

SUBCOOLED BOILING EFFECT ON DISSOLVED GASES BEHAVIOUR

M. ZMÍTKO
Nuclear Research Institute Řež plc.



J. SINKULE†, V. LINEK
Institute of Chemical Technology

Prague, Czech Republic

Abstract

A model describing dissolved gasses (hydrogen, nitrogen) and ammonia behaviour in subcooled boiling conditions of VVERs was developed. Main objective of the study was to analyse conditions and mechanisms leading to formation of a zone with different concentration of dissolved gases, eg. a zone depleted in dissolved hydrogen in relation to the bulk of coolant. Both, an equilibrium and dynamic approaches were used to describe a depletion of the liquid surrounding a steam bubble in the gas components. The obtained results show that locally different water chemistry conditions can be met in the subcooled boiling conditions, especially, in the developed subcooled boiling regime. For example, a 70% hydrogen depletion in relation to the bulk of coolant takes about 1 ms and concerns a liquid layer of 1 μm surrounding the steam bubble. The locally different concentration of dissolved gases can influence physic-chemical and radiolytical processes in the reactor system, eg. Zr cladding corrosion, radioactivity transport and determination of the critical hydrogen concentration.

1. Introduction

A primary water chemistry of the pressurized water reactors is controlled with respect to assure an integrity of the primary pressure boundary, the fuel cladding integrity, and minimization of the radiation fields and occupational radiation exposure. For this reason, weak-alkaline, reduction conditions are kept in the primary coolant. The reduction conditions are maintained by an overpressure of hydrogen which suppresses a generation of oxidizing species by radiolytical processes in the reactor core.

In the WWER units, the hydrogen overpressure is maintained by ammonia dosing into the primary coolant where hydrogen and nitrogen is generated by its subsequent radiolytical and thermolytical decomposition. During a normal operation, concentration of dissolved hydrogen and nitrogen is in range of 25-35 ccSTP H_2/kg and 10-15 ccSTP N_2/kg , respectively. Ammonia concentration varies from plant to plant, typically between 10 and 40 ppm. Such level of dissolved hydrogen guarantees the oxygen concentration in the VVER and PWR units below 5-10 ppb.

However, a zone can be found in the reactor core where the fuel cladding temperature may exceed a saturation temperature at given pressure and where a subcooled boiling occurs. An existence of the subcooled boiling can influence a behaviour of the dissolved gases and be responsible for a formation of their locally different concentration levels. It is considered that a local depletion in a dissolved gas in relation to the bulk of coolant can occur by eg. hydrogen stripping into the steam bubbles that subsequently escape from the surface into the bulk flow where condensate. Because of a depletion in dissolved hydrogen, a shift of radiochemical reactions can follow in favour of the oxidizing species production in such zone, and finally a different water chemistry conditions can be established. In this connection, a critical hydrogen concentration is considered. This concentration is defined as a concentration of hydrogen that is still able to suppress radiolytical production of the oxidizing species.

A phenomenon of the formation of locally different water chemistry conditions due to a subcooled boiling effect is considered mainly with respect to a possible acceleration of zirconium cladding corrosion and an effect on corrosion product behaviour and radioactivity build-up on the primary system surfaces.

So, the main objective of this study was to analyse conditions and mechanisms leading to formation of a zone with different concentration of dissolved gases, eg. the zones depleted in dissolved hydrogen in relation to the bulk of coolant.

2. Thermal-Hydraulic Assessment

A WWER-1000 unit was chosen for detail analysis of the dissolved gases behaviour. The first of all, thermal-hydraulic conditions of the WWER-1000 unit were analysed with respect to a possible formation of locations in the reactor core working in subcooled boiling regime, an extent and intensity of the subcooled boiling process. The thermal-hydraulic assessment was based on a simplified model of the fuel channel where a surface heat flux q_w , the coolant temperature T and cladding surface temperature T_w were determined. The assessment was performed for the following parameters:

Primary system pressure (saturation temperature), P : 15.7 MPa (T_s : 345.8°C)

Core inlet temperature, T_i : 289 °

Average linear heat rate of the fuel rod, q_{la} : 15.8 kW/m

Average heat flux on the cladding surface, q_{wa} : 550 kW/m²

Fuel rod outer diameter, d : 9.144 mm

Fuel rod length, L : 3.5 m

Coolant flow velocity in the core (considered as input data), v_L : 4 m/s

Radial coefficient of the power distribution in the core, K_r : 1.2

Axial coefficient of the power distribution in the core, K_z : 1.45

Results of the thermal-hydraulic assessment show that there is a number of the fuel channels working in the subcooled boiling regime, ie. where the cladding temperature is reaching saturation temperature ($T_w = T_s$). Temperature distribution in the reactor core is shown in Fig.1 in form of isotherms for the coolant and cladding surface temperatures. Distribution of the heat flux, and the coolant and cladding surface temperatures in the axial fuel channel ($r = 0$) is given in Fig.2.

3. Modelling of Dissolved Gases Behaviour

Two different approaches were considered in development of a model of dissolved gases behaviour. An *equilibrium model* describes a process of saturation of the steam bubbles by dissolved gases or ammonia as an equilibrium process where the equilibrium concentration of the gas in steam (ie. its solubility level) is reached. In the opposite, a *dynamic model* describes the saturation process with respect to its dynamics. A reaching of the chemical equilibrium state is considered as a time-dependant process where the final equilibrium state need not to be reached.

