



Research Paper

A procedure for solving transient nonlinear thermal problems of high burn-up nuclear fuel rods in a light water reactor

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HIGHLIGHTS

- Half boundary method is applied to thermal problems of high burn-up fuel rods.
- Thermal responses of nuclear fuel rods under heat-up, RIA and LOCA are simulated.
- Nonlinear material properties are involved in the calculation below 3500 K.
- Thermal behaviors of nuclear fuel rods with and without central hole are compared.

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ABSTRACT

To ensure the safety of the high burn-up nuclear fuel rods (NFRs) in existing reactors, thermal behaviors of NFRs have been analyzed extensively. In this paper, an accurate and efficient procedure, called half-boundary method (HBM), is applied to solve the one-dimensional transient heat conduction problems of high burn-up NFRs with temperature-dependent material properties. HBM saves computation cost since it only needs to calculate the second-order matrix in the simulation. Compared with the low burn-up condition, the conductivity drops significantly in the rim zone of the high burn-up NFR. The huge temperature gradient in the radial direction render the nonlinear material properties affecting the temperature distribution greatly. In addition, the model contains a helium layer, so the radiation heat transfers are considered in this paper. The heating up process of a low burn-up nuclear fuel is first simulated, and these results are compared with those from reference to verify the accuracy of HBM in transient thermal problems of NFR. The high burn-up NFRs with and without central hole in heat-up process, reactivity initiated accidents (RIAs) and loss of coolant accidents (LOCAs) are then simulated. The results show that the NFR with the central hole (NFRCH) is safer than the NFR without the central hole (NFRWCH), and the temperature distribution of high burn-up NFR is higher than that of low burn-up NFR. The pellet, which is near the central axis, is going to melt when a critical RIA happens, while the inner surface of the cladding will melt first when serious LOCA happens.

1. Introduction

The nuclear power is one of the most important sources of energy, and because of its inherent radioactivity, the safety of the nuclear power plant is critical. The NFR is the heat source of the reactor in a nuclear plant and acts as the first shield of radiation protection. Some existing NFRs have been changed to high burn-up. To obtain the results of the steady-state and transient-state heat transfer responses of the high burn-up NFRs in the water cooling reactor, many experimental tests and numerical simulations have been carried out. The NFR with a central hole has been used in VVER-1000. Su et al. [1–3] analyzed one-dimensional transient heat conduction problems of high burn-up NFRs

and simulated the thermos-hydraulic behaviors of a NFR of a pressurized water reactor during insertion and partial loss-of-flow by improved lumped parameter formulation, where Hermite approximation was used in both works. Soba and Kudryashov et al. [4,5] presented the temperature distribution in high burn-up NFRs. Some numerical simulation codes, such as FRAPTRAN [6], SCANAIR [7,8], FROBA [9] and THEATRE [10], have been developed to analyze the thermal behaviors of NFRs with nonlinear material properties in response to accidents like RIAs and LOCAs. Besides, kinds of commercial simulation software were also developed, for example, ABAQUS was used to study the temperature and heat flux changes in a NFR [11], and ANSYS was used to analyze the thermal-mechanical behaviors of NFRs [12].

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In this paper, the HBM [13–15] is used to simulate the thermal responses of NFRs to RIAs and LOCAs. HBM handles the first-order derivatives as independent variables, then derives the relationship between arbitrary node in domain and the nodes on half-number boundaries. In this way, the matrix order of HBM is not determined by the element numbers in the domain but only one order larger than the dimensional number of the model. For instance, in a one-dimensional problem, a second-order matrix is built in the calculation processes of HBM. Therefore, the builds of huge-order matrices and the arduous matrix inversion that are required in finite volume method (FVM) and finite element method (FEM) are avoided. Besides, two variables such as temperature and heat flux are calculated synchronously in computation. Variables at any node within the domain could be associated with both temperature and heat flux on only half of the boundaries, rendering the name of half-boundary method. In addition, no uniform grid or constant grid size is required. This method looks like the boundary type method, but no Green function is needed, and thus HBM has a better applicability. To consider the actual operation situations of NFRs in response to accidents, nonlinear material properties are included.

2. Physical and mathematical models

The NFR model (shown in Fig. 1(a)) consists of a uranium dioxide (UO_2) pellet which is used to produce heat, a zirconium alloy cladding and a gap located between the pellet and the cladding. The gap is filled with helium as a thermal conductivity gas to protect the fuel rod. Also, the pellet has a rim (dash line area in Fig. 1) since it is a high burn-up NFR. Due to the axisymmetric temperature distribution and the neglected axial heat transfer behavior, the numerical model is simplified to a one-dimensional problem. Benefit from the advanced manufacturing [16–18], an improved NFR model with a hole in the center of the pellet is possible which is displayed in Fig. 1(b). The hole is also filled with helium.

