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Research Article

Minimize fission power peaking factor in radial direction of water-cooled and water-moderated thermionic conversion reactor core*

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Abstract

The paper investigates the possibility for reducing the radial power peaking factor k_r inside the core of a water-cooled water-moderated thermionic converter reactor (TCR). Due to a highly nonuniform power density, the TCR generates less electric power and the temperature increases in components of the thermionic fuel elements, leading so to a shorter reactor life.

A TCR with an intermediate neutron spectrum has its thermionic fuel elements (TFE) arranged inside the core in concentric circles, this providing for a nonuniform TFE spacing and reduces k_r. The water-cooled water-moderated TCR under consideration has a much larger number of TFEs arranged in a hexagonal lattice with a uniform pitch. Power density flattening in a core with a uniform-pitch lattice can be achieved, e.g., through using different fuel enrichment in core or using additional in-core structures. The former requires different TFE types to be taken into account and developed while the latter may cause degradation of the reactor neutronic parameters; all this will affect the design's economic efficiency.

It is proposed that the core should be split into sections with each section having its own uniform lattice pitch which increases in the direction from the center to the periphery leading so to the radial power density factor decreasing to 1.06. The number of the sections the core is split into depends on the lattice pitch, the TFE type and size, the reflector thickness, and the reactor design constraints. The best lattice spacing options for each section can be selected using the procedure based on a genetic algorithm technology which allows finding solutions that satisfy to a number of conditions.

This approach does not require the reactor dimensions to be increased, different TFE types to be taken into account and developed, or extra structures to be installed at the core center.

Keywords

Thermionic converter reactor, thermionic fuel element, power peaking factor, lattice pitch, genetic algorithm, optimization.

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Introduction

The use of thermionic converter reactors (TCR) for nuclear power systems (NPS) will make it possible to build a cost effective compact independent heat and electricity source.

Instead of zirconium hydride and sodium-potassium eutectics (Kuznetsov VA 1977) normally used in TCRs with an intermediate neutron spectrum as the moderator and the coolant respectively, water is used in pool-type water-cooled water-moderated TCRs (Lazarenko et al. 2006), which has a positive effect on the reactor safety. And the output electric power can be increased by increasing the efficiency and the number of the thermionic fuel elements (TFE). Still, the key advantage of any TCR is its compact design, which enables it to be factory-assembled and delivered to the deployment site with no complex transport operations (Krotov et al. 2011).

A water-cooled water-moderated converter reactor for a small NPP (AIST-MP), capable to serve as a cost effective independent heat and electricity source, is described in (Krotov et al. 2011, Maslov 2011). With the expected TFE efficiency of 20-25%, the reactor's 2142 TFEs generate 2 $MW_{(el)}$ of electric power.

A cooperation of J SC «SSC RF-IPPE named after A.I. Leypunsky», FSUE «SRI SIA «LUCH» and JSC «Afrikantov OKBM» has presented an innovative design of a small NPP based on a thermionic nuclear system for supply of power to remote facilities in the Arctic region (Fig. 1). The system's power of 10/100 $kW_{(el)}$ is ensured by 106 and 331 TFEs successfully verified in the TCR of the Yenisey NPS (Small thermionic nuclear power plant 2016).

Such a large number of TFEs in the core is arranged in a hexagonal lattice, in contrast to the arrangement in concentric circles as in a traditional TCR with an intermediate neutron spectrum. This defines the reactor dimensions and contributes to the natural coolant circulation in the core, and, so, to the NPS cost effectiveness.

