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Review of Pool Boiling Enhancement Techniques

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ABSTRACT

Many industrial applications recently are utilizing from the pool boiling to treat heat, including power plants, cooling and refrigeration applications, and electronics cooling applications like data centers. The high efficiency of pool boiling is becoming very important to improve and develop systems performance and to lessen the fuel and energy loss or consumption. This literature review gathers the existing knowledge as possible on the pool boiling enhancement techniques. Paying attention on the challenges and development associated with these techniques. The examination involves studying basic principles of pool boiling focusing on factors like heat transfer rate and the technical specifications for surface and fluids. Then, it goes deeper reviewing the methods of enhancement, including surface treatment methods, surface modification and liquid physical properties. The goal of this review is to propose as a valuable resource for researchers, engineers, and students seeking a comprehensive understanding of the current state of pool boiling enhancement techniques. By strengthen diverse research findings and identifying gaps in knowledge, this review contributes to the ongoing pursuit of more efficient and sustainable heat transfer solutions for diverse industrial applications.The abstract needs to summarize the content of the paper.

Nomenclature

A ¼ dispersion constant
C g ¼ mass fraction of noncondensable (¼qg=qm)
c p ¼ specific heat capacity at constant pressure (J/kg K)
D ¼ diffusion coefficient (m2/s) ~g ¼ gravity vector (m/s2)
ge ¼ Earth's normal gravity (m/s2) H ¼ Heaviside step function
h ¼ grid spacing for macro region
h ev ¼ evaporative heat transfer coefficient (W/m2 K)
hfg ¼ latent heat of vaporization (J/kg) k ¼ thermal conductivity (W/m K) L ¼ width of computational domain (m) l o ¼ characteristic length scale (m)
M ¼ molecular weight (g/mol)
p ¼ pressure (Pa) q ¼ heat flux (W/m2)
R ¼ radius of computational domain or bubble (m)
R o ¼ radius of dry region beneath a bubble (m) R1 ¼ radial location of the interface at y ¼ h/2 (m)
R ¼ universal gas constant (J/mol K) r ¼ radial coordinate (m)
T ¼ temperature (C or K) t ¼ time (s)
t o ¼ characteristic time scale (s)

Introduction

Pool boiling is a heat transfer process which includes the boiling of a liquid on a heated surface in a pool of the same liquid. [1] One of the first researchers to investigates the effects of various pool boiling enhancement techniques on water at low pressure using Rectangular fins, fluidized particulate beds, and surface finishes. The pool boiling phenomena which have been researched because of its effective dissipation of heat and its wide uses of applications in different sectors such as space craft cooling, and nuclear reactors cooling. The pool boiling process consists of the creation and expansion of vapor bubbles on the heated surface, which eventually detach up to the surface, resulting in the cooling effect. An assessment of the effectiveness of heat transfer in pool boiling typically involves the examination of factors like the heat transfer coefficient and critical heat flux (CHF) [4]. Studying the mechanisms and optimizing heat transfer in pool boiling holds significant importance in enhancing the effectiveness of heat transfer systems.
One method is the use of surface structure modification, such as micro/nanostructures, to increase the active nucleation site density and promote bubble growth and departure [5] [6] Another method is the use of modified surface specification or can be called as surface treatment, which can improve pool boiling performance by improving wickability and facilitating micro-convection [7]. Additionally, numerical simulations have been employed to study pool boiling phenomena and optimize heat transfer [4] [8].
In recent years, there has been a significant surge in interest in improving heat flux within the realm of boiling heat transfer methodology. This interest stems from its considerable potential to mitigate risks associated with nuclear power plants and to optimize the performance of direct steam generators. [9],[10] ,[11]. Fig. 1.

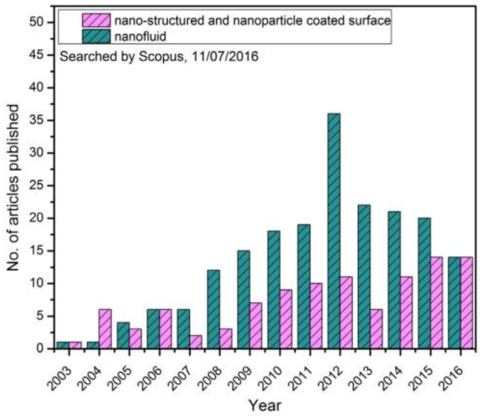

Figure 1. Chart shows the research article trend in pool boiling heat transfer.[12]

The importance of pool boiling studies in the new era of industrial evolution is vital, as the new electronics generations, high efficiency processors, nuclear reactor etc.. is developing very fast, Also the need of the reduce power consumption and lowering the operational costs and taking climate change into considerations as pool boiling meets the requirement of what industry needs.

