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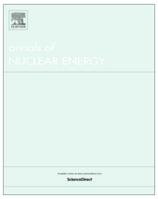

Transient 3D heat transfer analysis up to the state of Dryout in fuel rods

Rodolfo Ienny Martins [*], Renato Raoni Werneck Affonso, Maria de Lourdes Moreira, Paulo Augusto Berquó de Sampaio

Instituto de Engenharia Nuclear (IEN/CNEN), Rio de Janeiro, Brazil

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ABSTRACT

In this paper, we analyze the coupled transient heat transfer problem consisting of a nuclear reactor's fuel rod and its intrinsic coolant channel, through the development of a computer code written in Fortran and based on the finite element method. Our physical model has as basis a three-dimensional fuel rod coupled to a one-dimensional coolant channel. A homogeneous mixture is used to represent the two-phase flow in the coolant channel. The coupled heat transfer problem is solved in a segregated manner through an iterative method. As case studies, we present analyses concerning the behavior of the hottest fuel rod in a Pressurized Water Reactor, during a shutdown in which the residual heat removal system is lost (loss of the reactor's coolant pumps). These studies contemplate cases where the condition of the fuel rod's cladding is ideal or presents ballooning. Analyses are also performed for two circumstances of positioning of the fuel inside the rod: concentric and eccentric. We obtained as results that the eccentricity in the fuel of a fuel rod causes higher temperatures to appear on the side of the cladding to which the fuel dislocates. A situation that reverses in the fuel, with the temperature increasing in the opposite direction of the displacement. We also found that the ballooning causes local effects of critical consequence, with the melting temperature of the UO_2 being exceeded even in cases of balloonings of modest dimensions. All the simulations presented the Dryout phenomenon at the same height of the fuel rod and at similar instants of time.

1. Introduction

For the comprehensive study of the transient heat transfer in a nuclear reactor's fuel rod, especially one which possesses deformations, and its coolant channel, the use of a three-dimensional (3D) model is essential. However, the computational cost to analyze such a problem, adopting this kind of model, is considerably high. To mitigate the cost and still acquire a detailed profile for the temperature in the rod, in this work we avoid the use of the Navier-Stokes equations by assuming a one-dimensional (1D) coolant channel, while employing a three-dimensional geometry to model the fuel rod.

Since we also desire to analyze accidental conditions in which the coolant (light water) exceeds its saturation temperature, two-phase flow must be considered. A simple way to model such regime is to assume a homogeneous mixture for its description, which implies the use of enthalpy to represent the coolant channel's energy equation.

As a model that uses both temperature and enthalpy was achieved, it became impractical to generate a fully coupled method for the solution of our equations. Thus, the iterative method we called "internal iterations" was implemented, in which the specified coupled heat transfer problem is solved in a segregated manner.

Several other physical attributes are assumed in our model, as well as many correlations to estimate the thermal-hydraulic aspects of the problem. All of them will be briefly described in the following sections, together with how the numerical discretization of the pertinent equations was accomplished and the iterative method implemented.

We also discuss how the developed program was verified and present case studies in which the behavior of the hottest fuel rod in a Pressurized Water Reactor (PWR) is analyzed during a shutdown wherein the residual heat removal system is lost (loss of the reactor's coolant pumps). These studies contemplate cases where the condition of the fuel rod's cladding is ideal or presents ballooning. Analysis are also performed for two circumstances of positioning of the fuel inside the rod: concentric and eccentric.

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[*] Corresponding author.
E-mail address: rodolfoienny@gmail.com (R.I. Martins).

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Nomenclature

Nomenclature

A	area (m)
a	height (m)
Cp	isobaric specific heat (J kg^{-1} °C^{-1})
Cv	isochoric specific heat (J kg^{-1} °C^{-1})
C_κ	isobaric or isochoric specific heat (J kg^{-1} °C^{-1})
D	diameter (m)
h	specific enthalpy (J kg^{-1})
h_c	heat transfer coefficient (W m^{-2} °C^{-1})
k	thermal conductivity (W m^{-1} °C^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
p	pressure (Pa)
P	perimeter (m)
q'	linear heat generation rate (W m^{-1})
q''	heat flux (W m^{-2})
q'''	volumetric heat generation rate (W m^{-3})
r	radius (m)
S	surface
t	time (s)
T	temperature (°C)
V	volume (m^3)
x, y, z	directions x, y and z
x	flow quality
x_{eq}	equilibrium quality
α	void fraction
δ	deformation
ρ	density (kg m^{-3})
τ	time when the shutdown begins (s)

