10 kWe Heat Pipe Reactor Battery Design for Underwater Vehicles

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1. Introduction

Most of the battery systems used for small underwater vehicles are chemical energy sources such as electrochemical cell or rechargeable battery, and their operation time are only dozens of hours to several days. However, new missions, such as long-term undersea reconnaissance, have recently demanded higher specifications for the undersea power system. Nuclear power sources featuring compact integrated structure, high power capacity, long operating time, and high reliability can meet these needs. Especially, heat pipe cooled reactor have the advantages of low decay heat emission, inherent reactivity control, and no additional pressurized system. 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.

Various heat pipe cooled reactors have been designed and researched. For example, Kilopower[1] is a sodium heat pipe cooled heat pipe that can generate 1 to 10 kW electric power by Sterling Engines. HOMER [2] is a series of heat pipe cooled reactors applied for the moon and mars missions, featured with UN or UO2 fission fuel, and the 235-uranium enrichment is more than 90%. Potassium or sodium heat pipes are adopted as cooling method, and a Stirling engine is used to generate 25kWe electricity in HOMER. The thermoelectric conversion efficiency of the HOMER reactor is more than 20%. SAIRS [3] is a kind of sodium heat pipe cFooled fast reactor controlled by drums and featured with 100kWe electrical power. As a special feature, Alkali metal thermoelectric converter (AMTEC) with thermoelectric is selected as energy conversion system. Westinghouse developed eVINCI [4], a special-purpose heat pipe reactor, based on the technology accumulated during the demonstration of LANL's KiloPower. The size of the reactor is designed to can be constructed in a 20' ISO container. The power conversion system is decided as the supercritical CO_2 Brayton cycle which has the advantages of being easily connected to a nuclear reactor, high-temperature operation, low maintenance cost, and easy modularization. Table 1 summarizes these kinds of heat pipe reactors based on the heat pipe working fluid, energy conversion system, reactor reactivity control method, reflector, and shielding material. In addition to this, various studies on heat pipe reactor are ongoing by individuals and research institutes [5-8].

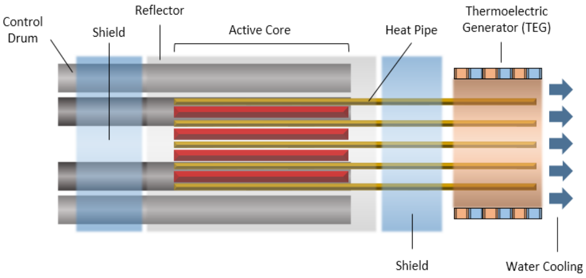


Fig. 1. Conceptual design of heat pipe reactor battery

In this study, a 10 kWe miniature heat pipe reactor system is conceptually designed. 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. In addition, it is evaluated whether various safety requirements can be satisfied even under accident conditions such as a single heat pipe failure.

2. Heat Pipe Reactor Battery Design

Although there are no examples of use on small underwater vessels, heat pipe reactor is being studied and used by various groups shown in Table 1. In this study, a 10 kWe heat pipe reactor battery system is conceptually designed through a literature review of these various heat pipe reactor designs. This battery features sodium heat pipe cooling channels and a thermoelectric power conversion system with efficiencies greater than 10%.

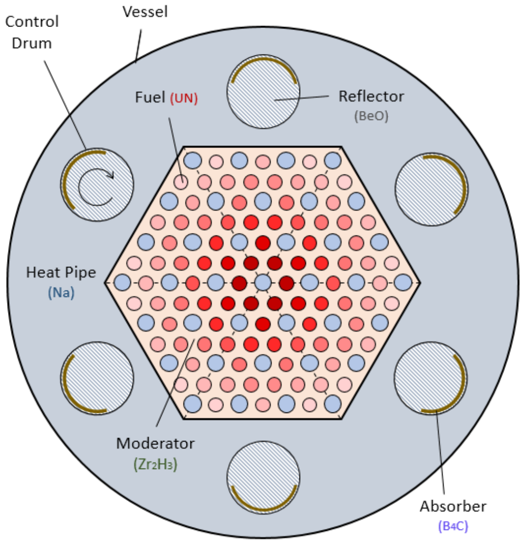


Fig. 2. Conceptual design of reactor core

Table 1. Design and Status of Heat Pipe Reactors

Parameters	Kilopower	HOMER	SAIRS	HP-STMCs	eVINCI
Power	1-10 (kWe)	25 (kWe)	110 (kWe)	110 (kWe)	0.8 (MWe)
HP fluid	Na	Na/K	Na	Li	Na/K
HP temperature	1050 (K)	880 (K)	1100 (K)	930 (K)	1500 (K)
HP material	Haynes-230	SS-316	Mo-14Re	SS-316	Mo-14Re
HP number	8 (EA)	61 (EA)	60 (EA)	204 (EA)	126 (EA)
Fuel	U-Mo	UN/UO_2	UN	UN	UN
Clad Material	Haynes-230	SS-316	Re	Re	-
Reflector material	BeO	Be	BeO	BeO	BeO
EC system	Stirling	Stirling	AMTEC	STMC	sCO_2 Brayton
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

