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CRITICAL ANALYSIS OF POOL BOILING CORRELATIONS

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Norbert Radek[1] – *orcid id:* 0000-0002-1587-1074
Łukasz J. Orman[1] – *orcid id: 0000-0002-2221-1824*
Stanislav Honus[2] – *orcid id: 0000-0002-1039-2154*
Jacek Pietraszek[3] – *orcid id: 0000-0003-2851-1606*
[1]Kielce University of Technology, **Poland**
[1]VŠB-Technical University of Ostrava, **Czech Republic**
[3]Krakow University of Technology, **Poland**

Abstract: The manuscript describes the problem of boiling heat flux determination with the focus on nucleate boiling mode. It presents the boiling phenomenon on the bare surface and provides a review of the correlations that can be used for modelling purposes. Two most commonly applied correlations were validated against the experimental results. One of them showed significant discrepancies, which might be attributed to the conditions of the research and possible variations in the morphology of the heater. The other correlation proved to be successful in determining heat flux.
Keywords: boiling, correlation, heat flux, model

1. INTRODUCTION

The research on boiling is quite widespread throughout the scientific world among heat transfer researchers and covers both pool and flow boiling modes (Maciejewska and Piasecka, 2017; Strąk et al., 2018; Hożejowski and Hożejowska, 2019, Pastuszko et al., 2020). However, the experimental results need to be described mathematically in order to precisely predict the heat flux exchanged during boiling. It is of utmost importance for heat exchangers' design as well as the safe operation of systems utilising boiling in their operation.

There are many models and correlations, nevertheless none has been accepted fully by the scientific community. The majority of the correlation can only work within a small range of heat fluxes and/or material and fluid properties. There are many limitations that hamper a widespread use of the equations available in the literature. There are, however some that are more commonly applied and these will be presented in the paper. The aim of the manuscript is to provide a review of the correlations and compare the most common ones with the current experimental data adopted from literature regarding heat flux exchanged during boiling of pure ethyl alcohol in order to assess their usefulness for the prediction of heat flux values.

High-efficiency heating of liquids, particularly water, is a highly significant industrial concern (Orman and Chatys, 2011; Dabek et al., 2016), given that hot water is widely used, for instance, in removing graffiti from railway vehicles (Radek et al., 2019). Modifications to heating surfaces and components operating in hot liquids hold considerable importance (Radek et al., 2020). In the case of plastic components operating adjacent to heating elements, additional thermal stress and reduced strength must be considered (Kuciel et al., 2019), and any impurities generated during operation (Szataniak et al., 2014) need to be removed from these liquids (Radzymińska-Lenarcik et al., 2018). These issues significantly impact management methods in industries involved in producing hot liquids or contaminating them, such as the automotive industry (Ulewicz, 2018; Pacana et al., 2021) or machinery (Borkowski et al., 2012; Siwiec et al., 2020). Properly modeling automated heating processes requires extensive use of Design of Experiments (DOE) techniques (Pietraszek and Skrzypczak-Pietraszek, 2015; Pietraszek et al., 2020), and their supervision inspires the development of measurement techniques (Dominik et al., 2013; Gądek-Moszczak et al., 2019) and appropriate staff training (Radek et al., 2023).

2. BOILING MODELLING AND CORRELATIONS

Modelling of boiling has been the focus of attention for decades. A respected and highly cited correlation was proposed in (Rohsenow, 1952), where the Nusselt number (Nu) equals:

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

with C, n and m being constants and Re and Pr: Reynolds and Prandtl numbers, respectively. The subscript “b” refers to a bubble, while “l” to „liquid”. A transformation of this formula leads to the expression for the heat flux (q):

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

In the above equation C, s are constants, the wall and saturation temperatures are T_w and T_{sat}, while c_p is specific heat, g is gravitational acceleration, r is heat of vaporization, μ is viscosity, σ is surface tension ρ is density: of liquid (l) or vapour (v).

Another type of correlation was presented in (Stephan and Abdelsalam, 1980). Here, four equations have been proposed for different kinds of boiling fluids. The correlations use non-dimensional values of liquids' properties. Thus, it is the experimentally – derived set of formulas.

In the paper by (Heider and Webb, 1997) another correlation can be found. The authors assumed that liquid phase during boiling flows in the direction of the heater to places of bubble creation to cover the void after the previous bubble, which left. As a consequence the rotational movement develops within the tank. The phenomenon of the creation of vapour bubbles means that the transfer of mass and heat is unsteady. Laminar forced convection mode is mostly responsible for heat exchange. The authors proposed this equation for the heat flux:

$$q = 2\sqrt{\pi \lambda_l \rho_l c_{pl} f}\, D^2 N (T_w - T_{sat}) \left[1 + \left(\frac{\pi 0{,}66C}{\mathrm{Pr}_l^{\frac{1}{6}}}\right)^n\right]^{\frac{1}{n}} \tag{3}$$

The symbol λ is thermal conductivity, f denotes a frequency of bubbles' creation, while D is the diameter and N is the density of locations where bubbles are created. N can be calculated from (Benjamin and Balakrishnan, 1997). The values of the constants C, n were given in (Heider and Webb, 1997) for chosen fluids.

