Determination of Effective Temperature at in-pile Study of Nuclear Fuel

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Abstract. In this work we describe the method to calculate the creep rate of uranium-gadolinium oxide fuel through the effective temperature of fuel samples. Effective temperature characterizes the creep rate with uneven temperature distribution during operation of fuel. Modern modeling technologies presented in ANSYS software were used to calculate the effective temperature. The calculations are compared with measures from in-pile experiments. The results of this work are extremely important for the licensing of new type of nuclear fuel.

1. Introduction

Long-term operation of the nuclear reactor is ensured by an initial reserve of reactivity, which must be compensated since the beginning of the reactor life-time. One of the ways of this compensation is the embedding of burnable absorbers. Currently, physicists pay great attention to the nuclear fuel with gadolinium oxide (UO_2–Gd_2O_3). Gadolinium has a high neutron capture cross section, easily integrates with the fuel and burns out without additional swelling [1–7].

The radiation creep plays a big role in determination of pellet-cladding mechanical interaction (PCMI). In the work [6] it has been shown thermal creep rate of uranium-gadolinium fuel (UGF) at temperatures 1150 – 1450°C, but in this case athermal creep component takes place to be. In our paper we investigate radiation creep rate at temperatures 550 – 950°C, because at these conditions radiation thermal creep makes the greatest contribution in PCMI.

To develop methods for determining the properties of UGF, the experimental device was created that would provide the work with samples. During the experiment it is possible to obtain the value of the total deformation of the samples, and it strongly depends on temperature, which is uneven in the volume of samples. Our work is devoted to the development of methods for determining the effective temperature that clearly corresponds to a particular creep rate. Similar studies have been conducted previously [8, 9] for uranium dioxide.

Our work is structured as follows: in the section 2, we derive the formula for further calculation of the effective temperature. In the section 3 we describe the process of the modelling of the temperature distribution inside the volume of the nuclear fuel samples and specify the basic physical and chemical properties of fuel. In section 4 we describe results of modeling

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temperature distribution, provide the comparison between the results of modeling temperature distribution and of measuring on the experimental device called RCFG ("radiation creep of fuel with gadolinium"), give the main conclusions and discuss further prospects.

2. Effective temperature

Creep strain highly depends on temperature. So it needs the effective temperature — constant temperature in volume of the sample and the corresponding creep rate at an uneven temperature field.

The form of the sample is a hollow cylinder with an inner radius of r_1 and an outer radius of r_0 and a height of L. We introduce the cylindrical coordinate system $\{r, \varphi, z\}$ with the beginning at the center of the lower plane of the sample. Assume $T(r, \varphi, z)$ is a temperature distribution over the sample. Creep strain is a function of stress, time, temperature, neutron flux and the properties of material. In the first approximation the dependence of creep rate below 900°C [10] is:

$$\dot{\xi} = A\sigma^n(r) \exp\left(-\frac{Q}{RT(r,\varphi,z)}\right), \tag{1}$$

where $\dot{\xi}$ — the creep rate (s^{-1}); A — the constant ($\mathrm{Pa}^{-n}\cdot\mathrm{s}^{-1}$) depending on neutron flux density material properties; $\sigma(r)$ — mechanical unaxial stress, Pa; n — the constant power index; Q — specific activation energy ($\mathrm{J\cdot mole}^{-1}$); R — universal gas constant ($\mathrm{J\cdot mole}^{-1}\cdot\mathrm{K}^{-1}$).

When the sample is compressed, plane-sections hypothesis is valid. According to it the strain rate at any point of the radial section is constant.

The force F acting on the sample can be determined, by the pressure of the loading device. Then

$$\sigma = \frac{F}{\pi(r_0^2 - r_1^2)} = \frac{1}{\pi(r_0^2 - r_1^2)} \int_0^{2\pi} d\varphi \int_{r_1}^{r_0} r\sigma(r,\varphi)dr \tag{2}$$

So we can write:

$$T_{\mathrm{ef}}(z) = \frac{Q}{R}\left[\ln\left(\langle\exp\left(\frac{Q}{RT(r,\varphi,z)}\right)\rangle_s\right)\right]^{-1}, \tag{3}$$

where $\langle\exp\left(\frac{Q}{RT(r,\varphi,z)}\right)\rangle_s$ defines the average value of the function $\exp\left(\frac{Q}{RT(r,\varphi,z)}\right)$ by area S of section z.

Partition the cylinder into K rings of radius, in M cylindrical sectors and in N parts in height. We assume that in each elementary volume of the partition the temperature is constant. Denote the temperatures in each partition region $T(r_i, \varphi_j, z_k) \equiv T_{ijk}$. Then the formula (3) is written as:

$$T_{\mathrm{ef}_k} = \frac{Q}{R}\left[\ln\langle\exp\left(\frac{Q}{RT_{ijk}}\right)\rangle_{ij}\right]^{-1}, \tag{4}$$

where $\langle\exp\left(\frac{Q}{RT_{ijk}}\right)\rangle_{ij} \equiv \frac{1}{KM}\sum_{i=1}^{K}\sum_{j=1}^{M}\exp\left(\frac{Q}{RT_{ijk}}\right)$.

