Nuclear Engineering and Technology 49 (2017) 1629–1635

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Effect of central hole on fuel temperature distribution

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ARTICLE INFO

Article history:
Received 5 February 2017
Received in revised form
15 June 2017
Accepted 21 July 2017
Available online 18 August 2017

Keywords:
Annular Fuel
Fuel Crack
Fuel Performance
Gap Conductance
Solid Fuel
Temperature Distribution

ABSTRACT

Reliable prediction of nuclear fuel rod behavior of nuclear power reactors constitutes a basic demand for steady-state calculations, design purposes, and fuel performance assessment. Perfect design of fuel rods as the first barrier against fission product release is very important. Simulation of fuel rod performance with a code or software is one of the fuel rod design steps. In this study, a software program called MARCODE is developed in MATLAB environment that can analyze the temperature distribution, gap conductance value, and fuel and clad displacement in both solid and annular fuel rods. With a comparison of the maximum fuel temperature, fuel average temperature, fuel surface temperature, and gap conductance in solid and annular fuel, the effects of a central hole on the fuel temperature distribution are investigated.

1. Introduction

It is fundamental to the future of nuclear power that reactors be able to run economically compared with other forms of power generation. As a consequence, the development of an understanding of fuel performance and the embodiment of that knowledge in computer codes allow for more realistic predictions of fuel performance. This in turn leads to a reduction in operating margins and improved operating economics.

In the reactor core, uranium nuclear fission produces energy and fission products. This energy is transferred through the gap to the clad, and then coolant takes the energy from the clad. As shown in Fig. 1 [1], the difference between fuel and clad conductivity and also the gap conductance value causes temperature distribution in the fuel rods. Temperature distribution results in fuel cracks that cause fuel segments to move near the clad. The mentioned phenomena and fuel swelling cause changes in the gap conductance value. Perfect prediction of gap conductance value is very complex and difficult. By considering fuel and clad thermal expansion, fuel relocation, and fuel swelling, and also clad creep strain, the developed program can predict a reliable value for gap conductance and also for fuel temperature distribution.

In Fig. 1, T_{fc} is the maximum fuel temperature, T_{fs} is the fuel surface temperature, T_{ci} is the clad inside temperature, T_{co} is the clad outside temperature, T_{ox} is the oxide layer temperature, and T_b is the Coolant bulk temperature.

The overall aim of this project is to develop an analytical capability to analyze the thermal and mechanical performance of commercial pressurized water reactors and Vodo-Vodyanoi Energetichesky Reactor (VVER) reactors using the developed MATLAB software program called “MARCODE.”

Fuel rod behavior is determined by thermal, mechanical, and physical processes such as densification, swelling, fission gas generation, fission gas release, and irradiation damage. Any fuel rod performance analysis code must include two parts: thermal and mechanical. The thermal and mechanical parts include governing equations such as the heat conduction equation. Thus, the dimension of the equation is also an important parameter. In most of the fuel rod models, theoretical and computational efforts are reduced by decreasing the geometric dimensions. The codes can mainly be classified into steady-state and transient codes. Although there are some two- and three-dimensional code developments, most codes are one dimensional, well developed, and widely used.

In the present work, we study steady-state thermomechanical performance of a typical nuclear fuel element consisting of UO_2 fuel and zircaloy cladding. Models of the thermal and mechanical properties of the materials are used in a series of finite difference simulations to study the effects of the central hole on the

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http://dx.doi.org/10.1016/j.net.2017.07.022

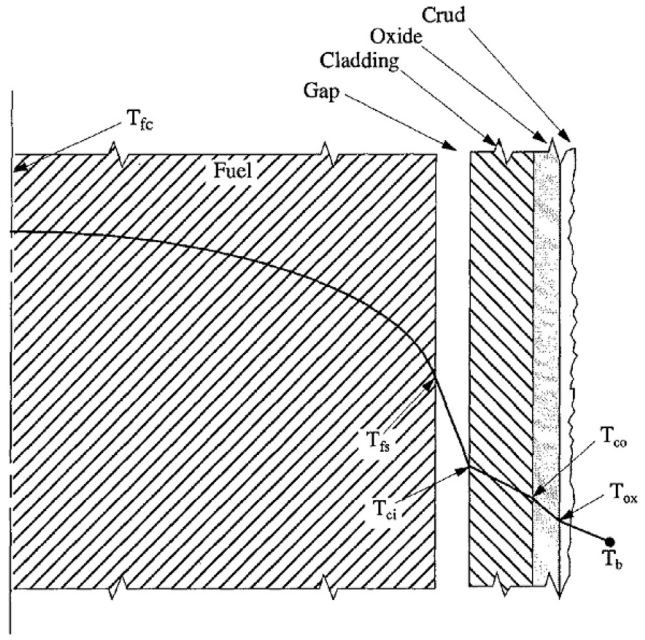

Fig. 1. Schematic of fuel temperature distribution.

temperature profile [2]. For this purpose, one-dimensional computer codes are developed to simulate the thermomechanical performance of solid and annular fuel.

