Sludge Deposition Models on Secondary Side Tubes of Steam Generators

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1. Introduction

ATHOS is a computer code developed by EPRI for thermal hydraulic analysis of a steam generator (SG) secondary side [1]. This code is capable of calculating the sludge deposition rate and deposited sludge thickness in the secondary side of an SG. ATHOS uses Kern-Seaton's model for the prediction of deposition rate of sludge in the secondary side of a steam generator in pressurized water reactors. This model explains that the fouling rate is the difference between the growth and removal rate of the deposit as expressed in Eq. 1.

$$\frac{dm_f}{dt} = \dot{m}_g - \dot{m}_r \tag{1}$$

The right hand side of this equation is the rate of deposit formation in unit time and unit area and this is equated with the difference of the deposition (growth) and reentrainment (removal) rate of the sludge in a unit area of the surface of heat transfer tubes.

dm_f/dt = sludge deposition amount per unit area and time (Kg/m^2s)

The solution of Eq.1 is given as follow:

$$x_f = \frac{\dot{m}_g}{E}\left(1 - e^{-Et}\right) \tag{2}$$

where E is a re-entrainment coefficient(1/s).

2. Sludge Deposition and Precipitation Models

2.1 Sludge Build-up Models

The key possible mechanisms for depositions of particles on a heat transfer surface are as follows:

- Turbulent deposition
- Boiling enhanced deposition
- Temperature effect on the heat transfer surface.

Eq.1 can be recast in terms of these three mechanisms to produce the first order ordinary differential equation.

$$\frac{dm_d}{dt} = \rho_l C_p (K_{boil} + K_{turb}) - Em_d \tag{3}$$

The solution of this first order ordinary differential equation is given as:

$$m_d = \frac{\rho_l C_p (K_{boil} + K_{turb})}{B}\left(1 - e^{-Bt}\right) \tag{4}$$

In this equation, m_d is the deposit mass per unit surface area in a certain time t, ρ_l is the liquid density, C_ρ is the particulate concentration, and the K terms are deposition velocities for the two mechanisms

2.1.1 Turbulent deposition

The model coded in ATHOS uses the constants suggested by Beal and Chen [2]. The total turbulent deposition coefficient is given by the equations

$$K^+_{turb,m} = \begin{cases} aSc^b + b_1\left(t_p^+\right)^2 & [t_p^+ < 18] \\ aSc^b + b_1(\gamma)^2 & [t_p^+ > 18] \end{cases} \tag{5}$$

K^+_{turb} = turbulent deposition coefficient, u_d/u_τ

t_p^+ = particle relaxation time, $\rho_L \rho_p d_p^2 u_\tau^2 / 18\mu_L^2$

u_d , u_τ = Deposition, Friction velocity (m/s)

ρ_L , ρ_p = Liquid, Sludge particle density (Kg/m^3)

d_p = Sludge particle diameter (m)

μ_L = Liquid viscosity (Ns/m^2)

2.1.2 Boiling enhanced deposition

Asakura, et al. [3], based on saturated boiling, propose the following equation for boiling enhanced deposition.

$$K_{boil} = \frac{eq}{\rho_L h_{fg}} \tag{6}$$

K_{boil} = Boiling deposition coefficient (m/s)

e = Deposition efficiency

q = Heat flux (W/m^2)

h_{fg} = Latent heat vaporization (J/Kg)

The deposition efficiency or boiling effectiveness (e) represents the fraction of sludge particles

2.1.3 Temperature effect on the heat transfer surface

The temperature effect of a tube surface on sludge deposition is existed in the liquid area and the boiling effect is existed in the steam area where the void fraction is larger than zero. The sludge deposition effect of the surface temperature is expressed as,

$$\left(\frac{dx_f}{d\theta}\right)_d = \frac{k_1 C_b S \rho u F}{\rho_f A_s [1 + k_1(1 - S)]}(1 - \alpha) \tag{7}$$

2.2 Sludge Removal Models

Cleaver and Yates [4] modeled a re-entrainment process removing sludge on the heat transfer surface. Cleaver and Yates suggested that the turbulent liquid moves away from the surface in the pattern of a liquid burst. Therefore, the removal of a sludge particle from the surface was assumed because of the violent friction/shear movements.