2.1. Physical models

The ability to calculate accurately the performance of light-water reactor (LWR) fuel with high burn-up condition in response to accidents depends on both physical models and numerical simulation methods. Besides, the heat conductivity coefficients of most materials are varied. The inconsistent material properties will dramatically influence the results particularly for a big temperature gradient. Therefore, the current work considers the material properties as nonlinear and the material properties for different parts of the NFR are presented in detail in

this section. In this paper, the nonlinear material properties of pellet and cladding are referenced from Ref. [19].

2.1.1. Pellet

Pellet is made up of UO_2 whose melting temperature is 3120 K, and it generates heat by fission of uranium atoms. The heat generation rate was assumed to be constant in some papers [12,20]. The coefficient of heat conductivity, the specific heat capacity and the density of pellet are temperature-dependent, and are calculated using the following equations, respectively:

$$k_p(T_p) = 100/(6.548 + 23.533\tau) + 6400\exp(-16.35/\tau)/\tau^{2.5}, \quad (1)$$

$$C_{p_p}(T_p) = 52.1743 + 87.951\tau - 84.2411\tau^2 + 31.542\tau^3 - 2.6334\tau^4 - 0.71391\tau^{-2}, \quad (2)$$

$$\rho_p(T_p) = 10.963/\xi^3, \quad (3)$$

where $k_p(T_p)$, $C_{p_p}(T_p)$ and $\rho_p(T_p)$ are the thermal conductivity coefficient (unit: W/(m K)), the specific heat capacity (unit: J/(kg K)) and the density (unit: kg/m³) of the fuel pellet, respectively. They are dependent on T_p . Where T_p is the temperature of the fuel pellet in a range of 298.15 K < T_p < 3120 K, and $\tau = T_p/1000$, $\xi = 0.99734 + 9.0802 \times 10^{-6}T_p - 2.705 \times 10^{-10}T_p^2 + 4.391 \times 10^{-13}T_p^3$ for 298.15 K < T_p < 923 K and $\xi = 0.99672 + 1.179 \times 10^{-5}T_p - 2.429 \times 10^{-9}T_p^2 + 1.219 \times 10^{-12}T_p^3$ for 923 K < T_p < 3120 K.

2.1.2. Helium layer

The heat transfer behavior in the helium layer was assumed as a pure conduction process in some papers [20]. However, radiation and convection also happen in the helium layer [21]. The convective heat transfer has the smallest influence on the thermal behavior because the helium barely flows in the gap. In order to investigate the effect of the convective heat transfer in the helium layer, commercial numerical software ANSYS is used to calculate the thermal results of the helium layer with and without buoyant and they are shown in Fig. 2. From Fig. 2 it can be seen that there is no much difference between them. Thus, the convection is ignored in this paper. Compared with convection, radiation has a more signification effect on the thermal behavior due to the high temperature difference between the outer surface of the pellet and the inner surface of the cladding. The helium is assumed transparent, and the helium layer surfaces are assumed to be grey diffuse and the temperature of each surface is assumed to be uniform [22]. The material properties expressions are presented below:

$$k_h(T_h) = 0.0468 + 3.81 \times 10^{-4}T_h - 6.79 \times 10^{-8}T_h^2 \quad (4)$$

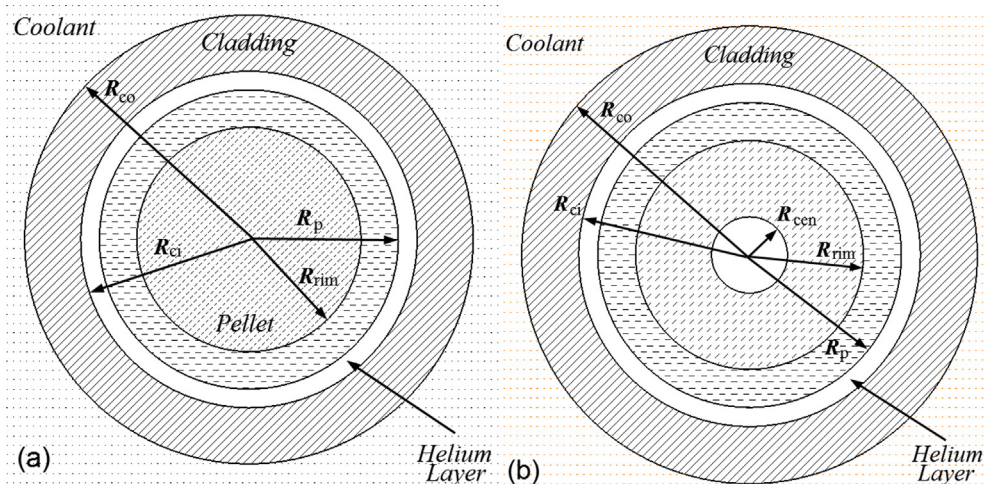


Fig. 1. Geometric sketches for the high burn-up NFR models with rims (the dash line area).

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