3.1 Equilibrium model

A depletion of the coolant in dissolved gases can occur at steam phase generation. If steam bubbles are equilibriumly saturated with a dissolved gas the following balance and equilibrium state is valid:

$$\begin{aligned}
 V_{L0} \rho_L &= V_L \rho_L + V_G \rho_G \\
 V_{L0} c_{L0i} &= V_L c_{Li} + V_G c_{Gi} \\
 c_{Gi} &= \psi_i c_{Li}
 \end{aligned}
 \tag{1}$$

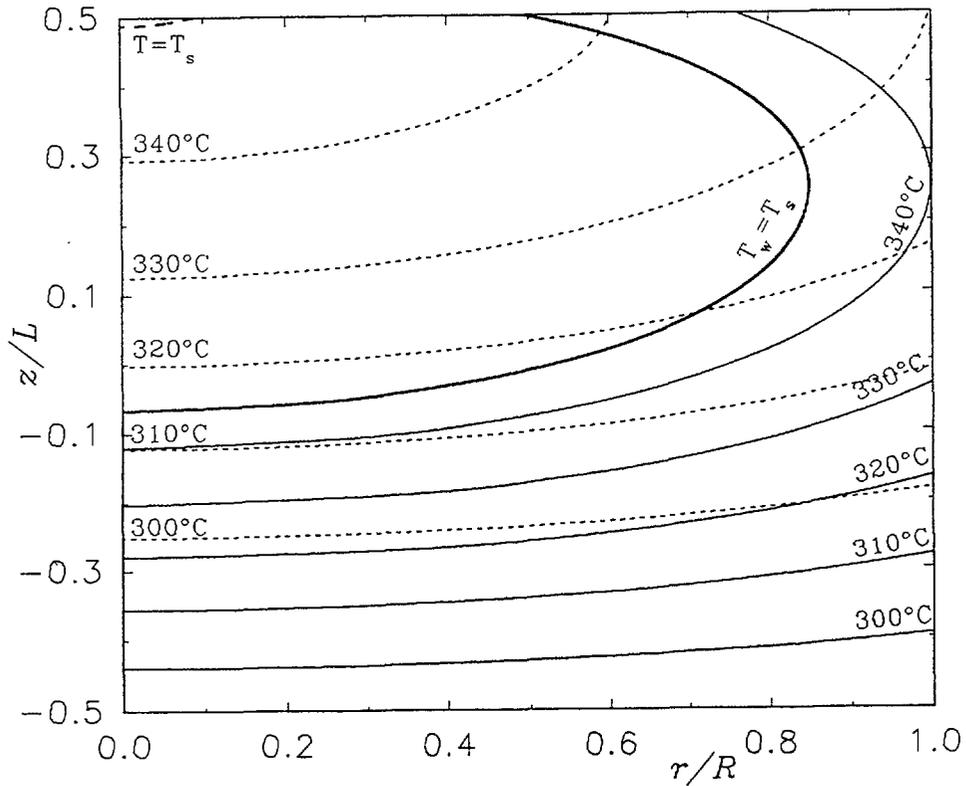


Fig.1 Thermal-hydraulic assessment of VVER-1000: Temperature distribution in the reactor core – isotherms for constant coolant (T) and cladding surface (T_w) temperature ($K_z = 1.45$, $K_r = 1.2$)

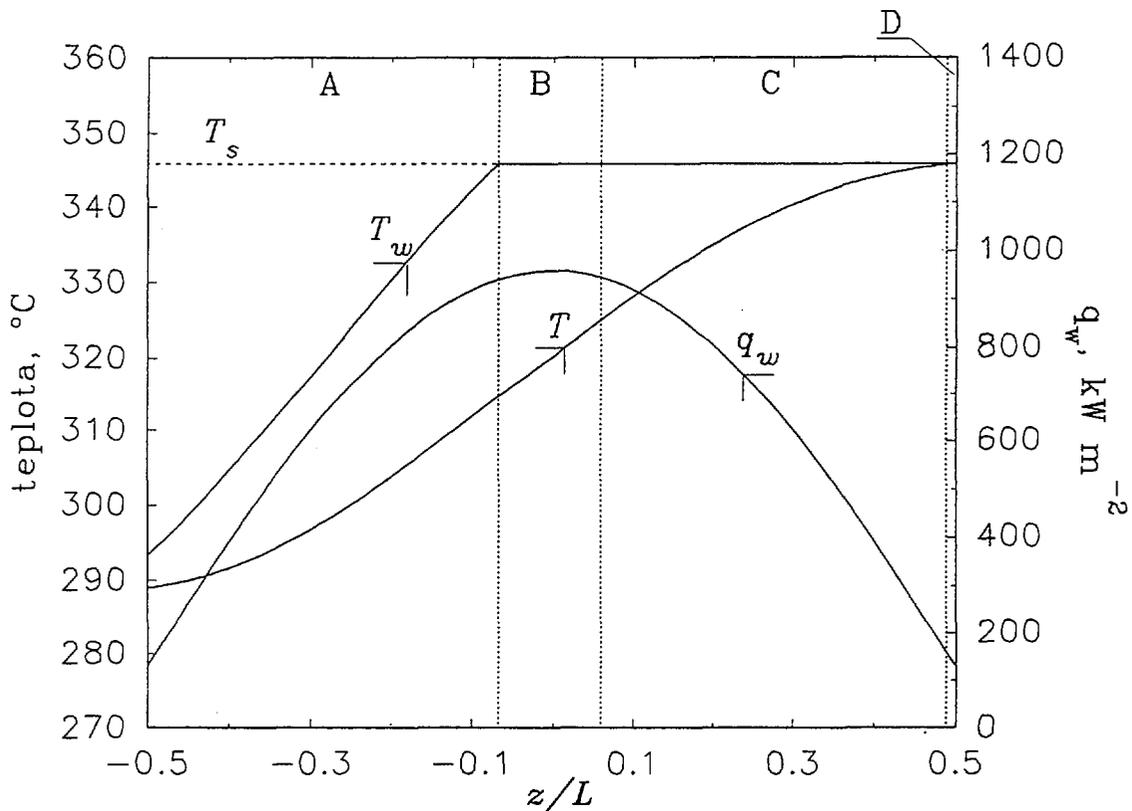


Fig.2 Thermal-hydraulic assessment of VVER-1000: Distribution of heat flux (q_w), the coolant (T) and cladding surface (T_w) temperature in the axial fuel channel ($r=0$); A – convective heat transfer, B – non-developed subcooled boiling, C – developed subcooled boiling, D – boiling

A distribution coefficient Ψ_i is calculated from the gas solubility values [2,3] as:

$$\Psi_i = \frac{22400 \rho_G}{H_{e_i} P M_{H_2O} \rho_L} \quad i = H_2, N_2, NH_3 \quad (2)$$

The index 0 in the equation (1) indicates an initial state of the liquid phase before the steam phase generation. A relative drop of concentration of the gas component i dissolved in the coolant c_L/c_{L0i} can be expressed in dependance on the steam phase fraction (ie. void fraction) $e = V_G/(V_G + V_L)$ as:

$$\frac{c_{Li}}{c_{L0i}} = \frac{\varepsilon \rho_G + (1 - \varepsilon) \rho_L}{\rho_L (\varepsilon \Psi_i + 1 - \varepsilon)} \quad (3)$$

An effect of the void fraction on a relative drop of concentration of dissolved nitrogen, hydrogen and ammonia is shown in Fig.3 for the given thermal-hydraulic conditions. It is evident that some significant depletion of the coolant in dissolved hydrogen and nitrogen occurs at the void fraction $e > 0.05$ (5%), ie. at relatively high steam phase fraction. This effect is caused by a high solubility of the both gases at given temperature in comparison with ambient temperature – the difference in 10-12 times. Hydrogen solubility is higher than nitrogen solubility so that the depletion in nitrogen is higher. On the other hand, the depletion in ammonia is negligible due to its very high solubility in water.

