NUCLEATE POOL BOILING HEAT TRANSFER
Review of Models and Bubble Dynamics Parameters

by

Andrijana D. STOJANOVIĆ*, Srdjan V. BELOŠEVIĆ, Nenad Dj. CRNOMARKOVIĆ, Ivan D. TOMANOVIĆ, and Aleksandar R. MILIĆEVIĆ

[a] Department of Thermal Engineering and Energy,
Vinca Institute of Nuclear Sciences, National Institute of the Republic of Serbia,
University of Belgrade, Belgrade, Serbia

Original scientific paper
https://doi.org/10.2298/TSCI200111069S

Understanding nucleate pool boiling heat transfer and, in particular the accurate prediction of conditions that can lead to critical heat flux, is of the utmost importance in many industries. Due to the safety issues related to the nuclear power plants, and for the efficient operation of many heat transfer units including fossil fuel boilers, fusion reactors, electronic chips, etc., it is important to understand this kind of heat transfer. In this paper, a comprehensive review of analytical and numerical work on nucleate pool boiling heat transfer is presented. In order to understand this phenomenon, existing studies on boiling heat transfer coefficient and boiling heat flux are also discussed, as well as characteristics of boiling phenomena such as bubble departure diameter, bubble departure frequency, active nucleation site density, bubble waiting and growth period and their impact on pool boiling heat transfer.

Key words*: pool boiling, critical heat flux, boiling crisis, prediction*

Introduction

Boiling represents the phenomenon of highly intensive phase change, significant for various industrial applications because of its very large heat transfer rates that can be achieved, but very complex and challenging for modelling. There is practically no field of industry where this heat transfer mode could not be applied: chemical engineering, biochemistry, petrochemical, nuclear power, thermal power plants, food industry, microelectronic device, computer data centers, electric vehicle*, etc.* Due to the large heat transfer during the changing phase from liquid to vapor, the boiling heat transfer has a higher heat transfer coefficient (HTC) regarding conduction and convection. Also, working life prediction accuracy of hot water boilers, thermal and nuclear power plants, refrigeration, and air conditioning units, largely depends on HTC modelling. However, the boiling crisis, which is characterized by a sudden heater temperature increase, potentially leading to heater damage or melting, constitutes a limit to this efficient heat transfer phenomenon. The physical nature of nucleate pool boiling is still far from being well understood despite the extensive investigation efforts by many scientists worldwide.

There are many empirical correlations and models for nucleate boiling in literature, each applicable to a restricted range of experimental conditions. A comprehensive review of nucleate pool boiling models with future prospectus is given in Ilić *et al.* [1]. Each model/correlation has its disadvantages because of the limitations of experimental conditions.

* Corresponding author, e-mail: andrijana@vinca.rs

As a result, no well-established theory exists for predicting the rate of heat transfer during boiling. Nevertheless, because of the practical importance of boiling heat transfer, thermal engineers have proposed various phenomenological models based on the insight gained from the experimental observations. In general, these models contain one or more empirical constants and have different levels of accuracies for different data sets. Until the complex physics of boiling is understood, the scope for improving such mechanistic models remains. Heat transfer rates could be improved by surface modification techniques that provide larger surface area, a higher density of nucleation sites, and smaller superheat for the phase change heat transfer. The accurate prediction of the critical heat flux (CHF), which can lead to heating surface destruction, is essential for the design and safe operation of high power density thermal systems such as boilers, heat exchangers, and nuclear reactors. In recent years, new boiling applications to the systems such as micro-mini scales, highly transient, or reduced-gravity conditions have come to light, so a full understanding of the boiling phenomenon is urgently required. This paper summarizes recent developments in the investigation of boiling phenomena and its characteristics - bubble dynamics parameters under nucleate pool boiling conditions, addressing main influencing factors, namely: effect of thermophysical properties, heat flux, liquid subcooling, wall superheat, contact angle, gravity, and pressure. This paper can be used in future works for facilitating the development of new models and correlations to achieve more reliable predictions.

Boiling heat transfer coefficient and boiling heat flux

The first study on nucleate pool boiling was performed by Nukiyama [2]. He distinguished different modes of pool boiling such as partial nucleate boiling, fully developed nucleate boiling, transition boiling, and film boiling. He has shown his results on the curve of the heat flux against the temperature difference which is called the boiling curve, fig. 1, [3]. Among the four stages of pool boiling heat transfer, the most effective heat transfer region is the nucleate pool boiling which is the region from the point of nucleation the point of CHF value. It consists of two parts: the isolated bubble region, where bubbles behave independently and the slugs and columns region, where bubbles start to merge and to depart from the heated surface using jets which then form large bubbles, or slugs, above the surface.

Modelling boiling requires many hypotheses whose validity cannot always be assessed. This results in a large number of different models, often with corrective factors. The results predicted by these models are sometimes far from the experimental results. Experiments in boiling also receive their share of difficulties. Phenomena are fast, bubbles interact, scales are multiple, material properties are not always well defined, especially wall roughness, and physical parameters are hard to measure in fluids. Boiling needs to be simplified in order to identify the role of the different mechanisms involved. An analysis of these works shows that major parameters affecting the HTC under nucleate pool boiling conditions are heat flux, saturation pressure and thermophysical properties of a working fluid. Many empirical and semi-empirical correlations for the determination of heat transfer values have been proposed which may supersede costlier experiments. Research efforts are directed towards the improvement of the boiling mechanism by lowering the surface tension between the boiling water and the solid surface [4, 5]. A significant influential parameter on boiling HTC is the liquid thermal conductivity and characteristics of the heated surface. Experimental conditions, such as gravitational force value [6], surface orientation [7], external fields [8], and boiling pressure [9] are some other parameters that affect boiling HTC. A comprehensive literature survey on parameters affecting nucleate boiling heat transfer performed by Pioro *et al.* [10] showed that the surface effects consists of thermophysical properties of the surface material (thermal conductivity and thermal absorption), the interaction between the solid, liquid, and vapor interface, and surface microgeometry (dimensions and shape of cracks and pores). Solid surfaces are typically characterized by microscopic imperfections (cavities) which act as embryos for bubble formation and growth. As a consequence, surface modification is one of the most promising ways to enhance boiling efficiency.

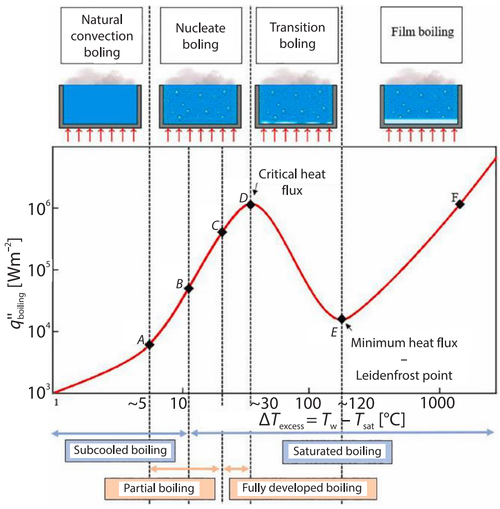

Figure 1. Pool boiling curve, [3]

Modelling studies

Once a bubble nucleates, it grows through evaporation of liquid at the liquid/vapor interface, fig. 2. A quickly growing, hemispherical shaped bubble can trap a thin layer of liquid between the growing bubble and the superheated wall (the micro-layer), and evaporation of this liquid contributes to bubble growth (q_{ml}). Another mechanism for bubble growth is through evaporation at the three-phase contact line (q_{cl}) once a dry patch forms on the surface due to partial dryout of the micro-layer. The growing bubble can also perturb the liquid adjacent to the bubble and disrupt the background natural convection boundary layer (q_{nc}), resulting in energy transfer by microconvection (q_{mc}). As the dry patch is rewet, transient conduction into the advancing liquid front can occur (q_{tc}). Because of the heat removed from the micro-layer nearby the three-phase contact line, the temperature in the vicinity of the nucleate site will drop greatly. When the bubble grows big enough, forces acted upon it, mainly the buoyancy in a gravitational field will make its departure from heating surface. Then the nucleate site will go through a recovering or waiting process until its superheat reaches the critical value and a new subsequent bubble forms again. Therefore, formation, growth, and detachment of the vapor bubble and the rate of heat transfer thereof require the knowledge of bubble dynamics parameters. These bubble dynamics parameters are nucleation site density, bubble departure diameter, bubble waiting period, bubble growth period, and bubble departure frequency. The determination of the boiling HTC can be done by using either empirical or semi-empirical correlations developed using bubble dynamics parameters.