Pool Boiling Enhancement Techniques

Pool boiling enhancement techniques involves surface structure design, using nanofluids, and modifying surface. Surface structuring means include creating micro-pillar surfaces, micro-pin-fins, and micro-finned structures to improve (HTC) and (CHF) [2] [13]. Nanofluids, which are base fluids with solid nanoparticles, have been utilized to enhance heat transfer performance in pool boiling. Different types of nanofluids, such as TiO_2, Al_2O_3, CuO, Fe_3O_4, ZnO, and SiO_2, have been used to enhance HTC and CHF. Surface modification techniques, such as electro-coating, etching, and acid-etching, have also been utilized to enhance pool boiling heat transfer. These techniques have shown improvements in HTC and CHF by changing surface roughness and creating super-hydrophobic surfaces [7] [14]. Overall, these techniques aim to improve the heat transfer performance in pool boiling applications.

In this work we will review the pool boiling enhancement techniques used in heat transfer applications. Thereafter, I will provide the results obtained from such techniques and their validation with data from experiments. The importance of this review comes in this period where there is a gap in the related researches articles and reviews, also it comes when the need for such review is very useful as the use of pool boiling techniques is trending to cool electronics and batteries of many applications. Mainly all the different pool boiling enhancement techniques falls in two categories which is the modifying the surface morphology and manipulation of surface features or other methods that used both techniques.

1. Modifying the Surface Morphology

Modifying the surface morphology is a pool boiling enhancement technique that involves altering the physical characteristics of the heating surface to improve heat transfer and CHF during pool boiling. The surface morphology can be modified in various ways, such as by introducing surface roughness, creating artificial nucleation sites, or using extended surfaces or fins [15].

Table 1. A summary of selected group of studies on CHF enhancement of different surfaces treatments in saturated pool boiling for the last ten years.

Reference	Testing Surface	Test fluid	Enhancement Method	Results gained
Patil et al. 2014 [19]	10 mm × 10 mm copper chips, specifically referred to as Chip 9 and Chip 12 with different microchannel geometries	Water	combined effect of electrodepositing microporous coatings on the fin tops of microchannels.	A maximum critical heat flux (CHF) of 3250 kW/m 2 was obtained for Chip 9 with fin width = 200 μm, channel width = 500 μm and channel depth = 400 μm at a wall superheat of 7.3 °C.
Mori et al. 2015 [20]	large heated surface on which the effects of the honeycomb porous plate and/or nanoparticle deposition were used.	The TiO2 nanoparticles (Aero-sil Corporation, Aeroxide TiO2 P 25)	Surface modification	Under the best performing surface modifications, the CHF for 10-mm-, 30-mm- and 50-mm-diameter surfaces was enhanced up to 3.1, 2.3, and 2.2 MW/m 2, respectively
Jaikumar et al. 2015 [21]	enhanced copper surface with porous fin tops on open microchannels,	FC-87	Surface modification	achieving a maximum Critical Heat Flux (CHF) of 37 W/cm2, representing a 270% enhancement compared to a plain chip
Minseok Ha et al. 2016 [22]	hierarchical copper microporous structures	DI water	patterning the microporous copper to allow vapor to escape	significant increase in critical heat flux (CHF) for unpatterned microporous structures compared to flat surfaces, as well as a 412% increase in CHF and a significant decrease in surface superheat for patterned microporous copper.
Kaniowski et al. 2017 [23]	Copper surfaces were modified to form microchannels with different geometrical properties.	Saturated deionized water and Novec-649	Modification of copper surfaces to form microchannels	The maximum heat transfer coefficient obtained exceeded 60 kW/m2 K.
Gheitaghy et al. 2017 [24]	horizontal circular surface with wirecutted inclined minichannels configurations	saturated water	the implementation of wirecutted inclined minichannels configurations on copper surfaces, with a focus on increased channel depth, decreased pitch, and orthogonal intersection of minichannels	The orthogonally intersected minichannels exhibited the highest HTC and CHF, with improvements of up to 170% and 65% compared to the plain surface.
Nirgude et al. 2017 [25]	copper test sections with orthogonally intersecting tunnel structured surfaces.	water and isopropyl alcohol.	development of orthogonally intersecting tunnel structures with varying dimensions on copper test sections using	orthogonally intersecting tunnel structures significantly affect heat transfer performance,

