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DESIGN OF A REACTOR INLET TEMPERATURE CONTROLLER FOR EBR-II USING STATE FEEDBACK*

by

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ABSTRACT

A new reactor inlet temperature controller for pool type liquid-metal reactors has been developed and will be tested in EBR-II. The controller makes use of modern control techniques to take into account stratification and mixing in the cold pool during normal operation. Secondary flowrate is varied so that the reactor inlet temperature tracks a setpoint while reactor outlet temperature, primary flowrate and secondary cold leg temperature are treated as exogenous disturbances and are free to vary. A disturbance rejection technique minimizes the effect of these disturbances on inlet temperature. A linear quadratic regulator improves inlet temperature response. Tests in EBR-II will provide experimental data for assessing the performance improvements that modern control can produce over the existing EBR-II analog inlet temperature controller.

INTRODUCTION

Precise control of reactor inlet temperature in advanced pool type liquid-metal reactors will be important for a number of reasons. First, inlet temperature has been proposed as a preferred control input for maneuvering at load.[1,2] Good load following requires that it be controlled in a precise manner. Second, small perturbations in inlet temperature will be introduced for the purpose of periodically monitoring the status of inherent shutdown mechanisms.[3] These perturbations must be precisely controlled so that they do not interfere with normal plant operation. Similar but separate perturbations of rod position and primary flowrate will also be introduced during which time reactor inlet temperature must be held constant with high precision. Third, the power-to-flow scram proposed for improving plant availability during primary system upsets[4] requires precise inlet temperature regulation. The above requirements, in light of experience at EBR-II that indicates that classical control is less than adequate for inlet temperature control,[5,6] point to the need for additional research.

The goal of this work is to determine whether improved control of reactor inlet temperature can be achieved in EBR-II, a prototype of the Integral Fast Reactor concept,[7] using modern control theory. Modern control appears to offer the potential for significant performance improvements over classical control for the inlet temperature control problem. This stems mainly from the use of unmeasured state variable information. This information, generated from a model of the process being controlled, is not used in classical control. Specific advantages over classical control include the ability to explicitly treat the temperature stratification phenomenon known to occur in the EBR-II reactor tank and the ability to minimize the effect on regulated inlet temperature of changes in reactor outlet temperature and primary flowrate which we assume we cannot control (disturbance rejection).

This paper describes the analysis and design of a state feedback controller to be used to control reactor inlet temperature in EBR-II. The experimental data characterizing mixing in the EBR-II primary system tank is reviewed. Processes are conjectured to account for observed behavior and a model based on the conservation equations is formulated. Parameter values in this model are estimated from experimental data. A state feedback controller is then designed to track a reactor inlet temperature setpoint, reject disturbances and improve the dynamic response. Simulation results are then presented. The controller has been implemented on a process control computer at EBR-II for tests to be performed in 1990.

ANALYSIS

The EBR-II plant consists of a primary system and a secondary system both using liquid sodium as the coolant and a saturated steam cycle. The primary system is located in a large double-walled tank as shown in Fig. 1. The two primary pumps take their suction directly from the tank, or cold pool, and deliver the flow to the reactor. There are two thermocouple rakes located in the tank, each running the vertical length of the sodium pool.

Experimental Data

The existing experimental data was reviewed and examined for evidence of buoyancy-induced stratification, for the existence of stagnant and well-mixed regions and for evidence of buoyancy-induced plumes. This analysis was facilitated by projecting in two dimensions (elevation and radial) temperature data from the thermocouple rakes and other instrumented temperature points and advancing forward in time to give a clear picture of the activity in the tank.[5]

The data examined falls into two categories. The first is the PICT series of tests[6] in which changes in the plant were essentially quasi-static. These tests provide data that characterize the tank at essentially steady-state operation at a number of operating points defined by primary flowrate, core power and reactor inlet temperature. These tests provide some insight into which regions of the tank are stratified and which regions are well-mixed.

The second set of data involves the SHRT test series.[1] In the loss of flow and loss of heat sink tests, coolant is introduced into the tank at a temperature significantly different from the bulk sodium temperature, providing indications as to the role of buoyancy in tank mixing.