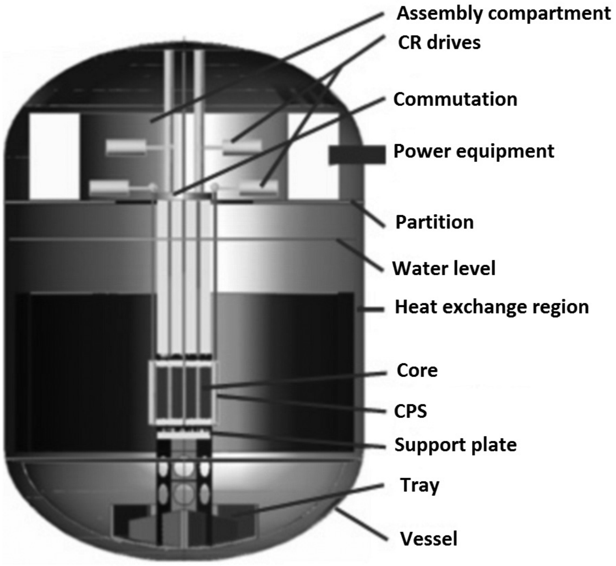

Figure 1. Conceptual design of an NPP based on a thermionic NPS

To compare with, the TCRs in the TOPAZ and Yenisey nuclear power systems had 79 and 37 TFEs respectively. Heat was removed by the forced coolant circulation in the annulus of each TFE (Kuznetsov 1977, Yarygin et al. 2016). The core was composed of TFEs arranged in concentric circles which provided for a nonuniform TFE spacing (Fig. 2). Such arrangement led to the radial power peaking factor k_r reduced considerably thanks to a minor increase in the moderator volume ratio in the direction from the core center to the periphery. The k_r value achieved in the TOPAZ TCR was equal to 1.05, which, in turn, had a positive effect on the TFE serviceability, the emitter and collector temperature modes, and the reactor electric power (Polous et al. 2013, Zabud'ko et al. 2004).

With a large number of TFEs arranged in concentric circles, the power density flattening through a nonuniform spacing leads to a greater core diameter.

On the other hand, with TFEs arranged in a uniform-pitch lattice, all other conditions being equal, it is not possible to influence the power density distribution.

Fig. 3 shows the dependence of the reactor electric power and the emitter temperature on k_r for the TOPAZ-type TCR (Polous et al. 2012, Linnik 2005). It can be seen that a growth in the power density nonuniformity leads to less electric power generated and a temperature increase.

It follows from the figure that the steady-state and continued operation of a TCR with the TFEs arranged in a uniform-pitch lattice requires k_r to be reduced.

Power density flattening in a core with a uniform lattice pitch can be achieved, e.g., through using different fuel enrichment in core or using additional structures inside the core. The former requires different TFE types to be taken into account and developed, while the latter may lead to worsened reactor neutronic performance; all this will affect the design's economic efficiency (Pupko and Kuz'min 1968, Sacco et al. 2007).

The paper investigates the possibility for reducing the radial power peaking factor in a core with a uniform lattice pitch. It is proposed that the core should be split into sections, each with its own uniform pitch which increases in the direction from the center to the periphery.

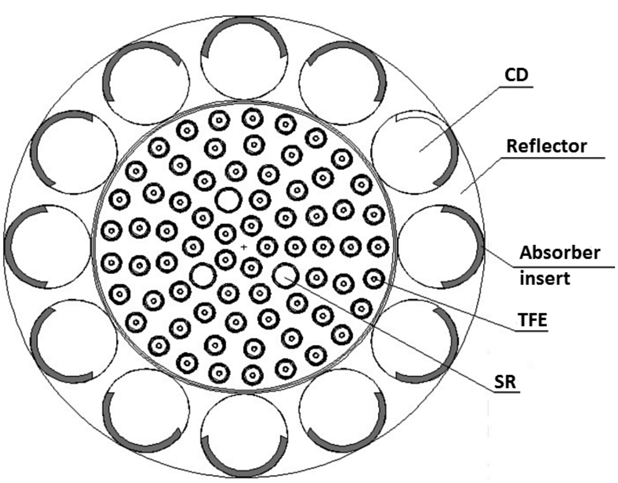

Figure 2. Cross-section of the TOPAZ-type converter reactor (Yarygin et al. 2016)

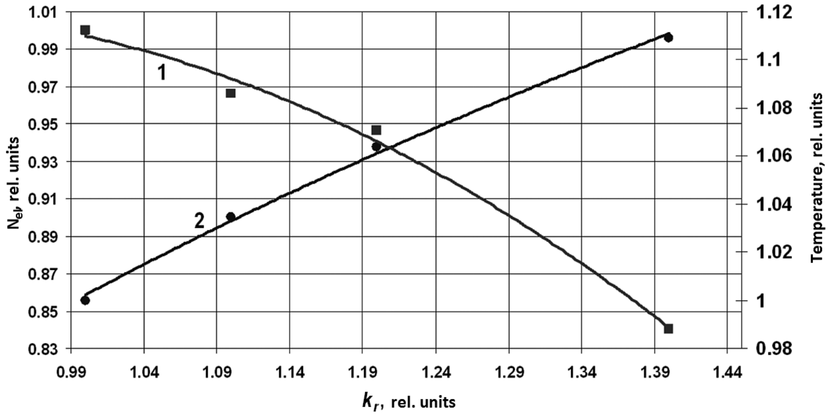

Figure 3. Dependence of the TCR electric power (1) and the emitter temperature (2) on the radial power peaking factor

Method to reduce k_r

The core of a water-cooled water-moderated TCR for an NPS is composed of TFEs arranged in a uniform-pitch hexagonal lattice. The core also contains reactivity control rods (CR), safety rods (SR) and displacers. The core is surrounded by a beryllium reflector (Fig. 4).

