Analysis of the cladding melt relocation along the surface of the fuel pin with help of the SAFR module

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Abstract. The presented work is dedicated to the development of approaches to simulate cladding melt relocation along the surface of the fuel pin. Development of the approaches is based on the results of the experiments carried out at the NSI RAS and IT SB RAS. Features of the melt relocation are studied in the experiments. It is demonstrated that the laminar film flow regime in the heated part of the fuel simulator is the main flow regime. Model of the melt relocation is constructed. This model is the part of the SAFR module of the EUCLID/V2 coupled code. It is shown that the proposed approaches allow simulating the melt relocation with good accuracy.

1. Introduction
The first stage of a severe accident in nuclear power station is accompanied by the destruction of fuel rods. The cause of the fuel rod destruction is a violation of the heat release in the core due to a decrease in the cooling rate for ULOF (Unprotected Loss off Flow) accident or a sharp increase in energy release for UTOP (Unprotected Transient Over Power) accident.

To analyze the consequences of severe accidents, algorithms based on modern understanding of the features of fuel elements destruction should be developed for the numerical calculation of such processes. The design of fast reactor fuel rods assumes the presence of both the active part, in which the main energy release takes place, and the blanket, in which the energy release is very small. The presence of a cold blanket part can seriously affect the relocation of the melt due to its solidification. One of the obstacles to the development of algorithms is the lack of reliable experimental data.

The presented work is dedicated to the development of approaches to simulate cladding melt relocation along the surface of the fuel pin. Development of the approaches is based on the results of the experiments that were conducted in the NSI RAS and IT SB RAS [1, 2].

2. Some results of the experimental investigation
Experimental investigations aimed at studying the features of the melt relocation along the cylindrical surface. The studies were performed for melt driven by gravity and shear stress. Experimental setup was designed to study the cladding relocation. The scheme of the experimental model is presented in Figure 1. The gas was heated to the melting temperature of the cladding imitator and was blown into the collector (1) through fittings (4). Gas entered through the system of holes in a vertical pipe 2. The system
of holes provided flow uniformity. The upper part of the test zone was made of quartz glass, which enabled visual observations. The length of the vertical pipe was sufficient for hydrodynamic stabilization of the gas flow.

![Figure 1. The scheme of the test section.](image1)

Melting of the cladding with and without an upward gas flow (argon) was visualized with help of the JET19 high-speed camera. Some results of the visualization of the melt relocation driven by shear stress are shown in the Figure 2.

![Figure 2. Visualization of the melt relocation driven by shear stress.](image2)

It was found that the melt was collected near the cold bottom of the fuel simulator (Figure 2 a). Interaction between the gas flow and melt was the cause of the instability growth of the melt in the lower part of the fuel element imitator, which subsequently led to the destruction of the melt and the appearance of droplets (Figure 2 b–d).
An experimental study of the model claddings melting was made on different cladding simulators: lead-bismuth, tin and zinc. The mass loss due to melting has been obtained. Some results will be shown in the following sections of the article.

3. The basic model of the SAFR code
SAFR code [3–5] was 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). SAFR module is the part of the EUCLID/V2 coupled code [6]. To simulate melting of the fuel rods, heat transfer problem is solved. To simulate melt relocation the system of the mass, energy and momentum equation is used:

\[
\begin{aligned}
\frac{\partial \rho S}{\partial t} + \frac{\partial \rho U S}{\partial z} &= \Gamma_m \\
\frac{\partial \rho h S}{\partial t} + \frac{\partial \rho h U S}{\partial z} &= q_w \Pi_w + q_c \Pi_c + \Gamma_m h_m \\
\frac{\partial \rho U S}{\partial t} + \frac{\partial \rho U^2}{\partial z} &= -S \frac{\partial \rho}{\partial z} + \Gamma_m U_m + \rho g S \sin \theta + \tau_c \Pi_c - \tau_w \Pi_w + \sigma \Pi_w \cos \theta \sin (z - z_i)
\end{aligned}
\]

where \( S \) is the cross section of the melt, m\(^2\); \( \Gamma_m \) is the mass source; \( q_w, q_c \) are the 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; and \( \theta \) is the contact angle.

The wall shear stress of the melt is calculated with help of the wall friction coefficient, presented in the work [7]:

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

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

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

4. Results of the simulation
SAFR was validated on the basis of the results of the experimental study [1, 8]. The comparison between experimental data and simulation results are shown in Figure 3 and Figure 4. Apparently, the presented model allows simulating the loss of mass during melting of the model shell with good accuracy. Differences are observed only for the smallest energy release for the tin shell. The lower rate of mass loss can be explained by its partial freezing on the cold lower part of the simulator (blanket) and a decrease in the drainage rate.
Figure 3. Mass loss due to melting (lead-bismuth): 1 – calculation; 2 – experiment (from left to right from right to left: 93 W; 170.5 W; 259 W).

Figure 4. Mass loss due to melting (tin): 1 – calculation; 2 – experiment (from left to right and from right to left: 91 W; 174.4 W; 262.2 W).

Conclusion
On the basis of the obtained data, the numerical code has been adapted and calculations have been performed. The shell melting and the melt motion on the surface of the fuel column simulator have been simulated. The calculation results are demonstrated to be in good agreement with the experimental results. The discrepancy between the calculation and experimental results can be explained by the uncertainty of the initial data.

The above results on the melting of the fuel rod shell simulator can be used to validate the calculation codes and methods for the analysis of thermal destruction of fuel rods.

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