It was shown by calculations that the steam phase fraction in the subcooled boiling regime can reach as maximum 2.5%, at the same time an average void fraction is less than 0.5%. At such conditions, the equilibrium model of the dissolved gases behaviour gives maximum depletion in hydrogen and nitrogen about 10%, and the average depletion only 2.5%.

3.2. Dynamic model

A depletion of the coolant in dissolved gases can also occur due to a steam flow inside the bubble or at the steam bubble growth process. Such a depletion has a local character, ie. it is related to the liquid surrounding the steam bubble, and is limited in time.

Subcooled boiling mechanisms

A heat removal from the fuel rods can proceed in qualitatively different mechanisms in dependance on the local heat flux q_w and local coolant temperature T . A **convection heat transfer mechanism** takes place when the fuel cladding surface temperature is below the saturation temperature at given pressure. If the convective transfer is not sufficient to remove the generated heat, a surface temperature exceeds the saturation temperature and steam bubbles are formed by nucleation, ie. a **subcooled boiling mechanism** is taking place.

Bubbles are predominantly formed on places with a proper geometrical microstructure. It is supposed that the steam generated on the fuel cladding surface flows through a stagnant bubble and re-condensates at a top of the bubble. The condensation heat is taken through a thinner boundary layer from here into the bulk of coolant. Because of a relatively big difference between the cladding surface and bulk coolant temperatures in this area ($T_s - T$), the bubbles have a small diameter and are sitting on the surface. This kind of subcooled boiling mechanism is called as a **non-developed subcooled boiling**. The bubbles are not escaping from the surface because a hydrodynamic drag force of the coolant flow is lower than a surface tension force keeping a bubble on the surface. A critical radius of the bubble, ie. a distance between a top of the bubble and the cladding surface at moment of an escape, can be expressed from a balance of the forces as follows [1]:

$$Y_b = 0,015 \sqrt{\frac{\sigma_L d_e}{\tau_w}} \quad \text{kde} \quad \tau_w = \frac{1}{2} f \rho_L v_L^2 \quad (4)$$

The critical bubble radius for the given thermal-hydraulic conditions is $Y_b = 1,14 \times 10^{-5}$ m.

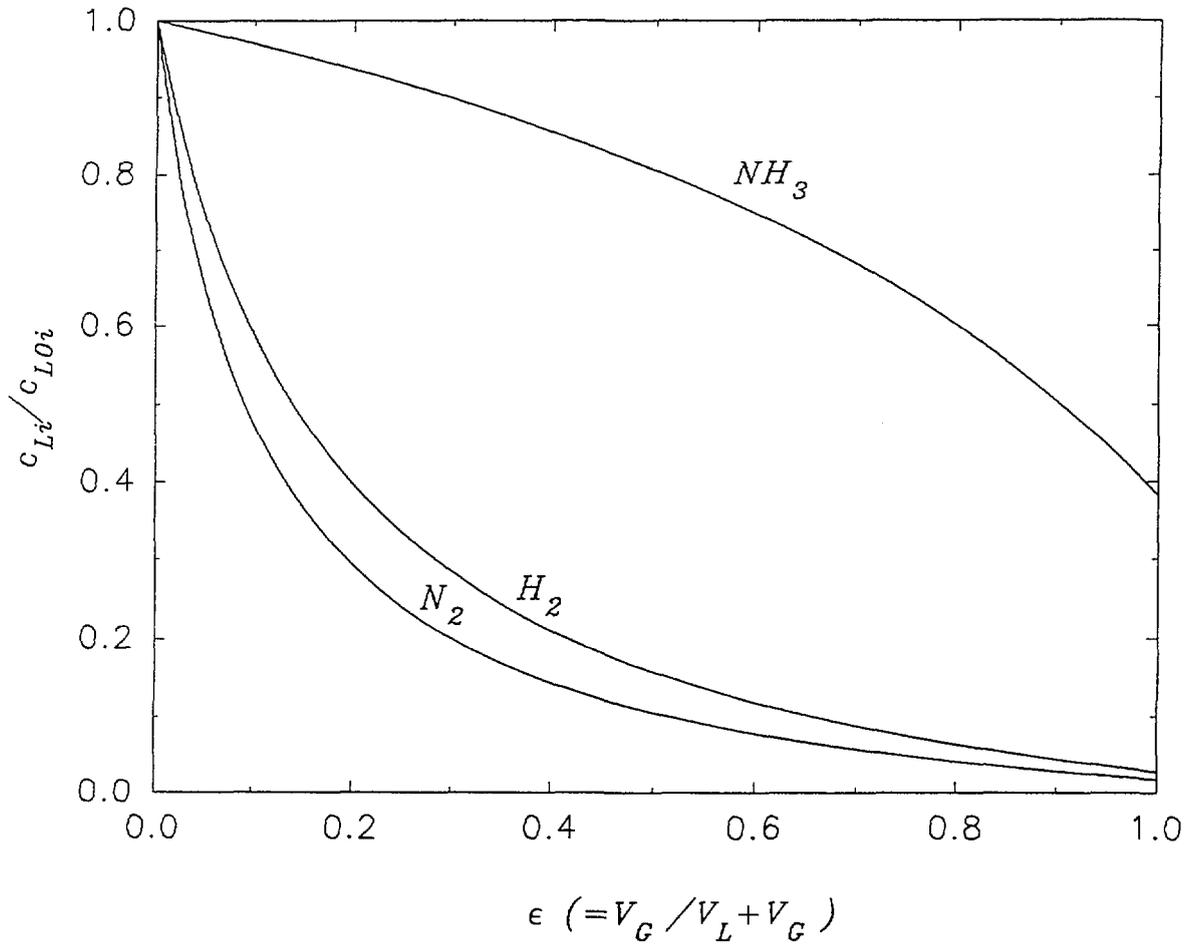


Fig.3 Effect of void fraction on relative drop of concentration of dissolved nitrogen, hydrogen and ammonia (results of calculations by the equilibrium model)