The MNCP code (MCNP 1997) and the ENDF/B-6 evaluated nuclear data library (ENDF/B-VI 1994) were used to model and calculate the core, with the neutron thermalization (Krotov and Son'ko 2009) taken into account.

This model contains 301 TFEs, and the core diameter is such that the rotary-type CRs or the control drums (CD) (see Fig. 2) installed in the side reflector are not efficient, so the reactor is controlled with the use of rods containing neutron-absorbing material. The displacers are hollow tubes serving to remove excessive water from the TFE vicinity which causes the water-uranium ratio (Bartolomei et al. 1989) and, accordingly, k_r to vary.

For the power density calculation, the CRs were assumed to be positioned at such height as would lead to the effective neutron multiplication factor equal to unity, that is, to a critical reactor state. With the uniform lattice pitch equal to the TFE diameter plus the gap, the k_r value was 1.39, and the maximum power density was as in the central TFEs. With such k_r, one can expect a 10% reduction in the output electric power as compared to the design value.

Fig. 5a shows the power density distribution with the core split into two sections. In the peripheral section occupying two TFE rows, the lattice pitch is 2% as large as in the central section.

It can be seen from the power density distribution that even a minor increase in the lattice pitch leads to a major reduction of k_r (to 1.12), that is, the power density on the reactor periphery grows due to a change in the water-uranium ratio in the two final TFE rows.

The core splitting into three sections (Fig. 5b) led to k_r reduced to 1.06. The pitches in each section are related as 1.0/1.02/1.04. Besides, water displacers were added on the periphery to reduce the power density in the peripheral TFEs.

The CRs at the hexagon apexes forming the central section required the channel cladding to be reshaped (the CR channel cladding is normally a regular steel cylinder). The core splitting near the TFEs adjoining the CRs leads to the formation of excessive water and, therefore, the power density grows. To remove excessive water, the tube cladding was designed as an elliptic cylinder which led to a reduced power density in the considered region (se Fig. 6).

In a general case, the power density distribution will depend not only on the lattice pitch but also on the TFE type and size, the reflector thickness, and the reactor design constraints. So, for the reactor with another TFE design and another material composition, as well as with a larger reflector thickness, the k_r reduction to 1.08 became possible with the core split into four sections (Fig. 7). The relations of the pitches in each section are 1/1.015/1.034/1.059. The thing is that, with the core split into three sections, a power density surge was observed in the TFEs on the outer edge of the central region, since the relative power density in the previous row fell to below 0.9.

It is worth noting that the core diameter was 5.7% as small with the minimum uniform lattice pitch, but this required the reactivity margin decrease to be compensated by a larger reflector thickness. The k_r value was equal to 1.20. The core diameter did not change with a large lattice pitch and the reactivity margin was larger, but the k_r factor was equal to 1.28. With the average pitch, the core diame-