			wire-electric discharge machining (Wire-EDM) process.	enhancing boiling heat transfer performance and reducing wall superheat
Ha et al. 2017 [26]	microporous surfaces.	deionized (DI) water.	Surface modification	modulating the vapor-jet through the pore network increases Critical Heat Flux (CHF) compared to a flat surface, based on hydrodynamic theory.
Udaya Kumar et al. 2018 [27]	copper substrate coated with graphene and carbon nanotubes	FC-72	the growth of carbon nanotubes (CNT) over the Graphene (Gr) coated copper substrates using the PECVD technique.	significant improvement in heat transfer coefficient (155%), critical heat flux (40%), and reduction in boiling incipience superheat (62%)
Shen et al. 2019 [28]	polished copper surface	ethanol	deposition of superamphiphobic coating of modified halloysite nanotubes (HNT) with fluoropolymer	dramatic improvement in boiling heat transfer on the coated surface, a drop of more than 35% in the onset of nucleate boiling, and a maximum heat transfer enhancement over 300% at 20 K surface superheat.
Može et al. 2020 [29]	Aluminum alloy disc with a diameter of 18 mm and a thickness of 4 mm	Saturated water at atmospheric pressure	The combination of chemical vapor deposition of a fluorinated silane to achieve superhydrophobicity and nanosecond laser texturing to render selected areas superhydrophilic.	significant increase in critical heat flux (CHF) and heat transfer coefficients at medium and high heat fluxes.
Elkholy et al. 2020 [30]	printed porous samples or fixtures used in the boiling experiments.	deionized water.	additive manufacturing (AM) to produce low-cost, porous polymer fixtures	increase boiling heat transfer coefficient at low heat fluxes by approximately 80%. And increasing the unit cell size was found to enhance the critical heat flux (CHF) by approximately 28% compared with the bare surface.
Moghadasi et al. 2022 [31]	fabricated copper surfaces and modified surfaces using surface photolithography	saturated water at atmospheric pressure	Surface modification	he study demonstrates that heat dissipation increases with higher additional area and active nucleation sites densities
Song et al. 2022 [32]	silicon.	high-purity deionized water.	Surface Modification (sand blasting)	significant improvements in critical heat flux and heat transfer coefficient with sandblasted surfaces, and a stronger correlation of CHF enhancement with the unified descriptor.
Li et al. 2022 [33]	pillar-structured surface	dielectric fluids	the application of mixed wettability to the pillar-structured surface in combination with the imposition of an electric field.	elay of boiling crisis, promotion of bubble departure on the pillar tops, and improvement of critical heat flux (CHF) and heat transfer coefficient through mixed wettability.
Bulut et al. 2023 [34]	copper chip with various modifications, including microchannels,	degassed water.	Surface modification	he best heat transfer performance observed on the pin-fins chip, with a heat flux of 243.75W/cm2 at 15.46°C, and the highest

	sintered surfaces, and pin fins			heat transfer coefficient (HTC) of 181.03 kW/(m2 oC) at a heat flux of 172.61 W/cm2 for the microchannel with single pin-fins.
Wang et al. 2023 [35]	surface with an extended thin film (ETFS)	Ethanol.	Surface modification	a significant CHF enhancement, the increase in CHF by approximately 110% compared to PS and 45% compared to the traditional pin–fin surface, and the identification of an optimal extended film height of 4.0 mm for maximum boiling heat transfer performance.