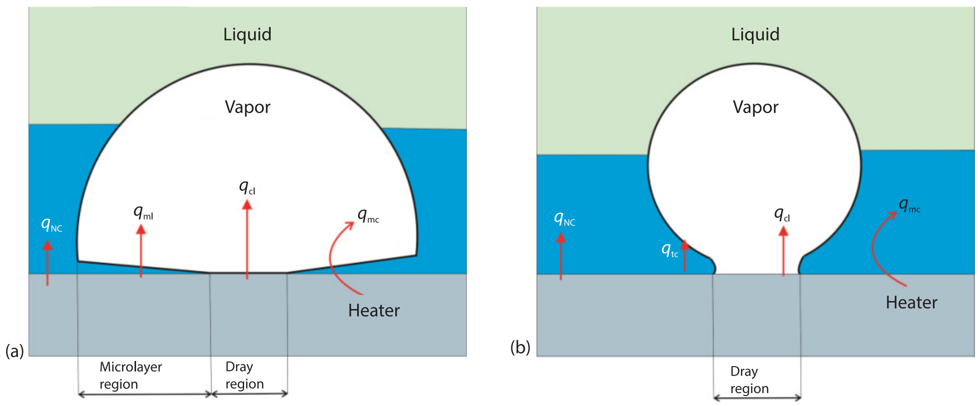

Figure 2. Physical mechanism of heat transfer during single-bubble nucleate boiling; (a) bubble growth period and (b) bubble departure period [11]

Many of the early models were based on bubble agitation/microconvection being the primary heat transfer mechanism. These models did not include phase change but relied on an analogy with forced convection, *i.e.*, the role of the bubble was to change the length and velocity scales used to correlate data (*e.g.*, Rosenhow 1952; Forster and Zuber, 1955; Forster and Greif 1959; Zuber 1963; Tien 1962). For example, the vapor-liquid exchange model proposed by Forster and Greif [12] assumed that bubbles act as micropumps which remove a quantity of hot liquid from the wall equal to a hemisphere at the maximum bubble radius, replacing it with cold liquid from the bulk. The heat transferred from a single site was the energy required to heat this volume of liquid from the bulk temperature to the average of the wall and bulk temperatures. Katto and Yokoya [13] developed a heat transfer model based on macrolayer evaporation. Haramura and Katto [14] and Pan *et al.* [15] developed their macrolayer model termed as near field phenomena considering the instability at the macrolayer interface as the main controlling parameter through the boiling process. Among the other efforts of near field model Pasamehmetoglu [16] described the phenomena by dry out of micro-layer (liquid layer of very small thickness below the growing bubble) and macrolayer. He *et al.* [17], Stojanovic *et al.* [18] and Pezo and Stevanović [19], numerically predicted the total boiling curve. They considered 3-D transient heat conduction through the heated wall to investigate the spatial variation of wall temperature. A summary of major existing correlations for pool boiling HTC is given in tab. 1.

Table 1. Heat transfer coefficient

Reference	Correlation	
[20]	$\dfrac{c_{pf}\Delta T}{h_{\mathrm{fg}}\mathrm{Pr}^{s}} = C_{\mathrm{sf}}\left[\dfrac{q}{\mu h_{\mathrm{fg}}}\sqrt{\dfrac{\sigma}{\mathrm{g}\left(\rho_{\mathrm{f}}-\rho_{\mathrm{g}}\right)}}\right]^{0.33}$	(2)
[21]	$\mathrm{Nu} = 0.44K_{*}^{0.7}\mathrm{Pr}^{0.35}$ or $\dfrac{h_{\mathrm{b}}l_{*}}{k} = 0.44\left\{\dfrac{1-10^{-4}qp}{\mathrm{g}h_{\mathrm{fg}}\rho_{\mathrm{g}}\mu}\dfrac{\rho}{\rho-\rho_{\mathrm{g}}}\right\}^{0.7}\mathrm{Pr}^{0.35}$	(3)
[22]	$h_{\mathrm{nc}} = 0.14\rho_{\mathrm{l}}c_{p\mathrm{l}}\left(\dfrac{\beta\mathrm{g}\Delta T_{\mathrm{sat}}\alpha_{\mathrm{l}}^{2}}{v_{\mathrm{l}}}\right)^{1/3}$	(4)
[21]	$\dfrac{h_{\mathrm{b}}l_{*}}{k} == 0.082\left[\dfrac{h_{\mathrm{fg}}q}{\mathrm{g}\left(T_{\mathrm{s}}+273.15\right)k}\dfrac{\rho_{\mathrm{g}}}{\rho-\rho_{\mathrm{g}}}\right]^{0.7}\left[\dfrac{\left(T_{\mathrm{s}}+273.15\right)c_{p}\sigma\rho}{h_{\mathrm{fg}}^{2}\rho_{\mathrm{g}}^{2}l_{*}}\right]^{0.33}\mathrm{Pr}^{-0.45}$	(5)
[23]	$h == 0.1\left(\dfrac{k_{\mathrm{l}}}{D_{\mathrm{d}}}\right)\left(\dfrac{qD_{\mathrm{d}}}{k_{\mathrm{l}}T_{\mathrm{sat}}}\right)^{0.67}\left(\dfrac{\rho_{\mathrm{v}}}{\rho_{\mathrm{l}}}\right)^{0.156}\left(\dfrac{h_{\mathrm{lv}}D_{\mathrm{d}}^{2}}{\alpha_{\mathrm{l}}^{2}}\right)^{0.371}\left(\dfrac{\alpha_{\mathrm{l}}^{2}\rho_{\mathrm{l}}}{\sigma D_{\mathrm{d}}}\right)^{0.35}\left(\dfrac{\mu_{\mathrm{l}}c_{p\mathrm{l}}}{k_{\mathrm{l}}}\right)^{-0.16}$	(6)
[11]	$h = 10\left(\dfrac{k_{\mathrm{l}}}{D_{\mathrm{d}}}\right)\left(\dfrac{qD_{\mathrm{d}}}{k_{\mathrm{l}}T_{\mathrm{sat}}}\right)^{c}\mathrm{Pr}^{0.1}\left(1-T_{r}\right)^{-1.4}\left(\dfrac{\rho_{\mathrm{l}}-\rho_{\mathrm{v}}}{\rho_{\mathrm{l}}}\right)^{0.33}\left(\dfrac{v_{\mathrm{l}}}{\alpha_{\mathrm{l}}}\right)^{-0.25}$, $c = 0.855\left(\dfrac{\rho_{\mathrm{v}}}{\rho_{\mathrm{l}}}\right)^{0.309}\mathrm{Pr}^{-0.437}$	(7)
[21]	$h_{\mathrm{b}} = 0.075\left[1+10\left(\dfrac{\rho_{\mathrm{g}}}{\rho-\rho_{\mathrm{g}}}\right)^{0.67}\right]\left[\dfrac{k^{2}}{v\sigma\left(T_{\mathrm{s}}+273.15\right)}\right]^{0.33}q^{0.67}$	(8)

Han and Griffith [22] consider that the heating surface consists of two regions, one that is influenced by the departing bubble – the area of bulk convection, and the other not influenced by the bubbles – the area of natural-convection. In the area of bulk convection, Han and Griffith assumed formation of a superheated thermal boundary-layer by transient heat conduction which induces bubble formation. Therefore, total heat flux can be expressed:

$$q = q_{\mathrm{NC}} + q_{\mathrm{BC}}$$

Mikic and Rohsenow [24] included the effect of heating surface characteristics into the model of Han and Griffith [22] and assume functional dependence of partial nucleate boiling heat flux on wall superheat. They neglected the contribution of evaporation total heat removal rate and derived an expression for partial nucleate boiling heat flux:

$$q = q_{\mathrm{con}} + q_{\mathrm{NC}} = \frac{K^2}{2}\sqrt{\pi(k\rho c_p)_{\mathrm{f}} f}\, D_{\mathrm{d}}^2 N_{\mathrm{a}} \Delta T + \left(1 - \frac{K}{4} N_{\mathrm{a}} \pi D_{\mathrm{d}}^2\right) h_{\mathrm{nc}} (T_{\mathrm{w}} - T_{\infty}) \tag{1}$$

where the parameter K is dependent on the area of influence of a bubble, and a value of 2 was assigned, N_{a}, D_{d}, and f are site density, departure diameter, and frequency of bubble, respectively. Equation (1) did yield the experimentally observed dependence of q on ΔT. It should be noted from eq. (1), that a quantitative prediction of the dependence of heat flux on wall superheat requires knowledge of several empirical constants.

