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THERMAL HYDRAULICS OF
STEAM GENERATOR SLUDGE

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ABSTRACT

A one-dimensional model of two-phase flow in porous media has been developed. The model considers a slab of porous medium on a horizontal non-porous surface, both under water. Heat is transferred from a vertical surface. The vapor, which is generated, flows vertically upward and the liquid is replenished by a counterflow. Under steady state conditions the mass flow rate of liquid equals that of vapor at every point along the flow path. The liquid saturation (ratio of liquid volume to pore volume) is maximum (0.895 the full mobile saturation limit) at the top surface and decreases with distance into the porous medium reaching a minimum value 0.2, the immobile saturation limit. At this point the liquid and the vapor velocities approach zero, which is also the transition point to liquid deficient region. The solution requires a minimum of five equations; continuity and momentum for the liquid and the vapor phases and energy. The momentum equations are extensions of the Darcy equation to the inertial flow regime in porous media. All five equations can be described as first order differential equations. They can be integrated with respect to distance into the sludge pile using the appropriate boundary conditions at the top of the porous slab and the transition point to "dryout" or at the bottom of the slab whichever comes first. The conservation of chemical species can be easily incorporated into the above system of equations.

A FORTRAN computer program was developed to solve the above set of equations. The solution yields the distribution of the liquid and the vapor velocities and pressures, the heat flux, the liquid saturation and the chemical concentration.

The test conditions in two published works (References [1], [2]) were simulated in order to determine the extent of the liquid penetration into the porous material. The predictions matched one set of data, which used a sludge sample obtained from a commercial steam generator, within a few percent. In a second set of tests, which used a different steam generator sludge, complete

fluidization of the bed was observed (Reference [2]). A good fit with this set of data was possible by using a higher value of permeability in the simulations. In a third set of tests which used synthetic sludge, (Reference [1]) large vertical cracks (chimneys) were formed in the top layers of the bed called the chimney region. This third case was modeled by assuming a higher effective permeability in the chimney region with good results.

INTRODUCTION

The sludge deposits on top of the tubesheet in commercial steam generators create regions of high susceptibility to tube corrosion. It is believed that the corrosion occurs when the sludge deposit becomes too deep for the liquid to penetrate freely. This leads to liquid deficient regions with high chemical concentrations on the tube surface.

Thermal hydraulics in sludge deposits of commercial steam generators was studied by Eckert, et al., Reference [1] and Baum and Greaney, Reference [2]. Eckert, et al., conducted experiments with a single tube and also with a square array of 9 tubes at relatively low pressures, 100 to 500 kPa (15-72.5 psia). Visual observations showed three distinct regions in the porous bed: A dryout region at the bottom containing superheated vapor; a capillary region above it characterized by a stationary bed; and a chimney region containing vertical cracks. There was also a layer of horizontal cracks between the chimney and the capillary regions with negligible height. They developed closed form solutions for the lengths of the capillary and the chimney regions which together defined the wetted length.

Baum and Greaney performed tests with a single tube at high pressures, 5.5 to 7.6 MPa (800-1100 psia). Porous material was packed in an annular gap around the tube. The materials which were tested include samples from two commercial plants. The wet region was assumed to be consisting of two regions: a mixed flow region on top and a divided flow region below it. An iterative solution was obtained for the combined regions.

The solution presented in this paper is similar to that of Baum and Greaney in that the boundary condition is matched iteratively. It differs from the above in several aspects: It uses a single flow structure where the vapor pressure is obtained from the Leverett function; the heat transfer is modified by porosity and liquid saturation (fraction of pore volume filled by liquid); it uses a pressure gradient equation which applies to flow beyond the Darcy regime; it allows specifications of porosity and permeability as a function of distance into the sludge.

ANALYTICAL MODEL

The primary objective of the analytical model presented in this paper is the determination of the wetted length. The wetted region is described by a single set of equations.

Figures 1 and 2 show the geometry and the flow field considered in this work. The conservation equations can be written for a differential element of height dx in the wetted region. The continuity for the liquid is given by,

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

where λ_{lg} is the vaporization rate per unit volume. V_{sl} is the superficial liquid velocity or "filter" velocity found by dividing the liquid volumetric flow rate by the cross sectional area. The continuity for the vapor can be written similarly,

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

The velocities of the liquid and the vapor phases can be related to the pressure gradients by the Kozeny-Carman equation, Reference [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 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, Reference [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 were calculated using the forms developed by Verma, et al., Reference [5].

$$K_{rl} = S_e^3 \quad (7)$$

$$K_{rg} = 1.2984 - 1.9832 S_e + 0.7432 S_e^2 \quad (8)$$

where S_e is the normalized saturation given by,

$$S_e = \frac{S_l - S_{lp}}{S_m - S_{lp}} \quad (9)$$

The values of the immobile saturation S_{lp} and the full mobile saturation S_m are 0.2 and 0.895 respectively, Reference [5].

The turbulent relative permeabilities, n_{rl} and n_{rg} were assumed to have the same values as K_{rl} and K_{rg} respectively.

