ESTIMATION OF VISCOUS SUBLAYER THICKNESS AND DISTRIBUTION OF IMPURITIES CONCENTRATION IN NUCLEATE BOILING

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ABSTRACT

A new model offered for describing impurities transport process in flow boiling. The development of the mathematical model of transport process and concentration behavior of dissolved impurities in the flow boiling without specifying the viscous sublayer thickness is impossible. The major goal of the present paper is development of a model to calculate the distribution of dissolved impurities concentration within viscous sublayer and estimate its thickness based on the analogy between heat conduction layer and viscous sublayer. The present model has been applied to the fully –developed nucleate boiling (macro-microlayer) model with acceptable agreement.

Key Words: viscous sublayer, impurities transport, flow boiling.

INTRODUCTION

A major objective of the nuclear power industry has been the development of models of the impurities concentration process and the resulting crevice chemistry. Controlling 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 of nuclear reactors and steam generators is an important concern; it is, therefore, of interest to be able to predict the behavioral effects of impurities in the system with respect to localized corrosion. Essentially non-uniform distribution of the dissolved impurities in boiling mediums 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. 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 the most cases, only the mass transfer between the near wall boiling layer and the main stream limits the increase of 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 is restricted to the viscous sublayer.

Distribution of dissolved impurities in nucleate boiling

Distribution of impurities concentration within the viscous sublayer in nucleate boiling can be defined by the equation of convection-diffusion (the conservation law).

$$\frac{\partial}{\partial t}((1-\alpha)c)+\nabla[(1-\alpha)(\vec{w}c-(D+\varepsilon)\nabla c)]+(1-\alpha)k_d gc=0 \tag{1}$$

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 coefficient of relative solubility of impurity between the steam and water .

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

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

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

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

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

$$\mathrm{div}\vec{\mathrm{w}}=\text{-g} \tag{3}$$

$$\frac{\partial c}{\partial t}+\nabla[(\vec{w}c-(D+\varepsilon)\nabla c)]+k_d gc=0 \tag{4}$$

As it is visible, in the two phase flow, in contrast to the single-phase, the divergence of velocity is not equal to zero even in incompressible fluids.
From equations (3), (4) it can be write

$$\frac{\partial c}{\partial t}+\nabla(\vec{w}c-(D+\varepsilon)\nabla c)-\nabla\vec{w}k_d c=0$$

$$\frac{\partial c}{\partial t}+\vec{w}\nabla c-\nabla((D+\varepsilon)\nabla c)+\nabla\vec{w}(1-k_d)c=0 \tag{5}$$

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

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

$$\frac{\partial}{\partial\xi}\left(D_\xi\frac{\partial C}{\partial\xi}\right)+D_\xi\chi^2\frac{\partial^2 C}{\partial\zeta^2}+Pe_q w_\xi\frac{\partial C}{\partial\xi}-Pe_u u_\xi\frac{\partial C}{\partial\zeta}+Pe_q\frac{\partial w_\xi}{\partial_\xi}(1-k_d)C=0 \tag{6}$$

Where, $x=\xi\delta$, $z=\zeta H$, $w_\xi=w_x\delta$, $u_\xi=u_x$, $D_\xi=D_x$, $\chi=\frac{\delta}{H}$, $Pe_q=\frac{q\delta}{(1-\alpha)i_{fg}\rho_f D}$, $Pe_u=\frac{U\delta^2}{DH}$

