Łukasz J. Orman, Andrej Kapjor
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DETERMINATION METHODS OF BOILING HEAT FLUX

METODY WYZNACZANIA GĘSTOŚCI STRUMIENIA CIEPŁA DLA WRZENIA

Łukasz J. Orman*
Kielce University of Technology, Poland
Andrej Kapjor
University of Žilina, Slovakia

Abstract

Boiling is a phase-change phenomenon, which is of significant practical application potential due to large heat flux values exchanged in the process. The paper provides an overview of calculation methods that enable to determine the values of pool boiling heat flux on smooth surfaces. The most commonly used correlations were analysed and the boiling phenomenon occurring on smooth surfaces has been discussed based on the experimental data. A modification of the Rohsenow model has been proposed with the values of the constants determined experimentally.

Keywords: boiling, correlations, heat transfer, heat flux

Streszczenie

Wrzenie to zjawisko związane ze zmianą fazy czynnika, które ma znaczny potencjał praktyczny z uwagi na wymianę dużych gęstości strumienia ciepła. Artykuł przedstawia metody wyznaczania gęstości strumienia ciepła wymienianego przy wrzeniu. Analizuje najczęściej stosowane korelacje i opisuje zjawisko wrzenia, odbywające się na powierzchniach gładkich, w oparciu o badania eksperymentalne. Zaproponowano modyfikację modelu Rohsenowa zawierającą nowe wartości stałych eksperymentalnych.

Słowa kluczowe: wrzenie, korelacje, wymiana ciepła, gęstość strumienia ciepła

1. INTRODUCTION

The boiling process enables to exchange large amounts of heat at very small temperature differences. This is both due to significant latent heat but also convention heat transfer. There are many parameters that have an impact on this thermodynamic phenomenon such as boiling liquid properties, thermophysical properties of the heater and it microgeometry, special orientation and etc. [1]. El-Genk and Bostanci [2] analysed the boiling performance at various surface inclination angles and found that for the angles above 90° and superheat above 13 K heat flux decreased with increasing angles. The findings were generally supported by the work of Priarone [3] who stated that heat flux at inclinations above 90° heat transfer is hampered due to bubbles' accumulation. However, for significant superheats and angles up to 90° no influence can be observed. Nishikawa and Ito [4] considered the impact of the boiling agents, which is mostly related to the surface tension characteristics. Its large value leads to the development of large bubbles. On the other hand, Henry and Kim [5] claim that the radius of the bubble at the departure stage depends on the forces acting within the bubble and outside of it during its growth. Apart from surface tension, thermo-capillary effects also play a role. Roughness is also very important. Nishikawa et al. [6] tested copper surfaces of different

*Kielce University of Technology, Poland, e-mail: orman@tu.kielce.pl

roughness (from 0.022 µm to 4.31 µm) and observed that boiling was intensified for rough surfaces, especially at reduced pressures. It might be related to increased density of nucleation sites as stated by Ribatski and Saiz Jabardo [7], who performed research on commercial refrigerants in the range of roughness values from 0.07 µm to 2.60 µm. Kang [8] focused his paper on the combined influence of roughness and special orientation. The author confirmed the favourable impact of roughness, especially for the vertical orientation of the heater.

Due to the considerable practical applications of the boiling process (for example in the refrigeration systems and installations). It is necessary to properly determine heat flux dissipated from the heater. It depends on the number of parameters and should be studied carefully, which is the focus of this paper.

2. BOILING ON THE SMOOTH SURFACES

Boiling is affected by the properties of the surfaces (especially roughness). Since no surface is perfectly smooth, boiling occurs on surfaces which have cracks, cavities and other types of irregularities. Figure 1 presents an example of the real surface, made of copper, with all the irregularities clearly visible with the help of the optical microscope (the height of the irregularities was up to 3.5 µm).

