Thermal analysis of a heat pipe nuclear reactor for space applications using CFD

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Introduction: A heat pipe nuclear reactor is a fully functional nuclear reactor that, even though it was conceptualized several decades ago, is getting more attention in the recent years. [1]. These reactors are considered microreactors because of their small energy output compared to commercial reactors (ranges between kWe and MWe of power relative to a regular 1000 MWe commercial reactor). The engineering of such a small reactor is greatly simplified, and it allows unattended operation, improved safety or black-start capability. Additionally, the small weight and volume of a microreactor ensures that they can be easily transported and factory manufactured.

In particular, a heat pipe nuclear reactor was conceptualized by Los Alamos National lab in the 60s, on which a solid-block core with fuel in holes inside the solid block. The heat pipes remove the heat from the block as the liquid in the heat pipe is vaporized. The heat is deposited in the condenser region of the heat pipe. The condenser region can be sized to accommodate multiple heat exchangers, such as one for power conversion and two for redundant decay heat removal. A space nuclear reactor will transform fission energy into electrical energy and heat that can be used for space applications. It is composed of a reactor core, shielding, energy conversion system and waste heat removal system. Nevertheless, nuclear space reactors are not being launched into orbit since the 80s for space applications because of the better development and adequacy of solar cells for the required missions [2]. However, new prospect missions that require a higher energy density such as ISRU, missions on shaded locations or far away from the sun, cannot completely rely on solar cells [3].

In this sense, the absence or minimal moving parts of a heat piper reactor is key to the reliability of a long-life decentralized energy generator. Additionally, the robust solid-state characteristics make it ideal for hazardous environmental conditions or potential damage during transportation. Current designs of heat pipe reactors can be found in Table 1, [4]– [6]. It is seen that there is no standard and that this field is undergoing significant research in the latest years. In the current paper, the heat pipe concept designed at Texas A&M will be depicted, and in particular the reactor core thermal analysis.

	Kilopower	*eVinci*	*MSR-B*
Institution	LANL	WEC	LANL
Power	1 kWe	5 MWe	2 MWe
HP fluid	Na	Na/K	K
HP temp	1050 K	930 K	920 K
Enrich.	93.1%	19.75%	19.75%

Table 1. Heat Pipe Micro reactors

Reactor Schematic Design: The heat pipe nuclear reactor developed consist of a hexagonal block as a unit cell with graphite as the block. Surrounding the unit cells, a Beryllium reflector and control drums are located. The full core is less than 2 meters in diameter.

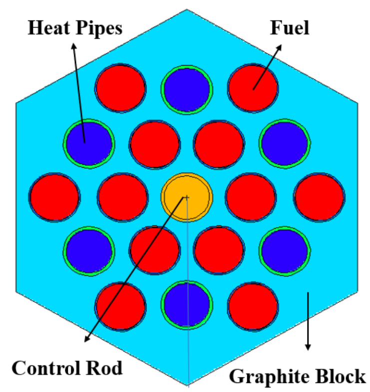

Figure 1. Unit Cell of the Heat Pipe Reactor

The fuel is composed of Uranium Oxide at three different enrichments (12, 15 and 19.75 %) for fuel optimization, and the heat pipe working fluid is Na with Stainless-Steel cladding. The design objective functions are the long core life time, two shut down mechanisms and a strong negative temperature reactivity coefficient. The inclusion of the central control rod for shut down creates an inherently safe design adding redundancy, so in case of failure of one mechanism, the reactor is still fully operable.

The neutronic economy of the current reactor design shows an almost uniform power distribution, with small peaking factor for each fuel rod.

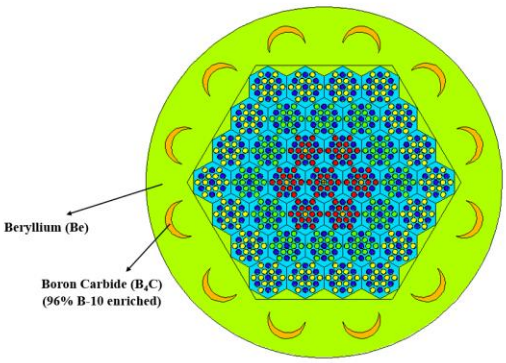

Figure 2. Full Core structure of the Heat Pipe Reactor

Steady State Thermal Analysis: With the current design, a preliminary thermal assessment of the reactor is performed using a computational model. For the current case a 1/12th geometry is used, assuming symmetry in the design. Additionally, the full height of the reactor is simulated, but comprising only the lower part of the heat pipe. The heat pipe internal vaporization is not modelled, and a constant temperature of 973 K is imposed as a boundary condition at the surface of the heat pipes. Additionally, the exterior surface of the reflector is assumed to be adiabatic. The Helium inside the fuel rods, is modelled as a solid to reduce the computational cost.

The model was developed using FLUENT 2019 R2, the mesh had around 10 million elements, and the average cell size is around 4.5 cm. An axial power profile taken from a neutronic code simulation was implemented in the fuel rods as a volumetric heat source. The temperature distribution can be seen in the Figures 3-4.

The simulation Figure of Merit is the temperature in the center of the Fuel Rod, as this would be the limiting factor if it exceeds the acceptance criteria. As seen in the Figures, the central temperature value of the fuel rods reaches a maximum of 1074 Kelvin, which is an acceptable value, well below the limit.

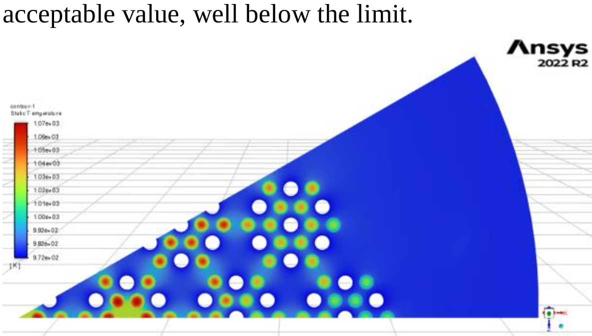

Figure 3. Radial View Temperature Distribution

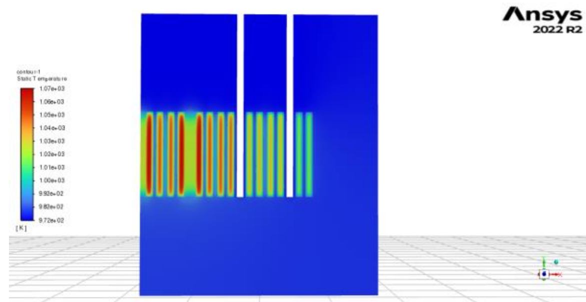

Figure 4. Axial View Temperature Distribution

Future Work: The present work has described the initial steps in the design of the heat pipe nuclear reactor in Texas A&M. The temperature analysis has shown an acceptable behavior of the reactor in operation. In the future, the reactor design will be coupled with a neutronic code to predict temperature distribution during transients. Additionally, an experimental facility [7] is being devoted to the study of heat pipes that will help in the validation and verification of future simulations.

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