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A MODEL FOR LMFBR CORE TRANSIENT ANALYSIS IN REAL-TIME

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Plant safety as well as plant availability can be significantly improved if functions such as data validation, plant state verification, and fault identification are automated. A methodology for automation of these functions was presented in Ref. 1. To implement this methodology, plant models that run significantly faster than real transient time are needed.

Such models for the intermediate heat exchanger and a once-through LMFBR steam generator were presented in Refs. 2 and 3. This paper discusses the modeling of LMFBR core transients. It is shown that with a proper choice of shape functions a nodal approximation of the coolant, cladding, and fuel temperature distributions leads to adequately accurate power and temperature predictions, as well as adequately short computation times.

From the point of view of operational safety, it is desirable to terminate a transient before sodium boiling is initiated in the core. Thus, only the modeling of the preboiling phase of core transients is discussed.

The energy conservation equations for a core thermal-hydraulic channel can be written

$$A_f \rho_f C_f \frac{\partial T_f}{\partial t} = - 2\pi r_f h_{fc} (T_f - T_c) + \gamma_f P$$

$$A_c \rho_c C_c \frac{\partial T_c}{\partial t} = 2\pi r_f h_{fc} (T_f - T_c) - 2\pi r_c h_{cs} (T_c - T_s) + \gamma_c P \qquad (1)$$

$$A_s \rho_s C_s \frac{\partial T_s}{\partial t} = - mC_s \frac{\partial T_s}{\partial z} + 2\pi r_c h_{cs} (T_c - T_s) + \gamma_s P$$

The subscripts f, c, and s denote fuel, cladding, and sodium, respectively, and: T = radially averaged temperature; A = cross-sectional area; ρ = density; C = specific heat; γ = fraction of power generated in a channel component; r = radius; h_{fc} = the fuel-cladding heat transfer coefficient; h_{cs} = the

coolant-cladding heat transfer coefficient; m = coolant flow rate; and P = linear power rate.

To determine the coolant, cladding, and fuel temperature distributions during a transient, the active core region of the channel is divided into nodes, and each temperature distribution in the ith node is approximated by

$$T_{s,i}(z,t) = T_s(Z_i,t) + y_i^s(t)\, f_i^s(z)$$

$$T_{c,i}(z,t) = T_{s,i}(z,t) + y_i^c(t)\, f_i^c(z) \qquad (2)$$

$$T_{f,i}(z,t) = T_{c,i}(z,t) + y_i^f(t)\, f_i^f(z)$$

where Z_i is the coordinate of the ith node lower boundary. The functions $y_i(t)$ are space independent within the ith node. The functions $f_i(z)$ are chosen to be the spatial temperature distributions in the ith node at steady-state conditions.

Equations (2) are inserted into Eqs. (1) which are integrated over each node to obtain the following set of differential equations.

$$\dot{y}_i^s = -\frac{mf_s(Z_{i+1})}{A_s\rho_s I_i^s} y_i^s + \frac{2\pi r_c h_{cs} I_i^c}{A_s\rho_s C_s I_i^s} y_i^c + \frac{\gamma_s Q_i}{A_s\rho_s C_s I_i^s} - \frac{\dot{T}_s(Z_i,t)\,\Delta Z_i}{I_i^s}$$

$$\dot{y}_i^c = \frac{2\pi r_f h_{fc} I_i^f}{A_c\rho_c C_c I_i^c} y_i^f - \frac{2\pi r_c h_{cs}}{A_c\rho_c C_c} y_i^c + \frac{\gamma_c Q_i}{A_c\rho_c C_c I_i^c} - \frac{1}{I_i^c}\left[\dot{T}_s(Z_i,t)\,\Delta Z_i + \dot{y}_i^s I_i^s\right] \qquad (3)$$

$$\dot{y}_i^f = -\frac{2\pi r_f h_{fc}}{A_f\rho_f C_f} y_i^f + \frac{\gamma_f Q_i}{A_f\rho_f C_f I_i^f} - \frac{1}{I_i^f}\left[\dot{T}_s(Z_i,t)\,\Delta Z_i + \dot{y}_i^s I_i^s + \dot{y}_i^c I_i^c\right]$$

where

$$I_i^k = \int_{Z_i}^{Z_{i+1}} f_i^k(z)dz,\ k = s,c,f;\ Q_i = \int_{Z_i}^{Z_{i+1}} P dz;\ \text{and}\ \dot{\ } = \frac{d}{dt}\ .$$