The creep strain of full sample is:

$$\varepsilon = L \cdot A_0 \exp\left(-\frac{Q}{RT_{\mathrm{ef}}}\right) = \int_0^L A_0 \exp\left(-\frac{Q}{RT_{\mathrm{ef}}(z)}\right) dz, \tag{5}$$

where A_0 is constant. So we have:

$$T_{\mathrm{ef}} = -\frac{Q}{R}\left[\ln\left(\langle\exp\left(-\frac{Q}{RT_{\mathrm{ef}}(z)}\right)\rangle_L\right)\right]^{-1}, \tag{6}$$

where $\langle \exp\left(-\frac{Q}{RT_{\text{ef}}(z)}\right)\rangle_L$ is the mean of function $\exp\left(-\frac{Q}{RT_{\text{ef}}(z)}\right)$ by sample length L.

In the case of partition into N parts in height we get

$$T_{\text{ef}} = -\frac{Q}{R}\left[\langle \exp\left(-\frac{Q}{RT_{\text{ef}_k}}\right)\rangle_k\right]^{-1}, \tag{7}$$

where $\langle \exp\left(-\frac{Q}{RT_{\text{ef}_k}}\right)\rangle_k \equiv \frac{1}{N}\sum_{k=1}^{N} \exp\left(\frac{Q}{RT_{\text{ef}_k}}\right)$.

Thus, for known temperature values at predetermined points, it is possible to calculate the effective temperature in the entire volume of the sample using the formula (7).

Activation energy can be established from 2 experiments with the same stress and different temperatures.

3. The modeling of the temperature distribution

Thus, we have specified internal heat generations and boundary conditions in Steady-State Thermal module of ANSYS Workbench. The modeling of the temperature distribution in nuclear fuel samples is shown on Fig. 1.

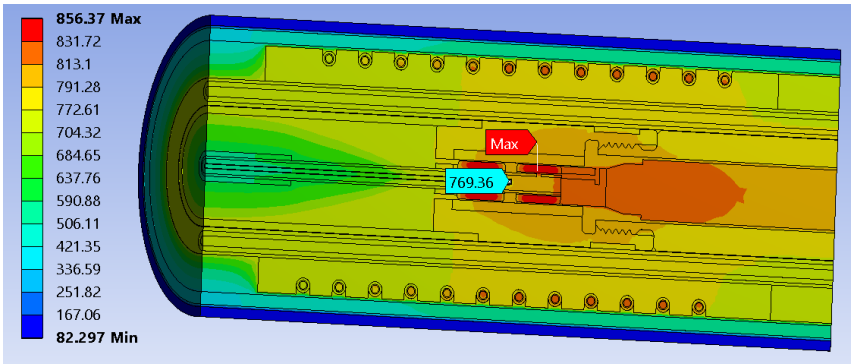

Figure 1. The modeling of the temperature distribution in nuclear fuel samples

Physical properties of UO_2–Gd_2O_3 were established in works [1, 2, 6].

We have calculated the effective temperature by formulas (4) and (7). We split the samples into 10 layers in height, in 3 parts in radius and into 4 radial sectors. We accept that irradiation device is symmetric with respect to its median plane and 4 radial sectors correspond to the half of the annular section of the sample, i.e., it's like to split the complete section into 8 sectors. We take the temperatures at each split point and calculate the effective temperature for each sample and two together. Activation energy 0.45 eV (or 11.4 kJ/mole) was used in calculations.

4. Discussion

The values of effective temperature are calculated for the respective thermocouple temperatures (for reference points) are summarized in the table 1.

The absolute error consists of several factors. The error in determining the heat generations (10%) and $8 - 10^{\circ}$C in our work. There is also an uncertainty of the values of thermophysical properties, which is $\sim 5 - 7\%$ and changes the result of the effective temperature by about 3 °C. We also take into account the error of calculating the heat transfer coefficient — 2%, which leads to a change in temperature by 2 °C.

We assumed that the dependence of the radiation creep rate on temperature is described by Arrhenius law. For UO_2 fuel this dependence is well confirmed at temperatures up to 900 °C.

To determine effective radiation creep rate, several experiments with two samples were carried out. But from these experiments it is impossible to determine the effective temperature, since the temperature is known only in the cavity between the samples. So we have constructed a mathematical and then numerical model of the irradiation device of the RCFG and perform its steady-state thermal analysis.

Table 1. Comparison of the temperature in the center of the cavity of the samples and the effective temperature

Temperature of the thermocouple in the center of the cavity, T_c °C	Bottom sample	Top sample	Both
550	614	605	610
600	665	649	661
730	800	791	795
770	833	828	830
830	915	911	912
870	940	932	936

The correspondence between the computational model and the physical (validation procedure) was based on experimental data and estimates. First of all, this is the known temperature in the center of the sample cavity, as well as the size of the gaps. These nuances have been taken into account, and checked their compliance in the results.

5. Conclusion

In our paper, we describe a method for finding the effective temperature corresponding to the entire fuel sample at uneven temperature distribution. This method is necessary to establish a correspondence between the creep rate of the sample and its temperature. To determine the creep rate, the device RCFG was created and tested in the RBT-6 reactor.

In conclusion we would like to mention that developed method of determining effective temperature can be used in the study of densification and for another types of fuel. And it would be interesting to research the creep rate dependence on nonstoichiometry, crystallite size, porosity in the spirit of works [10, 11].

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