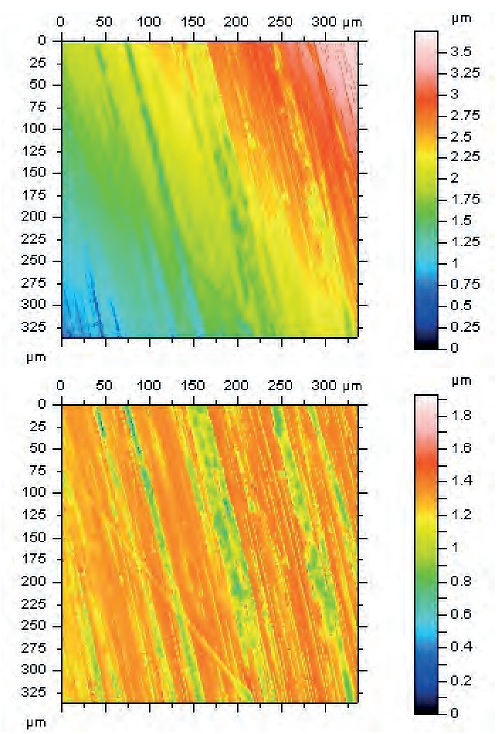

Fig. 1. Optical microscope images of the copper heater surface

The morphology of the surface was produced with fine emery paper. Consequently, it is very smooth. Also, as a result of this process, it has a groove – like pattern. This is due to the one-way movement of the emery paper on the surface. Some grooves are deeper, which might have been caused by a larger pressure exerted on the surface by the operator.

Boiling is initiated at locations where the irregularities occur, namely at cavities or cracks present on the surface. These sites are called ‘nucleation sites’ and, when they get activated, they serve as a location, where bubbles grow and from there they depart into the liquid pool. However, the subsequent bubbles are also created there. Thus, a single site operates continuously – after the departure of one bubble, the next one is being grown at the same location. The process of bubble growth in one site has been presented in Figure 2. The images were recorded with a high speed digital camera.

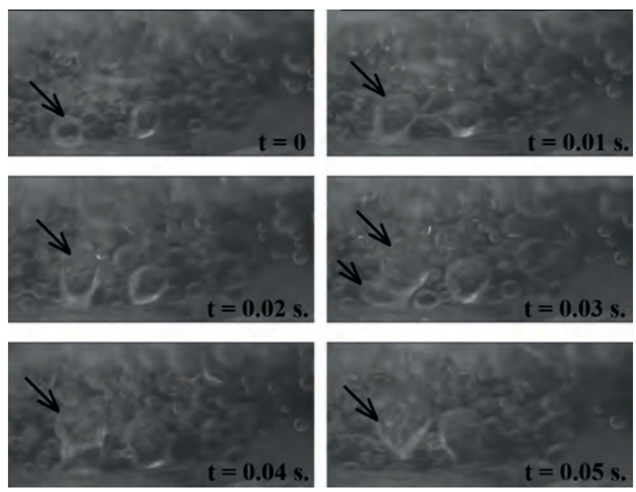

Fig. 2. Bubble growth on the copper heater surface; time interval between the photos: 0.01 s

Naturally, as the temperature of the heater increases, more and more nucleation sites become active. This leads to more heat being exchanged from the surface to the boiling liquid. Moreover, the generated bubbles can merge with each other both on the surface and in the liquid pool. Thus, large vapour bubbles can be observed at significant temperatures of the surface. Considerable vapour accumulation on the surface at large temperatures is an unfavourable phenomenon because a burnout of the surface can occur as a consequence. This is due to the difficulties in efficient heat removal to the pool of liquid.

The arrow in Figure 2 indicates a single bubble, which is quite small at $t = 0$, and with time it becomes

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larger (also by overtaking a smaller bubble at $t = 0.03$ s) until it departures at $t = 0.06$ s (the last image taken at $t = 0.05$ s presents the state just before the take off, when the bubble takes on a mushroom-like shape).

The condition of the surface as well as the material properties of both the surface and the liquid can play a significant role in the process of bubble grow and departure and should be considered for proper determination of the heat flux value transferred from the heater surface to the boiling agent.

3. BOILING HEAT FLUX CORRELATIONS

Determination of pool boiling heat flux has been the focus of many papers throughout the recent decades. Models and correlations have been proposed, however, only a few have been commonly applied. Nevertheless, it needs to be noted that they are still not fully accepted and rely mostly on experimental coefficients. This makes them less successful when new refrigerants come into the market.

