10 kWe Heat Pipe Reactor Battery Design for Underwater Vehicles

ESLAB
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1. Introduction

Comprehensively considering the reactor size, safety, and operation reliability**, the heat pipe reactor battery system** featured with a low noise level, a low-pressure gradient, and few moving parts is suitable for use in energy systems for underwater vehicles.

The purpose of this study is to design the heat pipe reactor battery system for underwater vehicles including a detailed reactor core analysis:

- Through neutronic analysis, the core design of the reactor battery system is evaluated, and the detailed power distribution of the core is derived.
- Based on the derived power distribution, a CFD analysis of heat transfer is performed to derive a temperature distribution within the core which is important for checking the material integrity.

[Design and Status of Various Heat Pipe Reactors]

Parameters	Kilopower	HOMER	SAIRS	HP-STMCs	This Study
Power	1-10 (kWe)	25 (kWe)	110 (kWe)	110 (kWe)	11.3 (kWe)
HP fluid	Na	Na/K	Na	Li	Na
HP temperature	1050 (K)	880 (K)	1100 (K)	930 (K)	950 (K)
HP material	Haynes-230	SS-316	Mo-14Re	SS-316	SS-316
HP number	8 (EA)	61 (EA)	60 (EA)	204 (EA)	37 (EA)
Fuel	U-Mo	UN/UO_2	UN	UN	UN
Clad Material	Haynes-230	SS-316	Re	Re	Zr Alloy
Reflector material	BeO	Be	BeO	BeO	BeO
EC system	Stirling	Stirling	AMTEC	STMC	TEG
Reactivity control	Rod	Drum	Drum	Drum	Rod/Drum

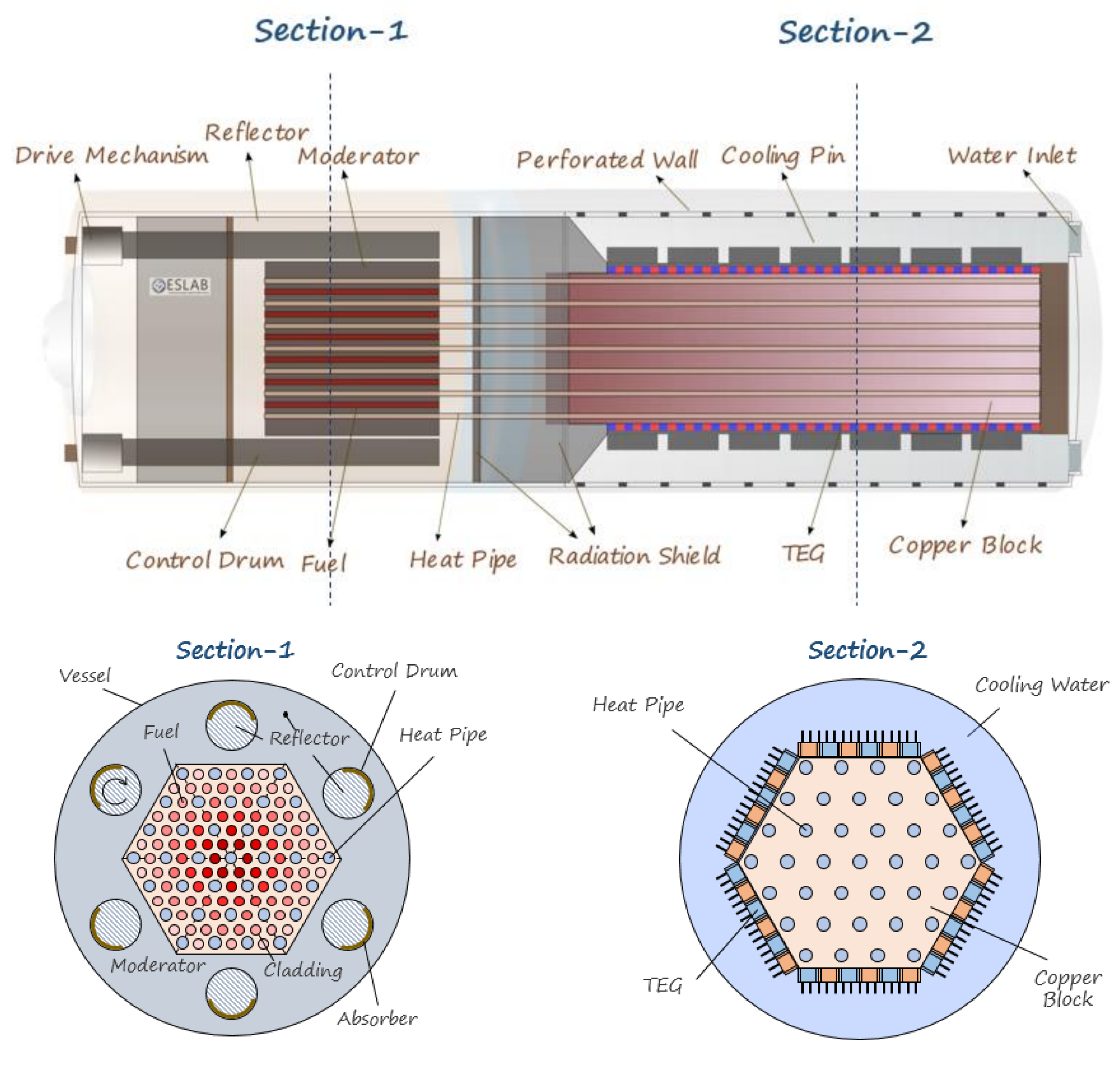
*Notes: STMC-Segmented Thermoelectric Module Converters, FPSE-Free Piston Stirling Engine, AMTEC- Alkali Metal Thermal-To-Electric Conversion, TI-Thermionic, EC-Energy Conversion, TEG-Thermoelectric Generator

