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FUEL RODS QUENCHING WITH OXIDATION AND PRECURSORY COOLING

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During a loss-of-coolant-accident in LWR fuel rods may be temporarily exposed thus reaching high temperature levels. The injection of cold water into the core, while providing the necessary cooling to prevent melting may also generate steam inducing exothermal oxidation of the cladding. A number of high temperature quenching experiments [1] have demonstrated that during the early phase of the quenching process, the rate of hydrogen generation increased markedly and the surface temperatures rose rapidly. These effects are believed to result from thermal stresses breaking up the oxide layer on the zircalloy cladding, thus exposing the inner surface to oxidizing atmosphere. Steam reacts exothermally with the metallic components of the newly formed surface causing temporarily local temperature escalation.

The main objective of this study is to develop and assess a one-dimensional time-dependent rewetting model to address the problem of quenching of hot surfaces undergoing exothermic oxidation reactions. Addressing a time-dependent problem is an important aspect of the work since it is believed that the progression of a quench-front along a hot oxidizing surface is an unsteady process. Several studies dealing with time-dependent rewetting problems have been published, e.g. [2]-[5], but none considers oxidation reactions downstream of the quench-front. The main difficulty in solving time-dependent rewetting problems stems from the fact that either the quench-front velocity or the quench-front positions constitute a time-dependent eigenvalue of the problem.

The model is applied to describe the interrelated processes of cooling and exothermic steam-metal reactions at the vapor zirconium-cladding interface during quenching of degraded fuel rods. A constant heat transfer coefficient is assumed upstream of the quenching front whereas the combined effect of oxidation and post dry-out cooling is described by prescribing a heat flux distribution of general form downstream. The model is solved analytically via a Green's function approach to yield the quenching velocity history. Numerical results compare favorably with published experimental data. The effect of heat distribution along the surface is studied parametrically.

ANALYSIS

The model solves the time-dependent heat conduction equation in a plate, which is subjected to an arbitrary heat flux distribution on its surface. Figure 1, shows schematically the process of top quenching of a single nuclear fuel rod and the notation used in this analysis. The model is applicable to both top and bottom flooding configurations. The fuel cladding is assumed to be insulated on its inner side facing the fuel pellets. In the analysis the outer surface is divided into two parts: a "wet" side - upstream of the quench front, where intensive cooling takes place and a "dry" side – downstream of the quench front, where relatively poor cooling exists.

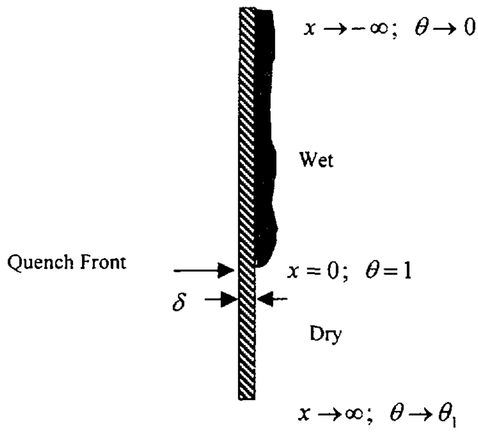

Figure 1 Schematic of top quenching of a single fuel rod

The mathematical formulation of the model in dimensionless variables takes the following form:

Wet side:

$$\frac{\partial \theta_w}{\partial t} = \frac{\partial^2 \theta_w}{\partial x^2} + P\frac{\partial \theta_w}{\partial x} - \theta_w,\ -\infty < x < 0,\ t > 0 \tag{1}$$

$$\theta_w(x,0) = 0,\ \theta_w(-\infty,t) = 0,\ \theta_w(0,t) = 1 \tag{2}$$

Dry side:

$$\frac{\partial \theta_d}{\partial t} = \frac{\partial^2 \theta_d}{\partial x^2} + P\frac{\partial \theta_d}{\partial x} - Q(x),\ 0 < x < \infty,\ t > 0 \tag{3}$$

$$\theta_d(x,0) = \theta_1,\ \theta_d(0,t) = 1,\ \theta_d(\infty,t) = \theta_1 \tag{4}$$

where θ_1 is the initial dry-side wall temperature, and length and time are scaled with respect to $\sqrt{k\delta / h}$ and $(\rho c_p \delta)/h$, respectively. The wet side heat transfer coefficient is denoted by h, δ is the cladding thickness and ρ, c_p, k are its density, specific heat at constant pressure and thermal conductivity, respectively. The dimensionless temperature, quenching velocity and heat flux, respectively, are then defined by:

$$\theta = \frac{T - T_{sat}}{T_o - T_{sat}},\ P = \frac{\rho c_p U}{\sqrt{kh/\delta}},\ Q = \frac{q}{h(T_o - T_{sat})} \tag{5}$$

with u and q denoting the dimensional quenching velocity and dry side heat flux, respectively. The dimensional rewetting and saturation temperatures are designated by T_0 and T_{sat}, respectively.

An approximate solution of the problem defined in (1)-(4) is outlined in [6, 7] and will not be repeated here. The model is based on splitting the solution into a steady-state part with non-homogeneous boundary conditions and a transient part with homogeneous boundary conditions as suggested in [8]. The solution results in a transcendental equation whose solution yields the dimensionless quench front velocity as a function of time. A solution can be obtained for any arbitrary heat flux distribution in the dry zone.

RESULTS AND DISCUSSION

A general heat flux function is postulated to account for the heat of oxidation and convection, conduction and radiation between the wall and the mixture of water vapor and droplets downstream of the quenching front: $Q(x) = Q_0 e^{-ax} \cos(bx)$. The parameter Q_0 can be positive or negative. A positive heat flux describes precursory cooling ahead of the quench-front, while negative heat flux represents heating by oxidation at some distance from the quench-front.

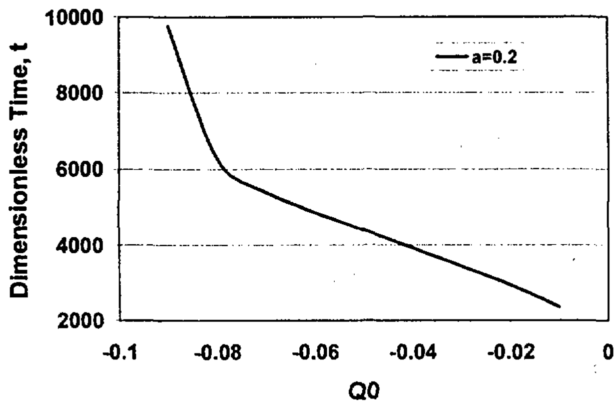

Figure 2: Time to reach steady state as a function of Q_0 ($\theta_1 = 9$)

It is generally shown that depending on the heat flux distribution in the dry zone, the quench-front velocity may decelerate or accelerate before reaching a steady value. The model predicts transient velocities before approaching steady state in cases, which are impossible to predict otherwise, such as the case of intense heat production due to oxidation near the quenching front. Figure 2 shows typical results for the dimensionless time required for the quench-front to attain a steady-state value when $Q_0 < 0$. Expressing some of the results in dimensional form it is shown that for $\theta_1 = 9$, i.e., initial temperature 1360 °C and $Q_0 = -0.01$ the dimensionless time required to reach steady-state is about 2000 which corresponds to about 6 min. This indicates clearly the importance of transient solution to understand the problem of quenching of oxidizing fuel rods.

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