Studies have been done for years on improving critical heat flux and heat transfer coefficient in pool boiling through surface modification, and researches are still ongoing. The modified Zuber hydrodynamic stability model been used for the analysis. [16], different factors can improve pool boiling effect. [17], i.e. There are different effects that can enhance heat transfer by modifying the heating surface, such as (a) increased surface area, (b) density of nucleation sites, (c) wetting properties, (d) reduction of instability wavelength and (e) capillary spreading or wicking. However, the exact role of each effect has not been demonstrated yet. Researchers have discovered many methods to enhance one or more factors for altering the heating surface and improving the heat transfer. It is still unclear how much each effect contributes to CHF enhancement. Several techniques that combine various methods for increasing CHF have been suggested. Table 1 demonstrate a summary of a number of studies on enhancing CHF by modifying the surface of a flat plate, grouped by the way of test fluid used, such as water, refrigerant, or organic fluid. [18]

Generally speaking, there exist two categories of surface modifications with regards to enhancing pool boiling, as indicated by current studies. The initial category involves the deliberate alteration or optimization of the heating surface in advance, encompassing actions like expanding surface area, augmenting nucleation site density, and introducing nanoparticles into the fluid, all of which are considered passive approaches. Conversely, the alternative approach involves the creation of specialized surfaces capable of dynamically adjusting their geometric properties or characteristics, such as wettability, throughout the boiling process; as a result, an improvement in HTC/CHF can be achieved without any degradation in CHF/HTC. [36].

Enhancement of heat transfer in pool boiling is consistently a notable and well-discussed subject matter. [37]. A range of studies have explored the use of modified surface morphology to enhance pool boiling heat transfer. [38] found that parabolic and stepped microchannels significantly improved heat transfer, with the latter showing a 169% enhancement. [39] similarly observed that wider and deeper microchannels, as well as thinner finned surfaces, led to better heat transfer. [40] and [41] both highlighted the role of surface finishes and wettability in reducing wall superheat temperatures and enhancing critical heat flux. [42] manufactured 3D thin wall grid structures using the selective laser melting technique on stainless steel with the aim of enhancing boiling. The findings revealed that the highest CHF value (303 W/cm2) observed in these instances was threefold greater than that of a smooth surface. The confinement of bubbles and dry-out spots near the surface, along with a reduction in flow resistance, was attributed to the 'partition effect'. Furthermore, an analysis of the mechanism behind the enhancement of CHF in these specimens was conducted by the authors, focusing on resistance limits and hydrodynamic instability.[43] manufactured hollow conical structures using 3D printing for the purpose of separating the liquid-vapor flow passage. This configuration is illustrated in Fig. 2(a) and (b). Subsequently, an enhancement in boiling performance was observed.

[44] The study presented copper pillars surfaces that were textured with various geometric arrangements using the supersonic spray-coated technique. The investigation focused on the performance of these surfaces in enhancing boiling heat transfer. The authors identified an optimal pyramid-base size of 0.91 mm on each side, which correlated with the highest values for HTC and CHF. Furthermore, the specific geometric arrangement was observed to promote bubble nucleation, resulting in the maximum HTC and CHF recorded at 20.2 kW/(m2 ·K) and 285 kW/m2, respectively, among the patterned surfaces. In comparison, the plain surface exhibited significantly lower values of 6 kW/(m2 ·K) for HTC and 189 kW/m2 for CHF. [45] the research findings illustrated that the honeycomb-structured surfaces exhibited an increase in Critical Heat Flux

(CHF) of over two times when compared to a smooth surface.

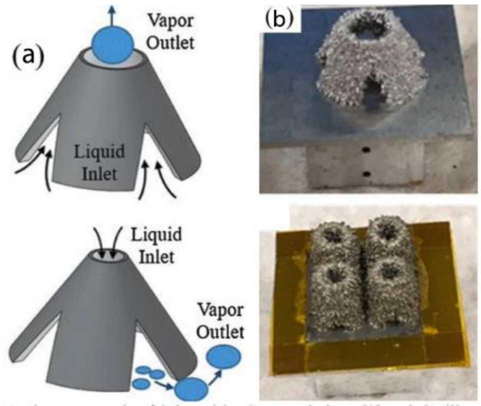

Figure 2. Schematic diagrams of pathways of liquid and vapor [43] and (d) photos of samples.

