2021 International Nuclear Atlantic Conference – INAC 2021
Virtual meeting, Brazil, November 29 – December 2, 2021

ISBN: 978-65-594-1256-3

Simulation of an Electric Power System based on Kilopower Project

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1. Introduction

Since the beginning of the space age, photovoltaic arrays, chemical batteries, and radioisotope generators have been the main source of electrical energy in space. The growing demands for more electrical power have raised the necessity for the development of nuclear reactors as a source of energy in space [1].

The power of the chemical battery drops drastically in days, being impractical for a long space mission. Solar energy, in turn, has a long lifespan, however, one generates only a few hundred watts. Also, they suffer from degradation caused by solar particles and ultraviolet radiation. And one must not forget that the intensity of solar energy drops drastically as the distance between the spacecraft and the sun increases [2]. Radioisotope batteries have a long useful life and are capable of generating a few hundred watts, but their main element, 238 Pu, is increasingly scarce [3].

Nuclear reactors, on the other hand, have high power and long duration. The SNAP 10A, the first American space reactor, was launched on April 3rd, 1965, and worked for just 43 days in orbit, when an electrical component has failed [2]. It then shut down and remained in this state ever since. From 1965 to the present day (2021) no other American reactor has been launched into space. They have been a little-explored technology in the US. Nevertheless, from 1970 to 1988 there were 32 launches of power reactors systems as a component of the Cosmos series of a Soviet Union spacecraft [1]. With the growing desire for exploration and colonization of the Moon and Mars, the space faring nations of the world have been reconsidering nuclear fission as a way to achieve this goal.

In the US, around 2013 an experiment called DUFF (Demonstration Using Flattop Fission) was performed. In the DUFF experiment a nuclear source generated heat, a heat pipe transferred the heat to a Stirling machine which, in turn, converted thermal energy into electrical energy [4]. The experiment was a success and the Kilopower project was born.

Several nations have started to look to nuclear reactors as a heat source generator to obtain electrical energy in space. In addition to the American Kilopower project [5], one may mention the European Union

(EU) Democritos project [6]. Also, with a brief Science Direct research, it is possible to find several articles indicating that Russia and China are also looking for ways to develop analogous technology.

2. Methodology

The Radioisotope Power System (RPS) operates below 500 We, while the Fission Surface Power System (FSPS) is designed to operate between 10 and 100 kWe. Kilopower's idea operates between the RPS and the FSPS, being able to produce between 1 and 10 kWe. Kilopower (figure 1) uses alkali (sodium) metal heat pipes to transfer thermal energy from a microreactor to the Stirling converters for the production of electrical energy. And water titanium heat pipes to transfer waste heat from Stirling converters to the space environment dissipation[7].

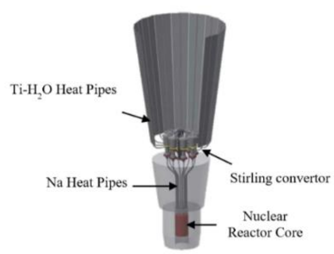

Figure 1: Kilopower [6]

The major objective of this work is to model an electric power generation system for space and remote places, analogous to the American Kilopower design. This system was divided into three parts: 1. Heat extraction system, 2. Stirling machine, and 3. Radiator system. The heat extraction system was simulated with the ANSYS Fluent with phase change, and the results were checked with experiments performed by the Advanced Cooling. Technologies - ACT team found in the open literature. ACT is responsible for the thermosyphons and heat pipes of the Kilopower project. The Stirling machine was analyzed with a mathematical model, which was created based on adiabatic analysis and dynamics analysis. Both were verified with computer simulation. The radiator system was simulated with a thermal steady-state, and phase change wasn't used in this model. The results obtained here were compared with the experiments realized by the ACT team.

3. Results and Discussion

In the Kilopower design the heat coming from the nuclear heat source arrives at the condensation ring, and is transferred from there to the heat plate. All the Stirling machines are attached to the same heat plate collector. This heat transfer process is reproduced in a computer simulation, all the heat transferred in the system just goes from the condensation ring to heat plate collector up to the base of all Stirling machines. The heat transfer is not constant across the heat plate collector surface, but for the most part, it comes pretty close to the 1080-Watt value of the experiments. The simulation results were between the range of 78% and 96 %, staying close to the value found in the experiments realized by the ACT team [9], and thus validates the simulation. These results are shown in Table 1.

Tabela 1:Results of Heat Extration System.

	Minimal valor between simulation vs ACT experiment.	Maximum valor between simulation vs ACT experiment.
Heat Extraction System	78%	96%

For the analysis of the Stirling machine, a thermodynamic model was developed based on the Schmidt analysis and the Adiabatic model proposed by Israel Urielli from Ohio University [8]. Schmidt's model is isothermal with sinusoidal volume variation. The fact that this model is isothermal is not consistent with a real cycle, because, in a real Stirling cycle, temperatures fluctuate. So the ideia is substitute the isothermal for an adiabatic condition from [8]. The Adiabatic model divides the Stirling engine into five parts: heater, expansion, regenerator, compression, and cooling. Temperatures fluctuate in each part of the engine. In the thermodynamic model developed for this work, temperatures will vary according to volume variation. For this, the adiabatic model was discretized and the volume variation equations of the Schmidt model were adopted. In this work, this new model is called thermodynamic model.

The results from the thermodynamic model were compared with a 3D SolidWorks simulation of the Kilopower Stirling machine. This 3D simulation was elaborated with the data found in the literature referring to the Kilopower Stirling machine [10]. With the thermodynamic model, a temperature value of 1146 K was obtained in the expansion zone, while in the 3D simulation of the Stirling machine a temperature of 1123 K was found. That is 98% of approximation in the expansion space, between the thermodynamic model and the 3D simulation of the Stirling machine. In the compression space the thermodynamic model found a temperature of 404 K, against the 400K obtained with the 3D Stirling machine simulation. In this case, a 99% approximation was obtained between them, in the compression space. These results are shown in Table 2.

Tabela 2: Stirling Engine Results

	Thermodynamic model vs Simulation at expansion space.	Thermodynamic model vs Simulation at compression space.
Stirling Engine	98%	99%

With the data released by the ACT team, a new 3D simulation was developed with the objective of characterizing the cooling system of the Stirling machines [9], and it was simulated utilizing the steady-state thermal. The target in this analysis is the heat conduction from the heat pipe to the aluminum fins. The simulation results are compared with the experiments data of the ACT team [9]. The temperature in aluminum fins stayed close at 97%. These results are shown in Table 3.

Tabela 3: Radiator Results.

	Comparison between Simulation vs ACT experiment.
Radiator System	97%

4. Conclusions

It was concluded that the simulation of the Kilopower heat extraction system was in a range of 78% to 96% compared to the ACT experiment.

The thermodynamic model of the Stirling machine was compared against 3D simulation of the Stirling machine and both results had excellent synergies with each other.

The simulation of the cooling system of the Stirling machines had a value very close to 97% with measurements.

Acknowledgments

The first author acknowledges the TERRA project for financing this work and the Nuclear Energy Division - ENU for the infrastructure provided to perform the analysis.

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