The overall conceptual diagram of the heat pipe reactor battery is shown in Fig. 1. 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 as shown in Fig. 2. For reactivity control, six reactive control drums containing B_4C neutron absorbing material are located outside the moderator, and LiH radiation shields are located on both side of the reactor core. In the electric conversion part, heat pipes connected to the reactor core are inserted into a copper matrix. With many advantages such as low maintenance risk, no moving parts, low noise level, small volume, and lightweight, 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. Lastly, the cold junction of TEG is connected to a large area heat sink and cooled by flowing coolant. Detailed parameter specification of the system is summarized in Table 2.

Table 2. 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

The electrical energy generation process in the entire heat pipe reactor battery system is a complex process of various physics including nuclear reaction in the core [9], determination of heat pipe limits [10], and energy governing equation of TEG [11] etc. Therefore, these multiple physics models are computed simultaneously for system design. In this article, the research on neutron physics and heat transfer in the core area is summarized especially.

3. Neutronic Analysis of Reactor Core

Since the fission is basically caused by the interaction between neutrons and fissile material, the reaction occurs non-uniformly depending on the local neutron density and neutron flux. (Most active in the center region, generally). In addition, the criticality and following fuel cycle length are also determined according to the lifelong behavior of neutrons including absorption, scattering, fission, etc. In this respect, neutronic analysis (McCARD) on core design is previously carried out to obtain the power distribution [12], and to evaluate the adequacy of the operation length on current reactor design.

3.1. Fuel Cycle Length

The neutrons generated by fission reaction are slowed down as they scatter in the moderator material (Zr_2H_3 in current design), and a chain reaction occurs as the moderated neutrons collide again with the fissile nucleus with a specific cross section [13]. Some neutrons are either captured by the surrounding materials including fission products or scattered by the reflector placed in the axial and radial directions [14]. Considering all these neutron behaviors, the reactor can reach the critical state when the multiplication factor exceeds 1. As a result of depletion calculation with 1,000 neutrons and 20 neutron generations, it can be seen that the UN fuel with 11% enrichment can be operated for more than 10 years without refueling, as shown in Fig. 3.

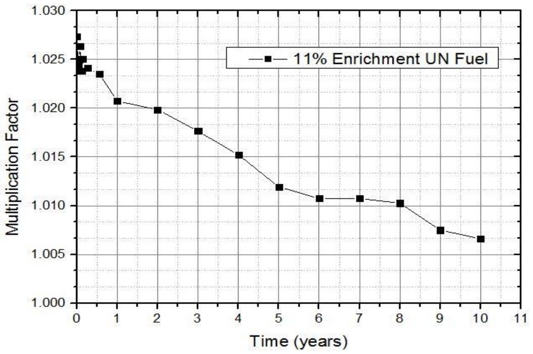
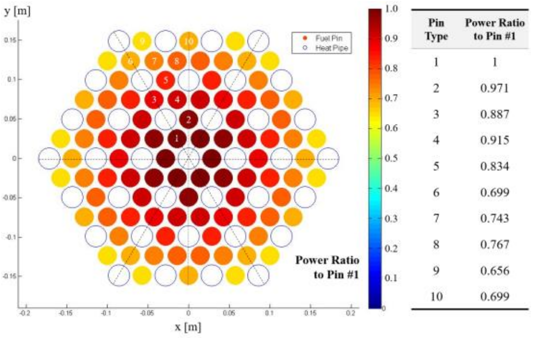


Fig. 3. Multiplication factor for exposure years

3.2. Power Distribution

As a result of neutronic transport calculation, the frequency ratio of fission reaction, i.e., the power distribution for each fuel pin is obtained as shown in Fig. 4, where the color bar and table represent the ratio of power to the maximum power fuel pin (#1). In this radial power distribution, the power peaking factor is calculated as 1.24. In the axial direction, neutronic simulation is performed by dividing a single fuel pin into 10 axial cells, and as a result, the axial power distribution is obtained as Fig. 5, where the axial power peaking factor is calculated as 1.24. In short, the total 74kW of heat is generated from all fuel pins according to the ratio of Fig. 4, and axially re-distributed in each pin following the axial power ratio of Fig. 5. The detailed power distribution derived from this neutronic analysis becomes the boundary condition for each fuel pin in the thermal CFD calculation.