[46] examined was the application of a copper cylinder at a centimeter scale as a heating surface; the outcomes indicated enhancements in both Critical Heat Flux (CHF) and Heat Transfer Coefficient (HTC) to some extent. Furthermore, certain scholars enhanced the process of nucleate boiling by using densely packed ferromagnetic beads. [47]. While some research has been carried out on macroscopic structured surfaces, it appears that studies in this area have experienced a significant decrease in enhancing boiling heat transfer. This decline can be attributed to the superior outcomes obtained through micro/nanofabrication methods and the increasingly stringent demands in contemporary applications.

Calculating CHF of pool boiling experiments used surface modifications

Rohsenow and Griffith bubble model of interference In 1955, [48] proposed a model for pool boiling CHF based on the trigger mechanism of bubble interference. The model assumes that circular vapor bubbles are separate and close together at first, and predicts that CHF will happen when the bubbles merge sideways and cover the surface with vapor. The model was expressed by the relation

$$q''_{CHF} = 0.012\, \rho_g\, h_{fg} \left(\frac{\rho_f - \rho_g}{\rho_g}\right)^{0.6} \quad (1)$$

[49] showed another way, which, similar to that of Rohsenow and Griffith, relies on individual bubble interference.

$$q''_{CHF} = \frac{1}{2}\left(\frac{\pi}{6}\right)^{\frac{5}{6}} (0.0119\,\alpha)^{\frac{1}{2}} \rho_g h_{fg} \left[\frac{2\sigma g(\rho_f - \rho_g)}{\rho_g^2}\right]^{\frac{1}{4}} \quad (2)$$

Zuber hydrodynamic instability model

Table 2 shows how different researchers suggest numerical values and/or empirical relations for dimensionless parameter K of the Kutateladze-Zuber equation for the horizontal, upward-facing orientation. [50]

Table 2. Summary of dimensionless CHF for horizontal upward-facing surfaces based on the Kutateladze-Zuber equation. [50]

Author(s)	Dimensionless CHF
Zuber [51], [52]	K = 0.131
Lienhard and Dhir [53][54]	K = 0.149
Chang [55]	K = 0.13
Watwe and Bar-Cohen [56]	$K = \frac{\pi}{24}\left(\frac{s}{s+0.1}\right)\left\{1 + \left(0.3014 - 0.01507\,L\sqrt{\frac{g(\rho_f-\rho_g)}{\sigma}}\right)\right\} * \left\{1 + 0.03\left[\left(\frac{\rho_f}{\rho_g}\right)^{\frac{3}{4}}\frac{c_{pf}}{h_{fg}}\right]\Delta T_{sub}\right\}$
Kirichenko and Chernyakov [57]	$K = 0.171\,\frac{(1 + 0.324 * 10^{-3}X^2)^{1/4}}{(0.018)^{1/2}}$
Ramilison et al. [58]	$K = 0.0044(\pi - \alpha)^3 R_a^{0.12}$
Bailey et al. [59]	K = 0.17
Kim et al. [60]	$K = 0.811\left(\frac{1+\cos\alpha}{16}\right)\left[\frac{2}{\pi} + \frac{\pi}{4}(1+\cos\alpha) + \frac{351.2\cos\alpha}{1+\cos\alpha}\left(\frac{R_a}{S_m}\right)\right]^{\frac{1}{2}}$
Wang et al. [61]	$K = \left[0.18 - 0.14\left(\frac{P}{P_C}\right)^{5.68}\right]$
Soziev and Khrizolitova [62]	$K = 0.16\left\{1 + \frac{[\sigma g(\rho_f - \rho_g)]^{\frac{1}{2}}}{P}\right\}^{1/2}$

Borishanskii [63]	$K = 0.13 + 4\left\{\frac{\rho_f \sigma^{\frac{3}{2}}}{\mu_f^2 \left[g(\rho_f - \rho_g)\right]^{\frac{1}{2}}}\right\}^{-2/5}$

