**EFFECT OF CHANGING THE OUTER FUEL ELEME-**

**NT DIAMETER ON THERMOPHYSICAL PARAMETER-**

**S OF RITM-200 REACTOR UNIT.**

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**Abstract**

The thermophysical calculations on the RITM-200 reactor unit is conducted to ascertain the possibility of optimizing the fuel element diameter without compromising the thermal constrains. These calculations included temperature distribution profile of the fuel rods at various fuel diameters, average coolant velocities and critical heat flux for nucleate boiling crisis analysis. It is demonstrated from the results achieved that an inverse relationship exists between the fuel rod diameter and the maximum fuel temperature. The average coolant velocity is observed to be directly proportional to the fuel rod diameter at a constant flowrate of G =9.38 kg/s. It is also determined that decreasing the fuel rod diameter below 6.9 mm which is the design fuel rod diameter will lead to boiling crisis.

**Keywords:** RITM-200 reactor, Pressurized water reactor, departure from nucleate boiling, Thorium-uranium fuel cycle, Uranium-plutonium fuel cycle.

# 1.         INTRODUCTION

The heat released in the reactor as a result of the fission reaction takes place in several forms. These include the release of heat as a result of the kinetic energy of fission neutrons, as well as from gamma rays of rapid fission, from gamma rays and β rays generated during the decay of fission products and, possibly, from neutrino radiation [1]. Since these various forms of heat generation are carried out by radiation particles, their energy turns to be weakened in various ways, which leads to the deposition of their energy in different places [2]. The thermophysical calculations conducted in this article takes account of the neutronic calculations already performed on the RITM- 200 reactor unit [3].

RITM-200 reactor unit is usually found in marine-based small modular reactors (SMR) such as the Artika, Sibir and Ural having a thermal and electric output power of 175 and 50 MW respectively [4, 5]. These SMRs above are considered nuclear icebreakers. RITM-200 stands for “Reactor Integralnii Transportnii Morskoi” or Integral Marine Transport Reactor of 200 MWth. The reactor unit is a pressurized water reactor (PWR) with fuel enrichment of 19 wt% [6]. RITM-200 reactor unit has 45% reduction in size, 35% mass reduction and 40% improvement in power compared to KLT-40S [7]. It has as part of the inherent safety features, control rods for emergency shutdown at the start, during operation or reactor trips [8].

From the neutronics calculations, results of the fuel lifetime of RITM-200 reactor unit at different fuel element diameters for the three dispersed fuel compositions showed that the highest fuel lifetime achieved by (238U+235U)O2 and (232Th+235U)O2 was attained at a fuel diameter of 6.9 mm [9]. For (232Th+233U)O2 dispersed fuel, the highest fuel performance was attained at fuel diameter of 8.9 mm. This is shown in fig 1.0 below.

FIG. 1. – Dependence of the duration of the nuclear fuel lifetime on the diameter of fuel rods with different dispersion fuels

The heat released in the reactor core considering each fuel assembly of the ***RITM-200*** reactor unit is examined by calculating the maximum energy released in the height and radius of the core [10]. The volumetric heat flux released into the fuel is calculated using the equation below:

 EQ.1

where *r* and *z* – radial and axial coordinates, respectively; *N*– thermal power of the reactor, MW; *nFA*– number of fuel assemblies in the core; *nFR* –number of fuel elements in the fuel assembly; RFR– radius of the fuel core, m; *H*core – height of the active zone, cm; k*r,* kz– the radial and axial power peaking factors [11]:

The velocity profile of the coolant is determined using the expression [11]:

 EQ.2

where *A*i– surface area of the fuel assembly passage section, m2; *ρ*i– the density of the coolant in the *i-th* section, kg/m3.

In determining the heat transfer coefficient in the *i-th* sections, the equation below is used [11]:

 EQ.3

where *Nu*i– the Nusselt number; *λ*i– the coefficient of thermal conductivity of the coolant in the *i-th* section, W/(m·K); *d*i– the equivalent diameter of the coolant in the *i-th* section, m.