Pin Type	Power Ratio to Pin #1
1	1
2	0.971
3	0.887
4	0.915
5	0.834
6	0.699
7	0.743
8	0.767
9	0.656
10	0.699

Fig. 4. Radial power distribution

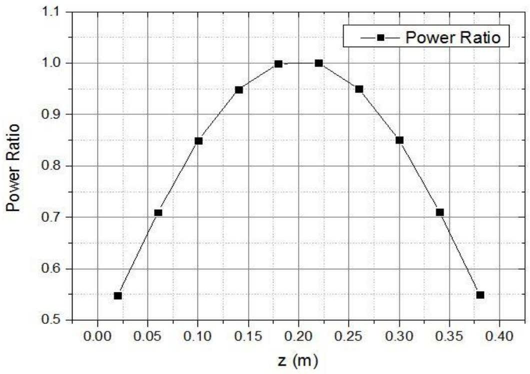


Fig. 5. Axial power distribution

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 section, a commercial CFD program, ANSYS FLUENT, is used to perform core heat transfer analysis and check whether the components of the heat pipe reactor meet the safety requirements.

4.1. CFD simulation setting

In the CFD simulation, a mesh grid structure is created for the fuel and moderator space which generates and transfers heat. The heat generation rate for each fuel is determined based on the detailed power distribution derived in the previous section. There is a 0.00011 m thin helium gap around the fuel and heat pipes, where radiation and conduction are the dominant heat transfer methods in this space. In order to increase the heat transfer efficiency of the system, the heat pipe hot side temperature is designed to be 950 K, and it is set as a boundary condition. It is assumed that all the generated heat escapes through the heat pipe, so an adiabatic condition is applied to the wall of the moderator. Material properties related to heat transfer are values that change with temperature. However, the simulation is conducted using the constant material property values at 1000 K since the temperature distribution of the entire core region is around 1000 K. Detailed information on the material properties constituting the reactor core is summarized in Table 3.

4.2. CFD simulation results

In this study, CFD simulation is performed for three conditions: (a) normal operating conditions, (b) single heat pipe failure condition, and (c) double heat pipe failure condition. Under each condition, the temperature distribution in the entire core area is derived and evaluated whether safety requirements are met. When the temperature of the material at each location approaches the melting point, it is determined that there is a problem with the integrity of the material.

Table 3. Material Properties used in CFD Simulation

Material	Property	Value
UN (fuel)	Conductivity (W/m-K)	23.27
	Heat capacity (J/kg-K)	250
	Density (kg/m3)	11300
	Emissivity	0.80
Zr_2H_3 (Moderator)	Conductivity (W/m-K)	19.6
	Heat capacity (J/kg-K)	692.4
	Density (kg/m3)	5660
	Emissivity	0.35
He (Gap)	Conductivity (W/m-K)	0.37
	Heat capacity (J/kg-K)	5200
	Density (kg/m3)	0.0536

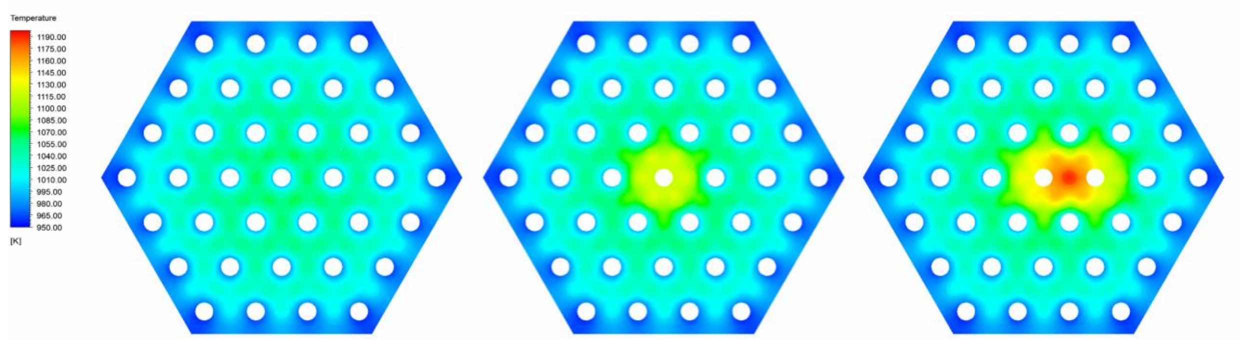


Fig. 6. Core temperature distribution under (a) normal operating condition, (b) single heat pipe failure condition, and (c) double heat pipe failure condition

As a result of the simulation, the heat transfer in the radial and vertical directions in the core is well calculated. In particular, the temperature distribution results at the hottest plane are shown in Fig. 6. In the normal operating condition, the reactor core temperature varies from 950 K – 1062 K. Since the temperature of all materials including UN fuel, moderator, and the heat pipe is much lower than the melting point, there is a sufficient safety margin.