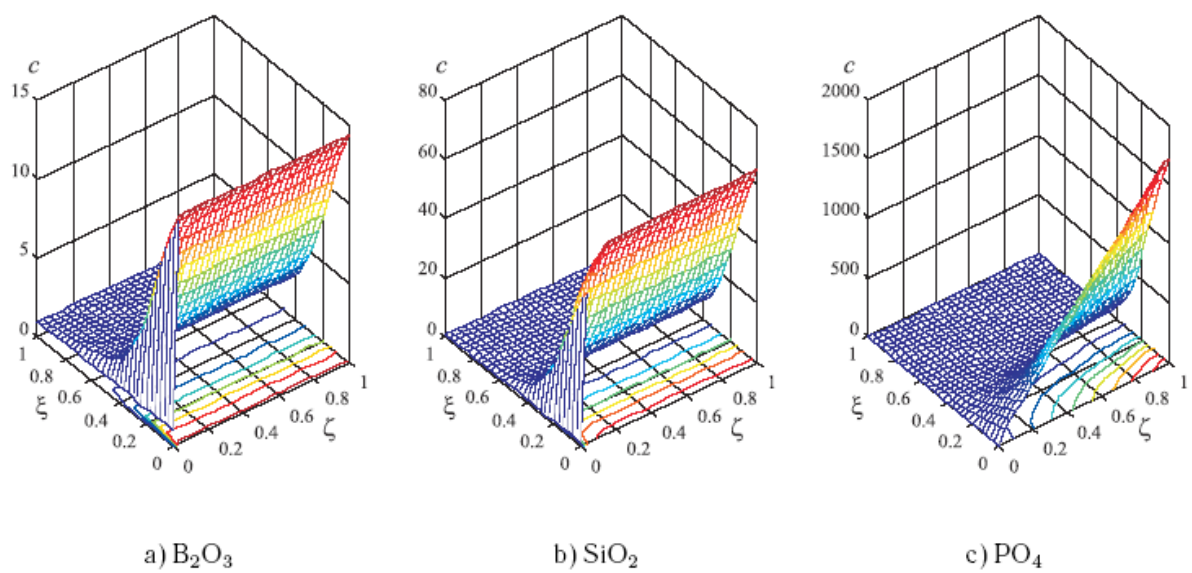
$C = c/c_b$, c_b is the volumetric concentration of impurities in the bulk fluid.

where, x and w_x respectively, are normal distance from the wall to the bulk flow and velocity component in the x direction and z is longitudinal distance.

The equation (6) is numerically solved using a finite- volume formulation and the related results have been shown in fig.1.The applied boundary conditions and input data are

$$\left.\frac{\partial C}{\partial \xi}\right|_{\xi=0} = 0,\ C_{\xi=1} = 1,\ C_{\zeta=0} = 1,\ Pe_q = 30,\ Pe_u = 1,\ w_\xi = \xi,\ u_\xi = \xi/2,\ \text{p=16 (MPa).}$$

The equation (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, for all of the impurities the maximum concentration 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) B_2O_3 b) SiO_2 c) PO_4

Fig.1. Variation of dissolved impurities concentration in the viscous sublayer

In order to calculate the spatial distribution of impurity in the boiling medium, it has been assumed that, within the boundaries of the sublayer (δ) the value of intensity of vaporization is constant (g =const) and outside its boundaries there is a fully- developed turbulent core. As an estimation of thickness of the viscous sublayer, 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 also significantly affected by the presence of walls due to no-slip conditions, viscous damping and kinematics blocking very close to the wall, and 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 a boundary layer with a sharp division between the laminar and turbulent regions, it is therefore assumed that heat and mass transfer in the turbulent region result entirely from turbulent inter change, that conductive effects are negligible, and further that in the viscous sublayer 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:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

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

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

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

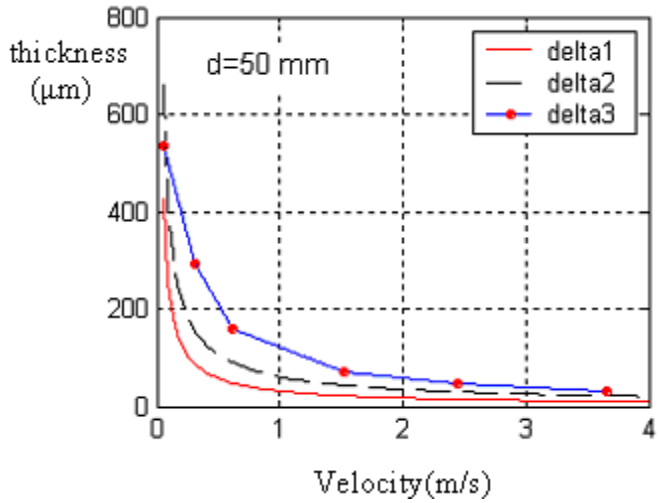
Table 1 provides experimental data of the viscous sublayer thickness for different pipe diameters and water velocities [1].