Judd and Hwang [25] developed a model similar to that by Mikic and Rohsenow [24], which accounted for micro/macrolayer evaporation at the base of the bubble. Therefore, they added the third term for micro-layer contribution the right-hand side of eq. (1), which is:

$$q_{\mathrm{e}} = V_{\mathrm{e}} N_{\mathrm{a}} \rho_{\mathrm{f}} h_{\mathrm{fg}} f$$

Using micro-layer thickness measured from experiments in which dichloromethane was boiled on a glass surface, and assuming that parameter K in eq. (1) had a value of $1.8^{1/2}$, they got a match with predictions of experimental data. Paul and Abdel-Khalik [26] experimentally found out that total heat transfer in pool boiling consists of three modes: heat transfer from evaporation – at intermediate and high heat fluxes, forced convection – in the intermediate region, and natural-convection – at low heat fluxes. Therefore, the total heat flux can be expressed:

$$q = q_{\mathrm{LH}} + q_{\mathrm{NC}} + q_{\mathrm{FC}}$$

Benjamin and Balakrishnan [27] developed a new model considering the following mechanisms:

– heat absorbed by the evaporating micro-layer, q_{ME},
– heat energy expended in the re-formation of the thermal boundary-layer, q_R, and
– heat transferred by turbulent natural-convection, q_{NC}.

Therefore, the total boiling heat flux is represented:

$$q = \frac{q_{\mathrm{ME}}\tau_{\mathrm{g}} + q_R \tau_{\mathrm{w}}}{\tau_{\mathrm{g}} + \tau_{\mathrm{w}}} + q_{\mathrm{NC}} \tag{9}$$

where the weighted sum of the first two fluxes is used because the two modes are complementary to each other.

From aforementioned, it can be concluded that all models on nucleate pool boiling can be divided into four major categories: bubble agitation models, vapor-liquid exchange models, latent heat and macro- and micro-layer evaporation models, and dry spot models. The bubble agitation models are based on the assumption that processes of bubble growth and detachment agitate the surrounding liquid to the heat transfer process (Rohsenow's model [20] and Zuber's [28] microconvection model). According to Liang and Mudawar [29], this type of model indicates that CHF will occur when neighboring bubbles coalesce radially, causing coverage of the surface with vapor. In the vapor-liquid exchange models, the moving bubbles are assumed to act as microscopic pumps which carry away the heat from the near-wall region and draws the cold fluid to the surface. This kind of model is not realistic. In the third group of models, evaporation of the liquid macro- and micro-layer has a major role, especially at high heat flux regime. The liquid layer which covers heated surface consists of micro-layer underneath the bubble and the macrolayer at the base of the coalescence bubble.

In his foundation work termed as *far field model*, Zuber [28] proposed one of the earliest models of CHF. According to his study, CHF is triggered by the Taylor/Helmholtz instability in the vapor-liquid interface of the vapor columns originating from the heating surface during the process of nucleate boiling. Hence, hydrodynamic instability leads to a breakdown in the process of vapor removal from the heating surface, which results in the entire dry out of the heated surface. This causes the surface temperature to increase dramatically, whereas in a temperature-controlled system, this causes a slight reduction in the heat flux. This model acts as a basic model for a number of researchers who applied it to a variety of pool boiling situations. However, Sadasivan *et al.* [30] pointed out the drawbacks of this model. Namely, this model does not take into account the temperature of the heating surface and CHF is entirely a function of the hydrodynamics of the vapor flow in the vapor columns above the heating surface. Therefore, the CHF takes place when the vapor-liquid interface of the escaped passage becomes unstable due to Helmholtz instability. Hence, the heating surface geometry relates to CHF through its boiling area and the hydrodynamic flow pattern, which the given geometric configuration generates.

Whereas the bubble agitation mechanism and Helmholtz-instability mechanisms cannot explain the continuity of pool boiling curve, the researchers carried out numerous experimental and modelling efforts on liquid layer evaporation mechanism. Haramura and Katto [14] and Pan *et al.* [15] presented another CHF theory that is based on the role of the macrolayer. The basic element of Zuber's model that hydrodynamic instabilities dictate the occurrence of CHF is incorporated into these models. However, in their model, controlling instabilities occur not at the walls of large vapor columns but rather at the walls of tiny vapor stems around active nucleate cavities that intersperse the liquid macrolayer on the heater surface itself. Although these models postulate the periodic supply of liquid macrolayer during nucleate boiling and CHF, other models highlight the significance of the evaporation of micro liquid layer and the decreasing of dry area of individual bubbles. Numerous studies have been done to investigate these complex transport processes, but due to experimental difficulties, only a few studies have focused on the micro-phenomena of such processes. For example, Cooper and Lloyd [31], experimentally confirmed the existence of a thin evaporating micro-layer beneath a growing bubble in nucleate pool boiling and they observed that the evaporation of the micro-layer contributed significantly to the growth of the bubble. However, there are a lot of differences among these models although they can explain CHF fairly well. Haider and Webb [32] took into account the following possible mechanisms that could lead to the high heat flux in nucleate boiling:

– transient conduction, and subsequent replacement of, the superheated liquid layer in contact with the heating surface,
– evaporation of a thin liquid micro-layer beneath the growing bubble, and
– circulation of liquid in the vicinity of a growing bubble due to thermocapillary effects at the vapor-liquid bubble interface.

Most of the experimental studies on CHF mechanism pointed out that the boiling curve around the CHF point is a continuous function of the wall superheat and the boiling mechanism does not change drastically at CHF, Nishio and Tanaka, [33]. However, it is expected that vapor and liquid transport balances would change. Zhao *et al.* [34] conducted a research on a new dynamic micro-layer model to predict theoretically CHF in transient and fully developed nucleate boiling regions for pool boiling on horizontal surfaces. According to their experimentally-validated model, the main boiling heat transfer mechanism was the evaporation of the micro-layer. The micro-layer thickness and the dry out area, as well as the wall heat flux, were formulated as functions of wall superheat. They also pointed out that with increasing wall superheat the micro-layer becomes thinner and both the evaporation and the partial dry out speed of the micro-layer increase. Das *et al.* [35] put forward an analytical model of heat transfer during pool boiling based on the macrolayer theory. It is based on micro-, and macro-layer evaporation on the heated surface. They have shown that transient conduction from the surrounding liquid influence evaporation at the final stage of the bubble growth. Their model could be applied to transient and steady-state heating.

Dry spots models, first proposed by Yagov [36, 37], are based on experimental observations of small dry spots on the heated surface during nucleate boiling. According to the direct visualization results [38, 39], some authors confirm the existence of hot spots at heated surface and that the main cause for CHF is the irreversible growth of a dry spot area on the surface. Also, Zhao and Williams [40] developed a new model to predict CHF based on the experimental observation of irreversible hot spots. Hot spots underneath the bubbles, at or above the CHF, shrink and expand periodically but never disappear. They are named irreversible hot spots. The authors assumed that CHF is triggered by these spots. They defined the instability criterion predict whether the instability occurs or not. Theofanous *et al.* [41] performed a nucleate pool boiling experiment using a high speed, high resolution camera. They observed the formation of hot spots within the bubble base identified as dry spots at high heat fluxes. Jung *et al.* [42] performed an experiment to explore single-bubble nucleate phenomena in a pool of water subcooled by 3 °C under atmospheric pressure. They concluded that the overall contribution of the micro-layer evaporation the growth of a bubble is relatively small and equals to 17% of the total heat transport, and the remaining 83% was supplied by heat transfer from superheated bulk liquid surrounding the bubble. They considered that CHF occurs as dry spot size increases faster than the increase in heat transfer through the wetted area, indicating that higher CHF can be achieved by either increasing the wetted fraction of the surface or by improving heat transfer through the wetted portions.

