Numerical simulation of melt relocation and heat transfer during severe accidents in the fast reactors

E V Ussov\(^1\), A A Butov\(^1\), I A Klimonov\(^1\), V I Chuhno\(^1\), N A Pribaturin\(^{1,2}\), N A Mosunova\(^3\) and V F Strizhov\(^3\)

\(^1\) Nuclear Safety Institute of the Russian Academy of Sciences, Novosibirsk Branch, Novosibirsk, 630090, Lavrentieva Street, 1, Russia
\(^2\) Institute of Thermophysics of the Russian Academy of Sciences, Siberian Branch, Novosibirsk, 630090, 1 Lavrentiev Ave., Russia
\(^3\) Nuclear Safety Institute of the Russian Academy of Sciences, Moscow, 115191, B. Tulskaya, 52, Russia

Abstract. Due to the revival of the interest to the development of fast reactors cooled by liquid metals, it is important to provide theoretical research of reactor’s safety. A detailed calculation of all stages of the accident from the beginning to the end requires knowledge of the laws for modeling of physical processes occurring in the reactor in an emergency. The most jeopardized are accidents with the destruction of the reactor core. The main objective of the proposed research is developing of models and numerical algorithms for calculation of core degradation. These models can be used in codes for analysis of severe accident in fast reactors. The presented paper contains descriptions of algorithms that are used to simulate melt motion on the surface of fuel pins.

1. Introduction
Simulation of severe accident in nuclear reactor is a key element in a safety analysis of nuclear power plants. There are some stages of core degradation. Coolant boiling and fuel rods melting are occurring during the first stage. Destruction of the fuel assembly is a key phenomenon at the second stage. The degradation of whole reactor core is a key issue at the third stage. The goal of presented paper is to develop models for fuel pins melting at first stage of core degradation.

There are several mechanisms of fuel element destruction in the fast reactors with oxide fuel. The first mechanism of fuel disruption is caused by abrupt power increase due to TOP (Transient Overpower) accident. Rapid power increase at a low heat removal rate may lead to fuel dispersion before the cladding is destroyed. The second mechanism is caused by melting of the cladding due to dry out of coolant film during the loss of coolant accident (LOCA). Due to high power-flux and low operating pressure, sodium vapour velocity may reach more than hundreds meters per second during the LOCA. This fact plays a significant role in the dynamics of melt relocation. In the present paper we describe models for second mechanism of destruction.

2. Brief description of the EVCLID/V2 code
To simulate severe accidents in the fast reactors, the EVCLID/V2 code has been developed by the Nuclear Safety Institute (IBRAE RAS) in a framework of the Federal Target Program “Nuclear Power Technologies of the New Generation for 2010-2015 and until 2020”. The EVCLID/V2 code contains
different modules that can solve different tasks. For example, the HYDRA-IBRAE/LM [1] code is able to simulate thermal-hydraulic processes in the nuclear power plants with liquid metal coolant, namely sodium, lead, and lead-bismuth. The Berkut code [2] can be used to calculate thermo-mechanical processes in fuel pins during accidents. The DN3D code has been developed to determine a heat release distribution in the reactor’s core. Simulations of the fuel pins destruction are provided by the SAFR/V1 module [3]. The SAFR/V1 code solves the heat transfer problem during melting of the fuel pins and calculates the melt relocation.

3. The SAFR/V1 basic equations
The SAFR/V1 code consists of two different modules. The first one solves heat transfer problem in solid and liquid state of materials. The second one solves the problems of melt relocation.

To solve heat transfer equation in solids, to determine the mass of the melt, and to simulate fuel assembly wrapper tube melting, the enthalpy formulation [4] of heat transfer problem is used. In comparison to the temperature formulation, the enthalpy formulation is more convenient, because enthalpy changes continuously during phase transition, in contrast to temperature.

$$\rho \frac{\partial h}{\partial t} = \text{div} (\lambda \cdot \text{grad}T) + Q $$  (1)

In the relation above $\rho$ is the density of the melt, kg/m$^3$; $h$ is the specific enthalpy, J/kg; $\lambda$ is the thermal conductivity, W/(m·K); $T$ is the temperature, K; $Q$ is the internal heat sources, W/m$^3$.

Enthalpy unambiguously determines the temperatures and phase state of control volumes.

$$h(T) = \begin{cases} f_s(T) = h_m + \int_{T_m}^{T} C_{ps}(\tau)d\tau, & T < T_m \\ f_l(T) = h_m + L + \int_{T_m}^{T} C_{pl}(\tau)d\tau, & T > T_m \end{cases}$$  (2)

$$T = \begin{cases} f_s^{-1}(h), & h \leq h_m \\ f_l^{-1}(h), & h_m < h < h_m + L \end{cases}$$  (3)

$$\varphi = \begin{cases} \frac{(h-h_m)}{L}, & h_m < h < h_m + L \\ 1, & h \geq h_m + L \end{cases}$$  (4)

Where: $C_{ps}$ is the specific heat in solid state, J/(kg·K); $C_{pl}$ is the specific heat in liquid state, J/(kg·K); $T_m$ is the melting temperature, K; $L$ is the latent heat of phase transition, J/kg, $\varphi$ is the melt fraction in control volume, $h_m$ is the melting enthalpy J/kg.