After consideration of the primary system configuration and the PICT and SHRT experimental data, the following physical processes are conjectured to occur in the tank. A variety of heat sources and sinks exist in the tank and contribute to thermal stratification of the sodium. Heat loss from the z-pipe (a pipe connecting the reactor outlet plenum to the IHX inlet) into the tank is dependent on the reactor outlet temperature and the temperature of the sodium at the top of the tank. Mass and energy enters the tank through leakage paths at the core outlet, bypassing the IHX, at a rate dependent on the reactor outlet temperature and the primary flowrate. Heat is redistributed within the tank by conduction from the reactor inlet pipe which takes its inlet from the top two thirds of the tank and then passes through the colder bottom of the tank. Heat enters the sodium pool through the insulation that separates the core from the sodium pool. Heat is conducted into the tank wall from the sodium pool. These sources and sinks are believed responsible for a vertical temperature gradient that is maintained between the top one-third of the sodium in the tank and the remainder of the sodium in the tank. The gradient appears to be dependent on the amount of mixing, which depends on the primary system flowrate, and on the magnitudes of the sources and sinks.

Three distinct axial regions exist in the tank sodium under both quasi-static and dynamic conditions. The region of coolant above the pump inlets is a hot stratified stagnant region. The region of coolant below it down to the bottom (outlet) of the IHX appears to be well mixed and couples the IHX outlet to the pump inlets. The region below this appears to be cold, relatively stagnant sodium.

A hot buoyant plume was observed to rise into the top of the tank from the IHX outlet during the loss of heat sink transient. Conversely, during the loss of flow transient a cold plume was observed to drop down into the bottom of the tank.

Conservation Equations

The requirement for real-time operation limits the order of the model that is used to generate the state feedback control law. The tank model must be limited to a few differential equations. Since solution of the Navier-Stokes equations entails a fine mesh, and hence a high model order, a lumped parameter approach to modeling was taken.

A nodalization of the tank consistent with the processes conjectured above is shown in Fig. 2. The transport of mass and energy between nodes is written in terms of thermal gradients and mixing terms. Mass and energy balances were written for each node to obtain a model of the form

$$\frac{d}{dt}\underline{x} = f[\underline{x}(t), \underline{u}(t), \underline{\alpha}] \tag{1}$$

and

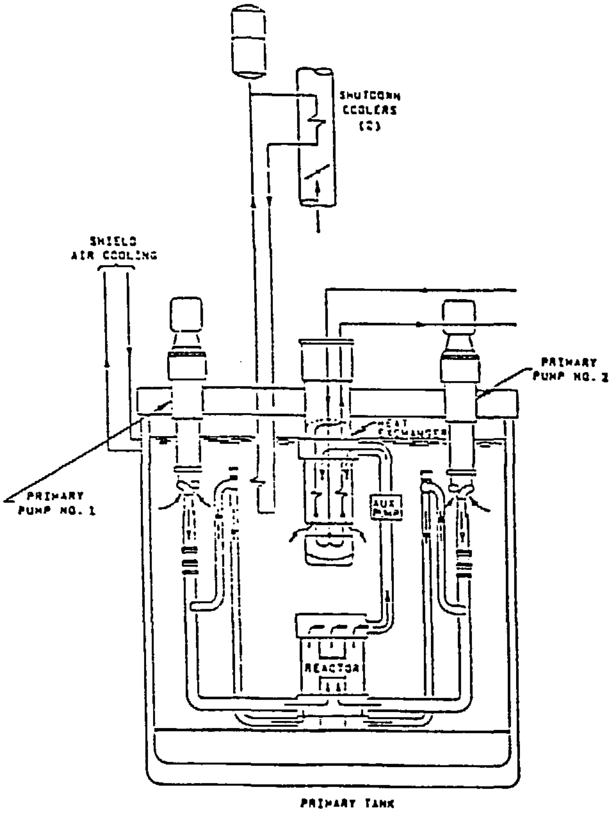

Fig. 1. The EBR-II Primary System.

