SPACE NUCLEAR REACTOR SP-100 THERMAL-HYDRAULIC SIMULATION

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ABSTRACT

Since 1983 it has been under development in the USA the project SP-100 of space nuclear reactors for electric generation in a range of 100 to 1000 KW-electrical powers. In this project the heat is generated at the core of a fast compact liquid lithium refrigerated reactor. Thermoelectric converters produce direct current electric energy and the primary and secondary loops flow is controlled by electromagnetic thermoelectric pumps (EMTE). In this work it is studied a system with a fast nuclear reactor, with similar characteristics to the SP-100, aiming at generating high electric power in space for a future application on the TERRA (Advanced Fast Reactor Technology) Project of IEAv (Institute for Advanced Studies). It will be presented the working principles, basic structure and operation characteristics of an electromagnetic thermoelectric pump (EMTE) for a liquid metal cooled nuclear reactor refrigeration loops flow control. In order to determine the operating point of the reactor, it is indispensable the simulation of the EMTE pump along with the other components of the system, once all the working parameters are connected. So, it has been developed a computer system, named BEMTE-3 (a FORTRAN micro-computer code), which simulates the primary and secondary refrigeration components of liquid metal cooled fast space reactor. This computer code also simulates the thermoelectric conversion, with the flow being controlled by the EMTE pump with thermoelectric converters, determining the system operation point for a given nominal operating power. The BEMTE-3 is used for the study of the SP-100 primary and secondary loops thermal-hydraulic simulation and for the calculation of the operating point of the system based on data from available projects.

1. INTRODUCTION

The proper supply of electric energy is one of the necessary factors for accomplishing space mission objectives, as well as, for the proper functioning of satellites and space stations. Among the possible energy sources for space applications one can highlight, in particular for large power, the utilization of space nuclear reactors with thermoelectric conversion [1].

Since 1983 it has been under development in the USA the project SP-100 of space nuclear reactors for electric generation in a range of 100 to 1000 KW-electrical powers. The heat is generated at the core of a fast compact liquid lithium refrigerated reactor. Thermoelectric converters produce direct current electric energy and the primary and secondary loops flow is controlled by electromagnetic thermoelectric pumps (EMTE) [2].
In this work it is studied a system with a fast nuclear reactor, with similar characteristics to the SP-100, aiming at generating high electric power in space for a future application on the TERRA (Advanced Fast Reactor Technology) Project of IEAv (Institute for Advanced Studies) [3]. It will be presented the working principles, basic structure and operation characteristics of an electromagnetic thermoelectric pump (EMTE) for a liquid metal cooled nuclear reactor refrigeration loops flow control. It will also be presented the BEMTE-3 computer code, used for the study of the SP-100 nuclear power reactor, primary and secondary loops simulation and for the calculation of the operating points of the systems, based on data from available projects.

2. BEMTE-3 SIMULATION CODE

In order to determine the operating point of the reactor, it is indispensable the simulation of the EMTE pump along with the other components of the system, once all the working parameters are connected, with the BEMTE-3 software [4]. The BEMTE-3 is a FORTRAN micro-computer code version, based in BEMTE code [5].

The BEMTE-3 code uses the basic equations for the calculation of the Seebeck electric tension generated by the thermoelectric converters, obtaining the electric current that circulates on the refrigeration channels of the pump. It also calculates also the magnetic field that results from the current circulation around the central magnet and the dynamic height supplied by the pump to the refrigeration loops, which is obtained from the iteration of the magnetic field with the useful electric current on each channel, using equations by Barnes and Blake [6, 7, 8].

The BEMTE-3 code simulates the primary and secondary refrigeration components of liquid metal cooled fast space reactor. This computer code also simulates the thermoelectric conversion, with the flow being controlled by the EMTE pump with thermoelectric converters, determining the system operation point for a given nominal operating power.

3. SP-100 SPACE REACTOR SIMULATED

The primary and secondary refrigeration loops of the SP-100 space reactor were simulated with the BEMTE-3 computer code for a nominal operation power (2.4 MW thermal) [9].

Figure 1 shows the cut view of the SP-100 reactor and the refrigeration loops. One can see the connections among the tubes and twelve EMTE pumps for the Lithium flow control in the reactor. Therefore the thermal power obtained from the core by each primary loop in this study is 0.2 MW thermal power, which becomes an input datum for the BEMTE-3 code.