Nusselt Number described by the expression is calculated as follows [11]:

 EQ.4

where Re and Pr stand for Reynold’s and Prandtl numbers

# 2.       NUCLEATE BOILING ANALYSIS

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In preventing the occurrence of heat transfer crisis in the reactor unit which is moderated and cooled with water, the critical heat flux is determined. Also, the ratio of critical heat flux to heat flux ** for all fuel diameters under study thus between 3.9 – 9.9 mm with interval of 1 mm is determined. When , it implies that fuel element at that diameter will experience some sort of heat transfer crisis.

The critical heat flux calculation is determined from the equation below [11]:

 EQ.5

where,°С;–saturation temperature at a given pressure, °C – specific volumes of steam and water at *t*s, m3/kg. The specific volumes of steam and water are generated from the (IAPWS) [12].

It is important to note that the empirical formular stated in equation 5 is used in this calculation since the pressure of the reactor RITM-200 of 15.7 MPa falls within the pressure range (i.e. from 14 to 17 MPa) [13].

# 3.        TEMPERATURE DISTRIBUTION OVER FUEL ELEMENT DIAMETER

The temperature distribution as seen in fig 2 demonstrates that the fuel temperature recorded is far below the limit of 500 – 600 oC. Hence, the thermal limits of the dispersed fuel [14] are satisfied.

FIG 2: Temperature distribution in fuel with different diameters.

The analysis of the coolant velocity across the fuel assembly through the different fuel element diameters show increase in average coolant velocity with increase in fuel element diameter. The velocity profile of the various fuel element diameters demonstrates a linear relationship with fuel element diameter. This is shown in table 1.

Table 1. AVERAGE COOLANT VELOCITIES FOR DIFFERENT FUEL ELEMENT DIAMETERS

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| d, mm | 3.9 | 4.9 | 5.9 | 6.9 | 7.9 | 8.9 | 9.9 |
| ν, m/s | 2.04 | 2.22 | 2.48 | 2.89 | 3.56 | 4.84 | 8.08 |

The coolant velocity across the fuel assembly through the *i-th* section is plotted to show the flow of the coolant through the axial section of the fuel element. In the mid-section, the higher energy release causes a decline in the density of the coolant hence the increase in coolant velocity. This is demonstrated in fig. 3 below.

FIG 3: Coolant velocity across the axial section of a fuel element.

Using the Industrial formulation 1997 for the thermodynamic properties of water and steam (IAPWS), [15] the thermodynamic quality (*x*) of the flow along the channel was obtained. The thermodynamic quality (*x*) for the reactor RITM-200 was determined to be a subcooled liquid flow which implied that *x* < 0 by solving equation 6 below.

 EQ.6

where *hi*connotes the enthalpy of the coolant at pressure *p* and temperature *Ti* in *i-th* section, kJ/kg; *h’’* and *h’* represents the enthalpy of steam and liquid at pressure *p*, respectively, kJ/kg; *P* denotes coolant pressure in the primary circuit, MPa.

The application of the Thom’s correlation was used in the evaluation of the boiling crisis in the various fuel element diameters. The results showed that boiling crisis will occur in the fuel element diameters less than 6.9 mm. This result implies that increasing the fuel diameter will not lead to boiling crisis, hence endorsing the recommendation of the neutronics calculations which proposed increase in fuel diameter to optimize fuel campaign. Fig. 4 below shows the result of the boiling crisis on the various fuel element diameters between 3.9 to 9.9 mm.

FIG 4: Dependence of  on the fuel assembly section.

Fig. 5 shows the results of the temperature distribution profile for saturation temperature, coolant temperature and outer clad temperature at 5.9, 6.9 and 7.9 mm.

Fig. 5: Temperature distribution profile.

# 4.        CONCLUSION

The thermophysical calculations conducted on the RITM-200 reactor unit showed that the temperature of fuel increases as the fuel element diameter decreases. This can be explained from the fuel burnup which is inversely proportional to diameter.

It is also established that the coolant velocity is proportional to the fuel element diameter which implies that increasing the fuel element diameter will lead to a higher heat removal by the coolant from the outer surface of the fuel clad.

