Initial Stage of Vapor Bubble Growth in Superheated Liquids

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***Abstract*---**The given report deals with problems of nucleate pool boiling investigations of liquids with presence of solid heating surfaces. Problems of liquid to vapor phase change are actual both in theoretical and experimental investigations at least last 50-60 years due to extremely high importance of phenomena in different technical and scientific applications. A lot of researches are devoted to problems of vapor bubble growth dynamic, which is one of the most important parameters of total phenomena indexes. Dominating in special technical literature vapor bubble growth models are describing so called asymptotic stage of bubble radius versus time ($R \approx f(\sqrt{a_l \tau})$), where bubble growth speed is decreasing. Logically, bubble growth speed $dR/d\tau$ somewhere in initial stage of evolution have to be maximal. To find these correlations, we try to use experimental optical methods as well numerical simulations.

***Key-Words*---**Vapor bubble growth, pool boiling, phase change, holographic interferometry.

I. INTRODUCTION

Processes of phase change (boiling and condensation) of liquids and their vapor have extremely high importance in different areas of advanced technologies and industries. Importance of problem quite recently was discussed in Rohsenow Symposium [1] of Massachusetts Institute of Technologies, where high attention was devoted to liquid-vapor (boiling) phase change problems. As it was noted by profesor *V.J.Dhir* [2], further researches in phase change heat transfer will be motivated by new technologies, such as microelectronic systems components cooling, safety and efficiency of different heat exchanging systems in power industry, nuclear and space applications, as well as in processing of newly designed materials. Investigations, both theoretical, both experimental, are carried out during at last last 60 years, despite that, boiling yet is the most efficient and at the same time the least understood phase change process (*C.Th.Avedisian,* [3]). One of the ways to get some advancement in problem`s solution will be exclusive possibilities of computational tools for theoretical (DNS – direct numerical solutions) and detailed analysis of previous obtained experimental data. Problem in the DNS application is high level of complexity in consecutive stages of vapor nuclei formation and growth on the solid heating surface, the following departure from solid, movement and eventual condensation in bulk of liguid.

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II. PROBLEM FORMULATION

Another way can be investigation of processes in molecular and nanometric level to understood psycics in micro- and macroscale. Advances in new instrumentation (high-speed infrared and liquid crystal thermography, laser induced fluorescence, nuclear magnetic resonanse etc.) will be important in new experimental researches. In the reports of *A.E.Bergles* [4] and *G.F.Hewitt* [5] there are specially emphasized importance and efficiency of specially designed and structured boiling surfaces to reach maximum heat flux density *(W/m²)*. A lot of researches are carried out by aim to find optimal correlations between experimental data and their mathematical description of different authors, ever available in scientific literature, and their mathematical description example, [6]. Analysis of problem shows necessity of further investigations in the dynamic and heat transfer in liquid-vapor phase change phenomena.

Present situation analysis [1] shows enomous possibilities abilities of computational methods to get maximum exact correlation between elementary process dynamic in microlevel and macroprocesses of heat transfer performance indexes in liquids pool boiling on solid surfaces. Authors of given report quite long time ago made an attempts [7,8,9] to investigate the dynamic of initial stage of nucleate boiling by means of quiet progressive instrumentation for these times: impulse and real time holographic interferometry, high speed photography and photoelectronic amplifier`s data recording. Results of studies allows to offer for discussion a mathematical simulation for analysis of vapor bubble behavior in the initial stage of vapor nuclei growth stage.

III. PROBLEM SOLUTION

An analysis of vapor bubble growth [8] in initial stage (near so called critical radius R_{cr}) shows essential dependence of bubble growth speed upon heat transfer resistance and kinetic processes to phase change onto the interface ``liquid-vapor``.

The thermal balance of growing vapor bubble can be written as:

$$4\pi R^2 \frac{dR}{d\tau} \rho_v h_{fg} = 4\pi R^2 k\left[T_{wall} - T_\infty(P_\infty)\right], \quad (1)$$

where: $$k = 1/(1/\alpha + \delta/\lambda_l), \quad (2)$$

k – summary heat transfer index from liquid to vapor inside of bubble, $W/(m^2 K)$;

δ – thickness of thermal boundary layer on ``liquid-vapor`` interface, m;

α – heat transfer index on ``liquid-vapor`` interface, W/m^2K;

λ_l – thermal conductivity of liquid, W/m;

h_{fg} - latent heat of evaporation, J/kg;

ρ_v – density of vapor, kg/m^3;

R – bubble radius, m;

$T_{wall}; T_{sat}$ – temperature of heating surface and saturation temperature of vapor accordingly pressure in system, K;

P_∞ – pool or system pressure, Pa.