$$E = -\tau_w \frac{\ln\left(1 - \frac{\alpha}{270}\right)}{75\mu} \tag{8}$$

τ_w = wall shear stress (N/m^2)
α = the fraction rate removed particles per a liquid burst in the turbulent flow, between 0.01 and 1×10-7

Mostafa [5] developed a correlation based on the assumption that the thickness of a fouling layer caused by a sludge removal process is proportional to the shear stress, the thickness of a fouling layer(x_f), and the reciprocal of a deposit intensity(Ψ)

$$\left(\frac{dx_f}{d\theta}\right)_r = k_2 x_f \frac{k_3 \rho u^2}{\Psi} = k_4 x_f \frac{\rho u^2}{\Psi} \tag{9}$$

3 Sludge Prediction Models

The solution of the first ordinary differential equation (Eq.1) proposed by Kern and Seaton gives the amount of sludge deposition. If the sludge growth rates by turbulent flow and liquid boiling are coupled into Eq.2 and substitute the re-entrainment constant, E, given in Eq.8, then finally the sludge deposition amount and thickness are able to be obtained as

$$t_f = \frac{\rho_L C_o \left(K_{boil} + K_{turb} \bullet \mu_r\right)}{\rho_f E}\left(1 - e^{-Et}\right) \tag{10}$$

t_f = sludge thickness
t = time
C = dimensionless sludge particle density (m^3/m^3)

However, Kern and Seaton's model was not able to express the surface temperature effect directly. And Kern and Seaton's model predicts the boiling effect takes place anywhere in the steam generator tube even though the secondary coolant inflow into the steam generator as a subcooled state and heated up to the saturation state as flows along the tubes. Therefore a new sludge deposition model is suggested in this study as introducing a void fraction into the model proposed by Mostafa. First of all, the sludge growth rate by temperature and boiling effects given in Eq.9 and 10 is rewritten as

$$\dot{m}_g = \frac{k_1 C_b S \rho u F}{\rho_f A_s [1 + k_1(1 - S)]}(1 - \alpha) + \rho_f C_b \frac{eq}{\rho_L h_{fg}} \alpha \tag{11}$$

The removal rate of deposited sludge is able to obtained using Eq.11 as

$$\dot{m}_r = k_4 \frac{\rho \rho_f}{\rho_L} \frac{u^2}{\Psi}(1 - \alpha) x_f \tag{12}$$

The prediction model of sludge deposition in Eq.1 transforms to the sludge deposited thickness and substitute Eq.11 and 12, then rearrange it.

$$\frac{dx_f}{dt} = \frac{1}{\rho_f}\left[\frac{k_1 C_b S \rho u F}{\rho_f A_s [1 + k_1(1 - S)]}(1 - \alpha) + \rho_f C_b \frac{eq}{\rho_L h_{fg}} \alpha - k_4 \frac{\rho \rho_f}{\rho_L} \frac{u^2}{\Psi}(1 - \alpha) x_f\right] \tag{13}$$

The time difference of sludge thickness is given as a first order differential equation of the sludge thickness and related parameters in Eq. 13. In order to solve this equation, the initial condition of the sludge thickness x_f = 0 at t=0 is applied and finally the sludge thickness is obtained as;

$$x_f = \frac{\left[\frac{k_1 C_b S \rho u F}{\rho_f A_s [1 + k_1(1 - S)]}(1 - \alpha) + \rho_f C_b \frac{eq}{\rho_L h_{fg}} \alpha\right]}{k_4 \frac{\rho \rho_f}{\rho_L} \frac{u^2}{\Psi}(1 - \alpha)}\left(1 - e^{-k_4 \frac{\rho \rho_f}{\rho_L} \frac{u^2}{\Psi}(1 - \alpha) t}\right) \tag{14}$$

With the equation given in Eq. 14, the sludge thickness deposited on the secondary side of steam generator tubes can be calculated as a function of a tube surface temperature and void fraction due to the phase change of secondary coolant along with the tube elevation.

4. Conclusions

ATHOS uses Kern and Seaton's model, but this model was not able to express the surface temperature effect and the realistic boiling effect. Mostafa's model was employed in order to include the temperature effect of the tube surface.

If ATHOS adopts the proposed model developed in this study, ATHOS is capable of include the temperature effect of the heat transfer surface. With that, ATHOS is able to predict the sludge thickness more precisely.

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