If an intensity of the steam generation is higher than its rate of condensation in the top of bubble, a bubble is growing and the bubble radius exceeds the critical bubble radius. In this case, the bubble escapes from the surface into the bulk of coolant where it condensates. Such state of the process is called as a *developed subcooled boiling*.

Non-developed subcooled boiling

A model used for analysis of a possible local depletion of the coolant in dissolved gases in surrounding of the stagnant bubbles is shown in Fig.4. A cylinder with height and diameter of Y_b is considered as a model stagnant bubble. Water evaporated on the surface ($y = 0$) flows through the bubble and condensates in the top of bubble ($y = Y_b$). Condensation heat is taken into the bulk of coolant through a boundary layer with thickness of $(d - Y_b)$. Thickness of the thermal boundary layer is expressed as $d = l_1/\alpha$. Dissolved gases diffuse into the steam bubble from the surrounding liquid through sides of the cylinder. Inside the bubble, the gases are flushed by steam toward the top of bubble and then diffuse through the boundary layer into the bulk of coolant. Numerical analysis showed that because of a low concentration of the gases in steam, a flow velocity of the steam-gases mixture in the bubble is practically the same as the flow velocity of the steam itself. Thus, a model for description of dissolved gases behaviour at the non-developed subcooled boiling conditions can be formulated as follows:

$$D_{Gi} \frac{d^2 c_{Gi}}{dy^2} - v_G \frac{dc_{Gi}}{dy} + k_{Lri} \frac{2}{Y_b} (c_{Li} - c_{Gi}/\psi_i) = 0 \quad (5)$$

$$v_G = q_b / \rho_G \Delta H_{vyp} \quad q_b = k_r (T_s - T)$$

with boundary conditions:

$$y = 0: \quad D_{Gi} \frac{dc_{Gi}}{dy} - v_G c_{Gi} = 0 \quad (6)$$

$$y = Y_b: \quad D_{Gi} \frac{dc_{Gi}}{dy} - v_G c_{Gi} = k_{Li} (C_{Li} - c_{Gi} / \psi_i)$$

The heat and mass transfer coefficients from the top of bubble k_T and k_{Li} , and the side diffusion coefficient k_{LRi} were calculated taking into account more realistic shape of the steam bubble – hemisphere (see Fig.5):

$$k_T = \frac{\lambda_L}{\delta} f(Y_b) = \alpha f(Y_b) \quad k_{Li} = \frac{D_{Li}}{\delta} f(Y_b) \quad k_{LRi} = \frac{D_{Li}}{Y_b} \quad (7)$$

where a correction factor $f(Y_b)$ expresses a changing distance of the bubble top from a border of the thermal boundary layer d at an one-way heat transfer or diffusion process in y -direction:

$$f(Y_b) = -\frac{2\delta}{Y_b} \left[1 + \frac{\delta}{Y_b} \ln \left(1 - \frac{Y_b}{\delta} \right) \right] \quad (8)$$

Results of calculations for a part of the fuel channel working in the non-developed subcooled boiling conditions are given in Fig.6. Concentration of hydrogen, nitrogen and ammonia in the liquid surrounding the stagnant steam bubbles is shown for the bubbles of maximum hydraulic stable radius at the given conditions ($Y_b = 1,14 \times 10^{-5}$ m). It can be seen that the difference of the dissolved gases concentration in comparison with their concentration in the bulk of coolant depends on temperature gradient between the cladding surface and the coolant ($T_s - T$) which determines the steam flow velocity through a bubble. Maximum depletion in the dissolved gases occurs at the beginning of the non-developed subcooled boiling when a number of bubbles on the cladding surface is relatively low.

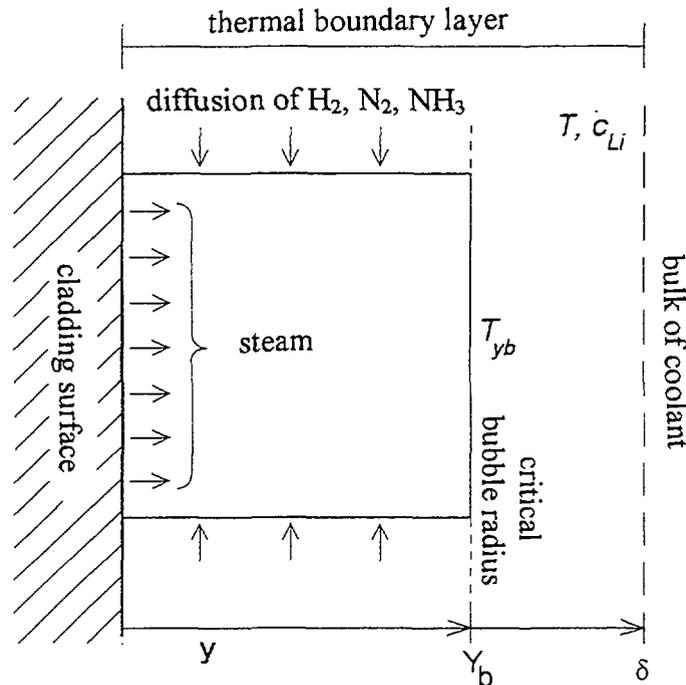


Fig.4 Model of a stagnant steam bubble used for analysis of local depletion of the coolant in dissolved gases in surrounding of the bubble (the dynamic model – non-developed subcooled boiling regime)