There are many possible SP-100 thermal hydraulic configurations. Figure 2 shows the thermal-hydraulic coupling scheme considered for the simulation. The reactor core is refrigerated by the primary loop, which exchanges heat in countercurrent with the secondary loop and the flow control for both loops is performed by the EMTE pump. The cold temperature of the thermal elements corresponds to the temperature of the cold leg of the secondary loop (TFS) and the hot temperature of the thermal elements corresponds to the
temperature of the hot leg of the primary loop (TQP). One can also see the radiator system, responsible for the heat excess dissipation.

Figure 1. SP-100 design.

Figure 2. SP-100 loops simulated configuration.
3.1. Termoelectric Electromagnetic Pump Simulated

The operation scheme of the EMTE pump of the SP-100 reactor can be seen in detail in Figure 3. There are four thermoelectric converters, two P type (which generate electric current the same direction they exchange heat, that is from the hot leg to the cold one), and two N type (which generate current in the opposite direction). There are six channels, being two central, hot (where Lithium from the hot leg of the primary loop flows) and four lateral, cold (where fluid from the cold leg of the secondary loop flows). Table 1 shows SP-100 EMTE pump data simulated [10].

Figure 3. SP-100 EMTE pump design.

Table 1. SP-100 EMTE pump parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Duct width</td>
<td>1.784 cm</td>
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<tr>
<td>Primary duct height</td>
<td>2.676 cm</td>
</tr>
<tr>
<td>Secondary duct height</td>
<td>1.157 cm</td>
</tr>
<tr>
<td>Active pump length</td>
<td>25.4 cm</td>
</tr>
<tr>
<td>Duct wall thickness</td>
<td>0.076 cm</td>
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<td>Thermoelectric length</td>
<td>0.30 cm</td>
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<tr>
<td>Thermoelectric material</td>
<td>SiGe/GaP</td>
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<tr>
<td>Magnet width</td>
<td>1.148 cm</td>
</tr>
<tr>
<td>Magnet height</td>
<td>7.41 cm</td>
</tr>
<tr>
<td>Magnet material</td>
<td>Hyperco-27</td>
</tr>
<tr>
<td>Magnet Curie point</td>
<td>1240 K</td>
</tr>
</tbody>
</table>
The structural scheme used for the EMTE pumps eliminates the need for permanent magnets for the generation of the magnetic field, allowing them to be compact and so considerably reducing the total weight. This scheme uses Hiperco-27 as ferromagnetic material, which has a high Curie temperature (about 1240 K). The magnet is used on “S” form approximated, and the channels for the tubes of the fluid to be pumped are between the magnet legs. Coupled thermoelectric converters are used for generation of the electric current that goes through the fluid channels and conductive plates closing the electric circuit, involving the central part of the “S” magnet and inducing, therefore, a magnetic field. The interaction between the magnetic field and the electric current produces the force to control the working fluid flow loop.

3.2. Simulation Results

Figure 4 shows the curves for temperature difference imposed to the thermal elements as functions of the mass flow for the SP-100 system. Figure 5 shows EMTE pump electrical current generated as function of the SP-100 temperature difference imposed to the thermal elements. Figure 6 shows the magnetic field generated as function of the electrical current. One can see that the lower the primary loop mass flow, the higher the temperature difference imposed to the thermoelectric converters terminals and therefore the higher the generated electric current, resulting in a higher magnetic field generation in the “S” magnet. So, the pump dynamic high will be higher the lower the mass flow. On the other hand, the higher the mass flow, the higher will be the head loss of the loop.

![Figure 4. EMTE pump temperature difference.](image-url)
Figure 7 shows the load curve of the SP-100 primary loop, for a tube length of 10 m and medium diameter of 1.91 cm (continuous line). The intersection of this curve with the pump
dynamic high points as a function of the mass flow determine the operation point of the system, namely 1.005 kg/s per EMTE pump. Therefore the total mass flow of the primary system is 12.06 kg/s. Figure 8 shows the load curve for the secondary loop (continuous line) and the dynamic high supplied by the pump for this loop, considering a correction factor of 0.8 for the magnetic field. Flow data of BEMTE-3 simulations are consistent [10, 11].

**Figure 7.** EMTE pump curve for the SP-100 primary loop.

**Figure 8.** EMTE pump curve for the SP-100 secondary loop.
4. CONCLUSION

The SP-100 project is yet not totally defined, and several studies about new configurations are in progress.

The EMTE pump must be designed in order to satisfy the refrigeration loop requirements. In this case, an operation point will be defined as a function of the system geometry and other parameters.

The BEMTE-3 computer code can simulate all the thermoelectric components of a thermoelectric energy conversion system used on a space reactor, as it is the case of the American project SP-100. The BEMTE-3 supplies reliable results, but new simulation models should be tested, in order to improve the studies of this important space system for electric energy generation.

REFERENCES