There are numerous attempts to numerically analyze pool boiling. To capture large deformation of the liquid-vapor interface, interface tracking methods were introduced. They represent a visualization technique that allows the scientists to identify and follow dynamic behavior of the interface of fluid [43]. They can be divided into three categories: front tracking methods, level set method, and volume of fluid method. Front tracking methods address the marked interface from an initial configuration and keeps the topology of the interface during the simulation. Volume tracking methods overcome the changing topology problems by dividing the domain into a union of disjoint solution regions. The boundary between these regions is the interface location. It is currently the best-established method. With level set method, the material boundary or interface is defined as a zero set of isocontour or isosurface of the given scalar field, but material volume is not well preserved. A level set (LS) method was introduced by Son *et al.* [44], a front tracking method (FT) by Juric and Tryggvason [45], and a volume of fluid (VOF) method by Welch and Wilson [46]. The most common and widely applied method is volume of fluid method. It keeps tracking the volume of each fluid phase with a sub-volume. This method is used by many authors for instance, Jia *et al.* [47] employed VOF interface capture method for 2-D numerical investigation of nucleate boiling of refrigerant R113. They used modified Height Function algorithm, smoothed evaporation model and the micro-layer model. Kunkelmann and Stephan [48] investigated nucleate boiling of water on a heating wall using the VOF method. Later, they extended and modified this method to simulate boiling of HFE-7100 refrigerant [49]. Their model incorporates mass, momentum, and phase transfer in fluid, contact line evaporation and transient heat conduction in the heating wall. The most recent study on nucleate boiling simulation using the interface tracking method is reported by Li *et al.* [50]. With this boiling model, they investigated interactions between bubbles forming at adjacent nucleation sites. It considers that a multi-phase flow with sharp property variances across an interface is treated as a continuous fluid whose properties vary from liquid phase to gas phase over a narrow range of values. Using the level set method as one of the widely-used interface tracking algorithms, the interface between phases is resolved and tracked. Stojanović *et al.* [18] and Pezo and Stevanović [19] performed a multidimensional numerical simulation of the atmospheric saturated pool boiling, taking into account the micro conditions at the heated wall surface. The applied modelling and numerical methods enable a full representation of the liquid and vapor two-phase mixture behavior on the heated surface, with included prediction of the swell level and heated wall temperature field. In this way, the integral behavior of nucleate pool boiling is simulated. Regarding previous models of boiling crisis which were based on an assumption about the two-phase mixture pattern at the heater surface in pool boiling at CHF conditions, this model calculates two-phase mixture structure based on the two-fluid model, *i.e.* on the solution of flow equations, without a need for any assumption about two-phase mixture pattern.

Characteristics of pool boiling phenomena

Bubble departure diameter

The bubble departure diameter is one of the most important parameters in heat transfer analysis. It is defined as the final or equivalent diameter of the vapor bubble after it departs from the heated surface during boiling. It can be obtained by experiment or by force balance. Various correlations for the determination of bubble departure diameter during boiling are presented in tab. 2. There are numerous correlations for predicting bubble departure diameter and they can be grouped into two types. One is based on Fritz correlation [51] and other does not. The correlations of the first type have tried to relate Bond number to the effects of fluid properties, pressure, superheat or Jacob number, heat flux, as well as surface properties, Fritz [51], Cole [53], Kutateladze and Gogonin [58], Jensen and Memmel [54], Kim and Kim [59], Fazel and Shafaee [60], and Hamzekhani *et al.* [61].

The correlations of the second type usually incorporate the bubble growth rate, Golorin *et al.* [62], Zeng *et al.* [63], Yang *et al.* [64]. Phan [55] proposed the energy factor defined as the ratio of energy needed to form a bubble with a contact angle to the energy needed to form a homogeneous bubble with the same diameter. Phan [56] also obtained theoretically the correlation eq. (14) under the condition of However, a drawback of Phan's correlation is its inability to predict the bubble departure diameter at high superheat and high sub-cooling. Zeng [63] believed that the unstable growth force would make the bubble depart. Each force should be defined to calculate the unstable growth force. Experimental and numerical investigations were also conducted on the bubble growth as well as the interaction and coalescence of adjacent bubbles.

Table 2. Bubble departure diameter

Reference	Correlation	
[51]	$D_b = 0.0146\theta\sqrt{\dfrac{2\sigma}{g(\rho_l - \rho_v)}}$	(10)
[52]	$D_b = (50\sqrt{27}\mathrm{Ja}\alpha\sqrt{\rho_l l\sigma})^2$	(11)
[53]	$D_b = \left(\dfrac{0.004T_{sat}c_{pl}}{\rho_v h_{lv}}\dfrac{\sigma}{\Delta\rho g}\right)^{1/2}$	(12)
[54]	$D_b = 0.19\left(1.8+10^5 K\right)^{2/3}\left(\dfrac{\sigma}{\Delta\rho g}\right)^{1/2}, \; K = \dfrac{\mathrm{Ja}}{\mathrm{Pr}_l}\left[\dfrac{\Delta\rho g}{\rho_l v_l^2}\left(\dfrac{\sigma}{\Delta\rho g}\right)^{2/3}\right]^{-1}$	(13)
[55]	$D_b = 0.626977 f(\theta)\left(\dfrac{\sigma}{\Delta\rho g}\right)^{1/2}, \; f(\theta) = \dfrac{2+3\cos\theta - \cos^3\theta}{4}$	(14)
[56]	$D_b = 1.94\left(\dfrac{\rho_l}{\rho_v}\right)^{-1/2}\left(\dfrac{\rho_l}{\rho_v}-1\right)^{1/3}\tan\theta^{-1/6}\left(\dfrac{\sigma}{\ddot{A}\rho g}\right)^{1/2}$	(15)
[57]	$D_b = 0.0012\rho^{*0.9}D_{bF}, \; D_{bF} = 0.0148\theta\sqrt{\dfrac{2\sigma}{g\Delta\rho}}, \; D_b = 2.5\cdot 10^{-5}\rho^{*0.9}\theta\sqrt{\dfrac{\sigma}{g\Delta\rho}}$	(16)

Active nucleation site density

Nucleate boiling, by definition, is characterized by the formation of vapor bubbles on a heated surface at certain preferred locations known as *nucleation sites* when the heating surface is maintained at a temperature of the liquid with which it is in contact. This *nucleation site density* is one of the most significant parameters in nucleate boiling, because with the increase in nucleation site density the HTC also increases. Namely, the existence of active vapor generating centers decreases the surface temperature not only near the generating center but also on the free surface, resulted in increasing the HTC. Therefore, a number of studies have been directed toward increasing the number of such sites by polishing, etching, sintering, and using coatings of various types on the heating surface. So, the nucleation site density can be defined as some cavities present on the heating surface on which vapor bubbles are growing. Griffith [22] defined the critical nucleation radius:

$$R_c = \frac{2\sigma T_{sat}}{\rho_v h_{lv}\Delta T_{sat}} \tag{17}$$

But not all cavities can be active vapor generating centers. Relatively large cavities filled with liquid cannot be active vapor bubble centers. Although there are many experimental studies reported in the literature to examine the nucleation site density and its dependence on the surface and liquid properties, most of them pertain only to specific surfaces and liquids, and it is difficult to generalize the conclusion. Kolev [65] proposed correlations for nucleation site density dependent on wall superheat and for various contact angles. Pioro *et al.* [10] in his review paper pointed out the following correlation for estimation of vapor bubble generating centers:

$$\sqrt{n} = 25 \cdot 10^{-8} \left(\frac{h_{fg} \rho_g \Delta T}{T_s \sigma} \right)^{1.5} \tag{18}$$

Basu *et al.* [66] proposed an empirical correlation including the effect of the contact angle on the active nucleation site density during forced convective boiling of water on a vertical surface based on their experimental data. From pictures of heater surface during subcooled flow boiling experiments on flat plate copper surface and a nine-rod (zircalloy-4) bundle, they measured the active nucleation site density. Based on their experimental observation, Benjamin and Balakrishnan [67] examined the surface-liquid interaction during the boiling phenomena and its effect on the nucleation site density. They found that the nucleation site density depended on surface micro-roughness, the surface tension of the liquid, thermophysical properties of the heating surface and the liquid and the wall superheat. Finally, following correlation in terms of the wall superheat ΔT_w, Prandtl number, a surface-liquid interaction parameter γ, and a dimensionless parameter θ, was proposed:

$$N_{np} = 218.8 \mathrm{Pr}^{1.63} \left(\frac{1}{\gamma} \right) \Theta^{-0.4} \Delta T_w^3 \tag{19}$$

A comparison of direct measurements of active nucleation site density from different authors has been shown in fig. 3. It can be observed from the figure that an increase in heat flux values results in increasing nucleation site density.

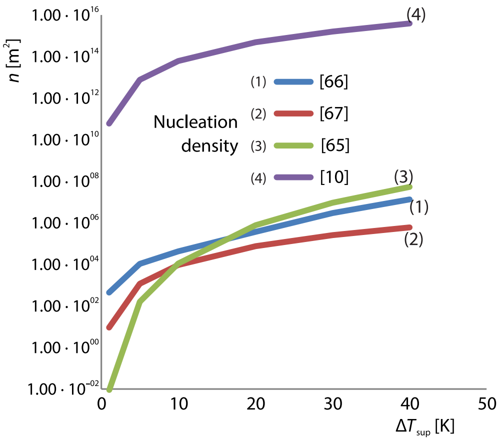

Figure 3. Comparison of direct measurements of active nucleation site density from different authors

Bubble waiting period

The bubble waiting period is another important parameter for determining the dynamics characteristics of nucleate pool boiling. Time taken by the thermal layer to develop before inception is termed the waiting period. There are many correlations from different authors for the bubble waiting period among which Han and Griffth's [22] is the most known. They obtained an analytical expression for the waiting period by assuming the liquid layer to be semi-infinitive:

$$\tau_w = \frac{9}{4\pi\alpha_l} \left[\frac{(T_w - T_\infty) R_c}{(T_w - T_s)\left(1 + \frac{2\sigma}{R_c \rho_v h_{lv}}\right)} \right]^2 \tag{20}$$

From the aforementioned waiting period relation, it can be seen that the waiting period is a dual function of R_c. Waiting time will first decrease and then increase with cavity size, however, it will continuously decrease as the wall superheat is increased. Van Stralen *et al.* [68] proposed a relation between bubble waiting period and bubble growth period for pure liquids which is three times longer than bubble growth period in the same nucleation cavity: $\tau_w = 3\tau_g$.