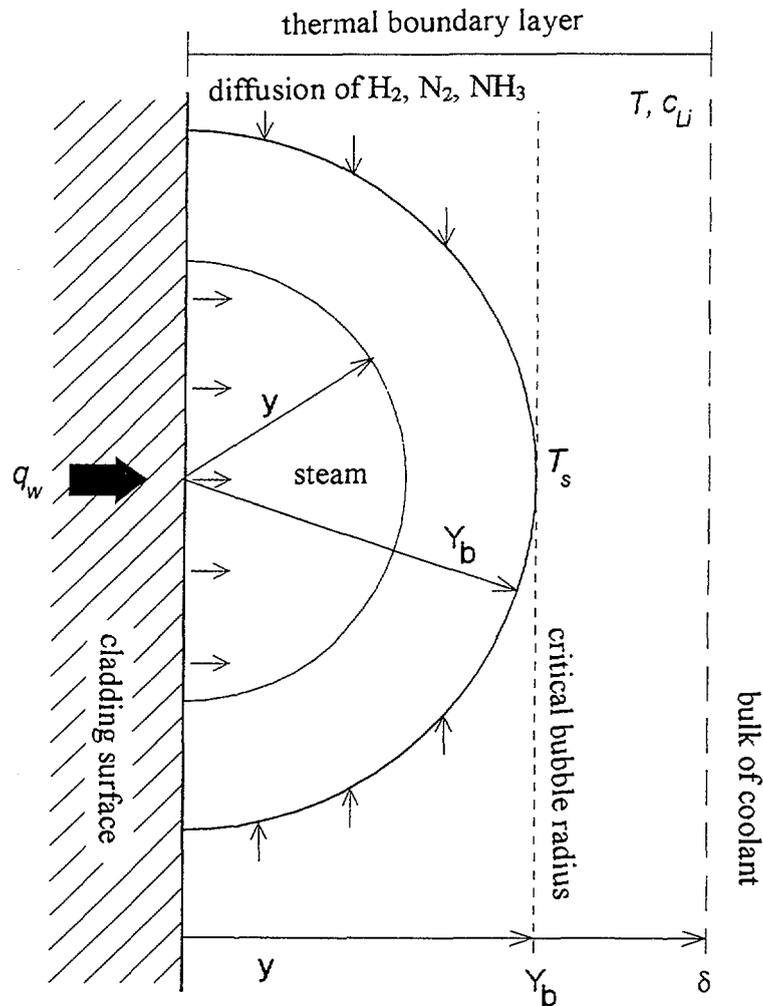


Fig.5 Model of a growing steam bubble with the critical bubble radius used for analysis of local depletion of the coolant in dissolved gases in surrounding of the bubble (the dynamic model – developed subcooled boiling regime)

The maximum depletion in relation to the bulk concentration can reach 15% for hydrogen, 35% for nitrogen and 27% for ammonia. Such depletion occurs in a 5 μm thick liquid layer surrounding the steam bubble and is not limited in time.

Developed subcooled boiling

A heat transfer mechanism connected with a development subcooled boiling starts play a role when the stagnant steam bubbles are not able to take away a generated heat. In this case, a volume of the steam bubble is growing until its radius reaches the critical one. Then, the bubble escapes from the surface into the bulk of coolant and condensates. Because of the low concentration of dissolved gases in the coolant, their effect on the rate of heat and steam transfer in the bubble is negligible. Then, the steam bubble growth can be modelled independently from a diffusion saturation of the bubble by dissolved gases. A schema of the model is shown in Fig.5.

A balance of steam in the bubble is described by an equation

$$\frac{d}{dt} \left(\frac{2}{3} \pi y^3 \right) = \frac{(2Y_b)^2 q_w}{\rho_G \Delta H_{vyp}} - \frac{\pi y^2 k_T (T_s - T)}{\rho_G \Delta H_{vyp}} \quad (9)$$

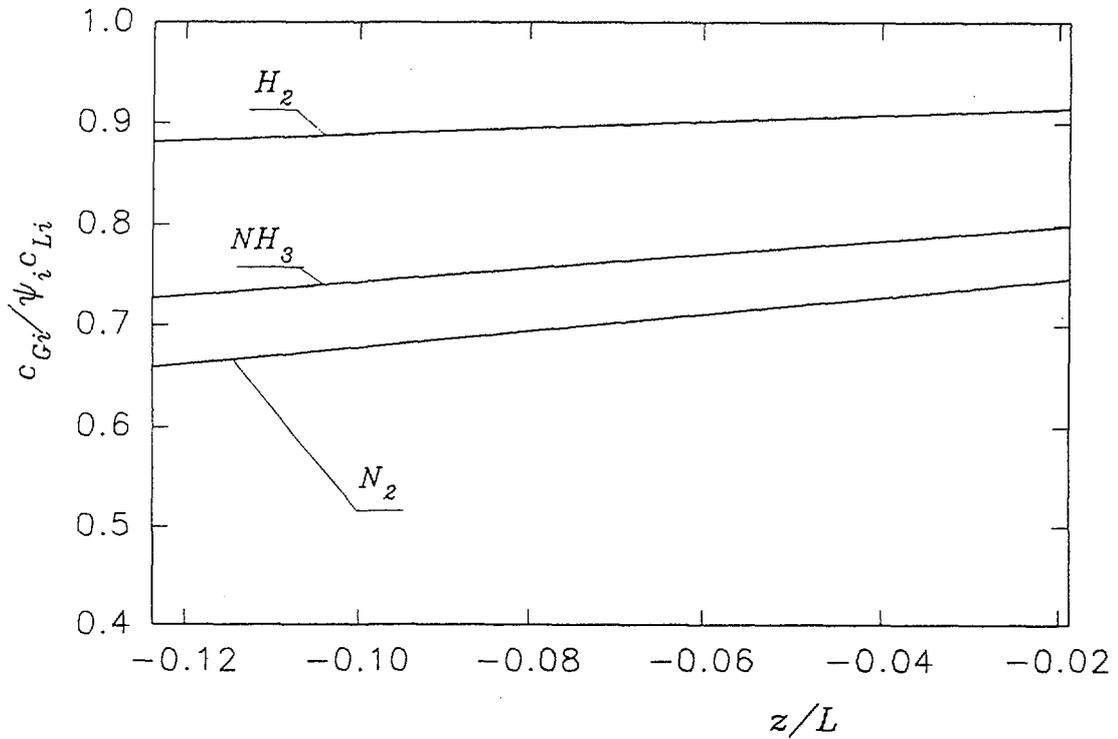


Fig.6 Calculated axial profile of concentration of dissolved nitrogen, hydrogen and ammonia related to its concentration in the bulk of coolant $c_{Gi}/\psi_i c_{Li}$ (the dynamic model – non-developed subcooled boiling area)