2. Manipulation of Surface Features Using Nano Technology

The concept of utilizing nanofluids in pool boiling to enhance the cooling systems was first studied by [64] This text explains how boiling heat transfer is improved by using copper nanoparticles, which have high thermal conductivity. Fig. 6 shows different nanofluids used in pool boiling experiments, such as alumina, silica, titania, and other materials. Many studies have used these nanofluids to increase CHF, and some results show that alumina and copper nanofluids can raise CHF by 171% and 176% respectively compared to water [65]. Research in the field of pool boiling enhancement through manipulation of surface features using nanotechnology has shown promising results. [66] demonstrated a 200% improvement in boiling heat transfer coefficient by electrophoretic deposition of ZnO nanoparticles. [67] critically reviewed the implementation of nanostructures on surfaces for enhanced boiling performance, emphasizing the need for further research. [27] discovered that growing carbon nanotubes over graphene-coated copper substrates significantly improved heat transfer coefficient and critical heat flux. [12] highlighted the potential of nanostructured surfaces and nanofluids in enhancing pool boiling, calling for improved correlation between modified surface properties and heat flux. [68] measured how well copper oxide nanoparticles water nanofluids can transfer heat by boiling. They looked at how different surfactants as additives affect this heat transfer, and also how the applied heat and nanofluids concentrations change it. They found that nanofluids had much lower heat transfer than water without surfactants.

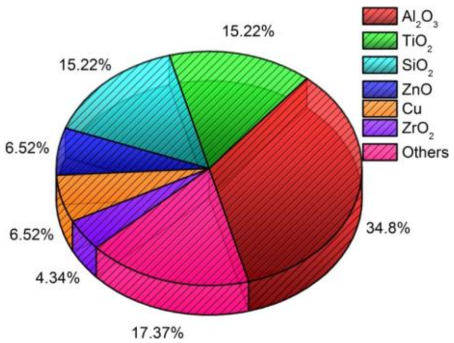

Figure 3. Nanofluids used in experimental investigation of pool boiling heat transfer [12]

[69] experimentally studied the pool boiling from flat copper heating surface for *Al*2*O*3 based water nanofluids within a range of concentrations of 0.01–0.5% Vol. Nanofluids boiling tests have been followed by water boiling tests on the same modified surfaces. They found that using the highest concentration nanofluids to create a nanoparticle-deposited surface led to higher PBHTC when water boiled on that surface.

[70] and [71] did experiments on pool boiling of ceria and tungsten oxide nanofluids in water with different amounts. They used a copper tube to heat the water and changed the heat and surface roughness. Results showed that ceria nanofluids improved heat transfer with 115 nm roughness and low heat for 0.007% concentration. But tungsten oxide nanofluids only improved heat transfer with 0.01% concentration and reduced it with 0.05%. This was because of how the nanoparticles changed the surface at different concentrations and roughness. Table 3 shows a summary of recent pool boiling experiments.

These studies collectively underscore the potential of nanotechnology in enhancing pool boiling performance.

Table 3. Summary of as selected experimental studies on pool boiling heat transfer using nanofluids last ten years.

Reference	Testing Surface	Testing Nano Fluid	Particle size, [nm]	Enhancement Method	Results gained
Tang et al. 2014 [72]	horizontal flat square copper surface	suspending δ-Al2O3 nanoparticles in base fluid refrigerant 141b (R141b)	-	se of δ-Al2O3 nanoparticles suspended in base fluids refrigerant 141b at different concentrations with and without surfactant SDBS.	that δ-Al2O3 nanoparticles enhance the pool boiling heat transfer characteristics for R141b at concentrations of 0.001 vol.% and 0.01 vol.% with and without the surfactant SDBS, but