2. Heat Pipe Reactor Battery Design

In this study, a 10 kWe heat pipe reactor battery system is conceptually designed.

- The designed heat pipe reactor is a thermal reactor capable of providing **74 kWt thermal power** and adopts **UN fuel** enriched to 11%.
- The **sodium heat pipes** transfer the heat in the core to the power generator, and **90 fuel rods** and **37 heat pipes** are arranged in a triangle array into **Zr_2H_3 moderator**.
- For reactivity control, **6 reactive control drums** containing **B_4C neutron absorber** are located outside the moderator, and **LiH radiation shields** are located on both side of the reactor core.
- A thermoelectric generator (**TEG**) is adopted as the **power conversion system**, and it converts the heat received from the heat pipe into about **10kWe power**.
- The cold junction of TEG is connected to a **large area cooling pin** and cooled by flowing coolant.

The overall conceptual diagram of the heat pipe reactor battery is shown below.



[Conceptual design of heat pipe reactor battery]

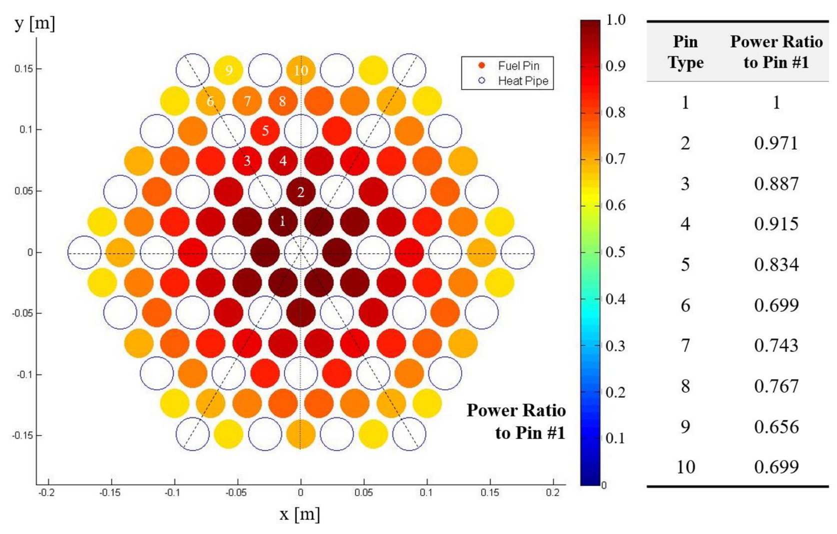
3. Neutronic Analysis of Reactor Core

The neutronic analysis (using McCARD code) on core design is carried out to obtain the power distribution, and to evaluate the adequacy of the operation length on the current reactor design:

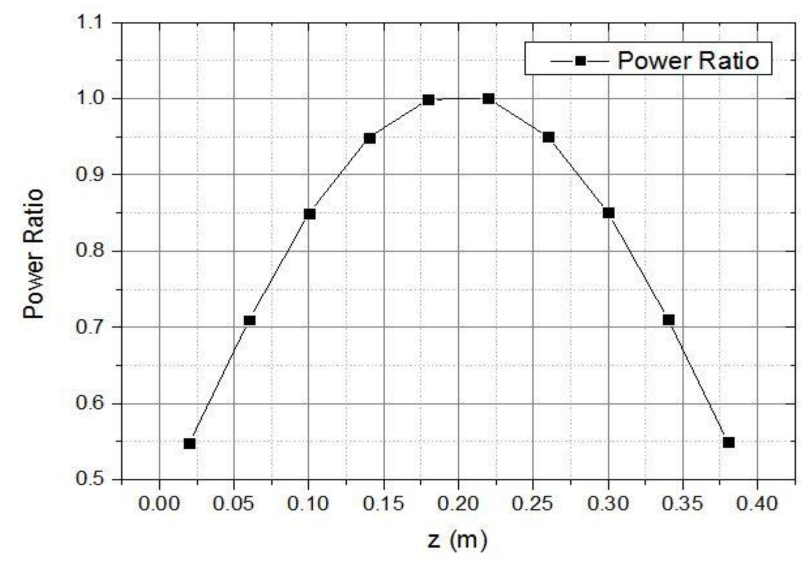
- The criticality and following fuel cycle length are determined according to the lifelong behavior of neutrons including absorption, scattering, fission, etc.
- The detailed power distribution of the core is derived by the behavior of neutrons according to the spatial arrangement of nuclear fuel, moderators, reflectors.

As a result of depletion calculation, it can be seen that the UN fuel with 11% enrichment can be operated for more than 10 years without refueling.

The total 74kW of heat is generated from all fuel pins and re-distributed in each pin following the power ratio of the figure below.



[Radial power distribution]



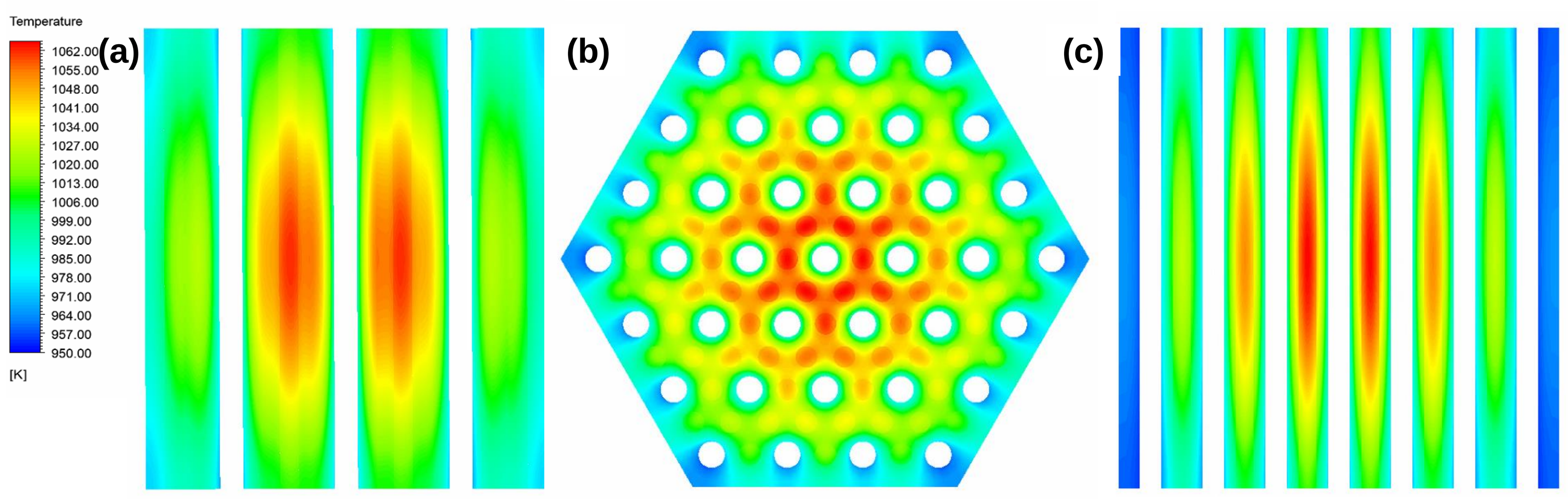
[Axial power distribution]