Assuming edge conditions $k \to \alpha$ in the case, when $\delta \to 0$. From the theory of molecular physics theory we can apply equation:

$$\alpha = \alpha_{lv} \frac{\sigma_l h_{fg}^2}{(2\pi \frac{K}{m} T_{sat})^{0.5} T_{sat}}, \quad (3)$$

where:

α_{lv} – index of "evaporation–condensation" on liquid–vapor interface, depends upon system parameters, and shows proportion between number of substance molecules, crossing liquid-vapor interface in both directions; for different liquids values of α_{lv} can be find in technical literature, index is dimensionless;

σ_l – liquid`s surface tension index, m^2/s;

m – molecular weight of liquid;

K – Boltzmann factor, J/K.

Formulae (3) contents vapor temperature T_{sat}, which is a function of steam pressure in inside of bubble - $P = f(R)$. Vapor temperature inside of bubble can be expressed as:

$$T_{sat} = T_\infty(P_\infty) + \Delta T(R, T_{wall}), \quad (4)$$

Maximum temperature difference, taking into account alternating pressure of vapor inside of nuclei:

$$T_{wall} - T_\infty = (T_{wall} - T_{sat\infty})(1 - \frac{R_{cr}}{R}) = \Delta T_\infty (1 - \frac{R_{cr}}{R}), \quad (5)$$

where: $R_{cr} = 2\sigma_l/(P_{wall} - P_\infty)$ –critical radius of vapor bubble.

Thickness of thermal boundary layer δ of liquid with variable temperature we can obtain from balance equations (1) and (2), considering linearly temperature distribution nearly liquid-vapor boundary:

$$\delta = \frac{2h_{fg}\rho_v R}{3c_l \rho_l (T_{wall} - T_\infty)}, \quad (6)$$

With quite simple mathematic transformations we can obtain the following expression for bubble growth speed (bubble radius versus time, $dR/d\tau$) determination:

$$\frac{dR}{d\tau} = \frac{\alpha \lambda_l \Delta T_\infty (1 - R_{cr}/R)}{\rho_v h_{fg} [\lambda_l + \alpha \frac{2}{3} \frac{h_{fg}\rho_v R}{\Delta T_\infty c_p \rho_l (1 - R_{cr}/R)}]}, \quad (7)$$

Equation (7) we can transform into the dimensionless form:

$$\frac{dX}{dFo} = Bi * Ja * \frac{1}{X} \frac{(1 - 1/X)^2}{(1/X - 1/X^2 + 2Bi/(3Ja))}, \quad (8)$$

In (8) the following dimensionless numbers were used:

$X = R/R_{cr}$ – dimensionless radius of bubble;

$$Fo = \frac{a_l \tau}{R_{cr}^2} \text{ – Fourier`s number;} \quad (9)$$

$$Bi = \frac{\alpha R_{cr}}{\lambda_l} \text{ – Biot number;} \quad (10)$$

$$Ja = \frac{c_p \rho_l \Delta T_{\max}}{h_{fg}\rho_v} \text{ – Jacob`s number.} \quad (11)$$

Equation (8) gives possibility to get characteristics (dimensionless, $dX/dFo = f(X)$ of bubble growth initial stage. Below is shown only one sample of numerical simulation for most common heat carrying liquid – water, atmospheric pressure; superheating 10*K*.

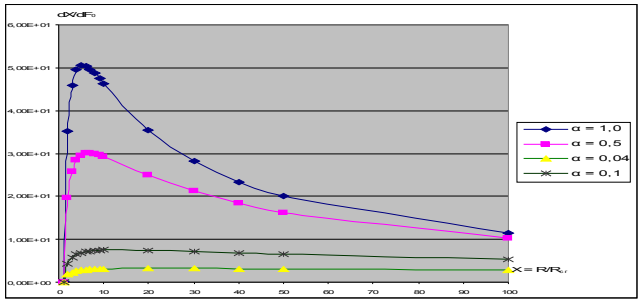

Fig. 1 Dimensionless characteristics $dX/dFo = f(X)$ of vapor bubble growth, water, *P=101.3kPa,* super-heating 10K. Value of α (0,04; 0,1; 0,5; 1,0) here means index of "evaporation-condensation" α_{lv} for water, varying from 0,004 to 1,0 in accordance of kinetic theory.

IV. CONCLUSIONS

An analysis of numerical simulations (8) for different combination of liquids and process parameters shows maximal speed dX/dFo of vapor bubble radius in region with dimensionless $X = R/R_{cr}$ values 3 to 6. Maximum of bubble growth speed strongly depends upon liquid-vapor kinetic index α_{lv} and parameters of system. We hope, that further investigations of vapor bubble dynamic investigations can help to understand process in whole and get universal correlations for heat transfer indexes prediction.

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