



Distribution of Impurities Concentration in Nucleate Boiling

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Abstract: The development of the mathematical model of mass transfer and diffusion process can determine the behavior of dissolved impurities in the flow boiling within viscous sublayer. Application of a new model to calculate the distribution of dissolved impurities concentration within viscous sublayer and estimation of its thickness based on heat conduction layer and evaporation layer (macro-microlayer model) is the major goal of this study.

Keywords: *Viscous Sublayer, Impurities Transport, Flow Boiling, Concentration Ratio*

1-Introduction

Control of the water chemistry norms in the primary and secondary circuits of nuclear reactors is one of the major problems in the operation of nuclear power plants. During the transient operation of nuclear reactors and steam-generators considerable changes have been observed in the concentration of impurities due to the results of the process called "hide-out and return". Hide-out is a complex process which depends on the local geometry, applied thermo-hydraulic conditions and the solubility characteristics of dissolved impurities. Corrosion in nuclear reactors and steam generators is an important concern; therefore it is very important to be capable of predicting the behavioral effects of impurities in the system with respect to localized corrosion. Essentially non-uniform distribution of the dissolved impurities in boiling medium can only rise in the viscous sublayer near the heating wall. In the fully-developed turbulent boundary layer the gradient of impurities concentration can not be observed beyond the boundaries of the viscous sublayer. The boiling of the solutions adjacent to the heating surface increases the local concentration of impurities in the liquid phase. The concentration of impurities in the liquid layer near the wall depends on the intensity of the vapor generation and mass transfer between bulk stream and the near wall- layer. In most cases, only the mass transfer between the near wall boiling layer and the main stream limits the increase in concentration near the wall. Based on the Prandtl and Taylor theorem the basic

resistance of the heat and mass transfer between the wall and the turbulent bulk fluid in the single-phase flow and similarly in the boiling flow are restricted to the viscous sublayer.

2- Theory and Results

Distribution of dissolved impurities in nucleate boiling

In a similar fashion to pool boiling heat transfer if the wall temperature rises sufficiently above the local saturation temperature pre-existing vapor in wall sites can nucleate and grow. The onset of nucleate boiling indicates the location where the vapor can exist in a stable state on the heating surface without condensing or vapor collapse. As more energy is input into the liquid (i.e., downstream axially) these vapor bubbles can grow and eventually detach from heating surface and enter the liquid phase. In fully developed nucleate boiling, the thermo-hydraulic conditions of stream near the boiling surface are irrespective of conditions in the bulk stream. The solubility of impurities in liquid phase is much more than in vapor, so through evaporation near heating wall the concentration of dissolved impurities in that region will increase. Vapor leaves the viscous sublayer and then liquid with its content of impurities from the bulk flow takes vapor place. The concentration of impurities within viscous sublayer will be stable due to diffusion of impurities from viscous sublayer to the bulk flow.

Distribution of impurities concentration within

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viscous sublayer in nucleate boiling is defined by the equation of convection-diffusion (the conservation law),

$$\frac{\partial}{\partial t}((1-\alpha)c) + \nabla[(1-\alpha)(\bar{w}c - (D + \varepsilon)\nabla c)] + (1-\alpha)k_dgc = 0 \quad (1)$$

where c is volumetric concentration of dissolved impurities in the viscous sublayer (kg/m^3), α is void fraction near the boiling surface, g is liquid volume vaporized per unit volume per second, and k_d is the coefficient of relative solubility of impurity between the steam and water. g is given by

$$g = \frac{q}{(1-\alpha)i_{fg}\rho_f\delta} g_x$$

where g_x is dimensionless distribution function defined as $\int_0^\delta g_x dx = 1$, and δ is the viscous sublayer thickness.