TableI. Viscous sublayer thickness (μm)

Pipe diameter (in)	Velocity(ft/s)					
	0.2	1.0	2.0	5.0	8.0	12
0.428			125	55	37	26
½			136	60	40	28
1		256	146	65	43	30
2	537	291	158	69	46	32
3	563	305	165	74	48	33

Fig. 2 shows the comparison of the experimental and analytical data of the viscous sublayer thickness based on the water velocity in a pipe (d=50 mm). As an estimation of thickness of viscous sublayer in the boiling channels, the hydro-dynamical analogy of heat transfer is used at the turbulent flow in the single-

phase and boiling regimes. For this reason, the heat transfer coefficient for the partial and fully-developed nucleate boiling must be obtained.



delta1: expression derived on the basis of the boundary layer theory
delta2: expression derived on the basis hydro dynamical analogy
delta3: experimental data
Fig.2. Influence of the velocity on the thickness of the viscous sublayer

In this section various correlations of heat transfer coefficient for the fully- developed nucleate boiling (FDB) offered in the works [2, 3, 4, 5, 6, 7] have been considered and compared.

Concerning the range of pressure and heat flux applied in the steam generators and water boiling reactors and also from the point of view of consistency with experimental data, the expression of Yagov et al [6] has been chosen.

$$h_{fdb} = 0.07\left[\frac{\lambda^2 q^2}{\nu\sigma T_s}\left(1+\frac{i_{fg}\Delta T}{2R_i T_s^{\,2}}\right)\left(1+\sqrt{1+800B}\right)+400B\right]^{1/3} \tag{9}$$

$$B = \frac{i_{fg}\left(\nu\rho_g\right)^{3/2}}{\sigma\left(\lambda T_s\right)^{1/2}}$$

Correlations for the partial nucleate boiling are usually equations that span the single-phase forced convection curve and the FDB curve. Very scarce information can be found in the open literature about the nature and causes for transition from partial boiling to fully- developed nucleate boiling. In the partial nucleate boiling the heat transfer in the low heat flux region is mainly associated with forced convection in the bulk liquid (macroconvection) and evaporation (latent heat). Within this region, the overall heat transfer coefficient depends on the mass flow rate.

As shown in fig. 3 in this paper for the partial nucleate boiling, linear dependence of heat transfer coefficient with the heating channel length has been offered. This figure also shows the variation of other two- phase flow parameters in different regions in boiling channel.

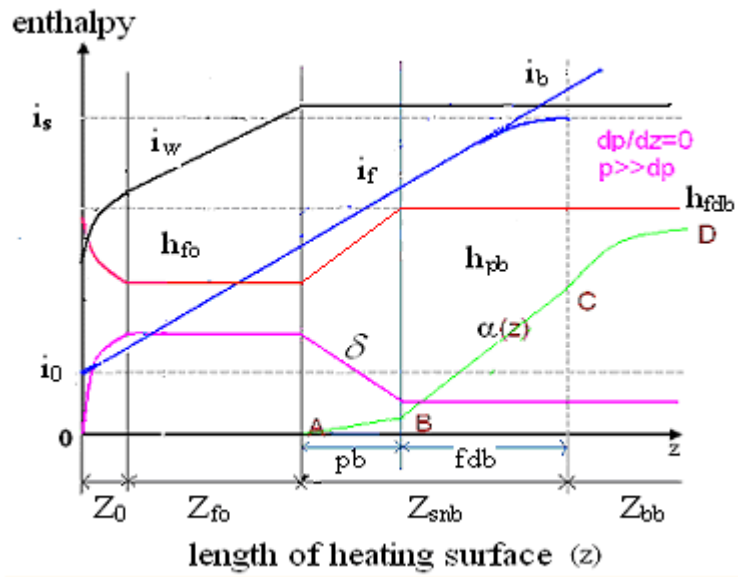


Fig.3. variation of two phase flow parameters (q=const)

Determination of onset of nucleate boiling point and incipient point of fully developed nucleate boiling:

Fig.4 provides the graphical method to determine the onset of the nucleate boiling point and incipient point of fully- developed nucleate boiling.