If Eqs. (2) are a good approximation of the temperature distributions in the active core region, adequately accurate solutions of Eqs. (1) can be obtained with very few nodes in this region (two or three). The use of a few nodes will lead to short computation times.

For the axial blanket segments of the channel, Eqs. (1) are transformed into an equivalent set by using a finite-differences scheme. The latter equations and Eqs. (3) are solved simultaneously with the point kinetics equations using the Gear[4] method for stiff differential equations.

To test this model, a series of unprotected loss-of-flow (LOF) and unprotected overpower (TOP) transients were analyzed for a typical oxide LMFBR. In these tests, five axial nodes were used in each channel (one in the lower blanket, two in the active core, two in the upper blanket). Symmetric as well as highly skewed axial power distributions were used. The predictions of this model were compared with those of a detailed finite-differences model (three nodes in the lower blanket, thirteen nodes in the active core, four nodes in the upper blanket). The finite-differences model has been validated with in-pile experimental data.[5,6,7]

The temperature distributions predicted for a fast LOF transient (the flow decays exponentially to 30% in 10 s) are shown in Fig. 1. Both models predict practically the same coolant and cladding temperature distributions. The maximum fuel temperature difference is ~1.2%. The power level predictions differ by ~0.3%. The computation time (IBM 3033) was 1/21 and 1/4 of the real transient time per channel for the proposed and the finite-differences model, respectively.

Similar results were obtained from TOP transients. For example, in a TOP transient, initiated by an uncontrolled rod withdrawal (20¢/s) the predicted maximum coolant and cladding temperatures at 10 s (approximate time of fuel melting initiation) differed by ~2 K. The maximum fuel temperature difference was ~0.5% The power level predictions differed by ~0.08%. The computation

time was 1/18 and 1/2 of the real transient time per channel for the proposed and the finite-differences model, respectively.

Since the methodology for on-line data validation, plant state verification, and fault identification is iterative,[1] the computation times of the finite-differences model are not adequately short. The computation times of the proposed model satisfy the requirements of this methodology and more than one channel can be used to represent the core. Few-node (two or three) finite-difference computations give inadequate temperature predictions (especially for transients where the power changes significantly).

In summary, this work shows that a nodal approximation of the coolant, cladding and fuel temperature distributions that is based on the shape functions given by Eqs. (2) leads to: (a) adequately accurate power and temperature predictions, and (b) computation times that satisfy the requirements of continuous on-line data validation, plant state verification, and fault identification.

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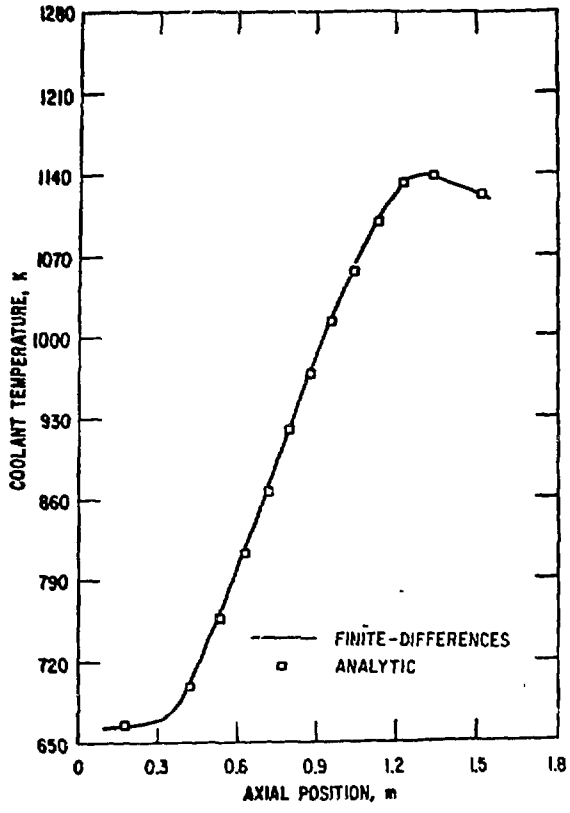