Superscript

★	dimensionless

Subscripts

0	of reference
a	anterior (value)
b	of bulk
c	of the cladding
ci	of the inner surface of the cladding
cn	of the coolant channel
co	of the outer surface of the cladding
Dryout	at the instance of Dryout
f	of the fuel
fc	of the center of the fuel
fn	final (position)
fo	of the outer surface of the fuel
f	of saturated liquid
fr	of the fuel rod
g	of the gap
g	of saturated vapor
ic	initial (position)
in	of the channel's inlet
m	of the homogeneous mixture
max	maximum value
med	medium, mean value
s	after the shutdown
ss	of steady state
sat	of saturation
w	of the outer surface of the fuel rod
(e)	in or of an specific element of the mesh
ϑ	of the "internal iterations"
$+$	central, in half the interval

2. Physical model

The three-dimensional transient heat conduction in the fuel rod is represented in this work by the variational formulation shown below:

$$\int_{V_{\mathrm{fr}}} \varphi \rho_\kappa C_\kappa \frac{\partial T}{\partial t}\, \mathrm{d}V_{\mathrm{fr}} + \int_{V_{\mathrm{fr}}} k_\kappa \vec{\nabla} T \cdot \vec{\nabla} \varphi\, \mathrm{d}V_{\mathrm{fr}} = \int_{V_{\mathrm{fr}}} \varphi q''' \kappa\, \mathrm{d}V_{\mathrm{fr}} - \int_{S_{\mathrm{fr}}} \varphi q''\, \mathrm{d}S_{\mathrm{fr}} \tag{1}$$

While, for the coolant channel's one-dimensional transient heat convection, the following differential form is employed:

$$\rho A_{cn} \frac{\partial h}{\partial t} + \dot{m} \frac{\partial h}{\partial z} = \int_{P_w} q'' \mathrm{d}P_w \tag{2}$$

A fuel rod consists essentially of three components: fuel (UO$_2$), gap (filled with helium gas) and cladding (Zircalloy-4). Thus, Eq. (1) must be solved for each one of them, condition from which the symbol κ derive. The properties of these components are considered to be temperature dependent, except for the densities, which are given by: $\rho_f = 10963.0$ kg m^{-3}, $\rho_g = 0.1785$ kg m^{-3} and $\rho_c = 6440.0$ kg m^{-3}. The properties of the coolant are also considered to be temperature dependent, with the exception of density in the two-phase regime, specified by Eq. (3):

$$\rho_m = \alpha \rho_{\mathrm{g}} + (1 - \alpha) \rho_{\mathrm{f}} \tag{3}$$

Regarding the components of the rod, we make use of the correlations recommended by the International Atomic Energy Agency (IAEA) (IAEA, 2006) for the thermal conductivities of the UO$_2$ (IAEA, 2006, p. 89) and the Zircaloy-4 (IAEA, 2006, p. 249), and for the isobaric specific heat of the UO$_2$ (IAEA, 2006, p. 25). For the isobaric specific heat of Zircaloy-4 the correlation of Zimmerer (Zimmerer, 1978) (as presented in Cacuci, 2010, p. 1542) is used. We also use correlations indicated by the IAEA (IAEA, 1997) for the isochoric specific heat (IAEA, 1997, p. 172) and the thermal conductivity (IAEA, 1997, p. 173) of the helium gas.

Concerning the coolant, the correlations of the International Association for the Properties of Water and Steam (IAPWS) are used for its properties, with emphasis in the Industrial Formulation 1997 (IAPWS-IF97), obtained from Cooper and Dooley (2007), Cooper and Dooley (2008), Daucik and Dooley (2011), Petrova and Dooley (2014).

In this work, the thermal energy generated in the fuel rod is considered to be deposited only on its fuel (in Eq. (1): $q_f''' = q_f'''(z,t), q_g''' = 0$ and $q_c''' = 0$). For our purposes, the nuclear reactor's power is important under two conditions: in normal operation (steady state) and after the shutdown. Our volumetric heat generation rate is given by Eq. (4):

$$q''' f(z,t) = \frac{q'_{max_0}}{\pi r_f^2} \cos\left(\frac{\pi z}{a_{\mathrm{fr}}}\right) \mathrm{f}(t) \tag{4}$$

The reactor's power after the shutdown arises essentially from fissions by delayed neutrons, and the decay of fission products and actinides. Eq. (5), adapted from Todreas and Kazimi (1990, p. 65), is used to estimate the contribution of the former:

$$\frac{\dot{Q}(t)}{\dot{Q}_0} = 0.0625 \exp\left[-0.0124(t - \tau)\right] + 0.9375 \exp\left[-960(t - \tau)\right] \tag{5}$$