The capillary pressure P_c is given by,

$$P_c = P_g - P_l \quad (10)$$

Leverett, Reference [6], has shown that capillary pressure versus liquid saturation data can be correlated in the following form.

$$f = 1.417 (1-S) - 2.120 (1-S)^2 + 1.263 (1-S)^3 \quad (11)$$

where f is the dimensionless pressure defined by,

$$f = \frac{P_c}{\sigma} \left(\frac{k}{\epsilon} \right)^{1/2} \quad (12)$$

The dimensionless saturation S is defined similar to S_e of Verma.

$$S = \frac{S_l - S_{lp}}{1.0 - S_{lp}} \quad (13)$$

The evaporation rate per unit volume is given by,

$$\lambda_{lg} = \frac{1}{A_c h_{fg}} \frac{d\dot{q}}{dx} \quad (14)$$

For a triangular pitched tube array the flow area is given by,

$$A_c = \cos(30) \times \text{Pitch}^2 - \frac{\pi D_o^2}{4} \quad (15)$$

The heat transfer rate per unit length can be obtained from,

$$\frac{dq}{dx} = U_o (T_p - T_s) \pi D_o \quad (16)$$

In calculating the overall thermal conductance, only the fraction of the tube surface in contact with liquid was considered to be significant.

$$U_o = 1 / \left(\frac{D_o}{D_i h_i} + \frac{D_o \ln D_o/D_i}{2 k_t} + \frac{1}{h_o S_{\ell} \epsilon} \right) \quad (17)$$

The primary side forced convection heat transfer coefficient was obtained using the Dittus-Boelter correlation.

$$h_i = \frac{k_{pl}}{D_i} 0.023 (Re)^{0.8} Pr^{0.4} \quad (18)$$

The secondary side boiling heat transfer coefficient was calculated by Thom's correlation, Reference [7].

$$h_o = 1094.5 e^{P_s/630} (T_w - T_s), P_s \text{ in psia, } T \text{ in } ^\circ F \quad (19)$$

Defining,

$$U_p = 1 / \left(\frac{D_o}{D_i h_i} + \frac{D_o \ln D_o/D_i}{2 K_t} \right) \quad (20)$$

the tube outside wall temperature can be found iteratively using,

$$T_w = T_p - q''/U_p \quad (21)$$

where,

$$q'' = U_o (T_p - T_s) \quad (22)$$

The concentration of chemical species can be calculated from a simple mass balance. The molecular diffusion and the chemical species mass carried by the vapor phase were neglected.

$$\frac{dC}{dx} = C \lambda_{lg} / \rho_l V_{sl} \quad (23)$$

where, C is the ratio of the local to the bulk chemical concentration.

The boundary conditions at the lower boundary of the wet region complete the definition of the problem, which are $S = 0$ and $V_{sl} = G$.

The first order differential equations for the velocities and the pressures can be solved by numerical integration along with the auxiliary equations, as an initial value problem.

The integration starts from the known values of pressure and saturation ($S_g = 0.895$) and an assumed value of liquid velocity, V_{sl} , at the top boundary and proceed until either V_{sl} or S reach a small value above zero. At this point the initial value of the liquid velocity is calculated using an iterative scheme to bring both the V_{sl} and the S within the convergence band which is arbitrarily defined as a factor of 400 reduction in velocity and $S \leq 0.005$. Convergence generally requires less than five iterations.

RESULTS AND DISCUSSION

A number of test cases presented in References [1] and [2] were simulated with the present analytical procedure. The data in Reference [1] was obtained

with a granular bed consisting of nickel particles. The porosity was given as 0.65 and the mean particle size as 28.3 μm . The corresponding permeability was obtained using Equation (5).

Figure 3 compares the Baum and Greaney data, Reference [2], to predictions of the analytical model presented here for sludges from two commercial plants. The lower data points and the lower line correspond to the Plant A sludge. The fit for Plant A sludge is excellent using the porosity and permeability given in Reference [2]. The upper data points and line correspond to the Plant B sludge. Baum and Greaney reported fluidization of the Plant B sludge bed throughout the tests. The fluidization must have caused the longer measured wetted lengths, which may be the reason for lack of a fit here.

Figure 4 shows four data points for wetted length from Eckert, et al., Reference [1]. The solid line represents our predictions. It follows the trend quite well but falls about 2.0 to 3.0 cm short at all points. This is most probably due to the chimneys in the granular bed which were produced by large volumes of low pressure vapor.

The effect of vertical cracks in the granular material bed or of fluidization of the bed material is to make it easier for the liquid to penetrate and the vapor to escape. A similar effect can be produced by increasing the permeability of the porous bed in computer simulations. This was done for the Eckert data, Reference [1] and for the Plant B sludge of Baum and Greaney, Reference [2].

