Features of the Numerical Solution of Thermal Destruction Fuel Pins Problems in the Fast Reactor

Usov E.V., Butov A.A., Klimonov I.A., Chuhno V.I., Nikolaenko A.V., Zhdanov V.S., Pribaturin N.A., Strizhov V.F.

1 Novosibirsk branch of Institute of problems of safe development of atomic engineering RAS, Novosibirsk, Russia

2 Institute of problems of safe development of atomic engineering RAS, Moscow, Russia

usovev@gmail.com

Abstract. In this paper the description of the basic equations which can be used for calculation of melting of fuel and cladding of the fast reactor, moving of the melt on a fuel pin surface and its solidification is presented. The special attention is given speed of calculation algorithms and fidelity of the phenomena which are observed at a stage of severe accidents in fast reactors.

For check of working capacity of initial models, numerical calculations of Stefan-type problems on front movement of melting/solidification in cylindrical geometry are presented. Comparison with the solutions received by known analytical methods is executed. For validation of the numerical realization of calculation algorithms the analysis is carried out and experiments in which melting of the model fuel pins of fast reactors was studied are chosen. On the basis of the chosen experiments calculation schemes taking into account initial and boundary conditions are prepared and modeling is performed. Modeling results are shown in the present paper. Estimation of calculation error of the basic physical parameters is done by results of the modeling and conclusions are drawn on a correctness of algorithms operation.

1. Introduction
Predictive modeling of the phenomena occurring at a stage of severe accidents in nuclear power facilities demands development and realization of new numerical algorithms. In particular, algorithms for calculation of melting processes of cladding and fuel, melting of fuel assembly (FA) hexcan wall, moving of the steel and fuel melt on a fuel pin surface and in inter-pin space, formations of blockage of cross-section in FA owing to solidification of the fuel and cladding melts. When higher the modeling accuracy provided with developed algorithms, then more low degree of conservatism which is put in a design of the nuclear facility at a stage of its designing that in turn allows achieving decrease in expenses for construction and, as consequence, increase of competitiveness of facility.

2. Models of fuel pin melting and core disruption
The numerical algorithm of the thermal problem of melting/solidification solution assumes that the temperature is defined in nodes of the calculation grid, which formation will be reviewed further.

The input information on a grid for the melting module is the set areas with various materials (regions in an input file) and quantity of radial and axial layers in them.
At the first stage there is a formation of a material grid: regions are divided into axial layers according to the preset quantity. Splitting into layers is necessary for the joint solution of problems melting and the melt moving.

Each cell of a material grid should be split into thermal cells according to the preset quantity of radial layers. But the numerical algorithm assumes the solution in grid nodes, on each of which it is necessary two thermal cells. To meet two these requirements material cells are divided into the doubled number of the set cells (semicells). Each thermal cell stores the temperature, enthalpy, a volume fraction of the melt and also thermodynamic quantities, such as density of a solid and liquid phases, viscosity of a liquid phase, heat conductivity of a liquid and solid phases, heat of melting of a cell material.

After setting of thermal cells thermal nodes of a grid on two neighboring cells for nod are formed, except extreme nodes on which it is necessary one thermal cell (semicell). Thus, each thermal node can get as to one material: both thermal cells belonging to nod, lie in one material cell; and on border of materials: thermal cells lie in different materials. The generated nodes of a thermal grid and the allocated control volumes are shown in figure 1 used further at construction of the numerical scheme.

![Nods of the thermal grid and control volumes](image)

3. Melt movement modeling
It is necessary to define for each material, on what side of thermal structure will move the melt corresponding to a material: on external or internal border.

The model of the melt movement is one-dimensional and assumes two modes of the melt running off. It is supposed in the basic mode that the melt moves in a film form [4-6]. In an additional mode, a so-called "continuous" mode, modeling of the melt moving as incompressible liquid in a round pipe at the preset pressure difference is possible. The additional "continuous" mode is possible only for "internal" running off, the model is switched to this mode in a special case at filling with the melt all available internal volume from the side of internal border of thermal structure, and for example, when
the melt completely fills an axial aperture in fuel pellets of the pin.

The one-dimensional calculation grid for a separate film is formed in coordination with axial layers and a material grid of thermal structure. Each calculation cell of a film corresponds to one axial layer and will be co-ordinates with it by the axial size. Such coordination is required for the joint solution of problems of melting and the melt moving. The radial size and radial borders of a cell of a film is defined by initial volume of a material in a liquid phase in a corresponding axial layer for external and internal running off. Thus, if in the given axial layer there is no material cell with a material corresponding to a film or in a material cell the melt is absent in the calculation beginning, the film cell will be all the same created, but with the zero radial size. In such cells of model the equations of the melt moving do not worked out.

Scheme of a calculation grid construction of a film for external running off is shown in figure 2.

![Figure 2. Formation of a calculation grid of a film: green color - a solid material, yellow color - a liquid material](image)

At the joint solution of problems of melting and the melt moving the quantity of cells of a film does not vary, the radial sizes and radial borders of cells however can vary.