Bubble growth period

The bubble growth period implies the amount of heat removed from the heating surface. Therefore, it has a strong effect on bubble dynamics. It is defined as the time interval between the moment when vapor bubble starts growing from a cavity, until the bubble departs from the heating surface. In other words, it is the time taken for a bubble to grow from its initial to its departure size before it is detached from the heated surface. Zuber [69] proposed the following correlation for bubble growth period in non-uniform temperature fields:

$$\tau_{\mathrm{g}} = \frac{D_{\mathrm{d}}^2}{16b^2 (\mathrm{Ja})^2 \alpha_{\mathrm{l}}} \tag{21}$$

where b is a constant whose magnitude is varied between 1 and $3^{1/3}$. Hatton and Hall [70] obtained correlation based on Plesset and Zwick`s [71] bubble growth period expression which is dependent on bubble departure diameter and nucleation cavity radius:

$$\tau_{\mathrm{g}} = \frac{\pi \alpha_l}{3} \left\{ \frac{(\rho_{\mathrm{v}} h_{\mathrm{lv}})^2 D_{\mathrm{d}} R_{\mathrm{c}}}{8 k_{\mathrm{l}} \sigma T_{\mathrm{sat}}} \right\}^2 \tag{22}$$

Bubble departure frequency

A very important bubble dynamics parameter for the determination of the HTC is bubble departure frequency. It is dependent on bubble waiting and bubble growth period and is defined as reciprocal of the time period of two nucleations during nucleate boiling.

Ivey [72] proposed three correlations with the product of departure frequency and the different power of departure diameter for three regions:
– hydrodynamic region in which buoyancy and drag forces predominate, eq. (23),
– transition region where buoyancy, drag, and surface tension forces are in the same order, eq. (24), and
– thermodynamic region where bubble growth dominates, eq. (25), tab. 3.

Table 3. Bubble departure frequency

$f \frac{D_{\mathrm{d}}^{1/2}}{\mathrm{g}^{1/2}} = 0.90$ (23)	$f \frac{D_{\mathrm{d}}^{3/4}}{\mathrm{g}^{1/4}} = 0.44\ \mathrm{cm}^{1/4}$ (24)	$f D_{\mathrm{d}}^2 = \mathrm{constant}\quad \mathrm{m^2/s}$ (25)

Usually, bubble departure frequency is expressed as the reciprocal of the summation of a bubble waiting time and bubble growth time:

$$f = 1/(\tau_{\mathrm{w}} + \tau_{\mathrm{g}})$$

As a large number of experiments have shown, the bubble departure frequency depends not only on wall superheat, thermophysical properties of the fluid, phase contact angle, cavity size, and interactions between neighboring bubbles but also on surface roughness [73]. Experimentally, it is measured by counting the total number of bubbles that emerged from a cavity during 1 scale of recording time. For instance, Hutter *et al.* [74] in their experiment on pool boiling of FC-72 with cavities on silicon, measured it as the average value of five successive bubbles. According to them, bubble departure frequency can be calculated as a ratio of the total number of bubbles to the time interval:

$$f = N_{\mathrm{bubble}} / t_{\mathrm{total}}$$

Determination of bubble departure frequency could not be possible without knowledge of bubble departure diameter, bubble waiting period, bubble growth period, surface tension, heat flux, and thermophysical properties of fluids. However, existing correlations do not fit well with the experimental values of other investigators. Therefore, a new correlation for bubble departure frequency should be developed taking into account other influencing parameters such as surface roughness, cavity size, system pressure, and different solid-liquid interaction parameters.

Surface modification and additives

There are numerous efforts to improve HTC by enhancing boiling surface using porous materials, sintered wires, and meshes, as well as fins [6, 75, 76]. Altering surface topography, based on the argument that it increases the liquid-solid contact area, leads to an increase in the portion of convection and promotes the appearance of active nucleation sites within the heterogeneous nucleation process thus contributing to the portion of latent heat. Likewise, Tang *et al.* [77], fabricated a nanoporous surface to investigate the boiling efficiency in a subcooled pool boiling area. They achieved a maximum of 173% improvement in HTC. Zhang and Kim [78] achieved significant heat transfer enhancement in the nucleate pool boiling regime by creating 1-D grown alumina nanoporous surface as well as by applying a hydrophobic Self-Assembled Monolayer coating. They found that for hydrophobic surface, bubbles carry away more heat from the surface which leads to reduced waiting time and huge internal/external convection. Jaikumar and Kandlikar [79] showed that the utilization of copper chips with micro-channels can increase HTC. Also, they applied porous coatings on fin tops which provided additional nucleation sites, creating a micro convection heat transfer mechanism and significantly enhanced HTC. Other studies [80, 81] showed that liquid-vapor pathways separation leads to a reduction in flow resistance between two countercurrent flows and a superior feeding of nucleation sites occurs which leads to a higher HTC. There are numerous attempts to enhance HTC by improving surface characteristics by applying hydrophobic/hydrophilic coatings [82]. By increasing the surface wettability, the density of nucleation sites decreases and this leads to a delay in the departure of fluid from the surface. Due to this fluid departure delay from the surface, bubble departure frequency decreases. Moreover, with a higher wettability, required liquid supplies for evaporation at micro-layers increase and as a result, CHF enhances. On the other hand, hydrophobic surfaces increase the number of nucleation sites and result in higher HTC. Betz *et al.* [83] enhanced both HTC and CHF by mixed hydrophilic and hydrophobic coatings of the surface. They found that hydrophobic zones enhanced HTC by promoting nucleation, while hydrophilicity enhances CHF by preventing the formation of an insulating vapor layer on the surface.

An important parameter that affects the efficiency of nucleate pool boiling heat transfer is wettability, which can be quantified as the contact angle. It is the ability of liquid to maintain contact with a solid surface. The contact angle is the angle formed by a liquid at the three-phase boundary where liquid, gas, and solid surface intersect. There can be distinguished two types of contact angle: static contact angle and dynamic, regarding the movement of the three-phase boundary. Mukherjee and Kandlikar [84] have studied numerically the effect of dynamic contact angle on nucleate pool boiling. It was shown that the advancing contact angle is always larger than the receding one. They also found that there was little effect on the bubble growth rate whether a static or dynamic contact angle was used. However, it affected the departure time significantly. Also, there are numerous efforts to investigate the effect of contact angle on the heat transfer of the hydrophilic surface [85, 86]. It is indicated that increasing wettability (contact angle) of the heating surface will reduce the active nucleation site density and bubble departure frequency, and thus weaken the heat transfer coefficient of the heating surface. Zhang *et al.* [87] numerically studied the influence of thickness and material properties of the solid wall on bubble dynamics and local heat transfer. They concluded that for the same material and bottom temperature, bubble growth time decreases with the wall thickness, while the departure diameter increases. Waiting time increases with decreasing thermal diffusivity of solid walls that will produce a thickened thermal boundary-layer. Among the aforementioned factors affecting boiling dynamic parameters, the least known effect is the effect of boiling surface characteristics on boiling heat transfer. The surface roughness may affect the HTC only when surface roughness changes coincide with the appearance of new vapor generation centers, thus widening the range of active cavities. In general, the effect of surface characteristics on the boiling process depends on thermophysical properties of the surface material (thermal conductivity and thermal absorption), interactions between the solid surface, liquid and vapor (wettability, adhesion, adsorption), surface microgeometry (dimensions and shapes of cracks and pores), *etc.* All these parameters affect the HTC simultaneously and are interlinked, but they are not still completely investigated. According to the literature, stable vapor bubble generating centers can be only those microgeometry elements that are not filled with liquid after vapor bubble departure. Besides surface wettability, the main parameters that determine this ability of a cavity to preserve a *ready* vapor nucleus are its shape and size. Kutateladze and Gogonin [58] suggested that it is impossible to estimate quantitatively the combined effect of various microgeometry parameters on the HTC.