The effective permeability of the Plant B sludge was increased from the reported value of 2.47×10^{-13} to $9.3 \times 10^{-12} \text{ m}^2$ throughout. The result of this exercise is shown in Figure 5. The Eckert tests were modeled by a highly permeable top section corresponding to the observed chimney region and a less permeable capillary region below it. The top section was assumed to extend 2.5 cm into the sludge and had a permeability of $4.6 \times 10^{-11} \text{ m}^2$. The bottom section had a permeability of $1.2 \times 10^{-11} \text{ m}^2$ which was calculated from the

reported porosity and particle size in Reference [1]. The transition was assumed to be linear from 2.5 to 3.5 cm into the sludge. The net result of this was to raise the prediction line by about 3.0 cm, as shown in Figure 6. The top section showed little resistance to liquid penetration. The physical significance of this becomes clearer when we look at the liquid saturation profiles.

Figure 7 shows the saturation profile for a bed of uniform porosity, 0.65, and permeability, $1.2 \times 10^{-11} \text{ m}^2$. The flatness of the profile in the last several centimeters may make accurate measurement of the wet length difficult especially at low heat flux. Figure 8 shows the change when a region of high permeability is assumed on top. The liquid saturation increases significantly at the start of the less permeable region. This would indicate a pool of liquid between the two layers. It is possible that the horizontal cracks observed by Eckert, et al., Reference [1] in the granular bed were caused by liquid which collected on top of a region of low permeability. The saturation profile in Figure 9 was calculated using a higher heat flux. The discontinuity in the liquid saturation profile is less pronounced. At still higher heat flux values the discontinuity practically disappears. A typical plot of a normalized chemical concentration is shown in Figure 10.

CONCLUSIONS

An analytical procedure and a corresponding computer program have been developed to predict the thermal hydraulics behavior and chemical concentration in porous media, with emphasis on computing the liquid penetration into vertical steam generator sludge. The model considers fixed granular beds in capillary flow regime. A "chimney" flow region characterized by vertical cracks in the top section of the bed is represented by increased permeability. The simulation of a granular bed with a highly permeable region on top of a less permeable one at the bottom predicts a highly liquid saturated region between the two layers and extends the wetted length deeper into the sludge.

FIGURE 1. TUBE/SLUDGE GEOMETRY

FIGURE 2. SCHEMATIC OF FLOW FIELD

FIGURE 3 - COMPARISON OF MODEL PREDICTIONS TO BAUM AND GREANEY DATA
(REFERENCE 2)

FIGURE 4 - COMPARISON OF MODEL PREDICTIONS TO ECKERT DATA
(REFERENCE 1)

FIGURE 5 - COMPARISON OF MODEL PREDICTIONS WITH INCREASED PERMEABILITY TO BAUM AND GREANEY DATA

FIGURE 6 - COMPARISON OF TWO REGION SIMULATION RESULTS TO ECKERT DATA

FIGURE 7 - LIQUID SATURATION PROFILE IN A
POROUS BED OF UNIFORM PROPERTIES

FIGURE 8 - LIQUID SATURATION PROFILE IN A POROUS BED
OF HIGH PERMEABILITY REGION ON TOP

FIGURE 9 - LIQUID SATURATION PROFILE IN A TWO REGION BED

FIGURE 10 - CHEMICAL CONCENTRATION RATIO

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Nomenclature

A_c	Flow area, m^2
C	Concentration ratio
D_o	Tube outside diameter, m
D_i	Tube inside diameter, m
d_p	Particle diameter, m
f	Normalized capillary pressure
g	Gravitational acceleration, m/s^2
h	Height, m
h_o	Secondary side film coefficient, W/m^2-K
h_i	Primary side film coefficient, W/m^2-K
k	Laminar permeability, m^2
K_{rg}	Vapor relative permeability in laminar flow, dimensionless
K_{rl}	Liquid relative permeability in laminar flow, dimensionless
k_t	Tube thermal conductivity, $W/m-K$
k_{pl}	Thermal conductivity of primary liquid, $W/m-K$
n	Turbulent permeability, m^2
n_{rg}	Vapor relative permeability in turbulent flow, dimensionless
n_{rl}	Liquid relative permeability in turbulent flow, dimensionless
P	Pressure, kPa unless stated otherwise
P_c	Capillary pressure, kPa
q''	Heat flux, W/m^2
Pr	Prandtl number
$\dot{q}$	Heat transfer rate, W
Re	Reynolds number

S	Normalized liquid saturation, dimensionless
S_e	Normalized liquid saturation, dimensionless
S_l	Liquid saturation, dimensionless
S_{lp}	Immobile liquid saturation, dimensionless
S_m	Upper limit of mobile liquid saturation, dimensionless
T_p	Primary liquid temperature, K
T_s	Secondary temperature, K
T_w	Tube outside wall temperature, K
U_o	Overall thermal conductance, W/m^2-K
U_p	Thermal conductance, W/m^2-K
V_{sl}	Superficial liquid velocity, m/s
V_{sg}	Superficial vapor velocity, m/s
X	Distance into the sludge, m
ϵ	Porosity, dimensionless
λ_{lg}	Volumetric vaporization rate, m^3/s
ρ	Density, kg/m^3
σ	Surface tension, kg/m
θ	Angle
μ	Viscosity, Pa.s

Subscripts

g	Vapor
l	Liquid

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