where the term on the left side of the equation (9) expresses the bubble volume growth rate. The first term on the right side is a volume flow rate of generated steam which is proportional to the heat flux through a square with side of $2Y_b$. The second term expresses a volume flow rate of the steam which is condensated on a bubble-coolant interface. An initial condition is:

$$t = 0: \quad y = 0 \quad (10)$$

A period of the bubble growth t_b , ie. time of the bubble existence before its escape from the surface, can be obtained by integration of the equation (9) with upper limit of $y = Y_b$. During this growth period, the bubble is continuously saturated with dissolved gases from the surrounding liquid by a diffusion process. Formulation and solution of a problem with a moving phase boundary is difficult, therefore a simplified model for description of the bubble saturation process was used. According to this simplification, it is considered that the bubble with critical radius Y_b is saturated by diffusion during the bubble growth period t_b . The following equations describe the bubble saturation process by diffusion:

A balance of the gas i (H_2, N_2, NH_3) in the bubble

$$\frac{2}{3} \pi Y_b^3 \frac{dc_{Gi}}{dt} = 2\pi Y_b^2 D_{Li} \left[\frac{\partial c_{Lbi}}{\partial y} \right]_{y=Y_b} \quad (11)$$

where c_{Gi} is a gas concentration in the bubble, and c_{Lbi} is a concentration of dissolved gas in the liquid surrounding the bubble.

A balance of the gas i in the liquid

$$\frac{\partial c_{Lbi}}{\partial y} = D_{Li} \frac{\partial^2 c_{Lbi}}{\partial y^2} \quad (12)$$

with boundary and initial conditions:

$$\begin{aligned}
 y = Y_b: \quad c_{Lbi} &= c_{Gi} / \psi_i \\
 y = \infty: \quad c_{Lbi} &= c_{Li} \\
 t = 0: \quad c_{Lbi} &= c_{Li} \quad c_{Gi} = 0
 \end{aligned} \tag{13}$$

An analytical solution of the equation system (11)-(13) can be found in the following form:

$$\begin{aligned}
 \frac{c_{Gi}(t)}{\psi_i c_{Li}} &= 1 - \exp(\beta t) \operatorname{erfc}(\sqrt{\beta t}) \\
 \frac{c_{Lbi}(t, y)}{c_{Li}} &= 1 - \exp\left[\beta t + (y - Y_b) \sqrt{\beta / D_{Li}}\right] \operatorname{erfc}\left(\sqrt{\beta t} + \frac{y - Y_b}{2\sqrt{D_{Li} t}}\right) \\
 \beta &= D_{Li} \left(\frac{3}{Y_b \psi_i}\right)^2
 \end{aligned} \tag{14}$$

A term $c_{Gi}(t)/\psi_i c_{Li}$ in the equations (14) expresses a level of saturation of the growing bubble by gas i in relation to its equilibrium concentration (ie. solubility) in the bulk of coolant. In a similar way, the term $c_{Lbi}(t, y)/c_{Li}$ expresses a concentration of dissolved gas i in the liquid surrounding the steam bubble in relation to its equilibrium concentration (ie. solubility) in the bulk of coolant. Then, a relative depletion of the liquid in dissolved gas i is expressed as a supplement to 1.

Results of the calculations are demonstrated in Fig.7 and Fig.8. The Fig.7 shows a concentration profiles of hydrogen, nitrogen and ammonia in the liquid surrounding the bubble in period of its growth. The bubble growth period τ_b calculated for the given thermal-hydraulic conditions is in range of 1-2 ms. Therefore, the calculated concentration profiles are valid only for times $t < \tau_b$. It can be seen from the figure that a deep depletion in dissolved hydrogen and nitrogen in liquid surrounding the bubble can occur in times below 1 ms, what is in the most cases the bubble growth period. Such a depleted layer of the liquid is very thin, units of μm . Moreover, the bubble growth process is a periodic one and the situation will repeat itself. A frequency of the steam bubble arising on the surface is in order of 1,000 times per a second, ie. 1 kHz.

A sense of the depletion extension and time period can be apparent from Fig.8. Here is shown a thickness of the liquid layer surrounding the bubble, l_0 , as a function of time for a different level of dissolved gas depletion. For example, it can be found from the figure that a liquid layer with 70% depletion in dissolved hydrogen (in average) will exist for 0.95 ms and its thickness will be maximally $l_0/Y_b = 0.11$, ie. $l_0 = 0.11 \cdot 1.14 \cdot 10^{-5} = 1.3 \cdot 10^{-6} \text{ m} = 1.3 \mu\text{m}$.

A similar picture as shown for dissolved hydrogen behaviour can be also found for dissolved nitrogen. Ammonia behaviour is different from that because of its high solubility, ie. ammonia depletion level in the surrounding liquid will be much lower. In the case of hydrogen and nitrogen, which are less soluble in the liquid, the time of a bubble growth is not sufficient for its saturation and the bubble contains only a part of the achievable equilibrium concentration at the moment of its escape from the surface.