2. Domain specification

In this work, the typical solid fuel that is used in Pressurized Water Reactor (PWR) reactors and a typical annular fuel that is used in VVER reactors are compared from the thermal performance viewpoint. Geometrical characteristics of the typical solid and annular fuel rods are presented in Table 1 [3]. The same linear power distribution is considered for both solid and annular fuel rods, as shown in Fig. 2 [3].

3. Program features

The program is written in MATLAB environment [4] as a steady-state, one-dimensional code. The code input parameters are geometrical characteristics, linear power, and burnup distribution. The aforesaid program analyzes the coolant and fuel temperature distribution by calculating complex thermal–mechanical coupling, as shown in Fig. 3.

Phenomena related to the change of gap thickness such as thermal expansion of fuel and clad, relocation of fuel fragments, densification and swelling of fuel, and cladding creep down have been considered in the mechanical modeling.

To enable a simple stress analysis that can calculate fuel and clad displacement, some assumption are used, which are as follows:

Table 1
Geometrical characteristics of solid and annular fuel rod.

Parameter	Solid fuel rod	Annular fuel rod
Fuel diameter (mm)	7.57	7.57
Clad outer diameter (mm)	9.1	9.1
Clad thickness (mm)	0.685	0.685
Central hole diameter (mm)	—	1.5
Fuel rod height (m)	3.53	3.53

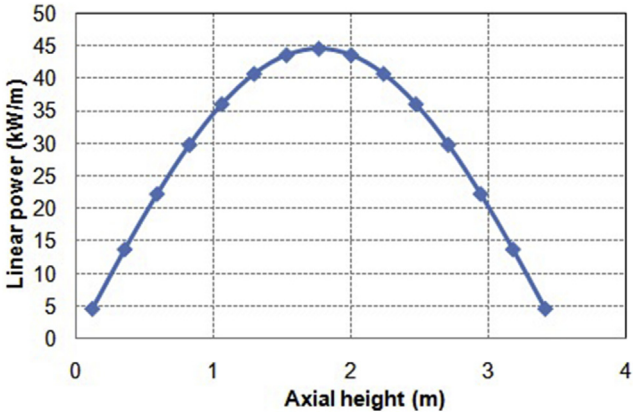

Fig. 2. Linear power distribution.

- The system is axisymmetric (no tangential variable).
- Although the fuel and cladding may move axially, planes perpendicular to the z-direction remain in plane during deformation (plane strain assumption).
- Owing to the fuel rod geometry, which is very long and thin, axial variations in any variable are neglected.
- Creep deformation is considered just for plastic deformation of cladding.

Stress analysis method is used to calculate fuel displacement using the following boundary conditions:

- There is no displacement at center of solid fuel pellet.
- The amount of radial stress in the fuel center hole surface is equal to the initial gap pressure.
- The amount of radial stress on fuel surface is equal to the initial gap pressure.

The important models that are used in the MARCODE program are listed in Table 2.

4. Governing equations

Fuel pellet displacement is calculated as follows [6]:

$$u(r) = \frac{1+\vartheta_f}{r}\int_{R_i}^{R_f} r\varepsilon_f^p dr + \frac{1}{2}Ar + \frac{B}{r}$$

$$A = \frac{2}{1+\vartheta_f}\left[-\frac{B\left(\vartheta_f - 1\right)}{R_i^2} + \frac{P_g\left(1-\vartheta_f^2\right)}{E_f}\right]$$

$$B = \frac{R_f^2 R_i^2}{\left(\vartheta_f - 1\right)\left(R_i^2 - R_f^2\right)}\left[-2P_g\frac{1-\vartheta_f^2}{E_f} + \frac{1-\vartheta_f^2}{R_f^2}\int_{R_i}^{R_f} r\varepsilon_f^p dr\right]$$

$$\varepsilon_f^p = \varepsilon_f^{th} + \varepsilon_f^{sd}$$

$$P_g = \frac{M_g R}{\frac{V_p}{T_{gas}} + \sum_{i=1}^{n}\left[\frac{\pi\left(R_f^2 - R_{ci}^2\right)l}{T_{gas}} + \frac{V_{hole}}{T_{gas}} + \frac{V_{sh}}{T_{gas}}\right]} \quad (1)$$

where ε_f^{th} is the fuel thermal strain; $\varepsilon_f^{sd}$is the fuel strain caused by swelling and densification; ϑ_f the Poisson's ratio; E_f the elasticity