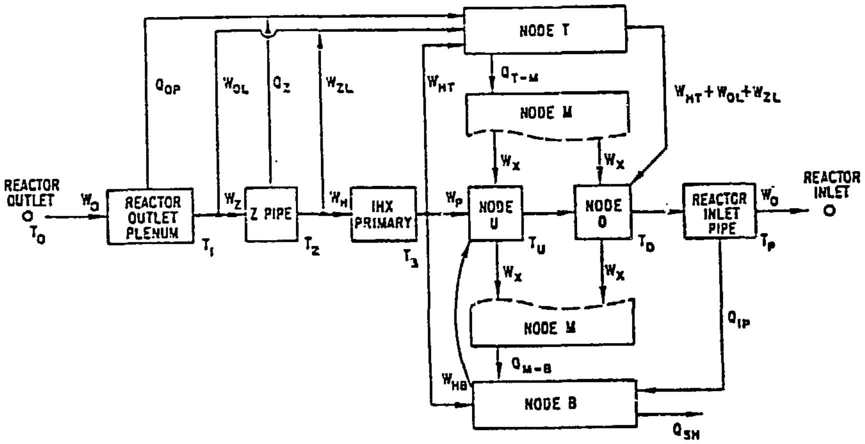

Fig. 2. Thermal-Hydraulic Nodalization of the EBR-II Primary Tank.

$$\underline{y}(t) = g[\underline{x}(t), \underline{u}(t), \underline{\alpha}] \tag{2}$$

where

$\underline{x}(t)$ = n×1 vector of state variables,
$\underline{u}(t)$ = m×1 vector of inputs,
$\underline{y}(t)$ = r×1 vector of outputs, and
$\underline{\alpha}$ = vector of model parameters.

The elements of the state vector are the node temperatures T_T, T_M, T_3, T_U, and T_D. The elements of the input vector are the reactor outlet temperature, the primary flowrate, the secondary cold leg temperature and the secondary flowrate. The output vector is the reactor inlet temperature.

Parameter Identification

The numerical values of several model parameters were determined directly from first principles. The remaining parameters were identified by performing a least squares fit of the model to PICT1 experimental data of Reference 6. Results of the fit are shown in Figs. 3 through 5.

DESIGN

The specific control objective is as follows. Reactor inlet temperature is to be controlled to a setpoint by varying secondary flowrate. This is to be done in the presence of arbitrary, but measurable, changes in three process variables: reactor outlet temperature, primary flowrate and secondary cold leg temperature. Modern control theory provides a means to control secondary flowrate in such a way that the effect of these disturbances on reactor inlet temperature is minimized.[9]

The controller designed to meet these objectives is shown in Fig. 6. It consists of two controllers that function together. The first is a state feedback controller that was designed to track a reactor inlet temperature, T_P, setpoint under the assumption that the IHX primary side outlet temperature, T_3, can be arbitrarily assigned. The second controller is an algebraic controller designed to deliver an arbitrary T_3 by appropriately changing the secondary flowrate, W_c.

It is assumed that the algebraic controller can instantaneously deliver the required T_3. This is a reasonable assumption. The response of T_P to T_3 is of the order of the tank mixing time constant, about a minute. On the other hand, the response of T_3 to W_c is of the order of the IHX thermal and secondary fluid inertia time constants, about 10 seconds.

The state feedback controller was designed around a linearized discrete-time version of the cold pool model. The form of the model is

$$\delta \underline{x}(k+1) = A\,\delta \underline{x}(k) + B\,\delta \underline{u}(k) + F\,\delta \underline{x}_d(k) \tag{3}$$

and

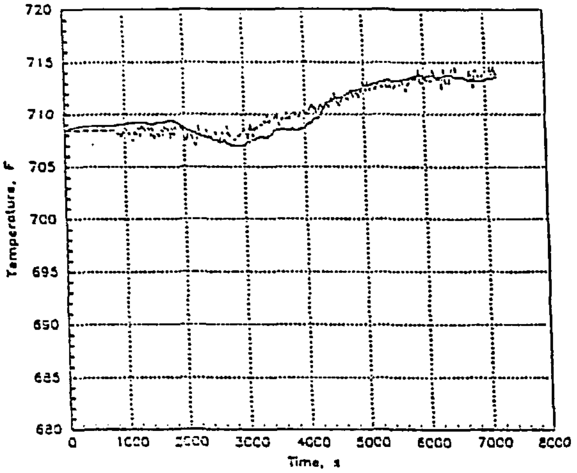

Fig. 3. Calculated Versus Measured Average Temperature in Top Node.

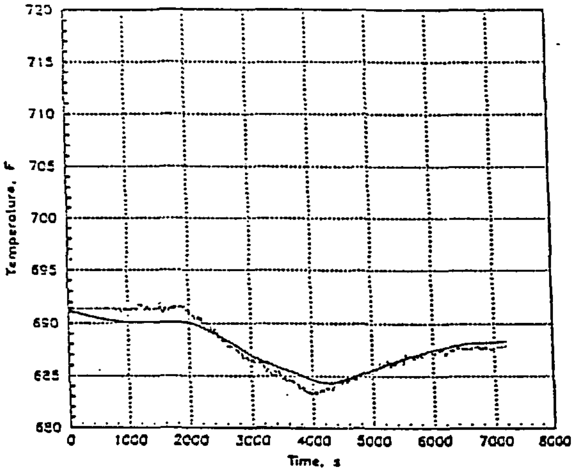

Fig. 4. Calculated Versus Measured Average Temperature in Bottom Node.

