Subcooled pool film boiling heat transfer from sphere: experiment and modelling

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Abstract. Experiments were conducted to study heat and mass transfer at film boiling on a metal sphere immersed into subcooled liquid. A model was elaborated to calculate the thickness of the vapor film and the speed of vapor flow in the film. The model also includes a detachment model for vapor bubbles lifting off the surface of the film. The model shows agreement with the results of the pool film boiling experiments with various liquids as well as for Leidenfrost drops. Quite reasonable agreement is also observed for the frequency of bubble detachment in saturated liquid. While processing the experimental data the calculations showed that the heat transfer into the bulk of liquid from vapor-liquid boundary is much more intense than expected. The effect is not determined solely by natural convection within the liquid as the heat flows determined by natural convection are two orders of magnitude less than those obtained. An attempt was made to determine the consequent heat transfer coefficient based upon experimental data for the frequency of bubble detachment from off the vapor film around the sphere. The abnormally high heat transfer detected could be important in practical applications.

1. Introduction
When trying to develop a model of film boiling upon the surface of an object immersed in subcooled liquid, the following difficulty arises. The flow of heat from the surface of the heated object is causing not only the evaporation of the liquid on the vapor film-liquid interface but also some unknown part of the heat flow is heating the liquid in the volume into which the heated object is submerged. To calculate correctly this effect is rather difficult, as virtually no data on the heat transfer coefficient from the surface of the vapor film directly into the subcooled liquid is available. In this work an attempt was made to determine this heat transfer coefficient based upon experimental data for the frequency of bubble detachment in subcooled pool film boiling on the metal sphere.

2. Experimental setup
The metal sphere under study (stainless steel, 10 mm diameter) was heated by an inductor up to a temperature of 2000 K. In the experiment, the sphere was placed on a ceramic stand in a special transparent ditch inside the inductor's coil, fig. 1. To prevent the surface of the sphere from oxidizing, the ditch was filled with argon. The temperature of the sphere during the experiment was determined by optical methods. When the sphere reached a set temperature, distilled water was fed into the installation from below.
The experiment was conducted at atmospheric pressure, subcooling of water ranged from 20°K to 90°K. The height of the water column over the metal sphere during the experiment was fixed and ranged from 10 to 180 mm. The process was recorded on Canon (MV500i) and Redlike (MotionScope1000) digital video cameras. The water temperature was measured by thermocouples of various types. Kistler (601A) and PCB (HSM 113A28) sensors were used to record pressure pulses. Among other parameters during the experiments were measured the shape and departure frequency of vapor bubbles from the upper forming of the sphere, fig. 2, 3.

3. Numerical model
On the basis of balance ratios, a model to calculate the thickness of the vapor film and the speed of vapor flow within it was formulated. The model is conceptually close to the model developed in [1]. However, our model is able to take into account the subcooling of the liquid to the state of saturation. The following assumptions were made, fig.4.
- Vapor film has axial symmetry;
- Vapor flow is laminar and stationary;
- Vapor and fluid properties are constant;
- Interphase surface is smooth; film thickness is much less than sphere radius $\delta \ll R$;
- Radiative heat transfer is negligible;
- The adhesion conditions are met at all contact and interphase surfaces;
- The transverse component of the vapor velocity caused by evaporation from the interface is neglected;
- Pressure gradient is the same in fluid and inside vapor film.

Using heat balance equation for each small element of the film surface we define heat flow for evaporation from interphase surface:

$$q = q_\lambda - q_c = \frac{\lambda}{\delta} (T_m - T_S) - \alpha (T_S - T_x),$$  \hspace{1cm} \text{(1)}

where $\alpha$ — heat transfer coefficient in case of developed natural convection in liquid upon vapor film surface. Vapor mass flow due to evaporation:

$$G = \int_0^\varphi \left( \frac{q}{h_{\text{eff}}} \right) df,$$  \hspace{1cm} \text{(2)}

here $f = 2\pi R^2 \sin \varphi \, d\varphi$ — interphase surface element, $h_{\text{eff}} = h_{lg} + c_p \, \gamma (T - T_s)$ — effective heat of vaporization. Mass flow rate can be defined also as:

$$G = \rho \bar{u} \delta,$$

here $\rho$ — vapor density, $\bar{u}$ — cross section mean vapor velocity, $s = 2\pi R \sin \varphi \delta (\varphi)$ — vapor film cross section. We can assume vapor flow within the film to be laminar with parabolic profile. Mean velocity in case of zero velocity on both vapor film borders:

$$\bar{u} = \frac{1}{\delta} \int_0^\delta u(y) dy = -\frac{1}{12\mu} \frac{\partial p}{\partial x} \delta^2.$$  \hspace{1cm} \text{(3)}

Pressure gradient along Ox axis (it runs along centerline of the film, fig.4) is defined as:

$$\frac{\partial p}{\partial x} = \frac{1}{R} \frac{\partial p}{\partial \varphi} = -\rho' g \sin \varphi.$$  \hspace{1cm} \text{(4)}
By means of equations (2) and (3), we obtain differential equation for film thickness:

\[ \frac{d\delta}{d\varphi} = \frac{1}{3\sin\varphi} \left( \frac{c_1}{c_0\delta^3} - \frac{c_2}{c_0\delta^2} - 2\delta \cos\varphi \right). \quad (5) \]

Here

\[ c_0 = \frac{\rho' \rho T_g}{12\mu R}, \quad c_1 = \frac{\lambda'(T_w - T_g)}{h_{eff}}, \quad c_2 = \frac{\alpha(T_s - T_w)}{h_{eff}}. \quad (6) \]

Border condition for this equation is defined by the axial symmetry of the film shape

\[ \frac{d\delta}{d\varphi} \bigg|_{\varphi=0} = 0. \quad (7) \]

So steam film initial thickness at \( \varphi = 0 \) is defined by equation

\[ \frac{c_1}{c_0\delta^3} - \frac{c_2}{c_0\delta^2} - 2\delta = 0. \quad (8) \]

The model was tested on experimental data, as for the pool film boiling of various liquids, as for Leidenfrost drops. The results were compared with the experimental data [1-3]. The model includes capillary (quasi-static) detachment mechanism for low growth rates, and inertial (for high growth rates) mechanisms vapor bubbles detachment from the surface of the vapor film. There is good agreement with the results of experiments to determine the detachment frequency in saturated liquid [4]. However, the use of the developed model to boiling of a subcooled liquid is difficult, as there is no data on heat transfer coefficient from the surface of the vapor film directly into the subcooled liquid.

4. Results

In processing of the experimental data the heat transfer coefficient was initially used, calculated in assumption of developed natural convection on a solid sphere. However it was found that this assumption leads a very significant (up to two orders) overestimation of the frequency of bubble detachment compared to the experiment. Thus, the calculation showed that the heat exchange at the vapor-liquid interface is much more intensive and is not determined solely by the natural convection in the liquid covering the steam film.

![Figure5](image_url)

**Figure5.** Heat transfer coefficient from vapor layer into bulk of subcooled water versus sphere temperature \( T_m \).

Using the developed model, based upon the experimental data obtained, the dependence of the heat transfer coefficient on the surface of the subcooled liquid versus the surface temperature of the sphere is obtained. A similar dependence is also defined on other parameters (from the estimated speed of vapor in the film, the thickness of the film, etc.), fig. 5-7. The abnormally high value of heat transfer coefficient could be important in practical applications.
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5. References

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