1) The conditions under which boiling will be initiated are [8, 9]:

$$(T_w)_{fo} = (T_w)_{fdb}$$

$$\Delta T_s = T_w - T_s$$

$$T_f(z) + \left[\frac{q}{h_{fo}}\right] = T_s + \psi q^n$$

$$\Delta T_{sub}\big|_{onb} = \left[\frac{q}{h_{fo}} - \psi q^n\right]$$

$$\psi q^n\big|_{onb} = 0.8q^{0.25} e^{-p/62} \tag{10}$$

$$\Delta T_{sub} = T_s - \overline{T}_f = \frac{q}{h_{fo}} - 0.8q^{0.25} e^{-p/62} \tag{11}$$

Subcooled nucleate boiling in channels exists in the region limited from the onset of the nucleate boiling point to the point at which the liquid temperature reaches the saturation temperature. Subcooled nucleate boiling is divided to the partial and fully- developed subcooled boiling.

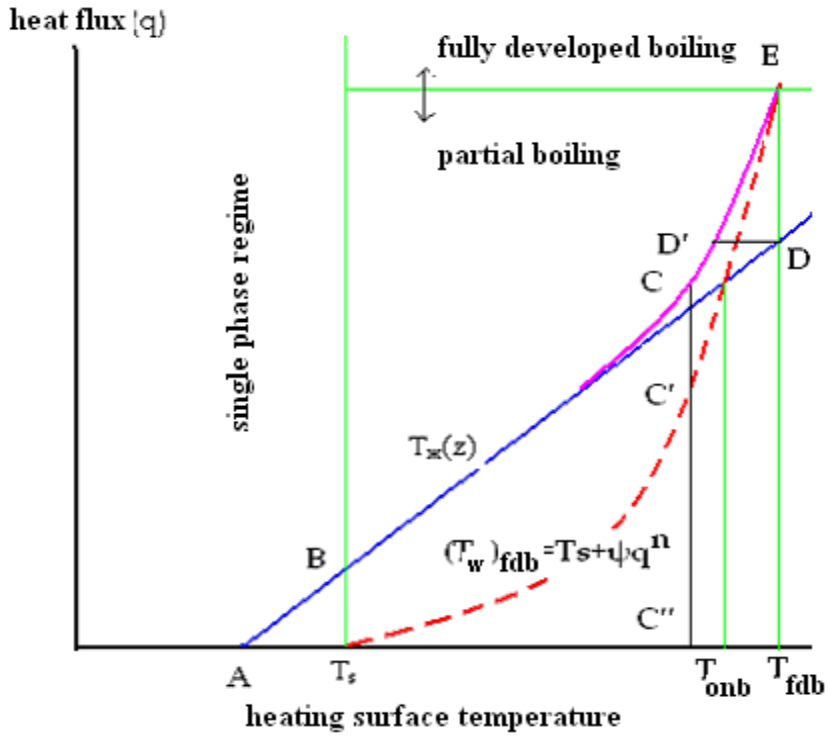


Fig.4. Determination of the onset of nucleate boiling point and incipient point of fully developed nucleate boiling.

As shown in fig. 5, in the partial nucleate boiling, the average heat flux consists of convective single-phase and the fully-developed boiling terms ($q= q_c + q_{fdb}$). In the fig. 5, on the basis of [8] the variation of (q_c/q) with (Z) has been shown. The heat transfer coefficient of fully developed nucleate boiling depends on the heat flux and the pressure and practically does not depend on the fluid velocity and subcooling. For this reason the temperature of the wall remains constant. Bowring in work [8] on the basis of experimental data has offered model with which it is possible to determine the incipient point of the fully-developed nucleate boiling. Bowring, based on experimental data covering a wide range of conditions and fluids correlated the heat flux at which boiling becomes fully-developed by the relation:

$$q(E)=1.4q(D) \tag{12}$$

Points E, D are presented in fig. 4. For the onset of nucleate boiling point ΔT_s can be expressed as:

$$\left(T_c\right)_{onb} - T_f(Z) = \frac{q(D)}{h_{fo}} = \frac{q(E)}{1{,}4h_{fo}} \tag{13}$$