4. CFD Analysis of Reactor Core

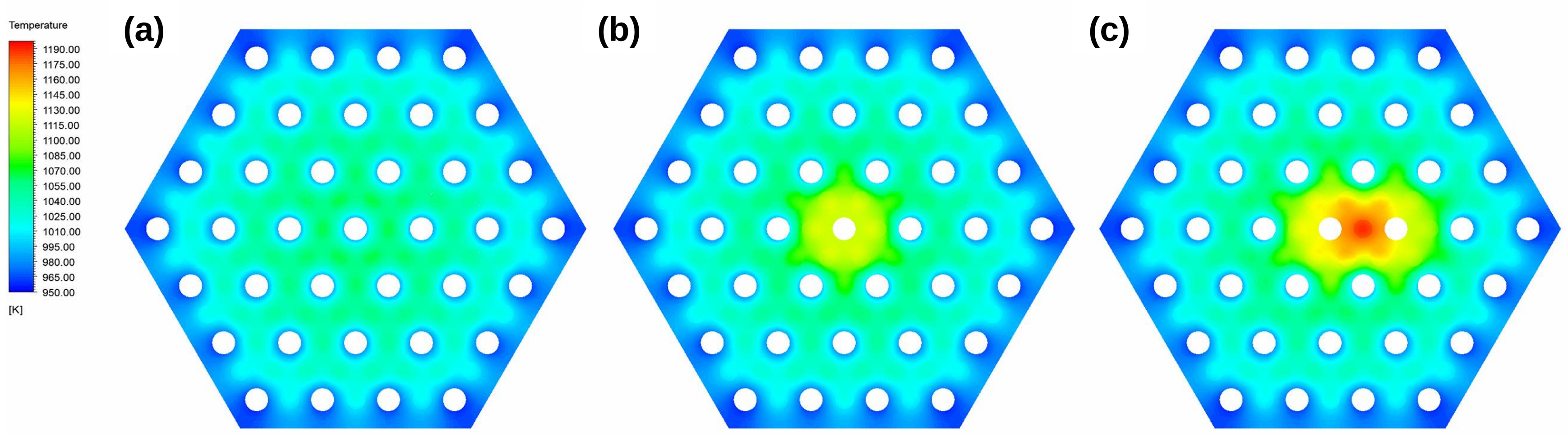
It is important to predict temperature distribution within the reactor core accurately to evaluate the material integrity. In this study, CFD simulation (using CFX code) is performed for three conditions: (a) normal operating conditions, (b) single heat pipe failure condition, and (c) double heat pipe failure condition.

As a result of the simulation, the heat transfer in the radial and vertical directions in the core is well calculated.

In all calculated simulation conditions, the temperatures of the reactor fuel and other materials are all below the safety limits.



Core temperature distribution at (a) Y-Z plane, (b) X-Y plane, and (c) Z-X plane in normal operation conditions



Core temperature distribution under (a) normal operating condition, (b) single heat pipe failure condition, and (c) double heat pipe failure condition

5. Summary

- A heat pipe reactor battery that can be mounted on a small underwater vehicle is designed and analyzed.
- Through neutronic analysis, it was evaluated whether the designed reactor core could secure sufficient fuel cycle length, and the power distribution for each fuel pin was obtained .
- By using the obtained power distribution of the fuel pins, CFD analysis of heat transfer inside the reactor core is performed.
- The designed reactor core has sufficient safety margins.