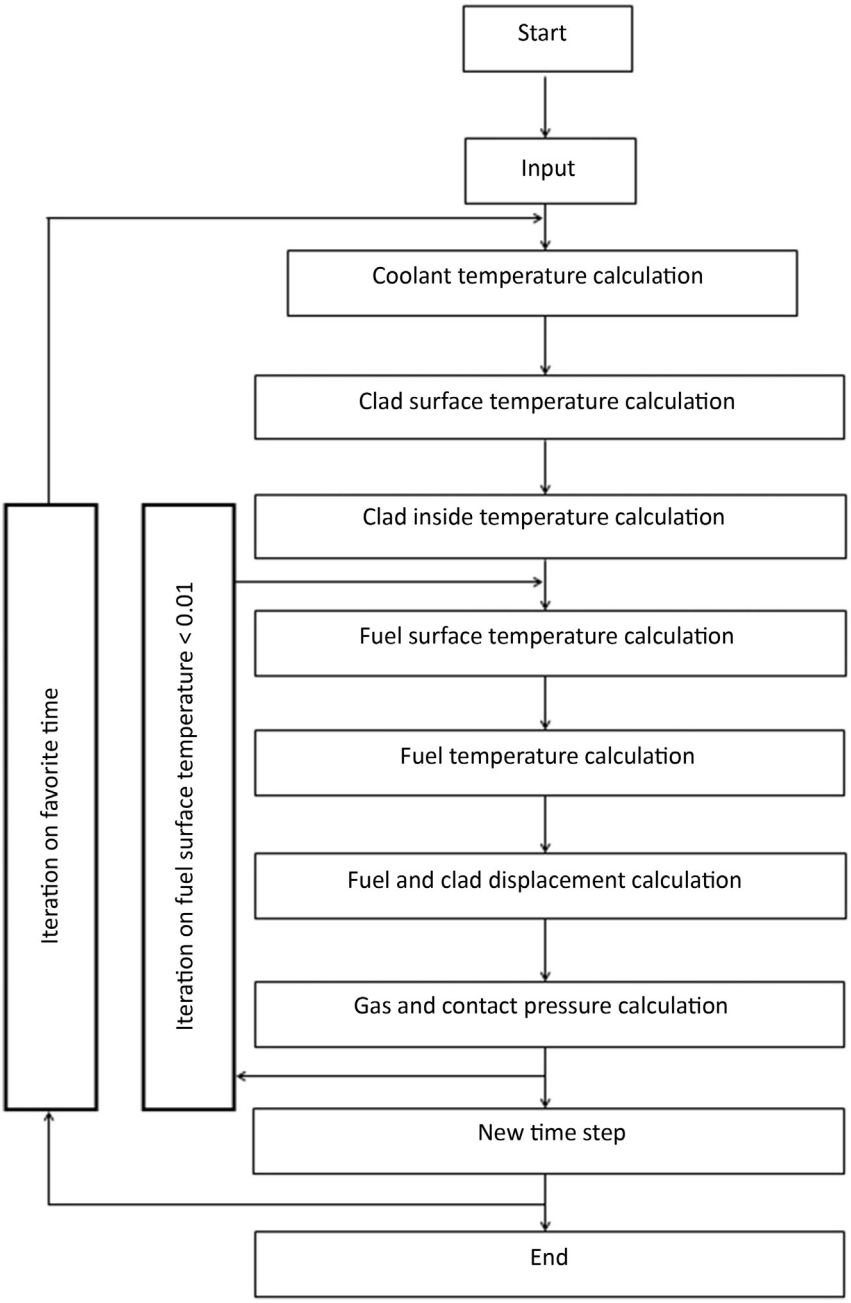

Fig. 3. Flow chart of MARCODE program.

modulus (MPa); R_f is the fuel pellet radius (m); R_i is the fuel central hole radius (m); P_g is the gas pressure in the gap (MPa); M_g is the moles of gas in the fuel rod, which is the sum of the moles of fill gas and released fission gases (moles); R is the universal gas constant (Pa.m^3/mole.K); V_P is the plenum volume (m^3); T_{gas} is the gas temperature (K); l the fuel rod length (m); V_{hole} is the volume of fuel central hole (m^3); V_{sh} is the fuel shrinkage volume (m^3); and R_{ci} is the clad inner radius (m).

