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A code for 3D calculations of the output characteristics for a single-cell thermionic fuel element of thermionic nuclear power plants for different applications

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Abstract

R&D has been conducted by a cooperation of Rosatom State Corporation's enterprises to build a line of autonomous small nuclear power plants (SNPP) of up to 1 MW_{el} to support government programs for the development of Russia's Arctic region. In terms of heat and electricity supplies in an installed electric power range of 10 to 100 kW_{el}, the most attractive solution is offered by highly autonomous, compact and easy-to-maintain SNPPs with an in-core thermionic system. The key component of a thermionic NPP is a thermionic fuel element (TFE), which structurally integrates fuel and electrogenerating elements. Experimental studies and tests of thermionic plants are complex and expensive, so emphasis in the design of TNPPs is placed on mathematical simulation of physical processes taking place in the TFE. The paper considers the results of a 3D numerical simulation for the thermal and electrical characteristics of a single-cell TFE for a TNPP as part of one of the feasible SNPP designs, based on the procedure developed using COMSOL Multiphysics, an advanced software platform, and called by the authors COMSOL-EGK-SC. Initial data have been formulated to calculate a single-cell TFE, stages are described for the TFE mathematical model development in the COMSOL-EGK-SC software environment, and numerical calculation results for the thermal and electrical performance based on experimental data on the current–voltage characteristics (CVC) of a thermionic converter (TC) and the results of a neutronic calculation for the possible structure of the TNPP core as part of an SNPP are presented.

Keywords: Thermionic NPP; Single-cell thermionic fuel element; Finite element analysis; 3D numerical simulation.

Introduction

Conversion of thermal energy to the electric energy released in the nuclear fuel fission reaction is considered one of the most efficient ways to solve a range of long-term ground and outer-space tasks concerned with sustained electricity supplies to consumers at a level of dozens or more kilowatts [1–3]. To support government programs for the development of the Russian Federation's Arctic region [4,5], R&D has been conducted by a cooperation of Rosatom State Corporation's enterprises to build a line of autonomous small nuclear power plants (SNPP) with a capacity of up to 1 MW_{el} satisfying to radiological, environmental and nuclear safety requirements [6]. The most attractive solution, in terms of heat and electricity supplies in an installed electric power range of 10 to 100 kW_{el}, is offered by highly autonomous, compact and easy-to-operate direct energy conversion SNPPs with an in-core thermionic system [7,8], which have confirmed their reference status by outer-space operations (Topaz nuclear propulsion system) and by ground tests (Yenisey nuclear propulsion system) [9,10].

At the present time, a project is being developed by a cooperation of Rosatom's enterprises to build a thermionic nuclear power plant (TNPP) for SNPPs intended for electricity and heat supply to installations in Russia's difficult-of-access and remote northland areas in conditions of no centralized power supplies and communication routes [6–8].

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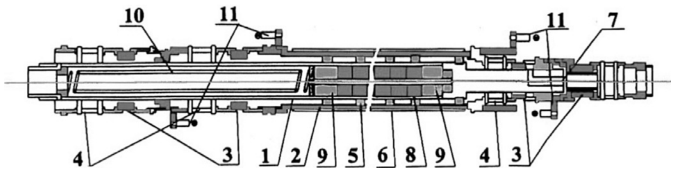

Fig. 1. Structural diagram of a single-cell SNPP TNPP TFE [8]: 1 – emitter; 2 – collector; 3 – sealed leads-in; 4 – bellows; 5 – spacers; 6 – electrical insulation; 7 – electrode gap; 8 – nuclear fuel; 9 – end reflectors; 10 – retainer; 11 – terminals.

The concept of the TNPP is based on the current technological advance, up-to-date designs, cutting-edge scientific achievements and hi-tech solutions. The key component of the TNPP is a thermionic fuel element (TFE) which structurally integrates electrogenerating and fuel elements. At large, the input and output characteristics of these devices are what the performance of the TNPP type under consideration depends on to a great extent. A single-cell TFE (Fig. 1) developed for the Yenisey nuclear propulsion system, which offers the best capabilities in terms of ensuring a long (reactor) life without degradation of the output characteristics, is considered as the potential choice for the base SNPP TNPP TFE [8,11].