Putting equation (10) in (13) we can obtain

$$\Delta T_{sub}(Z)_{fdb} = \left[\frac{q}{1.4h_{fo}}\right] - 0.8e^{-p/62}\left[\frac{q}{1.4}\right]^{0.25} \tag{14}$$

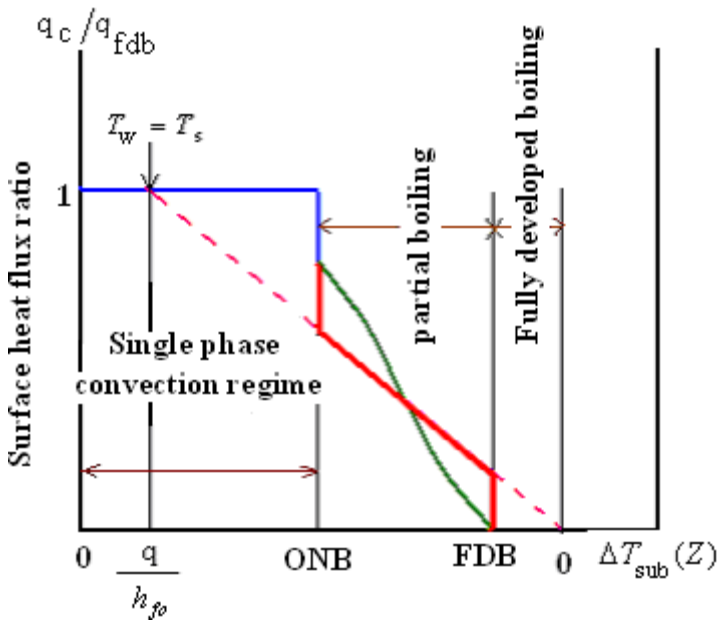


Fig.5. Bowring model

The variation of ΔT_{sub} through the channel length can be written as

$$\Delta T_{sub}(0) = T_s - (T_f)_i$$

$$Z_{bb} = \frac{\rho_f \mathrm{wd}}{4q}\left(h_s - h_{ж}^{вх}\right)$$

$$\Delta T_{sub}(z_{bb}) = 0$$

$$\Delta T_{sub}(\mathrm{z}) = (T_s - (T_f)_i)\left[\frac{4\mathrm{qz}}{\rho_f \mathrm{wd}\left((\mathrm{h_f})_i - \mathrm{h_s}\right)} + 1\right] \tag{15}$$

$$\Delta T_{sub}(\mathrm{z_{onb}}) = (T_s - (T_f)_i)\left[\frac{4\mathrm{q}(\mathrm{z_{onb}})}{\rho_f \mathrm{wd}\left((\mathrm{h_f})_i - \mathrm{h_s}\right)} + 1\right] = \frac{\mathrm{q}}{h_{fo}} - 0.8\mathrm{q}^{0.25}e^{-p/62}$$

From equations (7), (11), (14), (15)

$$z_{onb} = \left[\frac{43{,}5qw^{-0.8}d^{0.2}\nu^{0.8} - 0.8\mathrm{q}^{0.25}e^{-p/62}}{\lambda\left(T_s - (T_f)_i\right)} - 1\right]B_0 \tag{16}$$

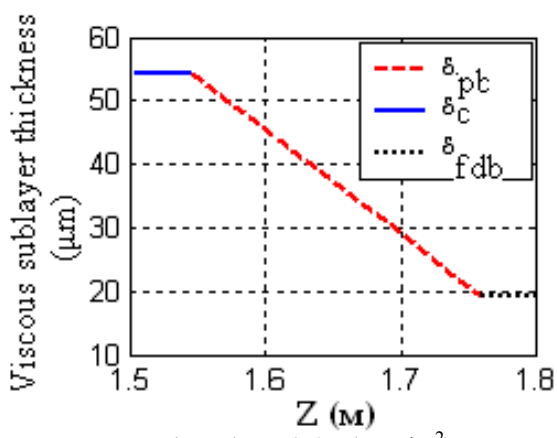
$$B_0 = \frac{\rho_f w d\left((h_f)_i - h_s\right)}{4q}$$

$$z_{fdb} = \left[\frac{\dfrac{q}{0.0322 w^{0.8} d^{-0.2} \nu^{-0.8} \lambda} - 0.8(q/1.4)^{0.25} e^{-p/62}}{\left(T_s - (T_f)_i\right)} - 1 \right] B_0 \tag{17}$$