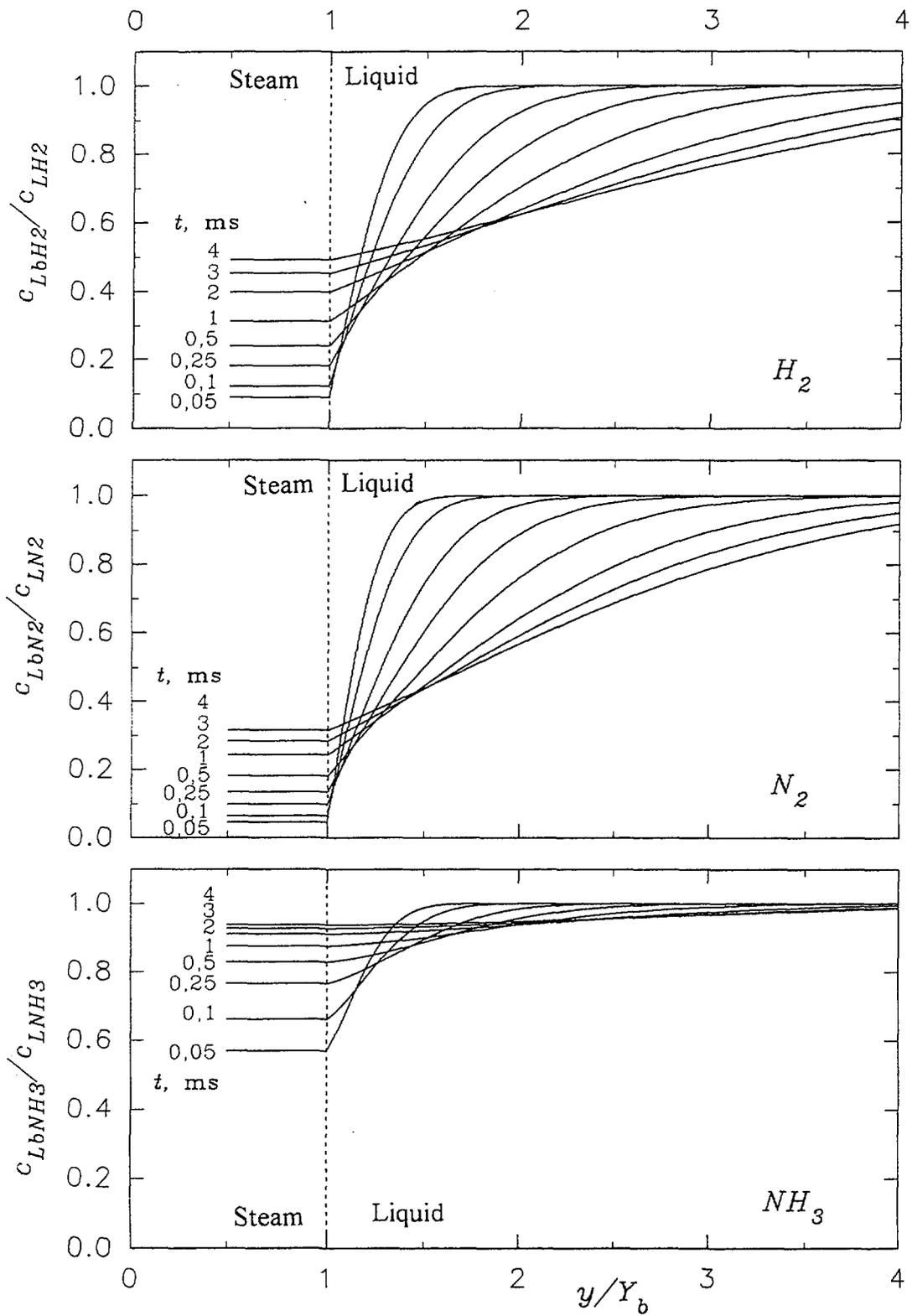


Fig.7 Calculated concentration profil of dissolved hydrogen, nitrogen and ammonia in the liquid surrounding a steam bubble in period of its growth c_{Lb}/c_{Li} (the dynamic model – developed subcooled boiling regime)