Researchers also attempted to find the influence of pressure, gravitational force value, surface orientation, and external fields on bubble dynamics parameters [6-9]. Some of the results have shown that the bubble growth rate decreases with an increase in pressure. Others [88], reported that the bubble departure frequency slightly decreases with an increase in pressure whereas, there is no influence of pressure on departure diameter and bubble waiting period. Kweon and Kim [89] experimentally found out that the electric field affects pool boiling in two aspects, including electro-hydrodynamic effects on bubble growth and bubble departure. They observed that by increasing the voltage of a non-uniform electric field the active nucleation site density, bubble departure frequency and velocity increase and bubble departure size decreases. Zhang *et al.* [6] performed an experiment of nucleate pool boiling of gas saturated FC-72 on smooth surface and micro-pin-fins under different heat fluxes in microgravity. They showed, that the average bubble departure radius in microgravity is much larger than in normal gravity. Besides, results showed that the micro-pin finned surface increase number of bubbles and decrease bubble size improving heat transfer from the heated surface.

Conclusion

The boiling process is an aggregate of many subprocesses and their interactions. Some of the subprocesses are better understood than others, but when it comes to their interactions our understanding is very limited. As briefly presented in this work, many studies with the objective to find efficient methods for increasing boiling heat transfer do not clarify the boiling phenomena itself, but rather help to better understand the conditions of vapor bubbles nucleation and interaction between active nucleation sites. Studies aimed at developing new generalized correlations for the HTC are deficient. With the advances of numerical models and the increase of computing power, CFD simulations are rapidly improving our knowledge of pool boiling heat transfer. Nevertheless, because of the complex phenomena involved, nucleate pool boiling is highly difficult to predict accurately.

Prediction of boiling phenomena strongly depends on micro-conditions in nucleation site, liquid superheat, the mass of evaporation per unit volume and time, as well as a void fraction and the two-phase mixture swelling level. One of the key unresolved issues in the prediction of nucleate and transition boiling heat fluxes is the knowledge of the density of active nucleation sites. Significant effort has to be made to provide detailed information so that hypotheses made in the development of models are proved with little doubt. The correlations of boiling characteristics, available in the literature, are aimed at surface modification and sensitive to experimental conditions. Studies have revealed that thermophysical properties of the surface material, interactions between the solid surface, liquid, and vapor, as well as surface microgeometry, affect the HTC but are not still completely investigated. Therefore, there is a need for new experimental research that should be conducted on simple geometries and should initially involve as few variables as possible. Considerations must be given to the development of new measurement techniques, as well. Existing numerical modelling studies also need to be improved to develop more generalized models that could be applied to most of the different pool boiling situations. These models should be almost mechanistic and free of empirical parameters or require only a limited number of adjustable parameters.

Acknowledgment

The research was funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

Nomenclature

b – width of the nucleation zone, [m]
c – constant in Jung's correlation
c_p, c_{pf}, c_{pl} – specific heat, [Jkg^{-1}K^{-1}]
C_D – interfacial drag coefficient, [–]
C_{sf} – empirical constant used in Rohsenow correlation
C^*_{sf} – empirical constant used in Pioro correlation
D – diameter, [m]
D_b, D_d – bubble departure diameter, [m]
f – bubble departure frequency, [s^{-1}]
g – gravitational acceleration, [ms^{-2}]
h_{fg}, h_{lv} – latent heat of vaporization, [Jkg^{-1}]
h, h_{nc} – heat transfer coefficient, [Wm^{-2}K^{-1}]
Ja – Jacobs number ($=\rho_l c_{pl}(T_w - T_{sat})/\rho_v h_{lv}$), [–]
Nu – Nuselt number ($=hL/k$), [–]
N_a – active nucleation site density, [m^{-2}]
Pr – Prandtl number ($=\mu c_p/k$), [–]
R_c – cavity radius, [m]
k – thermal conductivity, [Wm^{-1}K^{-1}]
K_* – area factor of the bubble departure
K – proportional constant for bubble diameter of influence
l_* – pool boiling characteristic dimension, water capillary length, [m]
n – density of nucleation sites, [m^{-2}]
p – pressure, [Pa]
q – heat flux, [Wm^{-2}]
q_h – volumetric heat rate, [Wm^{-3}]
q_b – volumetric heat source for bubble generation on the heater's surface, [Wm^{-3}]
q_{NC} – heat flux by natural convection, [Wm^{-2}]
q_{FC} – heat flux due to forced convection, [Wm^{-2}]
q_{BC} – heat flux in the area of bulk convection, [Wm^{-2}]
q_{LH} – heat flux due to latent heat, [Wm^{-2}]
q_e – evaporative heat flux, [Wm^{-2}]
q_{ME} – heat flux due to microlayer evaporation, [Wm^{-2}]
q_{CON}, q_R – heat flux due to transient conduction, [Wmï 2]
T – temperature, [K]
ΔT – wall superheat [K]
x – co-ordinate, [m]

Greek symbols

α – thermal diffusivity, [m^{2}s^{-1}]
β – empirical constant, [–]
θ – wetting contact angle
ρ – density, [kgm^{-3}]
ν – kinematic viscosity, [m^{2}s^{-1}]
σ – surface tension, [Nm^{-1}]
μ – dynamic viscosity, [Pa·s]
τ_g – bubble growth time, [s]
τ_w – bubble waiting time, [s]

Subscripts

b – boiling
c – condensation
e – evaporation
f – liquid phase
g – gas phase
l – liquid phase
p – particle
r – reduced property
s, sat – saturation
v – vapor phase
w – wall

References

[1] Ilic, M., *et al.* Boiling Heat Transfer Modelling: A Review and Future Prospectus, *Thermal Science, 23* (2019), 1, pp. 87-107
[2] Nukiyama, S., Maximum and Minimum Values of Heat Transmitted from Metal to Boiling Water under Atmospheric Pressure, *Journal of the Japanese Society of Mechanical Engineers* (in Japanese)*, 37*, (1934), pp. 367-374, (in Japanese), *International Journal of Heat and Mass Transfer, Vol.9,* (1966), 12, pp. 1419-1433. (in English)
[3] Cengel, Y., A.*, Heat Transfer: A Practical Approach*, McGraw Hill, New York, USA, 2003
[4] Najim, A., Pise, S., Boiling Heat Transfer Enhancement with Surfactant on the Tip of a Submerged Hypodermic Needle as Nucleation Site, *Applied Thermal Engineering, 103* (2016), pp. 989-995
[5] Xu, Z. G., Zhao, C. Y., Enhanced Boiling Heat Transfer by Gradient Porous Metals in Saturated Pure Water and Surfactant Solutions, *Applied Thermal Engineering, 100* (2016), pp. 68-77
[6] Zhang, Y.*, et al.,* Bubble Dynamics in Nucleate Pool Boiling on Micro-Pin-Finned Surfaces in Microgravity, *Applied Thermal Engineering, 70* (2014), 1, pp. 172-182
[7] Dadjoo, M., *et al.,* Influence of Orientation and Roughness of Heater Surface on Critical Heat Flux and Pool Boiling Heat Transfer Coefficient of Nanofluid, *Applied Thermal Engineering 124* (2017), pp. 353-361
[8] Abdollahi, A., *et al.*, Experimental Analysis of Magnetic Field Effect on the Pool Boiling Heat Transfer of a Ferrofluid, *Applied Thermal Engineering, 111* (2017), pp. 1101-1110
[9] Choon, N. K., *et al*., New Pool Boiling Data for Water with Copper-foam Metal at sub-atmospheric Pressures: Experiments and Correlation, *Applied Thermal Engineering, 26* (2006), 11-12, pp.1286-1290
[10] Pioro, I. L., *et al*., Nucleate Pool Boiling Heat Transfer. I: Review of Parametric Effects of Boiling Surface*, International Journal of Heat and Mass Transfer*, *47* (2004), 23, pp. 5033-5044
[11] Jung, D.*, et al.,* Nucleate Boiling Heat Transfer Coefficients of Pure Halogenated Refrigerants, *International Journal of Refrigeration, 26 (*2003), 2, pp. 240-248
[12] Kim, J., Review of Nucleate Pool Boiling Bubble Heat Transfer Mechanisms, *International Journal of Multiphase Flow*, *35 (*2009), 12, pp. 1067-1076
[13] Katto, Y., Yokoya, S., Behavior of a Vapor Mass in Saturated Nucleate and Transition Pool Boiling, *Heat Transfer – Japanese Research, 5* (1975), 2, pp. 294-305
[14] Haramura, Y., Katto, Y., A New Hydrodynamic Model of Critical Heat Flux Applicable Widely to Both Pool and Forced Convection Boiling on Submerged Bodies in Saturated Liquids, *International Journal of Heat and Mass Transfer*, *26* (1983) 2, pp. 389-399
[15] Pan, C., *et al*., The Mechanism of Heat Transfer in Transient Boiling, *International Journal of Heat and Mass Transfer*, *32* (1989), 7, pp. 1337-1349
[16] Pasamehmetoglu, K. O., Numerical modeling of a nucleate boiling surface, *Numerical Heat Transfer:* International Journal of Computational Methods – Part A: *Appl., 25* (1994), 6, pp. 703-719
[17] He, Y., *et al*., Numerical Study of High Heat Flux Pool Boiling Heat Transfer, *International Journal of Heat and Mass Transfer*, *44* (2001), 12, pp. 2357-2373
[18] Stojanovic, A., *et al*., Numerical Investigation of Nucleate Pool Boiling Heat Transfer, *Thermal Science*, *20* (2016), Suppl. 5, S1301-S1312
[19] Pezo, M., Stevanovic, V., Numerical Prediction of Critical Heat Flux in Pool Boiling with Two-Fluid Model*, International Journal of Heat and Mass Transfer*, *54* (2011), 15-16, pp. 3296-3303
[20] Rohsenow, W. M., A Method of Correlating Heat Transfer Data for Surface Boiling of Liquids, Technical report No. 5, Massachusetts Institute of Technology, Heat Transfer Laboratory, Cambrige, United States, 1951
[21] Pioro, I. L, *et al.,* Nucleate Pool Boiling Heat Transfer II: Assessment of Prediction Methods, *International Journal of Heat and Mass Transfer*, *47* (2004), 23, pp. 5045-5057
[22] Han, C. Y., Griffith, P., The Mechanism of Heat Transfer in Nucleate Pool Boiling – Parts I and II: *International Journal of Heat and Mass Transfer*, *8* (1965) pp. 887-913
[23] Stephan, K., Preusser, P., Heat Transfer and Maximum Heat Flux Density in the Case of the Binary and Ternary Thermal Fluid Mixtures (in German), *Chemie Ingenieur Technik*, *51* (1979), 37, pp. 649-679
[24] Mikic, B. B., Rohsenow, W. M., A New Correlation of Pool Boiling Data Including the Effect of Surface Characteristics, *ASME Journal of Heat Transfer*, *91* (1969), 2, pp. 245-250
[25] Judd, R. L., Hwang, H. S., A Comprehensive Model for Nucleate Pool Boiling Heat Transfer Including Microlayer Evaporation, *ASME Journal of Heat Transfer*, *98* (1976), 4, pp. 623-629
[26] Paul, D. D., Abdel-Khalic, S. I., A Statical Analysis of Saturated Nucleate Boiling along a Heat Wire*, International Journal of Heat and Mass Transfer*, *26* (1983), 4, pp. 509-519