From fig. 3 follows that after the evaluation of z_{onb} and z_{fdb}, it is possible to obtain the partial boiling heat transfer coefficient and the thickness of the viscous sublayer in different regions through the heating channel length.

$$h_{pb} = \frac{h_{fdb} - h_{fo}}{z_{fdb} - z_{onb}}\left(z - z_{onb}\right) + h_{fo} \tag{18}$$

$$\delta = \begin{cases} \lambda / h_{fo} \Leftarrow z < z_{onb} \\ \lambda / h_{pb} \Leftarrow z_{onb} \le z \le z_{fdb} \\ \lambda / h_{fdb} \Leftarrow z > z_{fdb} \end{cases}$$



p=5 (MPa), q=0.15 (Mw/m^2)
w=1 (m/s), d=10 (mm), $(T_f)_i$=220 (˚C)
Fig.6. Variation of the viscous sublayer thickness with the heating channel length

Fig. 6 shows the variation of the viscous sublayer thickness with the heating channel length in the single-phase convection, and partial and fully-developed nucleate boiling regions. The main reasons of this variation in the partial nucleate boiling region will be discussed as follow:

1- The increase of the flow velocity at constant mass velocity condition due to the decrease of the mixture density.

2- Change of geometry and roughness of the heating surface owing to bubbles appearance adjacent to the boiling surface.
3- Increasing the liquid turbulence near the boiling -surface owing to motion of the liquid induced by the growing and departing bubbles (bubble agitation).

In the fully developed nucleate boiling thermo-hydraulic conditions of the stream near the boiling surface are irrespective of conditions in the bulk stream.

Agree with new models offered for the fully -developed nucleate boiling the evaporation of the liquid macro-microlayer plays main role, especially at high heat flux conditions.

As shown in fig. 9, on the basis of macro-microlayer model, the heating surface consists of zones: 1- dry zone (center of bubble stem) 2- thin evaporating liquid films underneath the bubble (microlayer) 3- liquid macrolayer at the base of coalescence bubble.

The model is submitted in works [10, 11, 12]. 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 inserted in table 2 submitted in [15], and the relationship for calculating initial macrolayer thickness presented in [10], it is possible to predict the average sublayer thickness (δ) through which the total surface heat flux is conducted.

Table II.

Average heat flux q (Mw/м^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

$$\delta_0 = 0.00536\rho_g\sigma(\rho_g/\rho_f)^{0.4}(1+\rho_g/\rho_f)(i_{fg}/q)^2 \quad (19)$$

$$\delta_0 = 0.0107\rho_g\sigma(\rho_g/\rho_f)^{0.4}(i_{fg}/q)^2 \quad (20)$$

$$\delta_0 = 1.59q^{-1.527} \quad (21)$$

where δ_0 is macrolayer thickness (m), q heat flux (kw/m^2), i_{fg} latent heat of vaporization(kJ/kg).

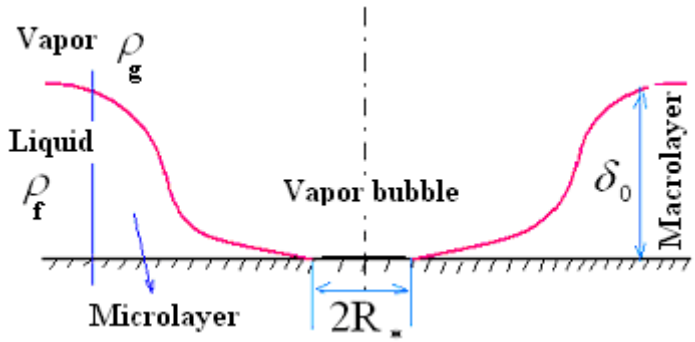


Fig.7. Schematic of macro-microlayer model

From table 2 at q=0.9963 – 1.58 (Mw/m^2) following result can be obtained.

