2021. 10. 21. - 22. KNS POSTER

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

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Introduction

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.
- 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)**.

Design of Micro Heat Pipe Reactor

Design of Micro Heat Pipe Reactor

- 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**.
- 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.

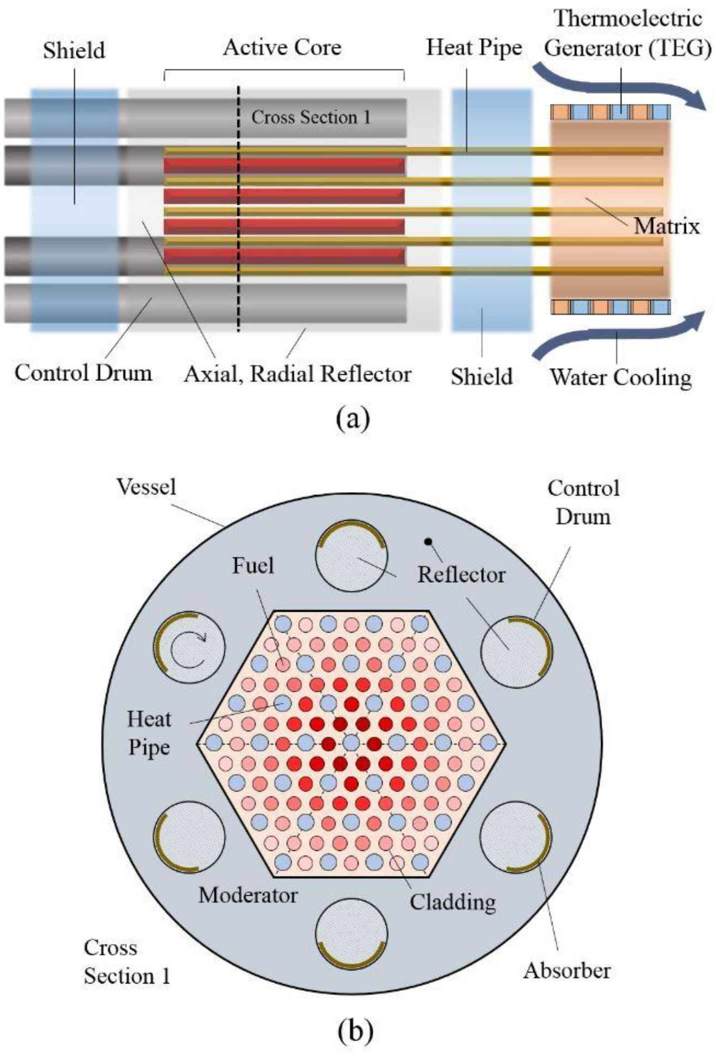


Figure 1. Design of Micro Heat-Pipe Reactor

Thermal Design Methodology

Reactor Core

- The core consists of nuclear fuel, heat pipes, and a moderator matrix between them. 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.
- 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.

