k_f}(3D_{fuel}^2) \quad (5)$$

(c) $$(T_{f,out} - T_{f,in}) = \frac{\dot{q}}{16k_f}(D_{fuel}^2) \quad (6)$$

3.2 Heat Pipe

With lumped parameter model, heat pipes are regarded by nodes, as shown in Figure 4, to calculate heat transfer between each node of the heat pipes in steady state. The thermal resistance is calculated based on the material, fluid properties and geometries of each part, and the temperature difference between the heat pipe evaporator and condenser as follows.

$$\begin{aligned} T_e - T_c = q\{&\frac{1}{2\pi r_0 L_e}\left[\frac{1}{h_e} + \frac{r_o - r_i}{2k_s}\right] \\ &+ \frac{1}{2\pi r_i L_e}\left[\frac{r_o - r_i}{2k_s} + \frac{r_i - r_w}{2k_w}\right] + \frac{1}{2\pi r_w L_e}\left[\frac{r_i - r_w}{2k_w}\right] \\ &+ \frac{1}{2\pi r_w L_c}\left[\frac{r_i - r_w}{2k_w}\right] + \frac{1}{2\pi r_i L_c}\left[\frac{r_o - r_i}{2k_s} + \frac{r_i - r_w}{2k_w}\right] \\ &+ \frac{1}{2\pi r_0 L_c}\left[\frac{1}{h_c} + \frac{r_o - r_i}{2k_s}\right]\} \end{aligned} \quad (7)$$

where L, h, r, k represent the length, heat transfer coefficient, radius, thermal conductivity of each region, respectively, and subscript e, s, w, c, o, i represent evaporator, shell, wick, condenser, heat pipe out side, shell-wick interface, respectively.

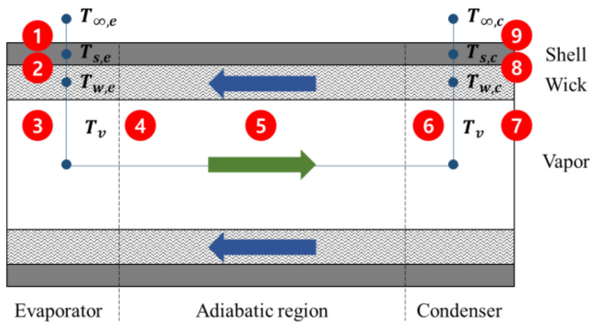


Figure 4. Heat Pipe Lumped Parameter Model

3.3 Thermoelectric Generator & Heat Sink

TEG converts heat into electricity using thermoelectric effects, which refers to a phenomenon involving heat and electricity. There are three typical thermoelectric effects and their governing equations are as follows:

- Seebeck Effect

$$E_s = \alpha \Delta T \quad \alpha : Seebeck\ coefficient \quad (8)$$

- Peltier Effect

$$\dot{q}_p = \pi j \quad \pi : Peltier\ coefficient \quad j : current \quad (9)$$

- Thomson Effect

$$\dot{q}_{th} = -\tau j \nabla T$$
$$\tau : Thomson\ coefficient \quad (10)$$

From the governing equations above, the electrical output generated by the TEG is induced as follows:

$$\dot{W}_n = n[\alpha I(T_h - T_c) - I^2 R] = nI^2 R_L \quad (R_L : Load\ resistance) \quad (11)$$

where n, I, T_h, T_c, R represent the number of TE modules, current flowing through the TE module, temperature of the TEG hot, cold side, electrical resistance, respectively. The maximum power conversion efficiency of TEG is as follows:

$$\eta_{th,max} = \left(1 - \frac{T_c}{T_h}\right) \frac{\sqrt{1 + Z\overline{T}} - 1}{\left(\sqrt{1 + Z\overline{T}} + \frac{T_c}{T_h}\right)} \quad (12)$$
$$(R_L/R = \sqrt{1 + Z\overline{T}})$$

4. Design Limitation Guidance

To ensure that the system is physically operable, operating restrictions are established in each region, and the user is guided if exceeded.

In the core area, the geometry validity is verified such that the diameter of the unit is greater than the sum of the diameter of the fuel rods and the heat pipes, and the radius of the unit is greater than the diameter of the fuel rods. In addition, core integrity is checked so that the maximum temperature of the core and matrix does not exceed 1700K and 1270K, respectively.

Physical factors that limit heat pipe operation exist and should be considered in the design. By calculating capillary limit, sonic limit, entrainment limit, boiling limit, and viscous limit from the code, user can check through the plot to see if the design conditions are within the heat pipe performance limits, as shown in Figure 5.

The heat flux through the heat sink in the TEG-Heat sink area must be designed to be lower than the onset of nucleate boiling (~6800 W/m^3). If this is exceeded, code will guide the user to modify it.

5. Concept Design of 100kW$_e$ Reactor

In this section, as an example of the design, the 100kWe micro heat pipe reactor is designed and introduced in this code. The overall execution screen of the code designed as previously described is shown in Figure 7. As guided at the bottom of the figure, the example is well designed within the design limitations. The core temperature profile is shown in Figure 6, where the temperature in each region is all designed below the safety limit with enough margin. User-configured values and calculation results are summarized in Table 1.

