THERMAL HYDRAULICS OF
STEAM GENERATOR SLUDGE

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INTRODUCTION

Experimental and analytical studies of thermal hydraulic processes in commercial steam generator tube sheet sludge have been previously reported^{1,2}. That work was performed because the authors believed that tubing corrosion occurs when the sludge deposit becomes too deep for the liquid to penetrate freely, leading to formation of a liquid deficient region with high chemical concentrations on the tube surface.

The primary objective of this work is to determine analytically the extent of liquid penetration into porous sludge. The secondary objectives are determinations of liquid saturation and chemical concentration profiles along the sludge covered tube length.

The method described in this paper differs from those used in previous works^{1,2} in that it allows specification of porosity and permeability as a function of distance into the sludge and, also, in some of the auxiliary equations used.

ANALYTICAL MODEL

The model considers a slab of porous medium on a horizontal nonporous surface, both underwater. Heat is provided by a vertical tube. The vapor flows vertically upward and the liquid is replenished by a counterflow. The thermal hydraulics along the wetted length are described by five first order differential equations. The continuity for the liquid and the vapor are given by,

$$\rho_l \frac{dV_{sl}}{dx} + \lambda_{lg} = 0 \quad (1)$$

$$\rho_g \frac{dV_{sg}}{dx} - \lambda_{lg} = 0 \quad (2)$$

where λ_{lg} is the vaporization rate per unit volume. V_{sl} and V_{sg} are the superficial velocities for the liquid and the gas phases. The densities for the liquid and the gas phases are represented by ρ_l and ρ_g .

The velocities can be related to the pressure gradients by the Kozeny-Carman equation.³

$$\frac{dP_l}{dx} = - \frac{\mu_l}{K_{rl}k} V_{sl} - \frac{\rho_l}{n_{rl}n} V_{sl}^2 + \rho_l g \quad (3)$$

$$\frac{dp_g}{dx} = - \frac{\mu_g}{K_{rg}k} V_{sg} - \frac{\rho_g}{n_{rg}n} V_{sg}^2 + \rho_g g \quad (4)$$

where μ_l and μ_g are viscosities, K_{rl} and K_{rg} are the relative laminar permeabilities, n_{rl} and n_{rg} are the relative turbulent permeabilities for the liquid and the vapor respectively, and k is the laminar permeability given by,

$$k = \frac{\epsilon^3 d_p^2}{150(1-\epsilon)^2} \quad (5)$$

and n is the turbulent permeability obtained from the Ergun's model.⁴

$$n = \frac{\epsilon^3 d_p}{1.75(1-\epsilon)} \quad (6)$$

The porosity is represented by ϵ and the particle diameter by d_p .

The relative permeabilities, K_{rl} and K_{rg} were calculated using the forms developed by Verma, et. al.⁵ The turbulent relative permeabilities, n_{rl} and n_{rg} were assumed to have the same values as K_{rl} and K_{rg} respectively.

Leveret⁶, has shown that capillary pressure P_c versus normalized liquid saturation S can be correlated in the following form.

$$f = 1.417 (1-S) - 2.120 (1-S)^2 + 1.263 (1-S)^3 \quad (7)$$

where f is the dimensionless pressure defined by,

$$f = \frac{P_c}{\sigma} \left(\frac{k}{\epsilon} \right)^{1/2} \quad (8)$$

where P_c is the difference of gas and vapor pressures, and σ is the surface tension.

The evaporation rate can be calculated from

$$\lambda_{lg} = \frac{1}{A h_{fg}} \frac{d\dot{q}}{dx} \quad (9)$$

where h_{fg} is the latent heat of vaporization.

The heat transfer rate $\dot{q}$ per unit length can be calculated in the usual manner by iterative techniques. Here the boiling heat transfer coefficient was calculated using Thom's correlation⁷, and adjusted by the porosity and the liquid saturation.

The concentration of chemical species can be obtained approximately from,

$$\frac{dC}{dx} = C \lambda_{lg} / \rho_l V_{sl} \quad (10)$$

The above first order differential equations can be solved by numerical integration as an initial value problem. The integration starts from the known values of pressure and liquid saturation with an assumed value of the liquid velocity at the top boundary and proceeds until either V_{sl} or S reach zero. At this point the initial value of the liquid velocity is adjusted using an iterative scheme to bring both the V_{sl} and S within convergence.

RESULTS AND DISCUSSION

Test results of liquid penetration into porous media were presented in Reference (1) and (2). The calculational procedure described here was applied

to these tests. A reasonable correlation to measured wetted lengths was obtained by using constant porosity and permeability for a set of tests where the porous bed maintained its integrity². A second set of tests where vertical cracks were observed in the top section of the granular bed¹ was also successfully represented by assigning a higher effective permeability to the top section. These results are compared to the test data in Figure 1. An interesting result of the two region representation of the sludge pile appears in the liquid saturation profile shown in Figure 2. There is a region of increased liquid saturation between the layers of high and low permeability. The horizontal cracks observed in the bed¹ may have been due to this phenomenon. Figure 3 shows the hypothetical chemical concentration profile. These results show that the cracks on top of a sludge pile supply the liquid necessary for deeper penetration into the sludge. By use of this method it is possible to identify tube locations within the sludge pile which are susceptible to corrosion, and thus, to provide guidance for planned nondestructive inspections.

FIGURE 1: COMPARISON OF TWO REGION SIMULATION RESULTS TO ECKERT DATA

FIGURE 2 - LIQUID SATURATION PROFILE IN A POROUS BED OF HIGH PERMEABILITY REGION ON TOP

FIGURE 3: CHEMICAL CONCENTRATION RATIO

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