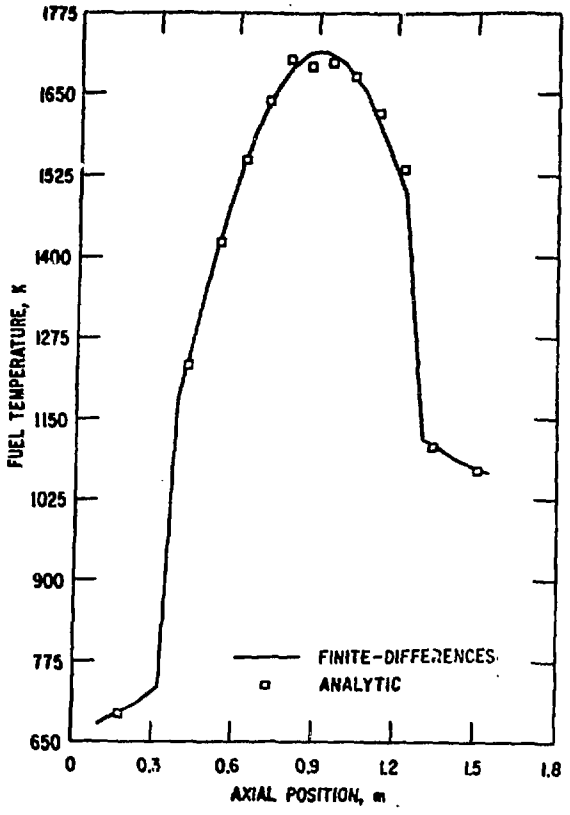

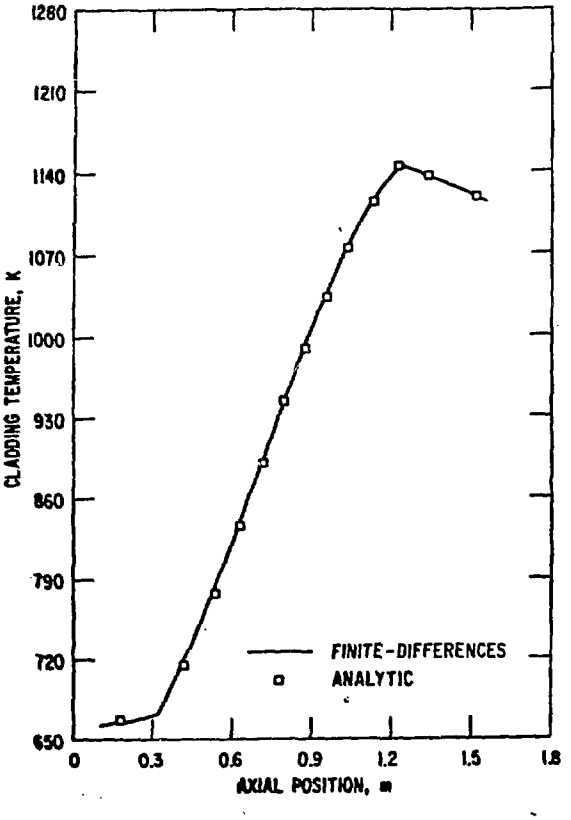

Figure 1. Predicted Temperature Distributions at 10 s into the LOF Transient