Problem statement

There are different coupled physical (neutronic, emission, plasma, adsorbing, thermoelectric, thermal-hydraulic, thermomechanical and other) processes taking place in a TNPP TFE. Experimental studies on and tests of thermionic plants are complex and expensive, so emphasis in the TNPP design is placed on mathematical modeling.

Such modeling makes it possible to predict the TFE output electric power and determine the TFE's internal parameters which cannot be measured directly in tests due to the specific design of a full-scale TFE (amount of heat released in a fuel element, distribution of the electrode temperature and potentials, etc.). Therefore, numerical simulation of the physical processes in single- and multi-cell TFEs, based on up-to-date 3D mathematical models, is a timely and practically important task.

The paper considers the results of a 3D numerical simulation for the thermal and electrical performance of a single-cell TFE as part of a feasible SNPP design, based on a procedure developed using COMSOL Multiphysics, an advanced software platform [12,13]. Called by the authors COMSOL-EGK-SC, this is a modification of an earlier procedure, COMSOL-EGK, developed by IPPE to calculate the performance of multi-cell TFEs. Input data have been formulated for the calculation of a single-cell (SC) TFE, stages are described for the TFE mathematical model development in the COMSOL-EGK-SC software environment [14], and numerical calculation results for the thermal and electrical performance based on experimental data on the TC CVC and the results of a neutronic calculation for the possible structure of the TNPP core as part of an SNPP are presented.

Comsol-EGK-SC

The existing procedures to calculate the TFE characteristics include a number of peculiarities and assumptions which frequently reduce to a great extent the accuracy of the calculation results. Primarily, this is explained by the fact that the majority of the mathematical models used in these procedures are one-dimensional. Another peculiarity is that all of them are narrow-oriented (used to calculate a particular TFE design) and do not enable high-quality calculation of a more geometrically complex TFE. So, an improved TFE calculation procedure is expected to ensure the transition from one-dimensional to 3D numerical calculation of the TFE characteristics, to take into account in detail the effects the properties of structural materials and fluids have on the thermal and electrical processes in the TFE, and to make it possible to calculate TFEs in a geometry other than the geometry of generation I TFEs (Topaz and Yenisey).

COMSOL Multiphysics is the code for finite element calculations on complex scientific and technical problems. The solution of any problem is based on numerically solved equations in partial derivatives by finite element method in one-, two- or three-dimensional measurements. Based on the COMSOL Multiphysics code, a procedure for the 3D calculation of the TFE thermal and electrical performance, called COMSOL-EGK, was developed by the authors at IPPE in 2012 [13,15,16]. It should be noted that COMSOL-EGK was developed to model multi-cell TFEs but was found to be unfit, in its original form, for calculating the characteristics of single-cell TFEs as part of an SNPP TNPP. So, calculation of a single-cell TFE required a modification of COMSOL-EGK which has resulted in a new code called COMSOL-EGK-SC.

Mathematical modeling of a single-cell TFE in the COMSOL-EGK-SC environment

TFE geometrical calculation model

The device under consideration has a complex structure consisting of diverse and interlinked components. The TFE calculation model, developed using geometrical modeling tools in the COMSOL-EGK-SC environment, is shown in Fig. 2. This model of a single-cell TFE has been developed in a 3D geometry. The figure presents a vertical cross-sectional view of the developed TFE model.

The peculiarities of a single-cell TFE lead to a high spatial non-uniformity of the heat fluxes and temperatures in its structural components.

Mathematical model of a single-cell TFE

The mathematical model of electrostatic processes in multi-cell TFEs, as it is implemented in the COMSOL-EGK code, [13,15,16] is based on a number of significant assumptions which do not make it possible to analyze the electrostatics in single-cell TFEs because of the electric current flowing differently in the TFE structural components, in other words,