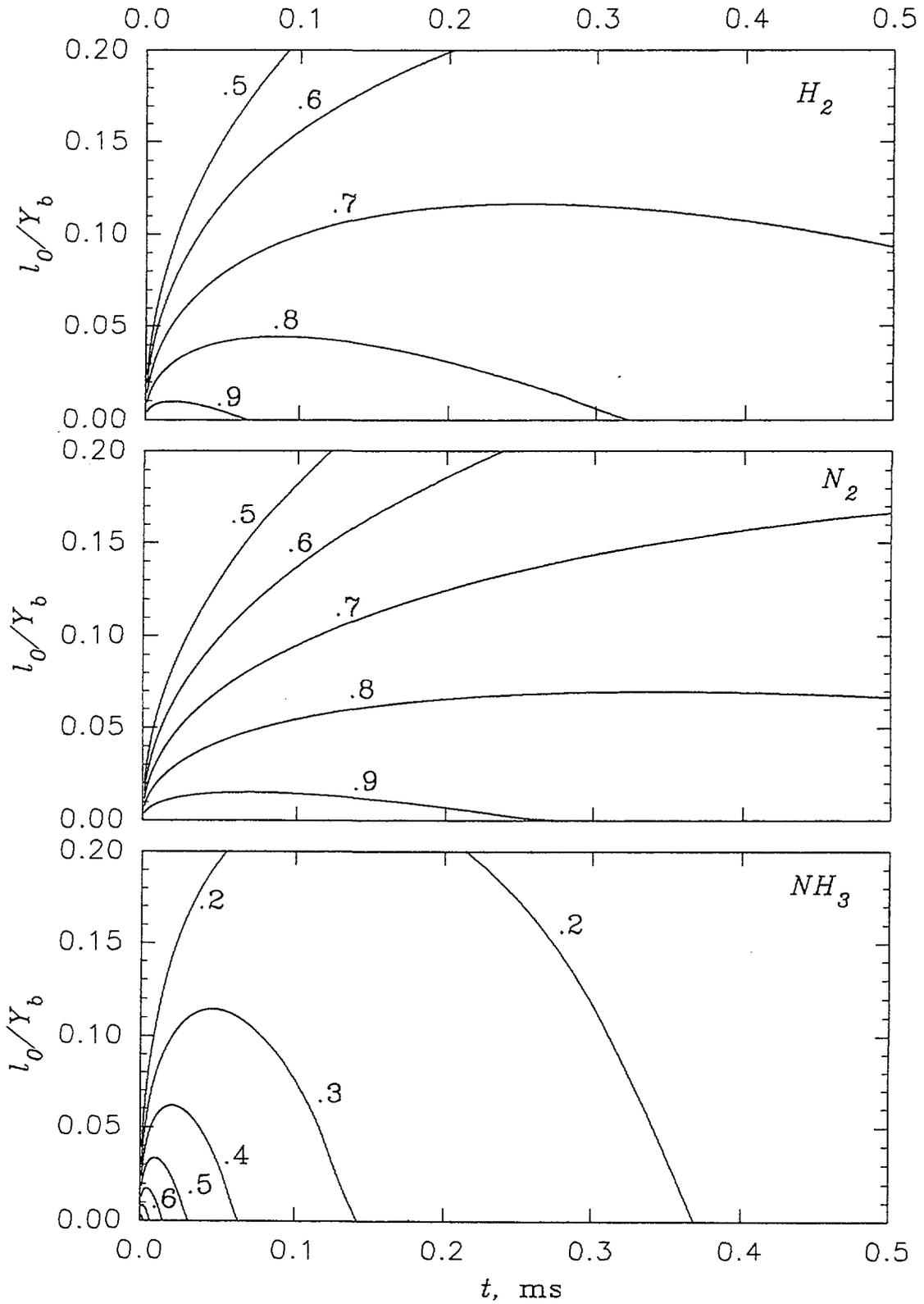


Fig.8 Thickness of the liquid layer surrounding a steam bubble (l_0) as a function of time for different level of dissolved gas depletion (the dynamic model – developed subcooled boiling regime)

Conclusions

The physic-chemical models describing behaviour of the dissolved gases (hydrogen, nitrogen) and ammonia in the subcooled boiling conditions of the pressurized water reactors were developed. Both, an equilibrium and dynamic approaches were used to describe a depletion of the liquid surrounding a steam bubble in the gas components. This depletion phenomenon is a consequence of the gas diffusion into the steam bubbles.

Results obtained by the equilibrium model indicate that a steam phase fraction in the subcooled boiling regime can reach max. 2.5%. For this condition, the general equilibrium depletion in dissolved hydrogen and nitrogen can be max. 10% that is not sufficient level from point of view of some significant change of the water chemistry conditions.

The dynamic model describes two different mechanisms of the subcooled boiling process - non-developed and developed subcooled boiling. In the case of non-developed subcooled boiling, stagnant bubbles are formed on the cladding surface. These bubbles are flushed by steam which is generated on the surface and re-condensates at a top of the bubble. A depletion of liquid in dissolved gases has a local character and is caused by a limited diffusion rate of the gases from surrounding into the bubble. It was found by calculations that the maximum depletion in dissolved hydrogen can reach 15%, in dissolved nitrogen 35%, and in ammonia 27%. The liquid layer surrounding the bubble affected by such depletion level is approx. 5 μm .

In the case of developed subcooled boiling, the gas depletion in the liquid phase has a local character and is a space and time limited. In principle, the level of depletion is not limited, but the deeper gas depletion the shorter period and smaller liquid volume is affected. The bubble generation, growth and escape from the surface is a periodic process which is repeated with a frequency in order of thousand times per a second. A significant gas depletion (eg. 70% hydrogen depletion in relation to the bulk of coolant) takes about 1 ms and concerns a liquid layer of 1 μm surrounding the steam bubble.

The obtained results show that locally different water chemistry conditions can be met in the subcooled boiling conditions, especially, in the developed subcooled boiling regime. An extension and duration of such locally different conditions is in range of micrometers and miliseconds, respectively. On the other hand, the radiolytical processes and reactions, causing a formation of oxidizing species and radicals, proceed in spurs of 1-2 nm that are formed by a high energy radiation, and take much shorter time. From the above, the locally different water chemistry conditions (dissolved gases concentration) can influence physic-chemical and radiolytical processes in the reactor system, eg. Zr cladding corrosion, radioactivity transport, and determination of the critical hydrogen concentration.

LIST OF SYMBOLS

c_{Li}	c_{Gi}	molar volume concentration of component i in bulk of coolant and in steam, mol/m^3
c_{Lbi}		molar volume conc. of component i in liquid surrounding a steam bubble, mol/m^3
d_e		ekivalent hydrodynamic diameter, m
D_{Gi}		molecular diffusivity of component i in steam, m^2/s
D_{Li}		molecular diffusivity of component i in liquid, m^2/s
erfc		complementary error function
f		friction factor, -
He_i		solubility of gas component i , $\text{Nml } i/\text{kg Pa}$ (or $\text{ccSTP } i/\text{kg Pa}$)
DH_{vyp}		evaporation heat of liquid, J/kg
$k_{LR,i}$		mass transfer coefficient of component i by a side diffusion, m/s
$k_{L,i}$		mass transfer coefficient of component i , m/s
k_T		heat transfer coefficient, $\text{W}/\text{m}^2 \text{K}$
l_0		thickness of liquid layer surrounding a steam bubble, m

M_i	molar weight of component i , kg/mol
P	total pressure in the system, Pa
r	radial axis, m
q_w	heat flux on the fuel rod surface, W/m ²
q_{wa}	average heat flux on the fuel rod surface, W/m ²
q_b	heat flux through a bubble, W/m ²
t	time, s
T, T_w	coolant and cladding surface temperature, °C
T_s	saturation temperature at given pressure, °C
V_L, V_G	liquid and steam volume, m ³
v_G, v_L	steam and liquid (coolant) flow velocity, m/s
y	an axis, perpendicular distance from the cladding surface, m
Y_b	critical bubble radius, m
z	axial axis, m
a	convective heat transfer coefficient, W/m ² K
d	thickness of thermal boundary layer, m
e	steam phase fraction in liquid (void fraction), -
l_L	thermal conductivity of liquid, W/mK
ρ_L, ρ_G	liquid and steam density, kg/m ³
s_L	liquid surface tension, N/m
t_b	time of a bubble growth, s
t_w	tangential forces on the surface, Pa
Ψ_i	distribution coefficient of gas i ($= c_{Gi}/c_{Li}$), -

REFERENCES

- [1] LEVY, S., "Forced Convection Subcooled Boiling Prediction of Vapour Volumetric Fraction", Int. Heat Mass Transfer, **10** (1967) 951.
- [2] HEITMANN, H.-G., "Praxis der Kraftwerk-Chemie", Vulkan Verlag, Essen 1986.
- [3] LANDOLD-BÖRNSTEIN, "Zahlenwerte und Funktionen", IV. Band, 4. Teil", Springer Verlag, New York 1976.
- [4] COLLIER, J.G., "Convective boiling and condensation", McGraw-Hill, London 1972.

NEXT PAGE(S)
left BLANK