The most widely used correlation was proposed by W.M. Rohsenow several decades ago. It is based on the assumption that the motion of the vapour bubbles is responsible for the heat exchange as a results of convection. Consequently, heat flux can be calculated with the general convection equation [9]:

$$\mathrm{Nu} = C\mathrm{Re}_b^n \mathrm{Pr}_l^m \tag{1}$$

where Nu, Re and Pr are the Nusselt, Reynolds and Prandtl numbers, while b and l refer to „bubble” and „liquid”, respectively. C, n and m are constants, which are determined experimentally. All the numbers (Nu, Re, Pr) and the constants are dimensionless.

Having conducted the necessary mathematical transformations, the following formula for the heat flux (q, in W/m^2) is obtained as a function of the difference between the wall temperature and the saturation temperature of the boiling liquid:

$$q = \left[\frac{c_{pl}(T_w - T_{sat})}{Cr}\right]^{\frac{1}{0.33}} \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}}\,\mu_l\, r\, \mathrm{Pr}_l^{-\frac{s}{0.33}} \tag{2}$$

The constants C and s depend on the type material and morphology of the heater as well as on the type of the boiling agent, T_w and T_{sat} denote wall and saturation temperatures (in K), respectively. The other symbols are: specific heat (c_{pl}, J/kgK), gravitational acceleration (g, m/s^2), heat of vaporization (r, J/kg), viscosity (μ, kg/ms) and density (ρ, kg/m^3) of the liquid (l) and vapour (v) phases.

Another set of correlations has been proposed by Stephan and Abdelsalam [10], based on the regression analyses of the experimental results. The set includes four equations for various boiling agents. Non-dimensional values of the fluids' physical properties were used in the developed correlations.

According to Heider and Webb [11], the liquid from the pool moves into the heater to the sites of bubble development in order to fill in the void after the previous bubble. Thus, a rotational movement of the liquid is created in the direction to the bottom of the bubble. The interaction area of a single bubble has been assessed as equal to two its diameters. The cyclical process of the creation of bubbles means that heat and mass transfer is unsteady and laminar forced convection is the dominant heat exchange mechanism. Superheated liquid is sucked after the departing bubble and undergoes evaporation within it. The following equation for the heat flux has been proposed [11]:

$$q = 2\sqrt{\pi\,\lambda_l\,\rho_l\,c_{pl}\,f}\ \times$$
$$\times\ D^2 N (T_w - T_{sat}) \left[1 + \left(\frac{\pi 0.66 C}{\mathrm{Pr}_l^{\frac{1}{6}}}\right)^n\right]^{\frac{1}{n}} \tag{3}$$

where λ – denotes thermal conductivity (W/mK), f is the frequency of bubbles' creation (s^{-1}), D – bubble diameter (m), N – density of nucleation sites in number of sites per square meter (which could be adopted from [12]), while the constants C and n were provided by the authors for selected boiling agents.

Chai et al. [13] created a non-linear model of pool boiling taking into account bubble growth and interactions between neighbouring nucleation sites. The authors provided numerical solutions of energy balance and bubbles' dynamics equations as well as the probability aspect of the bubble creation phenomenon. It was proposed that the boiling heat flux is a total of the natural convection heat flux (due to bubbles' agitation of the liquid pool) and the latent heat of vaporisation. The model adopted the equation for the density of nucleation sites according to [12]. The resulting equation for boiling heat flux takes the following form [13]:

$$q = 10^{-3}\frac{\lambda_l^2\left(T_w - T_{sat}\right)^3}{\sigma T_{sat} v_l} + \\ + \frac{\pi\, 218.8\,\mathrm{Pr}_l^{1.63}\,\mathrm{H}^{0.4}\left(\dfrac{\rho_v r}{\rho_l c_{pl}}\right)^4 C\,\lambda_l\, a_l \times}{2\,\xi^2\left(\dfrac{\lambda_w \rho_w c_{pw}}{\lambda_l \rho_l c_{pl}}\right)^{0.5}} \\ \times\left(\frac{0.3}{\xi} + \sqrt{\frac{0.09}{\xi^2} + \frac{12}{\xi}}\right) \tag{4}$$

where:

$$H = 14.5 - 4.5\left(\frac{R_a p}{\sigma}\right) + 0.4\left(\frac{R_a p}{\sigma}\right)^2 \tag{5}$$

$$\xi \quad \frac{\rho_v r}{\rho_l c_{pl}(T_w - T_{sat})} \tag{6}$$

The dimensionless constant C takes the values from 5 to 10, while R_a is the average surface roughness (in μm) and p denotes pressure (in Pa). The authors claim that the non-linearity is most evident, if the coefficient of conductivity of the surface material is low. The analysed model correctly correlated various experimental test results adopted from literature.