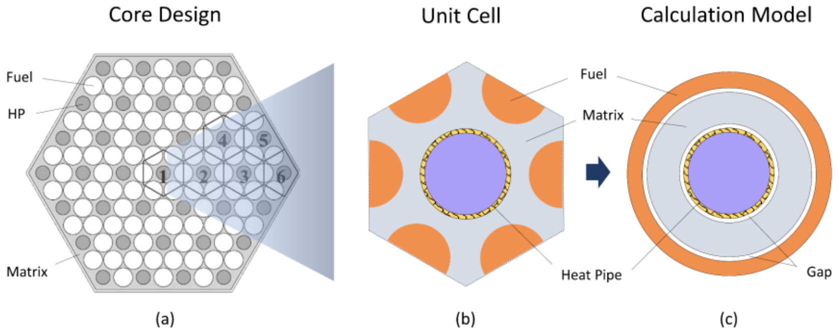


Figure 2. Reactor Core Cross Section, Calculation Model

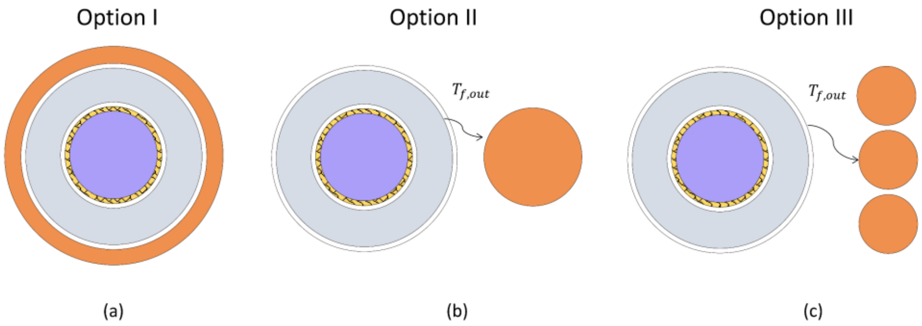
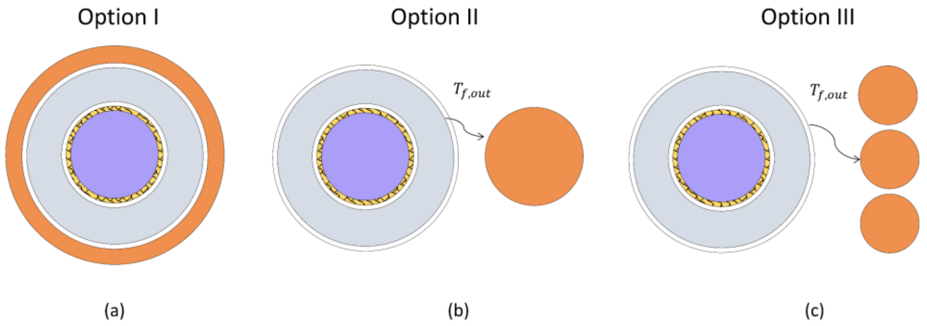


Figure 3. Equivalent Annulus Approximation, Modification

Reactor Core

- Thermal resistance at each part

Matrix - Heat pipe gap	$\left(T_{m,in} - T_{hp,w}\right) = \frac{q'}{h_{gap,m-hp}\pi D_{hp,w}}$
Inside the Matrix	$\left(T_{m,out} - T_{m,in}\right) = \frac{q'}{2\pi k_m} ln\left(\frac{r_{m,out}}{r_{m,in}}\right)$
Fuel - Matrix gap	$\left(T_{f,in} - T_{m,out}\right) = \frac{q'}{h_{gap,f-m}\pi D_{m,out}}$
Fuel rods (a)	$\left(T_{f,out} - T_{f,in}\right) = \frac{\dot{q}}{16k_f}\left(D_{f,out}^2 - D_{f,in}^2\right) + \frac{\dot{q}D_{f,out}^2}{8k_f}\ln\left(\frac{D_{f,out}}{D_{f,in}}\right)$
Fuel rods (b)	$\left(T_{f,out} - T_{f,in}\right) = \frac{\dot{q}}{16k_f}\left(3D_{fuel}^2\right)$
Fuel rods (c)	$\left(T_{f,out} - T_{f,in}\right) = \frac{\dot{q}}{16k_f}\left(D_{fuel}^2\right)$



(a) (b) (c)

Figure 3. Equivalent Annulus Approximation, Modification

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.
- The **temperature difference** between the heat pipe evaporator and condenser as follows.

$$T_e - T_c = q\{\frac{1}{2\pi r_0 L_e}\left[\frac{1}{h_e} + \frac{r_o - r_i}{2k_s}\right] + \frac{1}{2\pi r_i L_e}\left[\frac{r_o - r_i}{2k_s} + \frac{r_i - r_w}{2k_w}\right] + \frac{1}{2\pi r_w L_c}\left[\frac{r_i - r_w}{2k_w}\right]$$
$$+ \frac{1}{2\pi r_i L_c}\left[\frac{r_o - r_i}{2k_s} + \frac{r_i - r_w}{2k_w}\right] + \frac{1}{2\pi r_0 L_c}\left[\frac{1}{h_c} + \frac{r_o - r_i}{2k_s}\right]$$

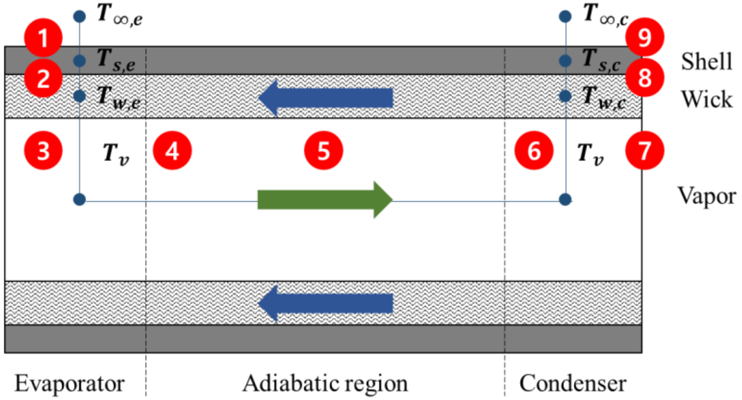


Figure 4. Heat Pipe Lumped Parameter Model

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	$E_s = \alpha \Delta T$ $\alpha : Seebeck\ coefficient$
Peltier Effect	$\dot{q_p} = \pi j$ $\pi : Peltier\ coefficient$ $j : current$
Thomson Effect	$\dot{q_{th}} = -\tau j \nabla T$ $\tau : Thomson\ coefficient$

- The **electrical output** generated by the TEG and the **maximum power conversion efficiency** of TEG are as follows.