On the basis of the conservation law (the continuity equation) for the liquid phase it is possible to write

$$\frac{\partial}{\partial t}(1-\alpha)\rho_f + \nabla((1-\alpha)\bar{w}\rho_f) + (1-\alpha)\rho_f g = 0 \quad (2)$$

By assuming constant values for void fraction, diffusion coefficient and intensity of vaporization in the viscous sublayer, we have

$$\text{div } \bar{w} = -g \quad (3)$$

$$\frac{\partial c}{\partial t} + \nabla[(\bar{w}c - (D + \varepsilon)\nabla c)] + k_dgc = 0 \quad (4)$$

As it is seen, in a two-phase flow, in contrast to the single-phase, the divergence of velocity is not equal to zero even in incompressible fluids. From Eqs. (3) and (4) we can write

$$\begin{aligned} \frac{\partial c}{\partial t} + \nabla(\bar{w}c - (D + \varepsilon)\nabla c) - \nabla\bar{w}k_dc &= 0 \\ \frac{\partial c}{\partial t} + \bar{w}\nabla c - \nabla((D + \varepsilon)\nabla c) + \nabla\bar{w}(1 - k_d)c &= 0 \end{aligned} \quad (5)$$

$$\begin{aligned} D\left(\frac{\partial}{\partial x}\left(D_x\frac{\partial c}{\partial x}\right) + D_x\frac{\partial^2 c}{\partial z^2}\right) + \frac{q}{(1-\alpha)i_{fg}\rho_f\delta}w_x\frac{\partial c}{\partial x} - \\ Uu_x\frac{\partial c}{\partial z} + \frac{q}{(1-\alpha)i_{fg}\rho_f\delta}\frac{\partial w_x}{\partial x}(1 - k_d)c = 0 \end{aligned}$$

Concerning Eq. (5) and the above-mentioned assumptions, the steady state two-dimensional equation of convection-diffusion can be derived in a dimensionless form, as follows:

$$\begin{aligned} \frac{\partial}{\partial \xi}\left(D_\xi\frac{\partial C}{\partial \xi}\right) + D_\xi\chi^2\frac{\partial^2 C}{\partial \zeta^2} + Pe_qw_\xi\frac{\partial C}{\partial \xi} - \\ Pe_uu_\xi\frac{\partial C}{\partial \zeta} + Pe_q\frac{\partial w_\xi}{\partial \xi}(1 - k_d)C = 0 \end{aligned} \quad (6)$$

where, $\xi = x\delta$, $\zeta = zH$, $w_\xi = w_x\delta$, $u_\xi = u_x$,

$$D_\xi = D_x, \quad \chi = \frac{\delta}{H}, \quad Pe_q = \frac{q\delta}{(1-\alpha)i_{fg}\rho_f D}$$

$$Pe_u = \frac{U\delta^2}{DH}$$

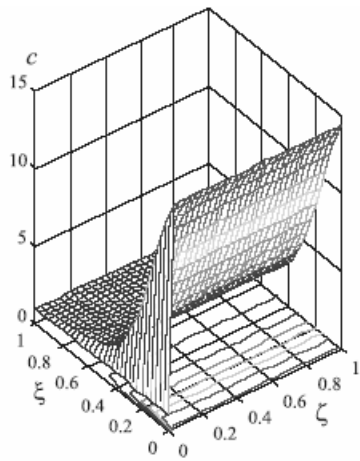
$C=c/c_b$ and c_b is the volumetric concentration of impurities in the bulk fluid, x and z are normal and longitudinal distances, respectively, and w_x is velocity component in the x direction.

Eq. (6) is numerically solved, using a finite-volume formula and the related results have been shown in Fig.1. The applied boundary conditions and the input data are as follows

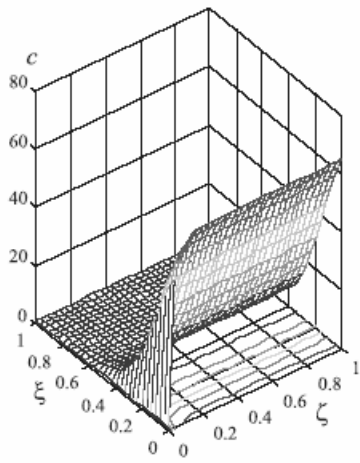
$$\left.\frac{\partial C}{\partial \xi}\right|_{\xi=0} = 0, \quad C_{\xi=1} = 1, \quad C_{\zeta=0} = 1, \quad Pe_q = 30,$$

