Numerical simulation of the molten fuel relocation in fuel rod

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Abstract. Thermal destruction of fuel rods is one of the most hazardous accidents in nuclear power plants. Fuel melt contains a lot of fission products that can release and start to transport along reactor loops. Relocation of the fuel melt can change the power of reactor due to feedback between density of materials and neutron field in reactor core. The presented paper contains a brief description of the ways to simulate fuel melting and molten fuel relocation. Basic equations, numerical approximation and closing relation are presented in the paper. The results of the simulation of the molten fuel relocation as a result of the fuel rod thermal destruction are discussed.

1. Introduction
Nuclear power is one of the most clean electrical energy sources. The main barrier hindering its further development is the serious consequences resulting in severe accidents with the destruction of the core. During this type of accident a lot of radioactivity can be released from the destructed core. For this reason, it is relevant to conduct studies to justify the safety of projected facilities.

The current paper is devoted to the study of processes with destruction of the reactor core. The motion and heat transfer of fuel melt during thermal destruction of fuel rods was chosen as the research object. The study of this phenomenon is very important for a detailed understanding of the accidents in nuclear power plants. Investigation of the fuel melt behavior is also important for determining the range of applicability of existing and developed calculation codes [1] to justify the safety of nuclear power facilities.

2. Basic method of numerical simulation
Most of the methods that can be used to simulate thermal destruction of the fuel rods were presented in the previous papers of the authors [2] – [5]. Solution of the thermal problem in fuel rods during melting and solidification of the melt, as well as the melting and solidification phenomena themselves, are simulated by solving the heat equation in the enthalpy formulation in two-dimensional r-z geometry. This approach allows us to determine position of melting front with good accuracy [6].

Simulation of the melt motion is carried out by solving a system of mass, energy and momentum conservation equations in a one-dimensional approximation. Basic view of the system is presented in [3] – [4]. An equation of the mass conservation is presented below:

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

where \( S \) is the cross section of the melt; \( \Gamma_m \) is the mass source; \( U \) is the velocity of the melt, m/s; \( \rho \) is the density of the melt. Numerical approximation is constructed with help of the finite volume method.
and “upwind” numerical scheme. “Upwind” scheme is the first order accuracy scheme. High-order numerical schemes were realized also: MLU [7] and MUSCL [8] schemes.

The system of equations is closed by relations on a wall friction and a wall heat transfer of the melt. These relations depend on flow regime. There are three different flow regimes: continuous flow, film flow and rivulet flow regimes. The first regime is used to simulate in-pile molten fuel relocation. The second and third regimes are used to simulate a motion of a molten fuel or a molten steel on surface of a fuel rod. Closing relation for continuous and film flow regimes were described in [3] and [4]. Closing relations for rivulet flow regimes are described below. At first we will assume that the transition from film flow to rivulet flow occurs when the flow pressure is not enough to destroy the contact line. In this case we have inequality [9]:

$$\rho U^2 \delta/2 < \sigma (1 - \cos \theta_w) - d\sigma/dT (T_w - T_m) \cos \theta_w,$$

where $\delta$ is the melt height; $\sigma$ is surface tension; $\theta_w$ is the contact angle; $T_w$ is the wall temperature; $T_m$ is the melt temperature.

To calculate cross-sectional area of the melt, wetted perimeters and as a result heat transfer rate and friction, it is necessary to know the number of rivulets and rivulets’ widths. The number of streams can be calculated using the approaches developed in [10] – [11]:

$$L = 25 \cdot \delta \cdot (3 \cdot Ca)^{-1/3}, \quad Ca = \mu U / \sigma,$$

where $\mu$ is the melt viscosity. Rivulet width $a$ can be calculated by means of relations presented in [12]:

$$a = 4.6 \lambda_c / We^{1/5}, \quad We = \sigma^2 \theta_w^2 / (g \lambda_c \mu^2), \quad \lambda_c = \sqrt{\sigma / (\rho g)}.$$

Rivulet cross-sectional area is equal to:

$$S_{riv} = a^2 / \sin^2 \theta_w (\theta_w - \sin 2\theta_w / 2)$$

Heat transferred from molten fuel to the surface of fuel rod can be calculated with help of the relation:

$$q_w = \alpha (T_w - T_m) S_{riv}$$

To calculate heat transfer coefficient between wall and molten fuel we use the relations for film flow regime [13]:

$$\alpha = Nu \lambda / \delta, \quad Nu = 35/17$$

3. Numerical simulation of the melt relocation in fuel rod

Some examples of the melt relocation are presented below to demonstrate an ability to simulate melt relocation. The problem of the melt relocation under shear stress is shown in the Fig.1. To simulate melt motion, MUSCL scheme was used. Fuel rod length was equal to 3 m. Initial length of the melt was equal to 0.10 m. The melt was placed at beginning of the fuel rod. Fuel rod radius was equal to 0.004 m. To simulate melt relocation we used 200 computational cells.

The results of the simulation were compared with analytical solution. This solution is an asymptotic solution for the task of the shear stress driven film flowing on the vertical substrate:

$$z = \sqrt{2 A \tau \mu},$$
where $\tau$ is the shear stress. The results of simulation correspond to analytical calculation with good accuracy.

Figure 1. Surface stress driven molten flow

To investigate molten uranium dioxide relocation during fuel rod thermal destruction, a model of the fuel rod was constructed. The model was 2 m long. There were three parts of the fuel rod. The first part was 1 m long. The second and third parts were 0.5 m long. The radius of fuel pellet was equal to 0.004 m. Heat release occurred in the central part of the fuel rod during 3 s. A power was equal to $2.4 \cdot 10^5$ W. The value of the power was closed to conditions during UTOP accident. Simulation was carried out for different coolant velocity: 50, 100 and 150 m/s. Calculated distributions of the materials at the end of the power rise are shown in Fig. 2 and Fig 3.

Figure 2. Calculated distribution of the materials at 2.88 s (150 m/s): red – molten fuel, green – solid fuel
Figure 3. Calculated distribution of the materials at 3 s (150 m/s): red – molten fuel, green – solid fuel

The mass of the fuel that left the central part of the fuel rod for different coolant velocity is presented in Fig. 5.

Figure 4. The mass of the fuel that left the central part of the fuel rod

As we can from the fig.4 the most part of the molten fuel mass left the central part of the fuel rod during several second. So the characteristic time of the first stage of the severe accident is the order of the several seconds. During this period of time the most part of the fuel melts and leaves central part of the reactor core.
Conclusion
The brief description of the numerical models that can be used to simulate molten fuel relocation is presented in the paper. On the basis of realized numerical model the simulations of the molten fuel motion are provided. The simulations have been made for different values of the coolant velocity. The quantity of the fuel mass that left fuel rod has been calculated.

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