It has also been determined from the graph of the dependence of on fuel assembly that boiling crisis as a result of heat removal from the system will only prevail in fuel element diameters below the design fuel element diameter of 6.9 mm. This shows that increasing the fuel element diameter which leads to a decrease in coolant volume and hence, reduced thermalization of the fast neutron will not lead to boiling crisis but rather enhance the heat removal as average coolant velocity increases with increasing fuel element diameter.

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##### **REFERENCES**

1. J. R. Lamarsh et al., “Introduction to nuclear engineering”, Upper Saddle River, NJ: Prentice Hall, 2001. Vol. 3. -P. 783.
2. Ozisik M. N. “Boundary value problems of heat conduction” – courier Corporation, 2002.
3. S. Alhassan, S. Beliavskii, V. Nesterov, “Core-optimization of RITM-200 Reactor Fuel Considering Thorium Fuel Cycle,” *Journal of Physics of Particles & Nuclei letter*, (2023), Vol. 20, No. 6, pp. 1523-1526. doi: 10.1134/S1547477123060031
4. D. E Savitsky, A. V Kuzmin, The calculation of the campaign of reactor RITM-200 //IOP Conference Series: Materials Science and Engineering. - IOP Publishing, 2021. - Vol. 1019. - no. 1. - S. 012057.
5. P. Degnan, A global perspective on prospects & challenges for the development and deployment of SMRs. – 2014.
6. V. V. Petrunin, Y. P. Fadeev, A. N. Pakhomov, K. B. Veshnyakov, V. I. Polunichev, I. E Shamanin, 2019. Conceptual Design of small NPP with RITM-200 Reactor. At. Energ. 125 (6), 365-369. <https://doi.org/10.1007/s10512-019-00495-4>.
7. A. K. Polushkin et al., “Implementation of the project for the construction and operation of a nuclear heat and power plant on the basis of a floating power unit with KLT-40C reactors” – 2000.
8. International Atomic Energy Agency. Advances in Small Modular Reactor Technology Developments: A Supplement to the IAEA Advanced Reactors Information System (ARIS). – IAEA, 2014.
9. S. Alhassan, S. V. Beliavskii, V. N. Nesterov, Evaluation of neutronic parameters for RITM-200 reactor unit considering (238U+235U)O2, (232Th+235U)O2 and (232Th+233U)O2 dispersed fuel using MCU-PTR // International Youth Russia-Africa Forum: Nuclear Education-Potential for successful regional development, St. Petersburg, Russia, 2023, pp. 58 – 66. doi: https://doi.org/10.48550/arXiv.2308.16195.

[10] V. I. Boyko et al., “Physical calculation of a nuclear reactor on thermal neutrons”, *Tomsk: Izd*. (2009).

[11] V. P. Koroleva, K. I. Zolotarev, L. A. Chernov, “Method of measuring the155Gd and157Gd content in absorbing materials of a reactor,” *Soviet Atomic Energy*, - T. 65. - No. 5. - S. 950-953 (1988).

[12] S. Beliavskii et al. “Effect of changing the outer fuel element diameter on thermophysical parameters of KLT-40S reactor unit,” *Annals of Nuclear Energy*, - T. 190. - S. 109877 (2023); doi: 10.1016/j.anucene.2023.109877

[13] A. Misnar Thermal conductivity of solids, liquids, gases and their compositions. – 1968.

[14] S. Beliavskii et al. “Effect of fuel nuclide composition on the fuel lifetime of the RITM-200 reactor unit,” *Annals of Nuclear Energy*, - T. 173. - S. 109105 (2022); doi: 10.1016/j.anucene.2022.109105

[15] W. Wagner, “Kretzschmar HJ International Steam Tables-Properties of Water and Steam based on the Industrial Formulation IAPWS-IF97: Tables, Algorithms, Diagrams, and CD-ROM Electronic Steam Tables-All of the equations of IAPWS-IF97 including a complete set of supplementary backward equations for fast calculations of heat cycles, boilers, and steam turbines,” *Springer Science & Business Media*, (2007).