$$Pe_u = 1, \quad w_\xi = \xi, \quad u_\xi = \xi/2, \quad p = 16 \text{ (MPa)}$$

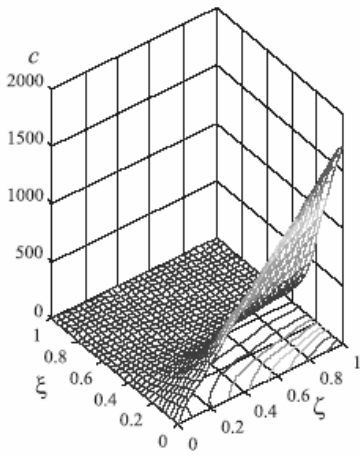
Eq. (6) has been solved for three dissolved impurities B_2O_3 , SiO_2 , and PO_4 with different coefficient k_d . As displayed in Fig.1, the maximum concentration of all impurities is located adjacent to the channel wall and the concentration of boric acid, with the highest coefficient k_d , will reach relatively faster to its maximum value.



a) B₂O₃



b) SiO₂



c) PO₄

Fig.1. Variation of dissolved impurities concentration ($C=c/c_b$) in the viscous sublayer.

In order to calculate the spatial distribution of impurity in the boiling medium, it is assumed that, δ , the value of intensity of vaporization, is constant within the boundaries of the sublayer ($g=\text{const}$), and outside

the boundaries there is a fully-developed turbulent core. As an estimation of the viscous sublayer thickness, the hydro-dynamical analogy of heat transfer is used in turbulent flow for the single-phase and boiling flows.

Estimation of the viscous sublayer thickness

Turbulent flows are significantly affected by the presence of walls due to no-slip conditions, viscous damping and kinematics blocking very close to wall, and also production of turbulent kinetic energy due to large gradients in mean velocity in the outer part of the near-wall region. In accordance with the concept of the boundary layer with a sharp division between laminar and turbulent regions, it is therefore assumed that heat and mass transfer in the turbulent region result entirely from turbulent interchange, that conductive effects are negligible, and further that in viscous sublayer the heat and mass transfer occur purely by conduction and diffusion, respectively.

The thickness of viscous sublayer in the single phase flow can be determined as follows [1].

$$Nu = 0.023 Re^{0.8} Pr^{0.4}$$

$$h_{fo} = 0.023 w^{0.8} d^{-0.2} \nu^{-0.8} \lambda \tag{7}$$

$$h_{fo} = \frac{\lambda}{\delta}$$

$$\delta = 43.5 \bar{w}^{-0.8} \nu^{0.8} d^{0.2} \tag{8}$$

The validity of the model and the derived equations describing distribution of dissolved impurities are laid on the coincidence of viscous sublayer thickness with evaporation layer thickness (macro-micro layer model).

According to new models offered for the fully-developed nucleate boiling, the evaporation of the liquid macro-microlayer plays a major role, especially, at high heat flux conditions.

As shown in Fig. 2, on the basis of macro-microlayer model, the heating surface consists of zones:

- dry zone (center of bubble stem)



- thin evaporating liquid films underneath the bubble (microlayer)
- liquid macrolayer at the base of coalescence bubble

The model is submitted in [2, 3, 4, 5]. The total average surface heat flux consists of two components: 1-convection heat transfer through macrolayer, q_{mac} 2-direct evaporation of the liquid in the microlayer, q_{mic} .

$$q = q_{mac} + q_{mic}$$

Using data as given in Table 1, and the relationship for calculating the initial macrolayer thickness, it is possible to predict the average sublayer thickness, δ , through which the total surface heat flux is conducted.

$$\delta_0 = 0.00536 \rho_g \sigma (\rho_g / \rho_f)^{0.4} (1 + \rho_g / \rho_f) (i_{fg} / q)^2 \tag{9}$$

$$\delta_0 = 0.0107 \rho_g \sigma (\rho_g / \rho_f)^{0.4} (i_{fg} / q)^2 \tag{10}$$

$$\delta_0 = 1.59 q^{-1.527} \tag{11}$$

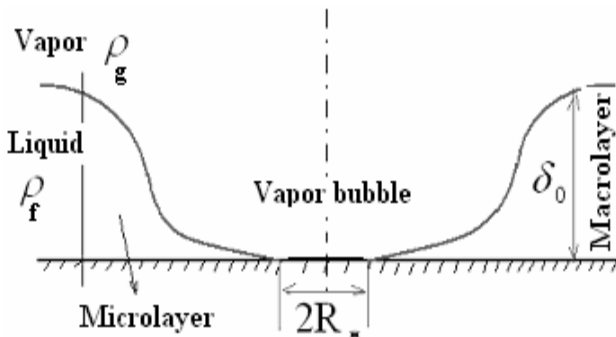


Fig.2. Schematic of macro-microlayer model.