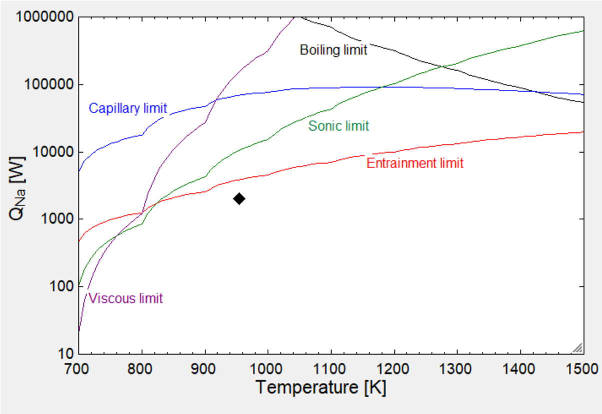


Figure 5. Heat Pipe Performance Limit

Table 1. Design of 100kW$_e$ Micro Heat Pipe Reactor

Design Parameter	Value
Core Thermal Power (kW$_t$)	665.2
Electric Power (kW$_e$)	100.3
Efficiency (%)	15.3
Core Diameter (m)	1.2
Heigh of Active Core (m)	1.2
Fuel Diameter (m)	0.03
Heat Pipe Working Fluid	Na
Heat Pipe Diameter (m)	0.045
Heat Pipe Length (m)	4.9
TEG Material	PbTe
TE Element Length (m)	0.0112
Number of TE Elements	119,669
T_{max_core} (K)	1070
$T_{fuel,surf}$ (K)	1050
$T_{hp,eva}$ (K)	968
$T_{hp,con}$ (K)	950.0
T_{h_TEG} (K)	950.0
T_{c_TEG} (K)	303.7
T_{c_sink} (K)	298.0

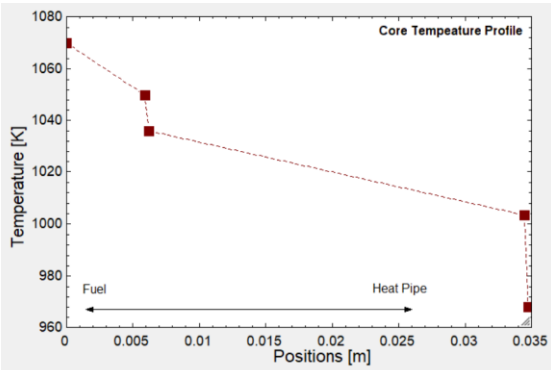


Figure 6. Core Temperature Profile

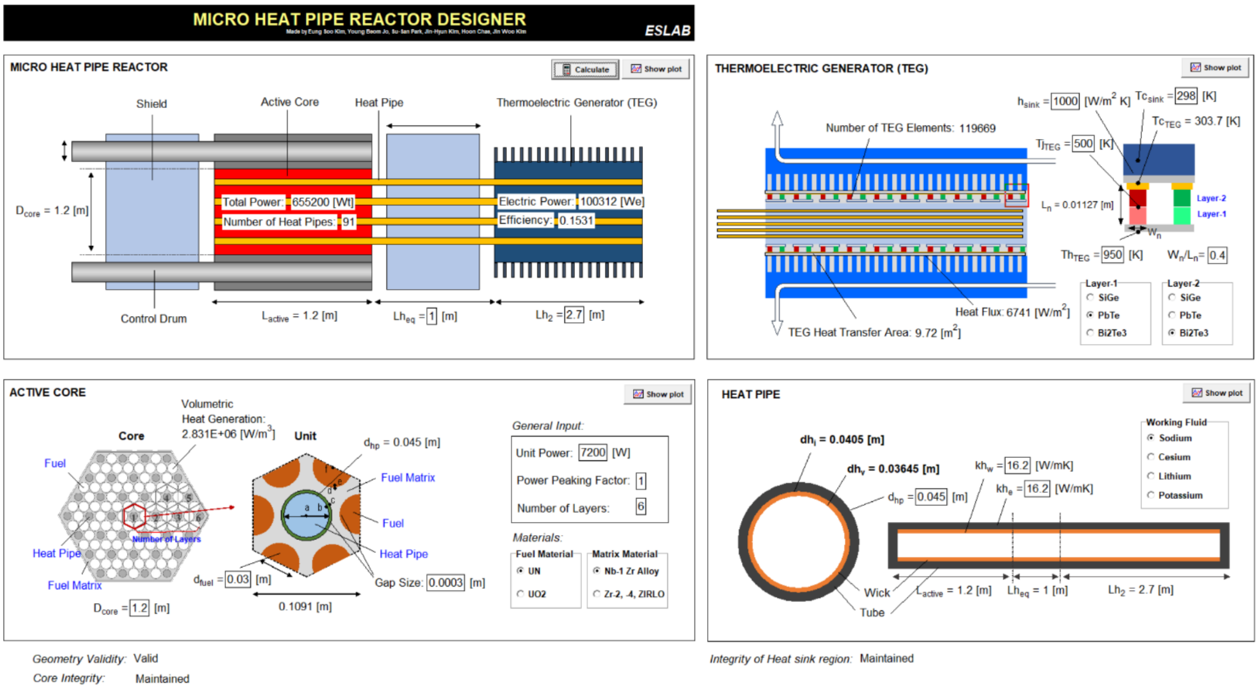


Figure 7. Code Execution Screen

6. Summary

This paper introduces the thermal design code of the micro heat pipe reactor system using EES. The reactor system module consists of a core, heat pipe and TEG, designed with temperature and heat flux between each module as a boundary condition. In the core region, heat transfer between components was calculated by equivalent annulus approximation. Lumped parameter model was used to calculate heat transfer between each node in Heat pipe. In the TEG region, thermal design is performed using energy governing equation of TEG. With this code, thermal design was performed on 100kW$_e$ power, and demonstrated feasibility of the code by obtaining reasonable temperature, heat flux results. It allows users to design with the desired value and to design within the physical range of operation. We developed engineering design code which is user friendly that allows users to easily check design results based on input parameters.

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