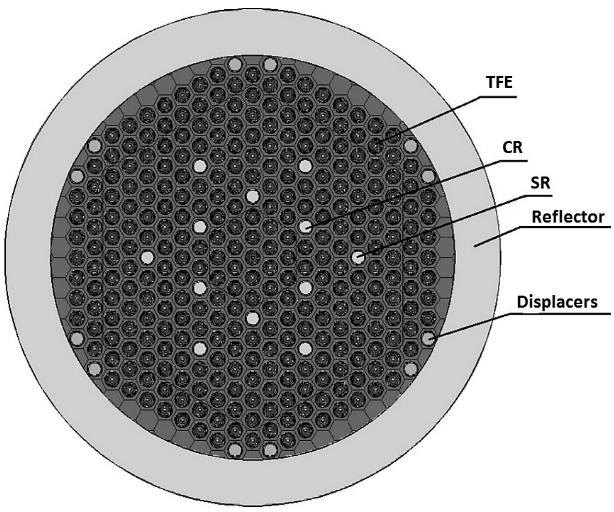

Figure 4. The core of a water-moderated water-cooled TCR

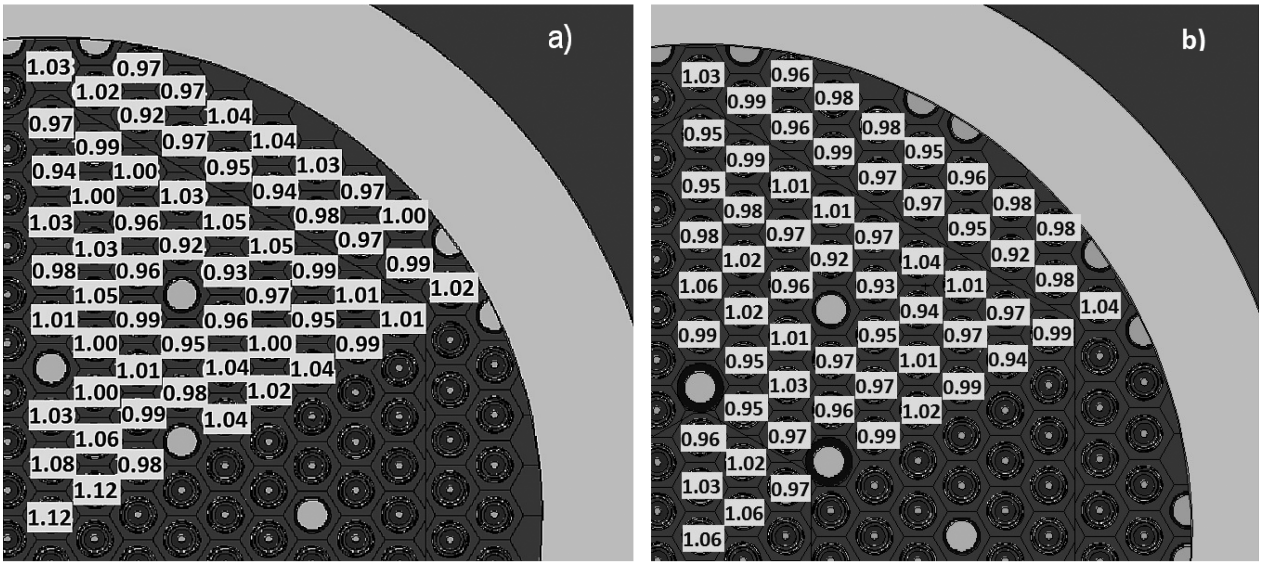

Figure 5. Power density distribution by fuel elements with the core split into two (a) and three (b) sections

ter was insignificantly smaller, and the reactivity margin coincided with the reactivity margin in the option with the core split into sections, and k_r was equal to 1.27.

Therefore, one may talk only about k_r being influenced exactly by the core splitting into sections with a uniform lattice pitch in each.

Such approach to power density flattening is useful when one needs to increase the TFE number without changing the core diameter. Thus, adding several tens of TFEs to the core with a specified diameter and the power density flattened (k_r equal to 1.08) thanks to a nonuniform spacing leads to the necessity to increase the diameter while k_r does not decrease to below 1.15.

And with the TFEs arranged in a hexagonal lattice and the core split into three sections, the k_r reduction to 1.10 can be achieved without changing the core diameter; the power density distribution by fuel elements for such case is shown in Fig. 8.

The pitches for each of the sections were found in this case using an optimization procedure based on a genetic algorithm technology (Konak et al. 2006, Gladkov et al. 2010, Alekseev 2011, Alekseev 2012). The search for the solution consisted in achieving such pitches that the k_r values did not exceed 1.10. The maximum and minimum lattice pitch limits were also taken into account. The relative power densities for the TFEs numbered 1 through 6 (see Fig. 8) were selected as the target functions. Eight experiments (calculations) were carried out for three factors (pitches). After the available information was analyzed, four more target functions (relative power densities for the TFEs numbered 7 through 10) were added.