[27] Benjamin, R., Balakrishnan, A. R., Nucleate Pool Boiling Heat Transfer of pure Liquids at Low to Moderate Heat Fluxes, *International Journal of Heat and Mass Transfer*, *39 (*1996), 12, pp. 2495-2504
[28] Zuber, N., On the Stability of Boiling Heat Transfer, *ASME Journal of Heat Transfer*, *80* (1958), pp. 711-720
[29] Liang, G., Mudawar, I., Pool Boiling Critical Heat Flux (CHF) – Part 1: Review of Mechanisms, Models, and Correlations, *International Journal of Heat Mass Transfer*, *117* (2018), pp. 1352-1367
[30] Sadasivan, P., *et al.,* Perspective: Issues in CHF Modelling – The Need for New Experiments, *Transactions of ASME Journal of Heat Transfer*, *117* (1995), 3, pp. 558-567
[31] Cooper, M., Lloyd, A., The Microlayer in Nucleate Boiling, *International Journal of Heat and Mass Transfer*, *12* (1969), 8, pp. 895-913
[32] Haider, S. I., Webb, R., A Transient Micro-Convection Model of Nucleate Pool Boiling, *International Journal of Heat Transfer*, *40* (1997), 15, pp. 3675-3688
[33] Nishio, S., Tanaka, H., Simplified Model Predicting Contact-Line-Length Density at Critical Heat Flux Based on Direct Observation of Boiling Structure, *JSME International Journal*, (2002), 45B, pp. 72-78
[34] Zhao, Y.-H., *et al.,* Unified Theoretical Prediction of Fully Developed Nucleate Boiling and Critical Heat Flux Based on a Dynamic Microlayer Model*, International Journal of Heat and Mass Transfer*, *45* (2002), 15, pp. 3189-3197
[35] Das, A. K*., et al.*, Nucleate Boiling Heat Transfer from a Structured Surface – Effect of Liquid Intake, *International Journal of Heat and Mass Transfer*, *49* (2006), 7-8, pp. 3487-3499
[36] Yagov, V. V., Is a Crisis in Pool Boiling Actually a Hydrodynamic Phenomenon, *International Journal of Heat and Mass Transfer*, *73* (2014), pp. 265-273
[37] Yagov, V. V., Heat Transfer under Nucleate Boiling: Possibilities and Limitations of a Theoretical Analysis, *Thermal Engineering*, *54* (2007), 3, pp. 173-179
[38] Chu, In-C., *et al.,* Observation of Critical Heat Flux Mechanism in Horizontal Pool Boiling of Saturated Water, *Nuclear Engineering Design*, *279* (2014), pp. 189-199
[39] Chu, In-C*., et al*., Visualization of Boiling Structure and Critical Heat Flux Phenomenon for a Narrow Heating Surface in a Horizontal Pool of Saturated Water, *International Journal of Heat and Mass Transfer*, *62 (*2013), pp. 142-152
[40] Zhao, H., Williams, A., Predicting the Critical Heat Flux in Pool Boiling Based on Hydrodynamic Instability Induced Irreversible Hot Spots, *International Journal of Multiphase Flow*, *104* (2018), pp. 174-187
[41] Theofanous, T. G., *et al*., The Boiling Crisis Phenomenon – Part I: Nucleation and Nucleate Boiling Heat Transfer, *Experimental Thermal and Fluid Science*, *26* (2002), 6-7, pp. 775-792
[42] Jung, S., Kim, H., An Experimental Method to Simultaneously Measure the Dynamics and Heat Transfer Associated with a Single Bubble during Nucleate Boiling on a Horizontal Surface*, International Journal of Heat and Mass Transfer*, *73* (2014), pp. 365-375
[43] Chen, F., Hagen, H., *A Survey of Interface Tracking Methods in Multiphase Fluid Visualization*, Open Access Series in Informatics, Visualization of Large and Unstructured Data Sets – IRTG Workshop, Dagstuhl Publishing, Germany, 2010.
[44] Son, G., *et al*., Dynamics and Heat Transfer Associated with a Single Bubble during Nucleate Boiling on a Horizontal Surface, *Journal of Heat Transfer*, *121 (*1999), 3, pp. 623-631
[45] Juric, D., Tryggvason, G., Computations of Boiling Flows, *International Journal of Multiphase Flow*, *24* (1997), 3, pp. 387-410
[46] Welch, S. W. J., Wilson, J., A Volume of Fluid Based Method for Fluid Flows with Phase Change, *Journal of Computational Physics*, *160* (2000), 2, pp. 662-682
[47] Jia, H. W., *et al.*, A Numerical Investigation of Nucleate Boiling at a Constant Surface Temperature, *Applied Thermal Engineering*, *88* (2015), pp. 248-257
[48] Kunkelmann, C., Stephan, P., The CFD Simulation of Boiling Flows Using the Volume of Fluid Method within OpenFoam, *Numerical Heat Transfer, Part A, 56* (2009), 8, pp. 631-646
[49] Kunkelmann, C., Stephan, P, A Numerical Investigation of Nucleate Boiling at a Constant Surface Temperature, *Applied Thermal Engineering*, *88* (2015), pp. 248-257
[50] Li, M., *et al.,* Nucleate Boiling Simulation Using Interface Tracking Method, *Nuclear Engineering and Design*, *369* (2020), 110813, pp. 1-10
[51] Fritz, W., Maximum Volume of Vapor Bubbles (in German), *Physikalische Zeitschrift*, *36* (1935), pp. 379-84
[52] Lee, H. C., Single Bubble Growth in Saturated Pool Boiling on a Constant Wall Temperature Surface*, International Journal of Multiphase Flow*, *29* (2003), 12, pp. 1857-74