Table1. Heat flux ratio used for the calculations.

Average heat flux q (Mw/m ²)	ΔT_s (K)	q_{mic}/q	q_{mac}/q
0.9963	21.6	0.89	0.11
1.165	23.5	0.856	0.144
1.44	26.4	0.82	0.18
1.58	29.9	0.788	0.212

Where δ_0 is the macrolayer thickness (m), q is the heat flux (kW/m²), i_{fg} is the latent heat of vaporization (kJ/kg).

From table 1, at $q=0.9963, 1.58$ (MW/m²) following results can be obtained.

$$(q_{mic}/q)_{ave} = 0.838$$

$$q = q_{mac} + q_{mic}$$

$$0.162q = q_{mac}$$

$$0.162 \frac{\lambda}{\delta} \Delta T_s = \frac{\lambda}{\delta_0} \Delta T_s$$

$$\delta = 0.162 \delta_0$$

Fig. 3 provides the comparison of the estimated viscous sublayer with the average layer thickness, derived based on the macro-microlayer model.

3- Conclusions

- 1) It is impossible to calculate the distribution of impurities concentration in the boiling medium without the estimation of the viscous sublayer thickness. Because of the fluid turbulent fluctuations associated with eddies beyond the viscous sublayer boundaries, and the impurities concentration remain practically homogeneous.

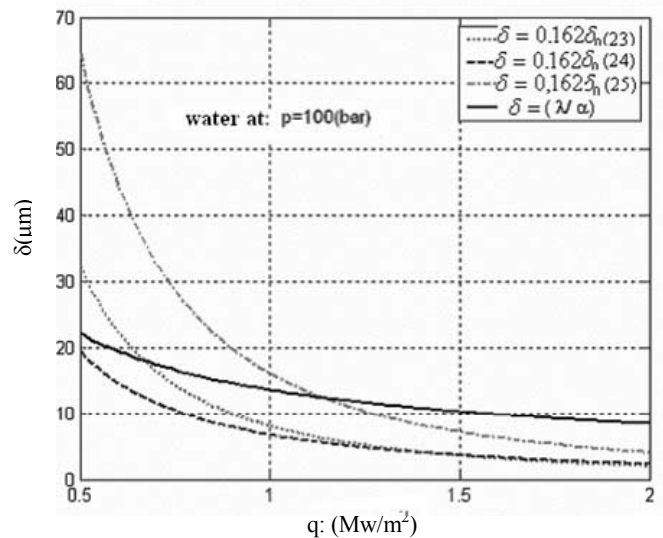


Fig.3. Comparison of the viscous sublayer thickness with the thickness calculated by the relation: $\delta=0.162\delta_0$.



- II) The comparison of the suggested model for the estimation of viscous sublayer thickness with macro-microlayer model has yielded satisfactory results.
- III) The viscous sublayer thickness for water ($pr \approx 1$) in the single-phase flow depends on fluid velocity, diameter of the channel and kinematic viscosity, and in fully -developed boiling, depends on the heat flux and pressure.
- IV) The behavior of multy- component system has not been considered in this research. The relevant interactions between the different impurities and probable changes in their distribution will be held in future works.

Nomenclature

$k_d = c_g/c_f$	Distribution coefficient
$c_g, c_f =$	Volumetric concentration of dissolved impurities in the steam and water
$D =$	Molar diffusion coefficient of impurities in water
g	Intensity of vaporization
w	Velocity vector
q	Heat flux
i_{fg}	Latent heat of vaporization
d, H	Diameter and length of the pipe
p	Pressure
T	Average temperature
h_{fo}	Heat transfer coefficient for total flow

Greek symbols

α	Void fraction
ε	Eddy diffusivity of momentum
δ	Thickness of viscous sublayer
λ	Thermal conductivity of liquid
μ	Viscosity of liquid
ν	Dynamic viscosity of liquid
ρ_f, ρ_g	Liquid and gas density
σ	Surface tension

Dimensionless quantities

Re	Reynolds number
Pr	Prandtl number
Pe	Peclet number
Nu	Nusselt number

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