There are three kinds of boundary conditions. The first one is defined temperature, the second one is defined heat flux, and the third is heat transfer with coolant. Also there is an additional kind of boundary condition. This type of condition allows adding radiation heat transfer from the surface of fuel pin.

Models that are based on the results of experimental studies give the best prediction in the simulation of fuel rod melting. Investigations of the fuel rods destruction in the fast reactors demonstrate that clad motion is strongly affected by the nonwetting behavior of molten cladding and $\text{UO}_2$ [5]. Relocation of the melt depends on the balance of the gravitational forces, friction forces.
between melt and surface of the fuel pins, and friction between melt and coolant. To simulate melt relocation, the system of mass, energy, and momentum conservation are solved.

\[ \frac{\partial \rho S}{\partial t} + \frac{\partial \rho S U}{\partial z} = \Gamma_m \]  
\[ \frac{\partial \rho S h}{\partial t} + \frac{\partial \rho S h U}{\partial z} = q_w \Pi_w + q_c \Pi_c + \Gamma_m h_m \]  
\[ \frac{\partial \rho S U}{\partial t} + \frac{\partial \rho S U^2}{\partial z} = -S \frac{\partial p}{\partial z} + \Gamma_m U_m + \rho g S \sin \theta + \tau_w \Pi_w - \Pi_c \tau_c + \sigma \Pi_n \cos \theta_n \delta(z-z_0) \]  

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

Some relations of the SAFR/V1 module for calculating friction and heat transfer are presented in the next section.

4. Closing relations for calculating friction and heat transfer

The relations that are used for calculation of wall shear stress and heat transfer are very important to simulate melt relocation in the reactor’s core. Wall shear stress determines the value of melt velocity and quantity of mass that moves away from center of the reactor’s core.

The wall shear stress can be calculated by means of the relation:

\[ \tau_w = \xi \rho U^2 / 8 \]  

where \( \xi \) is the wall friction coefficient. The value of the wall friction coefficient depends on flow regimes. For laminar and turbulent flow regimes the wall friction coefficient can be obtained using the next relations:

\[ \xi_{lam} = 64 / Re, \xi_{turb} = 0.316 / Re^{0.25} \]  

To calculate heat flux from the fuel pin surface to the melt we use an equation that is presented below:

\[ q_w = \alpha (T_w - T) \]  

\( \alpha \) is the heat transfer coefficient. For laminar film regime [6]:

\[ \alpha = Nu \lambda / \delta, \space Nu = 35 / 17 \]  

For turbulent liquid metal films [7]:

\[ \alpha = Nu \lambda / \delta, \space Nu = 2.25 + 0.01 \cdot Re^{0.8} \]  

5. Results of calculation

Validation of the EVCLID/V2 code was made on the basis of experimental data and tests that have an analytical solution. These tests are called analytical tests. The first analytical test allows verifying models of liquid steel relocation on UO_2 surface. The results of calculation are presented in the figure 1. We considered two different situations. The first one is a relocation excluding influence of surface tension on the leading edge relocation. The second one is the relocation including influence of surface tension between two materials. As we can see from the figure 1, the EVCLID/V2 code allows simulating melt relocation with and without surface tension with good accuracy.
To validate the EVCLID/V2 code, fuel bundle melting experiments were simulated. The experiments have been performed at the Argonne National Laboratory using sodium loop of the TREAT reactor [8]. The TREAT is a pulsed reactor that was designed and built by the Argonne National Laboratory. Gas-pressure-driven sodium loop (the R-Loop) was developed for providing tests with full-size LMFBR fuel bundles. The calculation results and their comparison with the experimental data are presented in the figure 2.

Experiments on UO$_2$ melting were simulated by the EVCLID/V2 code. Experiments were provided at the Argonne National Laboratory [9]. Calculation data are shown in the figure 3.

6. Conclusion
The approaches to simulation of fuel rod melting are presented in the current paper. The enthalpy formulation of heat equation was chosen to simulate fuel rods melting in fast reactors. The enthalpy formulation allows determining phase state of materials more accurately. Model of melt movement was offered. Models were verified based on some analytical tests and experimental results.

References
[1] Alipchenkov V M, Anfimov A M, Afremov D A et al 2016 Thermal Engineering 63 (2) 130
[2] Veprev D P, Boldyrev A V, Chernov S Y, Mosunova N A 2018 Annals of Nuclear Energy 113 237
[3] Usov E V, Butov A A, Klimonov I A et al 2017 J. Physics: Conf. Series 891 012171
[4] Alexiades V 1993 *Mathematical modeling of melting and freezing processes* (Hemisphere Publishing Corporation)

[5] Wright S A 1985 *Proc. of the Int. Topical Mtg. on fast reactor safety* (Knoxville) 2 p 839

[6] Butterworth D, Hewitt G F 1977 *Two-phase flow and heat transfer* (Oxford University Press)

[7] Gimbutis G I 1977 *J. Eng. Phys.* 32 (2) 115

[8] Grolmes M A, Holtz R E, Spencer B W et al 1974 *Proc. Fast Reactor Safety Meeting* (Beverly Hills) p 279

[9] Deitrich L W 1975 *Int. Working Group on Fast Reactors Spec. Meeting on Fuel Failure Mechanisms* (Washington)