[53] Cole, R., Shulman, H. L., Bubble Growth Rate at High Jakob Number, *International Journal of Heat and Mass Transfer*, *9* (1966), 12, pp. 1377-90
[54] Jensen, M. K., Memmel, G. J., Evaluation of Bubble Departure Diameter Correlations, *Proceedings*, 8th International Heat Transfer Conference San Francisco, USA, 1986, Vol 4, pp. 1907-1912
[55] Phan, H. T*., et al.,* A Model to Predict the Effect of Contact Angle on the Bubble Departure Diameter during Heterogeneous Boiling, *International Communication of Heat and Mass Transfer*, *37* (2010), 8, pp. 964-969
[56] Phan, H., T., *et al.,* Surface Wettability Control by Nanocoating: The Effect on Pool Boiling Heat Transfer and Nucleation Mechanism, *International Journal of Heat and Mass Transfer 52* (2009), 23-24, pp. 5459-5471
[57] Kocamustafaogullari, G., Ishii, M., Interfacial Area and Nucleation Site Density in Boiling Systems, *International Journal of Heat and Mass Transfer*, *26* (1983), 9, pp. 1377-87
[58] Kutateladze, S. S., Gogonin, I. I., Growth Rate and Detachment Diameter of a Vapor Bubble in Free Convection Boiling of a Saturated Liquids, *High Temperature*, *17* (1979), 4, pp. 667-71
[59] Kim, J., Kim, M. H., On the Departure Behaviors of Bubble at Nucleate Pool Boiling, *International Journal of Multiphase Flow*, *32* (2006), 10-11, pp. 1269-1286
[60] Fazel, S. A. A., Shafaee S. B., Bubble Dynamics for Nucleate Pool Boiling of Electrolyte Solutions, *ASME Journal of Heat Transfer*, *132 (*2010), 2, pp. 815021-815027
[61] Hamzekhani, M. M*., et al.,* Experimental Study on Bubble Departure Frequency for Pool Boiling of Water/NaCl Solutions, *Heat and Mass Transfer*, *51* (2015), pp. 1313-1320
[62] Golorin, V. S., Investigation of Mechanism of Nucleate Boiling of Ethyl Alcohol an Benzene by Means of High Speed Motion Picture Photography, *Heat Transfer, Soviet Research*., *10* (1979), 4, pp. 79-98
[63] Zeng, L. Z*., et al.*, A Unified Model for the Prediction of Bubble Detachment Diameters in Boiling Systems – I Pool Boiling, *International Journal of Heat and Mass Transfer*, *36* (1993), 9, pp. 2261-2270
[64] Yang C., *et al.,* Study on Bubble Dynamics for Pool Nucleate Boiling, *International Journal of Heat and Mass Transfer, 43* (2000), 2, pp. 203-208
[65] Kolev, N. I., Letter to the Editor, *Nuclear Engineering Design*, *239* (2009), pp. 187-192
[66] Hibiki, T., Ishii, M., Active Nucleation Site Density in Boiling Systems, *International Journal of Heat and Mass Transfer*, *46* (2003), 14, pp. 2587-2601
[67] Benjamin, R. J., Balakrishnan, A. R., Nucleation Site Density in Pool Boiling of Saturated Pure Liquids: Effect of Surface Microroughness and Surface and Liquid Properties, *Experimental Thermal and Fluid Science*, *15* (1997), 1, pp. 32-42
[68] Van Stralen, S. J. D., *et al.*, Bubble Growth Rate in Pure and Binary Systems: Combined Effect of Relaxation and Evaporation Microlayers, *International Journal of Heat and Mass Transfer*, *18 (*1975), 3, pp. 453-67
[69] Zuber, N., The Dynamics of Vapor Bubbles in Nonuniform Temperature Fields, *International Journal of Heat and Mass Transfer*, *2* (1961), 1-2, pp. 83-98
[70] Hatton, P., Hall, I. S., Photographic Study of Boiling on Prepared Surfaces, *Proceedings*, 3th International Heat Transfer Conference, AIChE, USA, 1966., 4 (2), pp. 24-37
[71] Plesset, M. S., Zwick, S. A., The Growth of Vapor Bubbles in Superheated Liquid*, Journal of Applied Physics*, *25* (1954), pp. 493-500
[72] Ivey, H., J., Relationships Between Bubble Frequency, Departure Diameter and Rise Velocity in Nucleate Boiling, *International Journal of Heat and Mass Transfer*, *10* (1967), 8, pp. 1023-1040
[73] McHale, J. P., Garimella, S. V., Bubble Nucleation Characteristics in Pool Boiling of a Wetting Liquid on Smooth and Rough Surfaces*, International Journal of Multiphase Flow*, *36* (2010), 4, pp. 249-260
[74] Hutter, C., *et al.,* Experimental Pool Boiling Investigations of FC-72 on Silicon with Artificial Cavities and Integrated Temperature Microsensors, *Experimental Thermal and Fluid Science*, *34 (*2010), 4, pp. 422-433
[75] Jaikumar, A., Kandlikar, S. G., Enhanced Pool Boiling for Electronics Cooling Using Porous Fin Tops on Open Microchannels with FC-87, *Applied Thermal Engineering*, *91* (2015), pp. 426-433
[76] Xu, Z., G., Zhao, C., Y., Influences of Nanoparticles on Pool Boiling Heat Transfer in Porous Metals, *Applied Thermal Engineering*, *65* (2014), 1-2, pp. 34-41
[77] Tang, Y., *et al*., Pool-Boiling Enhancement by Novel Metallic Nano Porous Surface, *Experimental Thermal and Fluid Science, 44* (2013), pp. 194-198
[78] Zhang, B., J., Kim, K. J., Nucleate Pool Boiling Heat Transfer Augmentation on Hydrophobic Self-Assembly Mono-Layered Alumina Nano Porous Surfaces*, International Journal of Heat and Mass Transfer*, *73* (2014), pp. 551-561

[79] Jaikumar, A., Kandlikar, S. G., Ultra-High Pool Boiling Performance and Effect of Channel with Selectively Coated Open Microchannels, *International Journal of Heat and Mass Transfer, 95* (2016), pp. 795-805
[80] Liter, S. G., Kaviany, M., Pool-Boiling CHF Enhancement by Modulated Porous-Layer Coating: Theory and Experiment, *International Journal of Heat and Mass Transfer, 44* (2001), 22 pp. 4287-4311
[81] Lee, C., Y., *et al*, Pool Boiling Heat Transfer with Nano-Porous Surface, *International Journal of Heat and Mass Transfer*, *53* (2010), pp. 4274-4279
[82] Fan, Li-Wu, *et al.*, Pool Boiling Heat Transfer on a Nanoscale Roughness-Enhanced Super Hydrophilic Surface for Accelerated Quenching in Water, *Applied Thermal Engineering, 109* (2016), Part A, pp. 630-639
[83] Betz, A. R., *et al*., Do surfaces with Mixed Hydrophilic and Hydrophobic Areas Enhance Pool Boiling, *Applied Physics Letters*, *97 (*2010), 14, pp. 141-165
[84] Mukherjee, A., Kandlikar, S. G., Numerical Study of Single Bubbles with Dynamic Contact Angle during Nucleate Pool Boiling, *International Journal of Heat and Mass Transfer*, *50* (2007), pp. 1-2, 127-138
[85] Li, Y.-Y., *et al*., A Predictive Model of Nucleate Pool Boiling on Heated Hydrophilic Surfaces, *International Journal of Heat and Mass Transfer*, *65* (2013), pp. 789-797
[86] Kim, S. J., *et al*., Surface Wettability Change during Pool Boiling of Nanofluids and its Effect on Critical Heat Flux, *International Journal of Heat and Mass Transfer*, *50* (2007), 19-20, pp. 4105-4116
[87] Zhang, L., *et al*, Influence of Heater Thermal Capacity on Bubble Dynamics and Heat Transfer in Nucleate Pool Boiling, *Applied Thermal Engineering*, *88* (2015), pp. 118-126
[88] Chen, H., *et al*., Experimental Investigations on Bubble Departure Diameter and Frequency of Methane Saturated Nucleate Pool Boiling at Four Different Pressures, *International Journal of Heat and Mass Transfer*, *112* (2017), pp. 662-675
[89] Kweon, Y. C., Kim, M. H., Experimental Study on Nucleate Boiling Enhancement and Bubble Dynamic Behavior in Saturated Pool Boiling Using a Nonuniform Dc Electric Field, *International Journal of Multiphase Flow*, *26* (2000), 8, pp. 1351-1368

Paper submitted: January 11, 2020
Paper revised: December 28, 2020
Paper accepted: January 1, 2021