Fuel densification occurs because of elimination of small porosity at the beginning of life; fuel swelling occurs because of generation of gas and solid fission products [7].

$$\varepsilon_{sd} = \frac{1}{3}\left(\frac{\Delta V}{V}\right)_{swell} + \left(\frac{\Delta L}{L}\right)_{dens} \tag{2}$$

where ΔV is the differential of fuel volume (m^3), V the fuel volume (m^3), ΔL the differential of fuel length (m), and L the fuel length (m).

The power source released by neutron fission, as well as the UO_2 low thermal conductivity, induces an important thermal gradient, particularly in the fuel, resulting in thermal dilatation. The associated stresses lead to pellet fragmentation at an early stage of the rod life. The relocation model is given as follows [1]:

$$u_{relocation} = -R_f + \sqrt{R_f^2 + \frac{1}{100}\frac{\Delta G}{G}\left(R_{ci}^2 - R_f^2\right)} \tag{3}$$

$\frac{\Delta G}{G}(\%) = 30 + 10Fbu$ LHGR < 20 kW/m
$\frac{\Delta G}{G}(\%) = 28 + Pfactor + (12 + Pfactor) \times Fbu$ LHGR < 40 kW/m
$\frac{\Delta G}{G}(\%) = 32 + 18Fbu$ LHGR > 40 kW/m

Table 2
Thermal mechanical and thermal hydraulic models in MARCODE program.

Models in MARCODE program	Reference
Fuel deformation	
Fuel thermal expansion	[1]
Fuel cracking	
Fuel swelling	
Fuel densification	
Effect of porosity on fuel thermal conductivity	
Fission product effect on fuel thermal conductivity	
Clad deformation	
Clad thermal expansion	[1]
Effect of coolant pressure on cladding deformation	
Cladding creep	
Pellet cladding interaction	
Gas thermal conductivity modeling in gap region	
Effect of fission gas release on gas thermal conductivity	[1]
Thermal hydraulic models	
Departure from Nucleate Boiling Ratio (DNBR)	[5]
Oxide layer effect	[2]
Crud layer effect	[1]

The fuel temperature distribution function [$T(r)$] is obtained as follows using the heat conduction equation [5]:

$$T(r) = T_{fc} - \frac{q \times r^2}{4\pi k_{fave}\left(R_f^2 - R_i^2\right)}\left[1 - \left(\frac{R_i}{r}\right)^2 - \left(\frac{R_i}{r}\right)^2 \mathrm{Ln}\left(\frac{r}{R_i}\right)^2\right]$$
$$R_i < r < R_f \tag{4}$$

Fuel average temperature is calculated using the following equation [5]:

$$T_{fave} = \frac{2}{R_f^2 - R_i^2} \times \left(\frac{T_{fc}\left(R_f^2 - R_i^2\right)}{2} - \frac{q\left(R_f^4 - R_i^4\right)}{16\pi k_{fave}\left(R_f^2 - R_i^2\right)} + \frac{q \times R_f^2}{8\pi k_{fave}} + \frac{q \times R_i^2}{4\pi k_{fave}\left(R_f^2 - R_i^2\right)} \times \left[R_f^2 \mathrm{Ln}\left(\frac{R_f}{R_i}\right) + \frac{R_i^2 - R_f^2}{2}\right]\right) \tag{5}$$

Fuel thermal conductivity is based on the expression developed by lucuta et al [12]. The effect of the dissolved fission products is reflected by a burnup and temperature-dependent factor "F_D." The effect of the precipitated fission products is reflected by the factor "F_P." The effect of the porosity is accounted for by the well-known Maxwell factor "F_M." The radiation effect is given by the factor "F_R." Therefore, the fuel thermal conductivity is calculated as follows:

$$k_f = k_o \times F_D \times F_P \times F_M \times F_R \tag{6}$$

Average conductivity is calculated with the following correlation using the numerical method for integral calculation:

$$k_{fave} = \frac{1}{T_{fc} - T_{fs}} \int_{T_{fs}}^{T_{fc}} k_f(T).\mathrm{d}T \tag{7}$$