$$(q_{мик}/q)_{ave}=0.838$$
$$q = q_{мак} + q_{мик}$$
$$0.162q = q_{мак}$$
$$0.162\frac{\lambda}{\delta}\Delta T_s = \frac{\lambda}{\delta_0}\Delta T_s$$
$$\delta = 0.162\delta_0$$

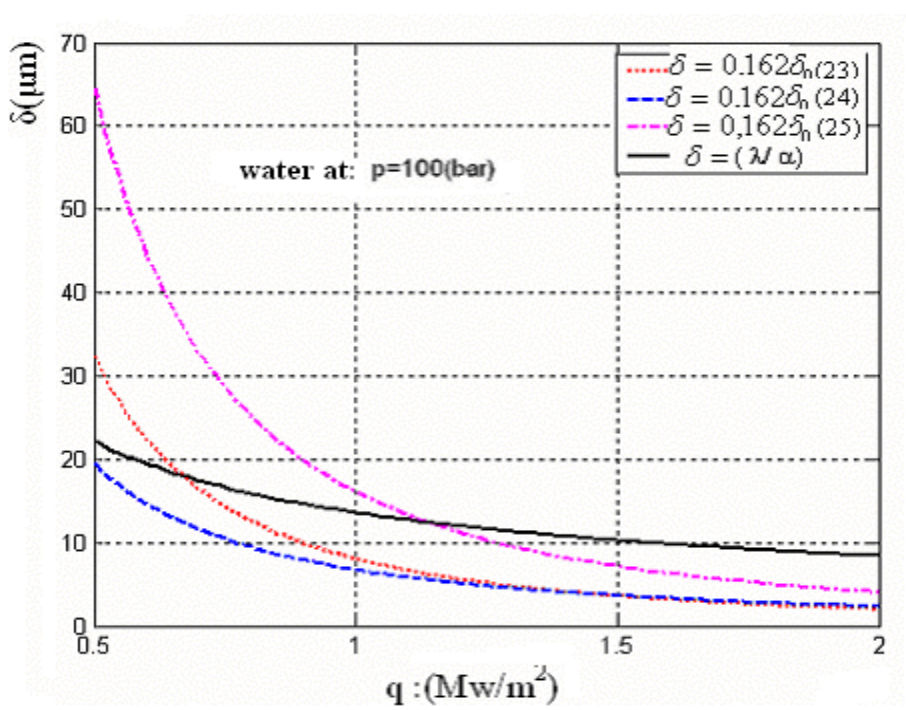


Fig.8. Comparison of the viscous sublayer thickness with thickness calculated by the relationship: $\delta = 0.162\delta_0$

Fig. 8 provides the comparison of the estimated viscous sublayer with the average layer thickness derived based on the macro-microlayer model.

Conclusions

1- The calculation of distribution of impurities concentration in the boiling mediums without the estimation of the viscous sublayer thickness is impossible. Because of the fluid turbulent fluctuations associated with eddies beyond the viscous sublayer boundaries impurities concentration remain practically homogeneous.
2- To distinguish different regions in the boiling channel the onset of nucleate boiling point and incipient point of fully -developed nucleate boiling have been derived. Expressions (16), (17) show the dependency of these points on the hydro-dynamic and thermodynamic parameters.
3- The comparison of the suggested model for the estimation of viscous sublayer thickness with macro-microlayer model has yielded satisfactory results.
4- The viscous sublayer thickness for water (pr≈1) in the single-phase flow depends on fluid velocity, the diameter of the channel and the kinematic viscosity, and in fully -developed boiling, it depends on the heat flux and pressure.

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
R, R_i	Ideal gas constant
M	Molecular weight
T	Average temperature
x	Normal distance from the wall
h_{fo}	Heat transfer coefficient for total flow
z_0	Entry region

Greek symbols

α	Void fraction
ε	Eddy diffusivity of momentum
δ	Thickness of viscous sublayer
λ	Thermal conductivity of liquid
μ	Viscosity of liquid
υ	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

Subscripts

s	Saturation
b	Bulk
w	Wall
pb	Partial boiling
fdb	Fully developed nucleate boiling
f	Fluid
g	Gas
c	Convection
snb	Subcooled nucleate boiling
bb	Bulk boiling
cr	Critical
onb	Onset of boiling
sub	Subcooling
i	Inlet
ave	Average

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