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

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

Design Limitation Guidance

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. 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. 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**.
- 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/m3).

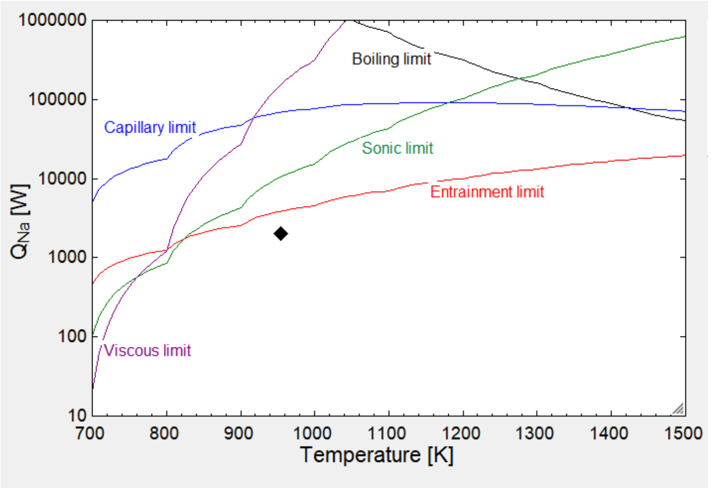
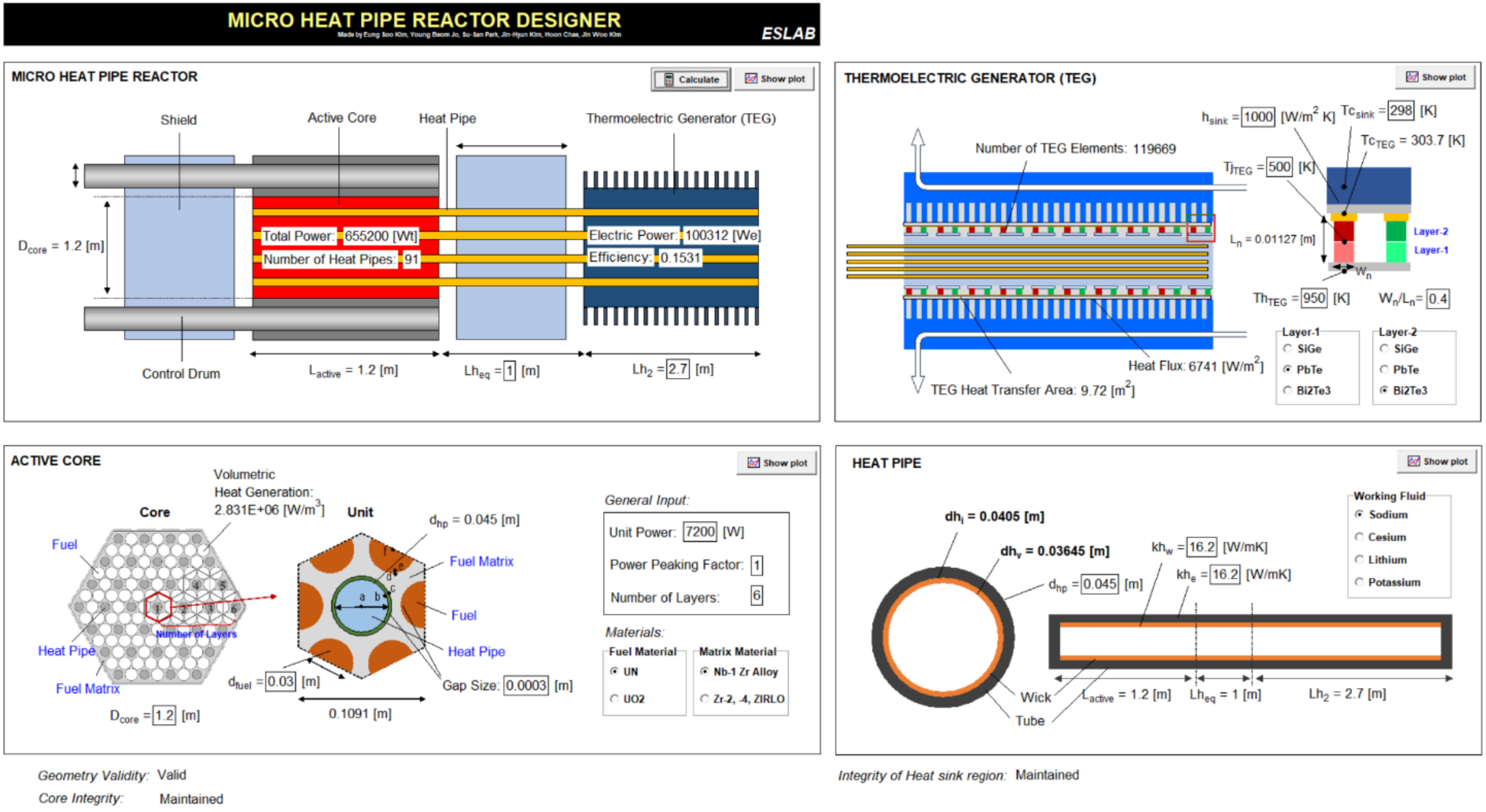