5. Validation of MARCODE program

In order to examine the prediction of the program during irradiation, results of the program are benchmarked with the FRAPCON-3 code [8] using the input parameter from the MANZEL test case [9]. The constant linear heat rate was set at 16.4 kW/m for 1,500 full power days for the zircaloy clad solid fuel rods. The fuel cladding gap width, plotted in Fig. 4, decreased dramatically from 130 μm to 57 μm due to fuel expansion and relocation on the 1st day, and then it increased because of densification. Cladding creep down and swelling caused a reduced gap size, and finally soft contact occurred. The predicted day on which soft contact would occur is the same for both codes (about 1,050 operating days or burnup of 27 GWd/TU; the MARCODE program underestimates the gap size during the densification process).

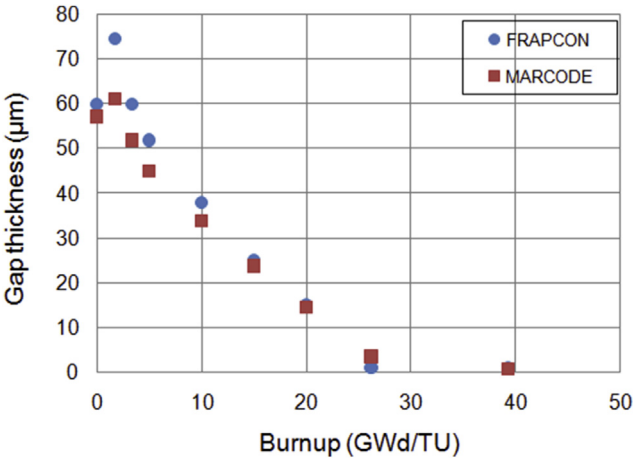

Fig. 4. Gap thickness distribution.

As shown in Fig. 5, the initial increase in fuel surface temperature is due to densification effects; subsequently, because of fuel swelling and cladding creep down, the gap is going to be closed and fuel surface temperature will decrease. It becomes constant after soft contact. The calculated maximum relative error of fuel surface temperature is about 3%, which occurred at a burnup of 1.7 GWd/TU.

Maximum fuel temperature is a very important parameter for code validation. Fuel temperature responds to many effects that take place during irradiation, such as fuel conductivity degradation, fuel densification, swelling, relocation, and other phenomena affecting the gap conductance value. Thus, a comparison of predicted maximum fuel temperature with that of FRAPCON-3 can be a good indicator of code qualification. The maximum fuel temperature during irradiation is shown in Fig. 6. Its variation versus burnup is the same as the fuel surface temperature, but it increases

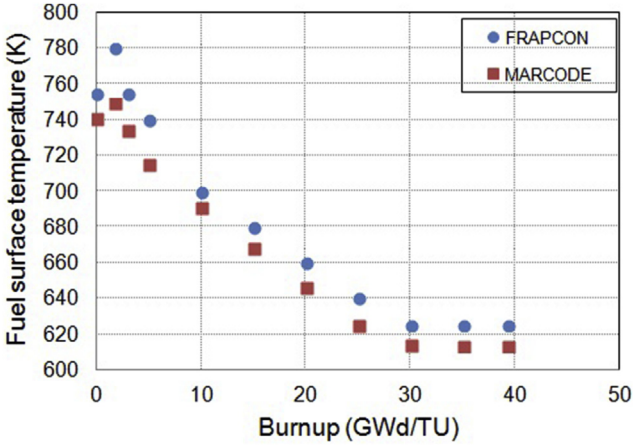

Fig. 5. Fuel surface temperature distribution.

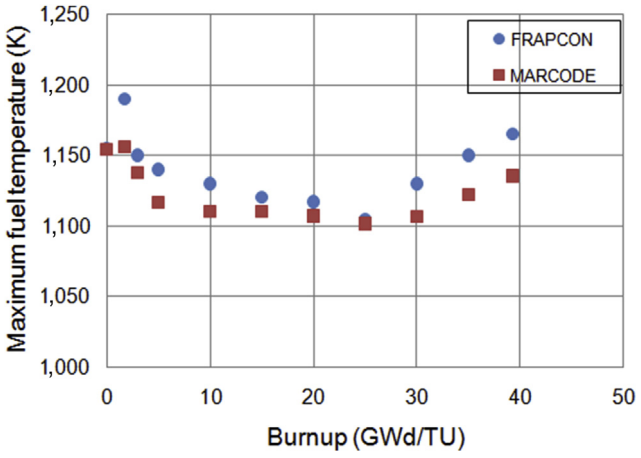

Fig. 6. Maximum fuel temperature distribution.