Quite recently a mathematical model has been proposed [14], where the temperature difference between the surface and the boiling liquid as well as macrolayer thickness and time were taken into account for heat flux determination. Apart from the model, the authors also found out that heat transfer through conduction across a microlayer was the major force in the case of nucleate pool boiling at high heat fluxes.

An overview of the models and mechanisms of the boiling phenomenon can be found in the review paper [15], which is focused on the application of boiling for nuclear reactors cooling. On the other hand, numerical simulations of boiling are also performed and analysed. Kamel et al. [16] worked on the concept of correcting the coefficient of the bubble waiting time and afterwards correlating it with the superheat temperature. The authors compared their model with the experimental results available in literature and obtained good agreement.

The correctness of the determination of heat flux using the Rohsenow's correlation has been tested using recent experimental data provided by Kaniowski and Pastuszko [17]. The calculation results according to the model [9], where the values of the constants were adopted from [18], have been shown in Figure 3 as curves "1" and "2", respectively. The figure presents dependence of heat flux (q) vs. temperature difference between the surface (T_w) and the saturated liquid (T_{sat}), referred to as boiling curves, for a copper surface on which distilled water boils.

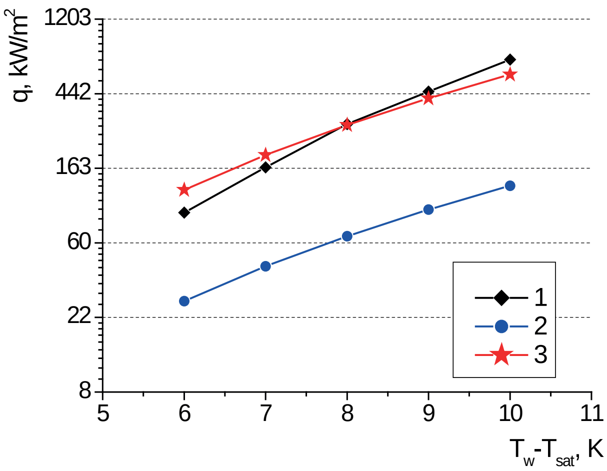

Fig. 3. Boiling curves: 1 – experimental data according to [17], 2 – calculation results according to the Rohsenow's correlation [9], 3 – calculation results according to the modified Rohsenow's correlation

As can be seen, the original Rohsenow's correlation failed to properly predict the experimental data (the calculated values were lower than the research results). However, the character of changes was properly addressed – the values were only vertically shifted. Thus, a modification of the original model was proposed. It was based on the idea of providing new values of the constants in equation (2) as follows: C = 0.01 and s = 0.65. Consequently, a significant agreement between the experimental and calculation results could be observed in Figure 3.

Another, and still not fully understood problem, is the issue of incorporating various modes of nucleate boiling heat transfer (as described in [19]) – from initial stage with only a few bubbles created on the surface through developed and fully developed mode into the new model. It is a large challenge and should be addressed in the future works. It also needs to be noted that increased efficiency of heat exchangers due to their proper morphology can help reduce the costs of heat exchangers operation. As an example, Janaszek and Kowalik [20] analysed a case study regarding a domestic heat exchanger.

4. CONCLUSIONS

The literature provides various models and correlations for boiling heat flux determination. Due to the complexity of the phenomenon, none of these models can be considered as successful in predicting the heat flux for all types of heaters and boiling agents. The most commonly applied correlation was proposed by Rohsenow and this has been validated in the present paper. Due to the significant differences with the experimental data, a modified correlation was proposed with two constants being changed. Thus, a very good agreement with the research data has been observed.

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