Analysis of different factors on the features of thermal destruction of a fuel pin

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Abstract. The presented work studies the influence of various factors that affect the specific features of fuel pins melting. For this purpose, fuel pins with different geometries and energy release are considered. Numerical simulation of melting is carried out using a program module for calculating the destruction of fuel rods. Comparison with theoretical calculations is made. The analysis of the convergence of calculations with respect to the time step value and the number of calculated cells along the radius and height is carried out. As a result of work with the use of numerical methods, the characteristic times of destruction of fuel elements during an accident with a loss of coolant flow rate (an accident of the ULOF type) and the dependence of weight loss on time are obtained under various conditions.

1. Introduction

Design and development of new types of reactor facilities requires justification of their safe operation. It is not always possible to create experimental reactor facilities or, at least, test benches to simulate emergency situations due to their high cost and poor scalability of the results obtained. For this reason, the most important physical processes occurring during accidents can be modeled using modern computing systems and mathematical modeling methods.

To analyze the processes of destruction of the core elements of promising reactors, a universal design code is being developed [1], which includes a module for calculating the destruction of the core and fuel elements (fuel elements) [2-4].

The module for calculating the destruction of fuel elements is intended for calculating the problems of modeling the melting of fuel elements in fast reactors. The problem of thermal destruction of a fuel element is complex; to simplify calculations, it is divided into two subtasks: the thermal problem during melting / solidification and the problem of dripping over the surface of a fuel element [2, 4].

To solve the thermal problem in modeling the fuel element melting, the heat conduction equation is solved in the enthalpy formulation in the cylindrical r-z geometry. To solve the dripping problem, a system of equations for the conservation of mass, energy, and momentum is used. The basic numerical scheme for convective terms is constructed using upwind approximation. High-order accuracy schemes have also been implemented in [5].

It should be noted that in the solution process, two types of computational grids are used. The first grid is necessary for solving the thermal problem, and the second is required for modeling the movement of the melt. In the process of calculation, there is information exchange between the grids. From the thermal problem, the following data are transmitted: on the amount of melt and its temperature, and on the outer radius of the intact part of the fuel element and the melt thickness. In the
opposite direction, information is also transmitted about the amount of frozen melt, its new temperature, and the magnitude of the heat flux that comes from the melt into the fuel element.

2. The basic model to simulate thermal destruction of the fuel pin
Simulation methods were developed to simulate severe accidents with core degradation in fast reactors with different fuel types (oxide, metallic and nitride) and different liquid metal coolant (sodium and lead). These methods were implemented in the SAFR module [2-4], being the part of the EUCLID/V2 coupled code [1]. To simulate melt relocation the system of the mass, energy and momentum equation is used:

\[
\frac{\partial \rho S}{\partial t} + \frac{\partial \rho U S}{\partial z} = \Gamma_m
\]

\[
\frac{\partial \rho h S}{\partial t} + \frac{\partial \rho h U S}{\partial z} = q_m \Pi_m + q_c \Pi_c + \Gamma_m h_m
\]

\[
\frac{\partial \rho S U}{\partial t} + \frac{\partial \rho S U^2}{\partial z} = -S \frac{\partial p}{\partial z} + \Gamma_m U_m + \rho g S \sin \theta + \tau_c \Pi_c - \tau_w \Pi_w + \sigma \Pi_w \cos \theta_w \delta(z-z_c)
\]

where \( S \) is the cross section of the melt, \( m^2 \); \( \Gamma_m \) is the mass source; \( q_m, q_c \) are heat fluxes from the fuel pin surface and coolant, respectively, W/m²; \( p \) is the pressure, Pa; \( U \) is the velocity of the melt, m/s; \( \tau_c, \tau_w \) is the wall and interfacial shear stress, H/m²; \( \sigma \) is the surface tension, N/m; \( \theta_w \) is the contact angle.

The wall shear stress of the melt is calculated with help of the wall friction coefficient that has been presented in the work [6]:

\[
\xi_w = \max \left[ 64 \Re^{-1} \left( 3 \alpha - 1 \right) / \alpha, 0.37 / \Re^{0.25} \right],
\]

Coolant shear stress \( \tau_c \) can be evaluated by the relation:

\[
\tau_c = \frac{\xi}{8} \rho U^2, \xi = 0.02.
\]

To simulate melting of oxide fuel and fuel pin cladding, the heat transfer problem is solved:

\[
\frac{\partial \rho h}{\partial t} = \nabla \cdot (k \nabla T) + Q.
\]

In the relation above \( \rho \) is the density of the material, kg/m³; \( k \) is the specific enthalpy, J/kg; \( k \) is the thermal conductivity, W/(mK); \( T \) is the temperature, K; and \( Q \) is the internal heat sources, W/m³.

It is known that, at relatively low nitrogen pressures above the surface of uranium nitride, congruent melting is not observed. There is decomposition into uranium (plutonium) and nitrogen. To determine the rate of dissociation of the nitride fuel during an accident, special models are used [7].

3. Fuel pin model
The calculations for two models of fuel elements with a steel cladding (Figure 1) and without it were compared. For calculation, the value of the radius of the cylindrical cavity was equal to 1 mm. Two values of the fuel thickness were chosen. For the first one it was equal to 3mm. And for the second it was equal to 5mm. Cladding thickness was equal to 0.5mm. Uranium dioxide (UO₂) was used as a fuel, and SS316 was used as a cladding material.
Figure 1. Schematic diagram of a fuel element simulator with a steel cladding of thickness "b". 
With a cylindrical cavity in the middle of the radius "r" and a fuel of thickness "a".

Using the software module for calculating the destruction of fuel pins [2-4], calculations were carried out for two different energy release: uniform along the fuel length and non-uniform (sin(x)-law).

To verify numerical methods, comparison between analytical and numerical calculation was provided. The model without cladding and with uniform energy release was chosen. The melting time can be evaluated with help of the relation:

\[ t = \frac{\lambda m + C_p (T_m - T_0) m}{N}, \]

where \( \lambda \) is the specific heat for UO\(_2\), \( C_p \) is the heat capacity, \( T_m \) is the melting point, \( T_0 \) is the initial temperature, \( m \) is the total mass of the fuel, and \( N \) is the energy release (W). The results are shown in Figure 2.

Figure 2. The melting times.

The results of the simulation of the mass loss are presented in Figure 3. The results of the calculation with uniform heat release are in a good agreement with the real experimental data [8-9]. With a non-uniform heat release, the substance melts non-simultaneously. So, we can see the "steps" in the figure.
The formation of "steps" is shown in Figure 4. It can be seen that part of the substance melts and begins to relocate, while the substance above has not yet warmed up to the melting point. A "step" is obtained in that period of time when one molten part has already flowed away, and the substance that melted later, has not yet reached the boundary of the fuel pin.

4. Conclusion
The fuel pin melting and the melt relocation along the surface of the fuel column have been simulated. It is demonstrated that the calculation results are in good agreement with the analytical data. Based on numerical data it is shown that the characteristic time of thermal destruction of a fuel element is from 10 to 100 seconds, depending on the conditions. The rate of weight loss with non-uniform heat release is qualitatively different from the rate of weight loss with uniform heat release.

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