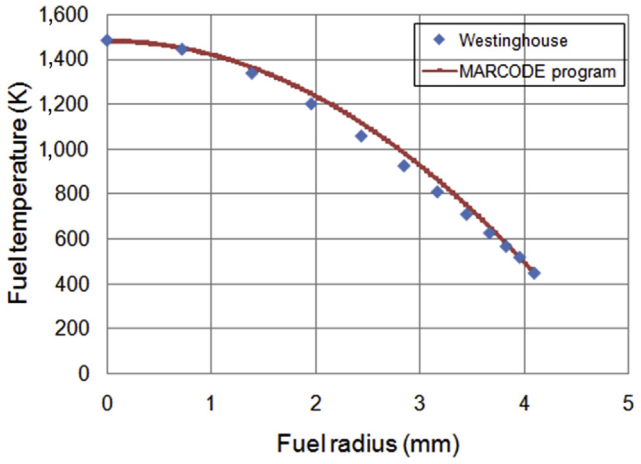

Fig. 7. Fuel radial temperature distribution.

after contact due to fuel conductivity degradation. The maximum relative error in the maximum fuel temperature calculation is about 2.6%, which occurred at a burnup of 1.7 GWd/TU.

A comparison has been made between the MARCODE program and a reference Westinghouse fuel rod. The reference Westinghouse fuel rod operates with a linear heat generation rate of 30 kW/m. The axial power shape is a cosine shape with a peak to average ratio of 1.3 [6]. Radial distribution of the fuel temperature at the peak axial node is compared with that of the FRAPCON-3 in Fig. 7, which shows that fuel surface temperature can be predicted well by the MARCODE program. The maximum relative error is <4%. Slight discrepancies in fuel temperature distribution may arise from the use of different methods for solving the heat conduction equation.

The Halden Ultra-High Burnup (HUHB) test fuel assembly was initiated by the Halden reactor project to demonstrate the effect of burnup on fuel thermal conductivity. The HUHB configuration of the assembly consisted of six rods, four of which were instrumented with centerline expansion thermometers. The rods were under irradiation in the Halden reactor, Norway, from September 1989 to 1997. Documented data for fuel center temperatures and linear heat ratings are available through early 1996, to a rod-average burnup of 76 GWd/TU [10]. The comparison between MARCODE program results and experimental maximum fuel temperature data for Rod 18 is shown in Fig. 8.

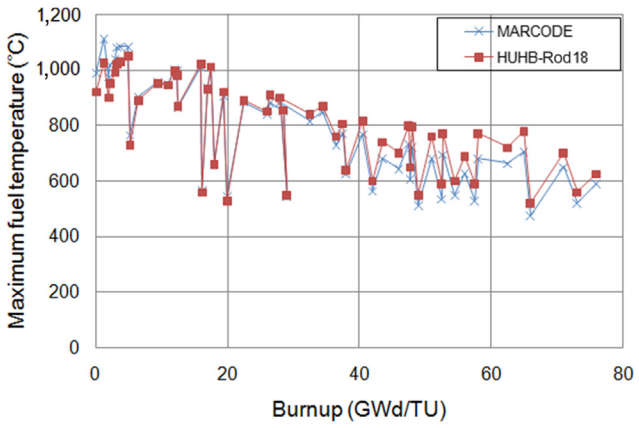

Fig. 8. Agreement between measured and predicted temperature for HUHB Rod 18.

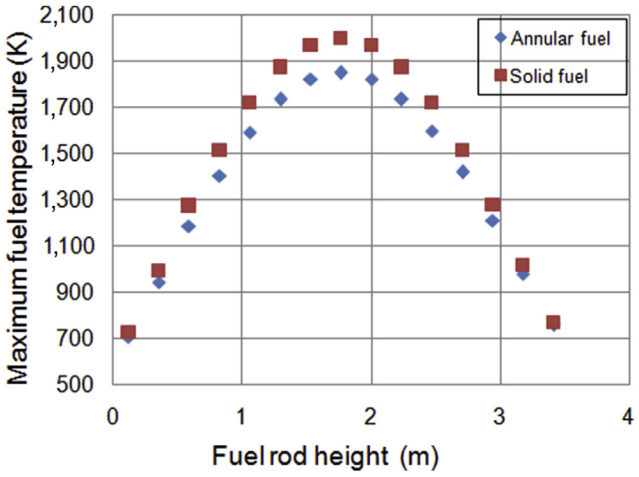

Fig. 9. Maximum fuel temperature distribution in solid and annular fuel.