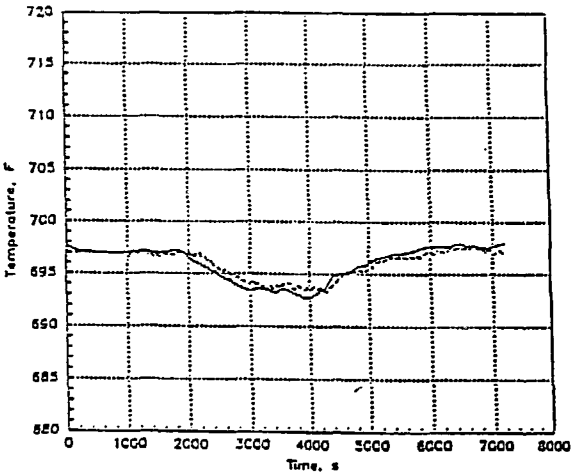

Fig. 5. Calculated Versus Measured Reactor Inlet Temperature.

$$\delta \underline{y}(k) = C\, \delta \underline{x}(k) \tag{4}$$

where

A, B, C = discrete time linearization matrices,
$\delta \underline{x}(k)$ = state vector of perturbed temperatures T_T, T_M, T_B, T_U, and T_D,
$\delta \underline{u}(k)$ = input vector of perturbed IHX primary outlet temperature,
$\delta \underline{x}_d(k)$ = disturbance vector of perturbed primary flowrate and reactor outlet temperature,
k = sample time.

The state feedback control law has the form

$$\delta \underline{u}(k) = -G[\delta \underline{x}(k) - \delta \underline{x}_r(k)] - G_r \delta \underline{x}_r(k) - G_d \delta \underline{x}_d(k) - K[\delta \underline{x}(k) - \delta \underline{x}_r(k)], \tag{5}$$

$$\delta \underline{x}_r(k) = (I - A)^{-1} [B \delta \underline{u}_r(k) + F\, \delta \underline{x}_d(k)],\ and \tag{6}$$

$$\delta \underline{u}_r(k) = [C(I - A)^{-1}B]^{-1} [\delta \underline{y}_r(k) - C\,(I - A)^{-1} F\, \delta \underline{x}_d(k)] \tag{7}$$

where $\delta \underline{y}_r(k)$ is the reactor inlet temperature setpoint. The first three terms in Eq. (5) guarantee steady-state rejection of reactor outlet temperature and primary flowrate disturbances. The last term is the linear quadratic regulator (LQR) gain matrix[10] and is used to shape the dynamic response of the reactor inlet temperature.

SIMULATION RESULTS

A series of tests in EBR-II is planned for 1990 to evaluate the controller and to more generally assess the prospects for modern control in a realistic reactor setting. Pre-test predictions are presented here for two of these tests.

Primary Flowrate Disturbance

This test is intended to demonstrate the ability of the controller to reject primary flowrate disturbances, preventing them from affecting the controlled variable, reactor inlet temperature. In this test, the reactor inlet temperature control algorithm will automatically adjust secondary flowrate to maintain constant reactor inlet temperature in the presence of a 5 percent step increase in primary flowrate while reactor power remains constant. This test will also provide additional data for characterizing the dependency of tank stratification on primary flowrate. This information will be used to further refine and validate the tank mixing model around which the controller was designed. The predicted reactor inlet