Figure 5. Heat Pipe Performance Limit

Concept Design of 100kW$_e$ Reactor

Concept Design of 100kW$_e$ Reactor

- As an example of the design, the **100kW$_e$** 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.



MICRO HEAT PIPE REACTOR DESIGNER

Made by Eung Soo Kim, Young Beom Jo, Su-San Park, Jin-Hyun Kim, Hoon Chae, Jin Woo Kim

ESLAB

MICRO HEAT PIPE REACTOR

D_{core} = 1.2 [m]

Total Power: 655200 [Wt]

Number of Heat Pipes: 91

Electric Power: 100312 [We]

Efficiency: 0.1531

L_{active} = 1.2 [m]

Lh_{eq} = 1 [m]

Lh_2 = 2.7 [m]

THERMOELECTRIC GENERATOR (TEG)

h_{sink} = 1000 [W/m^2 K]

Tc_{sink} = 298 [K]

Tc_{TEG} = 303.7 [K]

Number of TEG Elements: 119669

Tj_{TEG} = 500 [K]

L_n = 0.01127 [m]

Layer-2

Layer-1

W_n

Th_{TEG} = 950 [K]

W_n/L_n = 0.4

Heat Flux: 6741 [W/m^2]

TEG Heat Transfer Area: 9.72 [m^2]

Layer-1
○ SiGe
● PbTe
○ Bi2Te3

Layer-2
○ SiGe
○ PbTe
● Bi2Te3

ACTIVE CORE

Volumetric Heat Generation: 2.831E+06 [W/m^3]

d_{hp} = 0.045 [m]

d_{fuel} = 0.03 [m]

Gap Size: 0.0003 [m]

D_{core} = 1.2 [m]

0.1091 [m]

General Input:

Unit Power: 7200 [W]

Power Peaking Factor: 1

Number of Layers: 6

Materials:

Fuel Material
● UN
○ UO2

Matrix Material
● Nb-1 Zr Alloy
○ Zr-2, -4, ZIRLO

HEAT PIPE

dh_i = 0.0405 [m]

dh_v = 0.03645 [m]

d_{hp} = 0.045 [m]

kh_w = 16.2 [W/mK]

kh_e = 16.2 [W/mK]

L_{active} = 1.2 [m]

Lh_{eq} = 1 [m]

Lh_2 = 2.7 [m]

Working Fluid
● Sodium
○ Cesium
○ Lithium
○ Potassium

Geometry Validity: Valid

Core Integrity: Maintained

Integrity of Heat sink region: Maintained

Figure 7. Code Execution Screen

Concept Design of 100kW$_e$ Reactor

- 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.

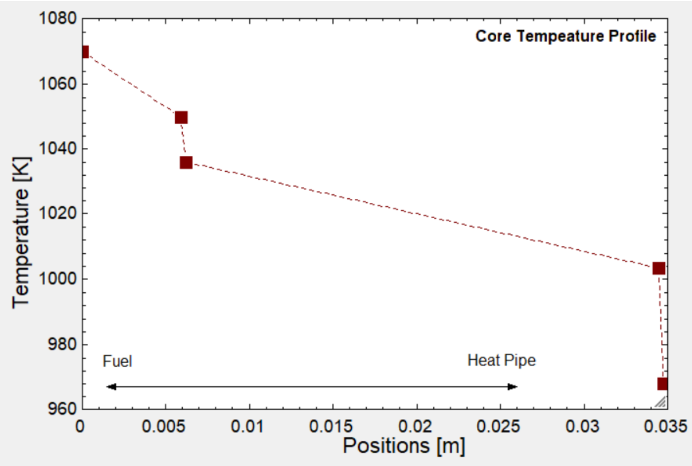


Figure 6. Core Temperature Profile

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

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

Summary

- The **thermal design code of the micro heat pipe reactor system using EES** is introduced.
- 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 **100kWe 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.

Thank you

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