6. Results

Axial distributions of maximum fuel temperature, average fuel temperature, and fuel surface temperature for solid and annular fuel at the beginning of the operating cycle are shown in Figs. 9–11, respectively.

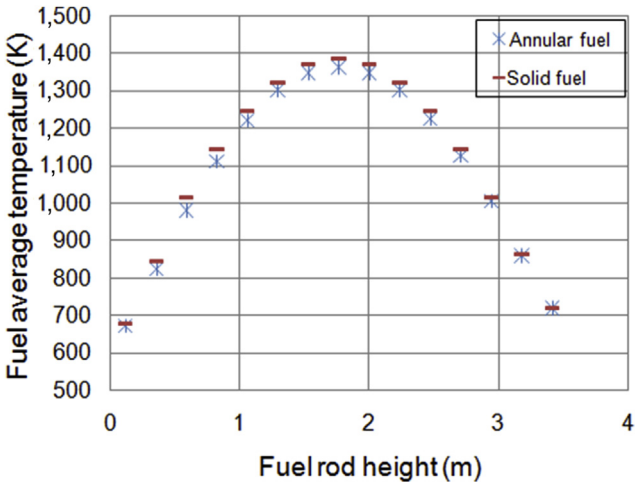

Fig. 10. Fuel average temperature distribution in solid and annular fuel.

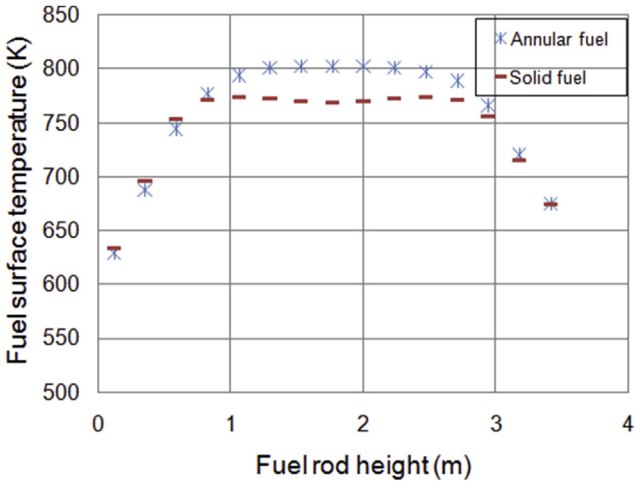

Fig. 11. Fuel surface temperature distribution in solid and annular fuel.

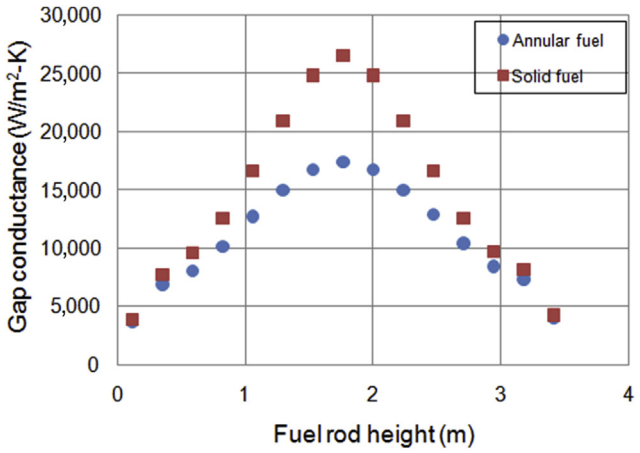

Fig. 12. Gap conductance distribution in solid and annular fuel.