In the two accident conditions, a situation in which the heat pipe close to the center is damaged is simulated. In general, this situation is the most dangerous for the safety of the reactor because the temperature at the center of the core is the highest [15]. Even in the most dangerous situation where two heat pipes are failing, the fuel temperature peaks at 1182 K, far below the melting point of UN fuel (2500K) [16].

5. Summary

In this paper, a heat pipe reactor battery that can be mounted on a small underwater vehicle is designed and analyzed. The reactor neutronic and thermal CFD model is used for optimal design and safety evaluation of the reactor core structure. Through neutronic analysis, the optimal core design to secure a sufficient fuel cycle length is derived. The power distribution for each fuel pin is obtained as a result of neutronic transport calculation. By using the obtained power distribution of the fuel pins, CFD analysis of heat transfer inside the reactor core is performed. As a result of the CFD simulation, the heat transfer in the radial and vertical directions in the core is well calculated. In the three calculated simulation conditions (normal operating condition, single heat pipe failure condition, and double heat pipe failure condition), the temperatures of the reactor fuel and other materials are all below the safety limits. In conclusion, the designed reactor features enough safety margin.

ACKNOWLEDGEMENTS

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REFERENCES

[1] McClure, Patrick R., et al., "Kilopower Project: The KRUSTY Fission Power Experiment and Potential Missions.", Nuclear Technology 206.sup1 (2020): 1-12.

[2] Poston, D.I., “The heat pipe-operated mars exploration reactor (HOMER)”, The Proceedings of Space Technology and Applications International Forum (STAIF-2001), AIP Conference Proceedings (2001):797-804.

[3] El-Genk, M.S., Tournier, J.M., “SAIRS – scalable AMTEC integrated reactor space power system”, Prog. Nucl. Energy 45 (2004): 25–69.

[4] Levinsky, A., Wyk, J.J., Arafat, Y., et al., “Westinghouse eVinci Reactor for Off-Grid Markets”, Transactions of the American Nuclear Society, Orlando, Florida (2018).

[5] P. McClure, D. Poston, “Design and Testing of Small Nuclear Reactors for Defense and Space Applications”, LA-UR-13-27054, Invited Talk to ANS Trinity Section, Santa Fe (2013).

[6] IAEA, “Advances in Small Modular Reactor Technology Developments”, A Supplement to IAEA Advanced Reactors Information System (ARIS) 2020 Edition (2020).

[7] Tournier, Jean-Michel, and Mohamed S. El-Genk., "Reactor Lithium Heat Pipes for HP-STMCs Space Reactor Power System.", AIP conference proceedings. Vol. 699. No. 1. American Institute of Physics (2004).

[8] Wang Chenglong et al., "Thermal-hydraulic analysis of a new conceptual heat pipe cooled small nuclear reactor system.", Nuclear Engineering and Technology (2020): 19-26.

[9] J. Byrne, “Neutrons, Nuclei, and Matter”, Dover Publications, Mineola, NY (2011): 259.

[10] Patrik Nemec, et al., “Mathematical model for heat transfer limitations of heat pipe”, Mathematical and Computer Modelling 57 (2013): 126-136.

[11] W. Thomson, “Account of researches in thermo-electricity” Proceedings of the Royal Society of London (1854): 49-58.

[12] Hyung-Jin Shim, et al. "McCARD: Monte Carlo code for advanced reactor design and analysis.", Nuclear Engineering and Technology 44.2 (2012): 161-176.

[13] V.F. Sears, “Neutron scattering lengths and cross sections”, Neutron News 3, No. 3 (1992): 26-37.

[14] Stacey., Weston M. “Nuclear reactor physics”, Wiley-VCH (2007): 29–31.

[15] IAEA, “Thermo-physical Properties of Materials for Nuclear Engineering: Tutorial and Collection of Data”, International Atomic Energy Agency, Vienna (2008).

[16] M.S. El-Genk, “Deployment history and design considerations for space reactor power systems”, Acta Astronaut. 64 (9) (2009).