In (Chai et al., 2000) a description of a new non-linear model of boiling was provided. The model considered the phenomenon of bubble growth as well as the cooperation with one another of the locations where bubbles are created. Numerical calculations were performed, too. The authors proposed that the total boiling heat flux should incorporate natural convection and the latent heat. The model used the equation from (Benjamin and Balakrishnan, 1997). The final formula for heat flux (q) was given in the paper as follows:

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

The value of C is within 5 ÷ 10. The parameter H is calculated taking into account mean surface roughness, pressure and surface tension. On the other hand ξ is calculated using vapour and liquid density, heat of vaporisation, liquid's specific heat at constant pressure and the difference between the wall and saturation temperatures.

In the article (Danish and Mesfer, 2019) a mathematical model was shown, in which the heat flux exchanged during boiling depended on the macrolayer thickness as well as time. It was also stated that conduction heat flux occurring through the microlayer proved to be a major force for fully developed nucleate boiling.

Currently, numerical simulations for modelling of boiling phenomenon are common. In (Kamel et al., 2022) the authors developed a concept of providing a correction to the value of the coefficient of bubble waiting time and afterwards interconnecting this with temperature. The comparison of this new model with research test results adopted from literature showed good agreement.

It must be emphasized that there are many other experimental correlations that are developed to mathematically describe the test results obtained by individual authors. However, they typically do not enrich the knowledge about the physical processes occurring during nucleate pool boiling.

3. BOILING ON THE SMOOTH SURFACE

Boiling occurs when the saturation temperature is reached, however usually the surface temperature needs to be a few degrees Celsius higher in order for the process to begin. At first isolated bubbles can be observed, but as the process continues the bubbles cover the whole heater area. In this case we are talking about the fully developed nucleate boiling, when vapour bubbles are everywhere on the heater and its surface cannot even be visible (fig. 1). The heat flux exchanged during this phenomenon is depended of the convective part (related to the fast movement of the bubbles in the liquid) and the phase change heat transfer linked with the transformation from the liquid phase into the vapour phase. It is associated with large value of the heat of vaporization. This makes the whole process a very efficient way of cooling (as long as the vapour patches are not developed on the heater, which reduces the heat flux and can lead to the destruction of the heater).

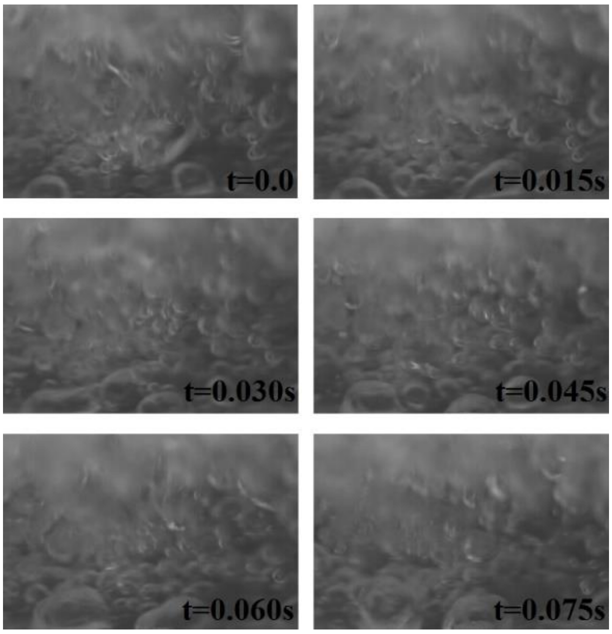

Fig. 2. Fully developed boiling mode on the horizontal surface, time interval: 0.015 s.

Naturally, the geometrical parameters of the surfaces play a substantial role in the boiling phenomenon. Thus, knowledge about the surface morphology is crucial when discussing this issue more closely. Bare surfaces might seem to be smooth in the macroscale, but the analysis with the optical microscope reveals that they are in fact quite irregular (fig. 2). They contain scratches an/or holes made during polishing or other surface treatment methods. The measure of these irregularities is the surface roughness typically expressed in μm. Figure 2 presents the relatively smooth surface, with the height of the hills possible to determine from the colour scale in the right part of the figure.

