Transient heat transfer analysis up to dryout in 3D fuel rods under unideal conditions through the development of a computer code

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In this report we present analyzes of the behavior of temperature in fuel rods with concentric fuel and perfect cladding, curved, and with dislocated fuel, through the development of a computer code written in Fortran [1, 2].
To analyze rods under the aforementioned conditions, a three-dimensional (3D) model is required. However, to keep the computational cost reasonable, it is sensible to avoid the use of the Navier-Stokes equations. Thus, we have chosen a physical model based on a 3D fuel rod coupled to a one-dimensional (1D) coolant channel.
Also aiming to study accidental conditions in which the coolant (light water) transcends its saturation temperature, turning into vapor, a homogeneous mixture is used to represent the two-phase flow (liquid-vapor) of a single component, and so the coolant channel's energy equation is described using enthalpy.
Because temperature and enthalpy are used in the model, our conjugated heat transfer problem is solved in a segregated manner.
The 3D transient heat conduction in the fuel rod is represented in this work by the variational formulation shown below:

$$\int_{V_{fr}} \varphi \rho c_k \frac{\partial T}{\partial t} dV_{fr} + \int_{V_{fr}} k \vec{\nabla} T \cdot \vec{\nabla} \varphi \, dV_{fr} = \int_{V_{fr}} \varphi q''' dV_{fr} - \int_{S_{fr}} \varphi q'' dS_{fr}$$

While, for the coolant channel's 1D transient heat convection, the following differential form is employed:

$$\rho A_{cn} \frac{\partial h}{\partial t} + \dot{m} \frac{\partial h}{\partial z} = \int_{P_w} q'' dP_w$$

As numerical model, the finite element method is employed for the spatial discretization of the pertinent equations. The Galerkin method, tetrahedral elements and linear base functions are adopted for the rod, whereas the least-squares method, linear elements and base functions are used for the channel. The discretization with respect to time, concerning both equations, is acquired through the Crank-Nicolson method. The meshes used in this report are produced by the means of the software GiD® [3], version 10.

As case studies, we analyze the shutdown transient of a PWR's hottest fuel rod in which the reactor's coolant pumps are lost.
Figure 1 represents the simulation of a rod with dislocated fuel:

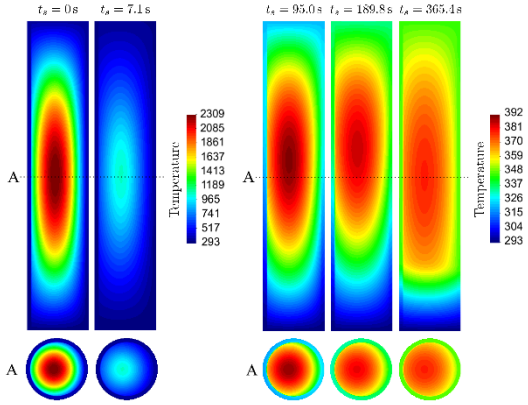

Figure 1. Temperature distribution in the rod with dislocated fuel at selected instants
Note: Reduced rod, height equals to five times the diameter (1:77).

As results of this study, we verified how the eccentricity of a fuel rod's fuel causes higher temperatures to emerge on the side of the cladding to which the fuel dislocates. A characteristic that inverses in the fuel, with the increase of temperature happening in the opposite direction of the displacement.
No significant effect was observed on the fuel rod temperature distribution due to the curvature analyzed.
Regarding the shutdown transient, in all the simulations the dryout occurred at the same height of the rod and at similar instants of time.

References

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