4. **Movement of the melting front in cylindrical geometry under 2nd kind of boundary condition**

The problem allows verifying the fuel melting models in the pin at known value of a heat flow. The hollow cylinder of 1 m length with internal and external radiuses 0.001 and 0.004 m accordingly is considered. Material density $\rho=11000$ kg/m$^3$, heat capacity of $C_p=300$ J/kg$^\circ$K$^{-1}$, thermal conductivity $\lambda_1=2.5$ W/m$^\circ$K$^{-1}$, melting temperature $T_m=3120$ K, heat of melting $L=260$ kJ/kg (corresponds to UO$_2$). The temperature in the start of process is equal to melting temperature, a material is solid.

Parameters are set by constants. On external border the heat flux is equal to 0, on external border - a constant heat fluxes $q=10$, 15 and 20 kW/m$^2$ are set. The chosen values of a heat flux correspond to values of a decay heat in fuel.

It is supposed that the temperature is identical everywhere in a firm part of the cylinder and is equal to melting temperature, i.e. $T_f(r, t) = T_m$, $R_i<r<\eta$. $R_i$ is the cylinder internal radius.

The approximate analytical solution of the given problem is given in [7]. Let us consider quasistationary approach [7] which is fair under a condition: $St = \frac{C_p(q/2\pi R_1/\lambda_1)}{L} \ll 1$, where $St$ is Stefan number. In this approach, all heat conducted from an internal surface of the cylinder is spent in melting. Using a heat balance condition, we obtaining:

$$\eta = \sqrt{R_i^2 + 2 \frac{R_i}{qL} \frac{R_i}{L}}.$$  \hspace{1cm} (1)

Calculation results on melt front movement are shown in figure 3. Good agreement of results with the analytical solution is visible.
The error of the melting front definition is 0.46%. Results show applicability of a code for calculation of fuel pins melting problems at the set heat flux.

During the testing and improvement of the described model following phenomena are studied also:
- Movement of a solidification front in cylindrical geometry;
- Solidification of an external layer of the two-layer cylinder (the analysis of a situation with a cladding melting at solid fuel column);
- Movement of the melt border under friction influence with a gas flow (sodium vapor).

Also checking of energy conservation is executed at a film flowing. In each problem the convergence analysis on a grid and time for an estimation of definition error of co-ordinates of melting/solidification front of materials was made.

5. **Calculation of experimental series in the TREAT reactor.**

Modeling of the experiments executed in ANL (USA) on 1 and 7-pins assemblages with sodium coolant [8] is executed for verification of model of cladding melting and running off.

The work purpose was comparison of experimental data on the phenomena observed at fuel pin melting and calculations on the developed code with severe accidental modules.

Experiments were executed in an experimental loop of TREAT reactor. The loop included the pressure head camera, section of entrance orificing, seven pin bundle type FFTF and the special tank simulating the reactor top plenum with free sodium level and a top gas plenum. The U-shaped loop represented the opened system. The input has been connected to a feeding tank of a high pressure, and an output to the waste tank with rather low pressure. The pressure difference between tanks was a driving pressure of circulation. Imitation of ULOF conditions was carried out by means of pressure dump in a gas plenum of a feeding tank.

The performance technique of experiments R3, R4 and R5 was identical. Experiment R4 began with rising of reactor power, a preliminary warming up of a loop and decrease of power to the level corresponding to nominal power. Further by some seconds timing was made for parameters stabilization. Then the flow rate through a loop decreased via pressure dump in a feeding tank. Flow rate decrease led to a loop warming up, boiling up of sodium and fuel pins melting. R3 test differed by geometry of a working section so in this experiment a working section represented the annual channel.

In experiment TREAT R3 the flow rate was set directly (unlike R4 and R5 in which input and output pressures were set).

For a substantiation of applicability of the developed calculation model to experimental facility various spatial and time steps have been performed.

Results of calculation of fuel rod housing temperature in comparison with experimental data are presented in figure 4. Good agreement of calculations till 12 second is visible. After 12 second the considerable divergence (up to 100°C) starts to be observed. It is connected with radial movements of fuel pin and a surrounding pipe with sodium that led to non-uniformity of warming up of housing as it
is specified in [9]. In this connection for check of modeling fidelity on the further time period, characteristic times of approach of events of the coolant boiling beginning, fuel pin drying and fuel pin housing melting were compared. The maximum definition error of these events is 2 s, at time of the boiling beginning (from the flow rate decrease beginning) 20 s and prior to the fuel pin housing melting is 24 s.

![Figure 4: Temperature of the fuel pin housing at the distance of 1.143 m from the centre of section with fuel. Test R3.](image)

For the obtained calculation results using described code the average error on temperature and relative error on flow rate and pressure have been calculated. For error calculation on temperature sections with abnormal behavior of temperature have been excluded. The arithmetic-mean error on a section of heat exchange without boiling (from 2nd to 12th second) in experiment R3 was 9.5 K.

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