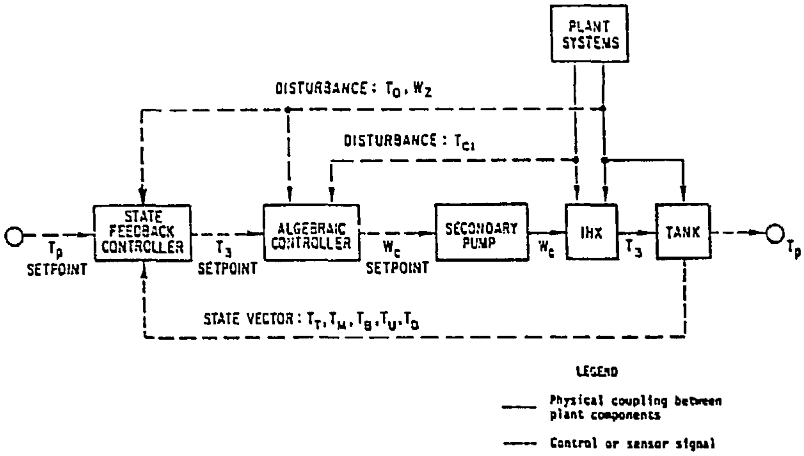

Fig. 6. Block Diagram of Reactor Inlet Temperature Controller

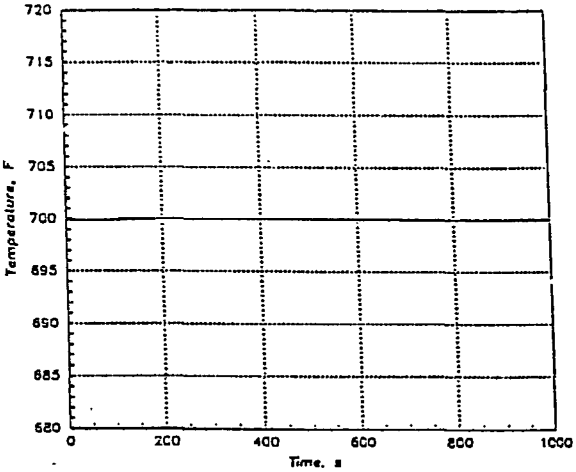

Fig. 7. Predicted Inlet Temperature for Primary Flowrate Disturbance.

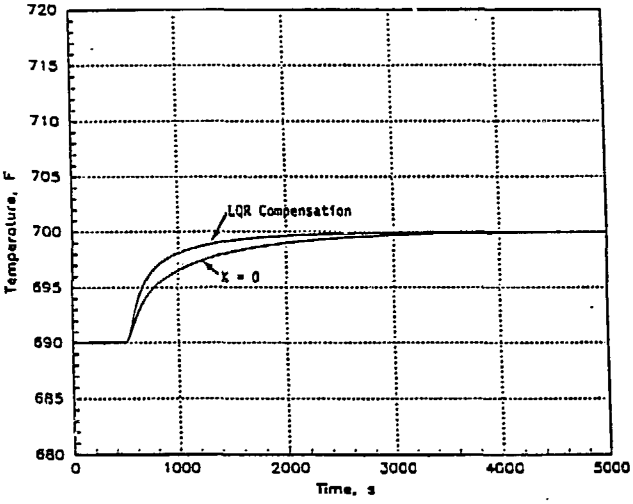

Fig. 8. Predicted Inlet Temperature for Step Setpoint Change.

temperature response is shown in Fig. 7. The simulation results indicate that the controller successfully rejects the primary flowrate disturbance.

Reactor Inlet Temperature Setpoint Change

This test is intended to demonstrate the ability of the LQR component of the controller to improve on the dynamic response of the controlled variable, reactor inlet temperature. In this test the reactor inlet temperature setpoint will be step increased from 690 to 700 °F. The controller will automatically adjust secondary flow to achieve a smooth transition to the new inlet temperature demand value.

The predicted temperature response is shown in Fig. 8 for two cases, with and without LQR compensation. In the first case, the gain matrix K was chosen to decrease, by a factor of two compared to the second case (K=0), the time taken for the inlet temperature to reach a given value in response to the setpoint change. These simulation results indicate that inlet temperature speed of response to a setpoint change can be increased beyond that of the open loop plant.

FUTURE WORK

Additional inlet temperature controller tests in EBR-II are envisioned subsequent to those described in this paper. In these tests we will further investigate the feasibility of the modern control approach to plant control in advanced liquid metal reactors. The tests will be performed in a sequence that takes development of the inlet temperature controller from its present state as a research problem to a final state as a controller suited to day-to-day plant operation. These tests will be performed in three phases. In the first phase, the measurements from the thermocouple rakes will be replaced by analytic measurements generated by an analytic observer. In the second phase, the controller will be extended to operate over the entire load range. In the final phase, a supervisory controller will be layered over the present controller to detect those severe upset events for which there is a more appropriate control mode and then switch to this mode.

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