As a result, the lattice pitches related as 1/1.018/1.055 have been achieved, leading to k_r = 1.10. And the smallest relative power density corresponds to the TFEs situated near

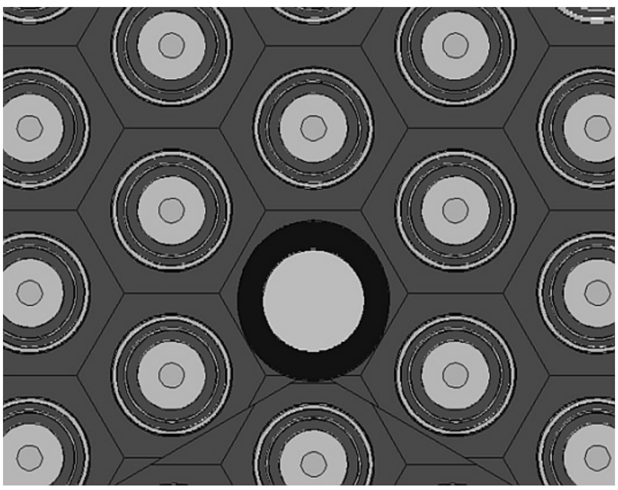

Figure 6. CR cladding in the form of en elliptic cylinder

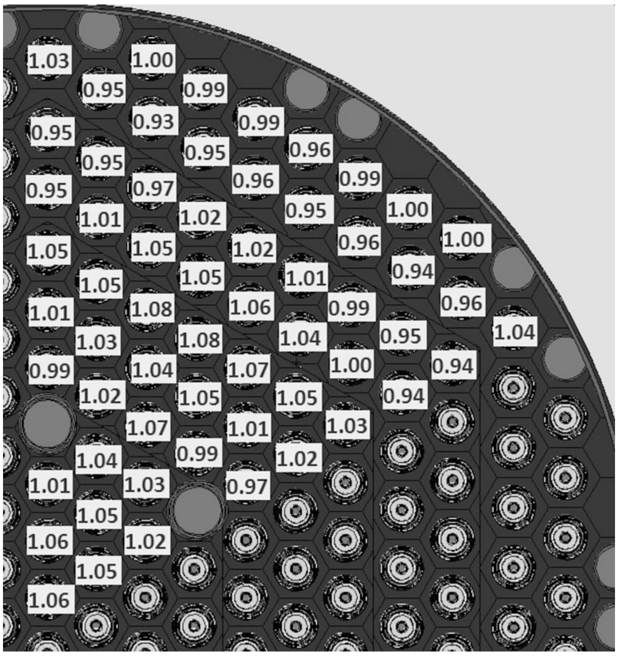

Figure 7. Power density distribution by fuel elements with the core split into four sections

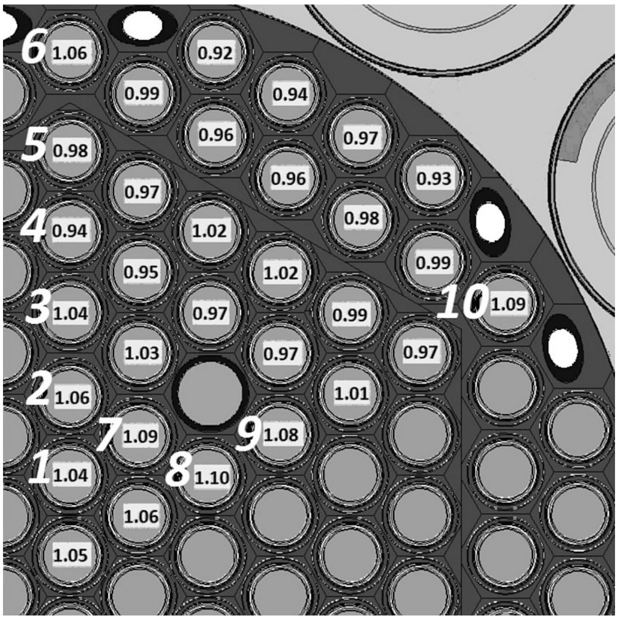

Figure 8. Power density distribution by fuel elements with the core split into three sections

the SR channels and, for individual TFEs, on the periphery. The power density on the periphery can be reduced by optimizing the shape and the positions of the water displacers.

The power density surge in the central TFEs takes place due to the excessive water formed as the result of the core splitting, that is, such surges can be suppressed through the optimization of the SR tube shape and position.

Conclusion

This paper investigates the possibility for reducing the radial power peaking factor inside a core with a uniform lattice pitch. The core splitting into sections, each having its own uniform pitch with the lattice pitch increasing in the direction from the center to the periphery, leads to the radial power peaking factor reduction to 1.06. This approach does not require the reactor dimensions to be increased greatly, different TFE types to be taken into account and developed, or extra structures to be used at the core center.

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