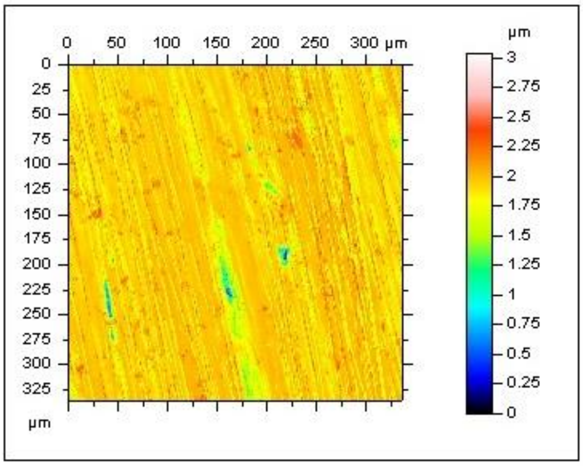

Fig. 2. Image of the bare surface from the optical microscope.

This surface was prepared using mechanical means and can have some irregularities due to the operation of the machining tools. Moreover, it was polished with fine emery paper and seems to be perfectly smooth (when the observation is made with the naked eye). The use of a microscope, however reveals the details of the surface morphology.

It needs to be added that any alternations to the heater morphology, made, for example, by mechanical or thermal means (such as lasers, which is also the focus of scientific attention of the authors), typically leads to the generation of micro and macro shapes of various dimension, which can improve heat transfer performance of the heater during boiling. This phenomenon can be very clearly visible for the small heat flux values. When the process is in the fully developed nucleate boiling, many of the differences diminish or even disappear. It this case, the performance of the heaters with the altered morphology can be quite similar to the bare surface experimental results.

3. RESULTS AND DISCUSSION

As mentioned earlier, there are many models and correlations for boiling heat flux. However, this study has been limited to two, which were presented in Section 2. The verification of the accurateness of these selected correlations has been conducted using very recent experimental data of pure ethanol boiling heat transfer available in (Golkar et al., 2021) and referred to as data "3" in Figure 3 (below). These results were obtained on the bare copper heater. Two most popular correlations were chosen for the comparison purposes: the one provided in (Rohsenow, 1952) with constants determined in (Pioro, 1999), which is presented as line "1" in Figure 3 and the other correlation given in (Stephan and Abdelsalam, 1980) and referred to as "2" in the figure below – the logarithmic scale was used for better visual representation of the research and calculation data.

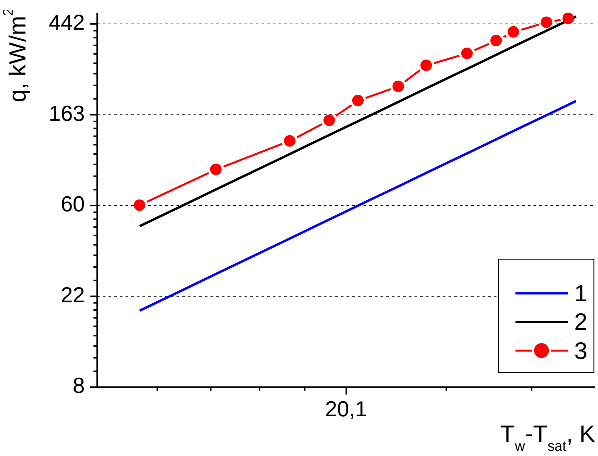

Fig. 3. Comparison of the experimental results (3) with the Rohsenow model (1) and Stephan&Abdelsalam model (2).

We can clearly see that the experimental test results are quite well correlated with the calculation results obtained with the fluid specific model presented in (Stephan and Abdelsalam. 1980). Despite the fact that the test data are slightly above the line describing the calculated heat flux (which is the black line), the differences are not significant – contrary to the data obtained with the correlation (Rohsenow 1952) with constants corrected in (Pioro 1999) – represented with the blue line. On the one hand, it can be explained by possible differences in sample preparation, but on the other by the assumptions of the model. It is, however clear that the use of other models and correlations can lead to even larger discrepancies between the experimental and calculation results.

3. CONCLUSION

The paper has been focused on nucleate boiling phenomenon occurring on bare surfaces. It turned out that the most precise correlation proved to be the one by Stephan and Abdelsalam. Despite a few decades since its creation, it proved to be quite successful when comparing with the very recent experimental research data of pure ethanol boiling heat transfer on the copper specimen. The classic correlation of Rohsenow did not offer much agreement with the experimental results. As is commonly known, up to date no widely accepted boiling correlation is available, thus research in this area is still needed to enable better modeling results for various heater material and liquid types. Another interesting subject is modelling of boiling on surfaces which were modified with various techniques.

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