As shown in these figures, the maximum temperature and also the fuel average temperature are higher in solid fuel than those of annular fuel, but the fuel surface temperature in solid fuel is lower than that of annular fuel. The gradient temperature in solid fuel is higher than that of annular fuel, so thermal expansion in solid fuel is greater than that in annular fuel. The thermal expansion effect

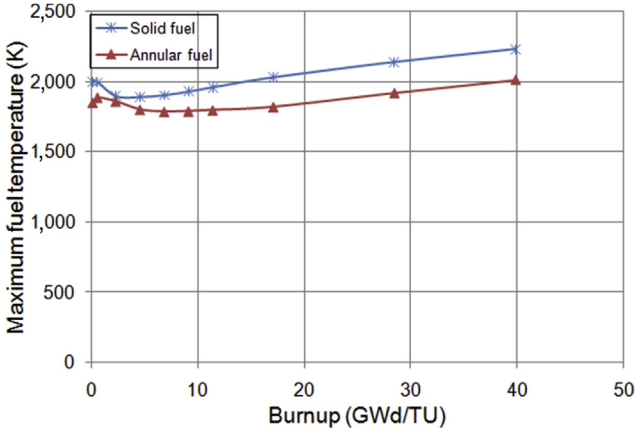

Fig. 13. Maximum fuel temperature versus burnup.

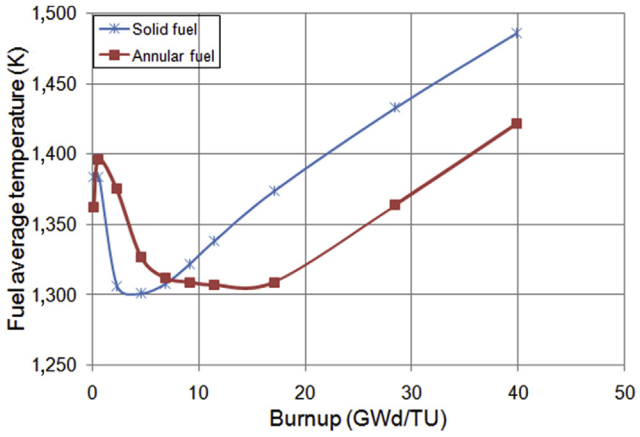

Fig. 14. Fuel average temperature versus burnup.

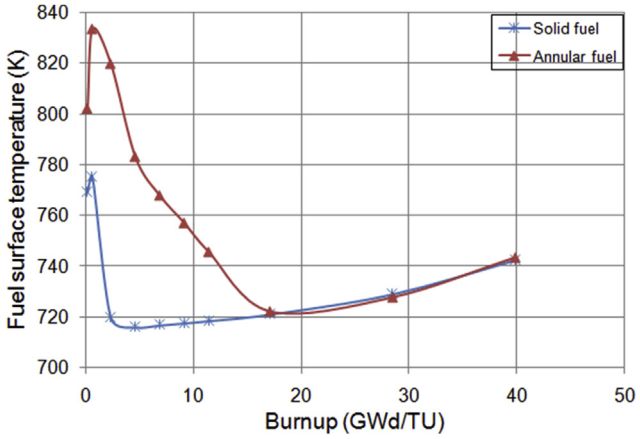

Fig. 15. Fuel surface temperature versus burnup.

and also the use of different displacement equations for solid and annular fuel cause a greater decrease in gap thickness in solid fuel in comparison with annular fuel. These phenomena finally lead to a higher value of gap conductance in solid fuel in comparison with that of annular fuel, as shown in Fig. 12.

Suppose that the power shape and value are constant during reactor operating time. The effects of fuel burnup on the maximum fuel temperature, fuel average temperature, and fuel surface temperature are shown in Figs. 13–15, respectively.

7. Conclusion

The effect of a central hole on fuel temperature distribution is studied in this report. Fuel center temperature and also fuel average temperature in solid fuel are higher than those of annular fuel, but for fuel surface temperature annular fuel has a larger value in comparison with solid fuel, as shown in Table 3. This phenomenon occurs because of greater fuel thermal expansion in solid fuel, which causes a decrease in gap thickness, resulting in a decrease of the fuel surface temperature value. By considering that fuel melting

Table 3
Comparison of maximum fuel temperature between solid fuel and annular fuel.

Parameter	Solid fuel	Annular fuel
Maximum fuel temperature (K)	1,998	1,848
Maximum fuel average temperature (K)	1,384	1,362
Maximum fuel surface temperature (K)	774	802
Maximum gap conductance value (W/m^2 K)	26,600	17,451

temperature of 2,800°C [11] is one of the most important safety criteria in the fuel system design procedure, from a temperature distribution viewpoint annular fuel is to be preferred to solid fuel because of its lower maximum fuel temperature. However, further study about the mechanical performance of fuel rods is needed to obtain better information for a comparison of the performance of solid and annular fuel rods.

Conflicts of interest

The authors have no conflicts of interest to declare.

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