					deteriorate the characteristics at 0.1 vol.% concentration without the surfactant SDBS.
Sarafraz et al. 2015 [68]	the heating section, and its roughness is strongly controlled by the nanofluid concentration due to the deposition of nanofluids.	dilute copper oxide water-based nanofluids at mass concentrations of 0.1–0.4%.	50	Surface treatmnt	include pH control, stirring, sonication, and the use of surfactants. The surfactants led to a higher pool boiling heat transfer coefficient compared to the absence of surfactants.
Manetti et al. 2017 [73]	copper surface with different roughness values, one corresponding to a smooth surface (R a = 0.05 μm) and another one to a rough surface (R a = 0.23 μm).	Al2O3-water based nanofluid with average particle size of 10 nm, tested at concentrations of 0.0007 vol.% and 0.007 vol%	10 nm	different volume concentrations of nanofluids	nanofluids can effectively enhance the heat transfer coefficient (HTC) during pool boiling, especially for low volumetric concentrations and moderate heat flux
Karimzadehkhouei et al. 2017 [74]	-	TiO2 nanoparticles/water and CuO nanoparticles/water nanofluids.	The particle size of the nanofluid is reduced when nanoparticles are added to the base fluid.	the addition of TiO2 and CuO nanoparticles to water to improve pool boiling heat transfer	he heat transfer performance was improved when TiO2 nanoparticles were added to pure water, with the lowest mass fraction (0.001%) showing the largest enhancement of around 15%
Abedini et al. 2017 [75]	circular channel and a vertical channel.	water-based nanofluids containing oxide nanoparticles (TiO2, Al2O3, CuO) with low concentrations of 0.1%, 0.5%, and 2.5% by volume,	The particle size of the nanofluid is 10 and 20 nm.	the measurement of convective heat transfer coefficient and nucleate boiling augmentation to study the behavior of nanofluids	the enhancement of convective heat transfer coefficient for nanofluids in the single phase regime, the augmentation of heat transfer rate by nucleate boiling, and the degradation of heat transfer rate for nanofluids in the subcooled regime, especially with increasing nanoparticle concentration.

Gupta et al. 2018 [76]	copper surfaces with Cu-Al2O3 nanocomposite coatings	saturated DI water	-	single-step electrochemical deposition technique to develop nanocomposite coatings.	Considerable improvement in the boiling heat transfer coefficient (BHTC) and critical heat flux (CHF) for Cu-Al2O3 nanocomposite coatings compared to the bare surface. The maximum critical heat flux and heat transfer coefficient are found to be 72.5% and 273% higher, respectively,
Dareh et al. 2019 [77]	different micro- and nanostructured surfaces prepared via the thermal spray coating method	alumina/water nanofluid.	-	thermal spray coating method to prepare different micro- and nanostructured surfaces.	higher critical heat flux (CHF) values for nanofluids boiling on test surfaces compared to the base fluid
Modi et al. 2020 [78]	plain substrate surface and nanoparticles-deposited surface.	alumina-water nanofluids at concentrations of 0.005 and 0.01 vol%	13	the deposition of nanoparticles on the surface to modify it for conducting pool boiling experiments with water	significant changes in bubble dynamic parameters, differences in thermal gradients field, and alterations in heat transfer partitioning when comparing water and nanofluids in single bubble-based nucleate boiling experiments.
Kamel et al. 2020 [70]	Horizontal copper tube	CeO2 - DI Water	50	Surface treatment	Increased with 70% with 0.007% Vol.
Pare et al. 2021 [79]	cylindrical copper block	prepared using distilled water and alumina nanoparticles of 40 nm size, with particle concentrations ranging from 0.01 wt.% to 1 wt%.	40 nm.	artificial neural network (ANN) with the LM (Levenberg Marquardt) algorithm for optimizing the structure of the model.	he development of an optimal ANN design, a 70% enhancement in pool boiling heat transfer with nanofluids compared to distilled water, improved thermophysical properties of nanofluids, enhanced surface wettability leading to increased heat

					transfer coefficients, and heat transfer deterioration on particle deposited surfaces with water.
Ba et al. 2022 [80]	copper horizontal tube with a thickness of 1 mm and a diameter of 22 mm	The testing nanofluid used in the experiment is prepared from halloysite nanotubes (HNTs) nanomaterials-based deionized water (DI water) with the presence of sodium hydroxide (NaOH)	in the range of 30-50 nm in diameter	Two-step method involving addition of HNTs to base fluid and homogenization with ultrasonication	The results indicate an improvement of PBHTC for halloysite nanofluids compared to the base fluid, with the best enhancement of 5.8% at 0.05 vol% concentration, attributed to lower superheat temperatures and a leftward shift in the boiling curve.
Kumaravelu et al. 2022 [81]	Ni-Chrome wire	Al_2SiO_5/H_2O and CeO_2/H_2O nanofluids	50 nm	the two-step method for preparing nanofluids, which involves dispersing Al_2SiO_5 and CeO_2 nanopowders in water.	significant enhancements in pool boiling heat transfer, with improvements of about 120.5 ± 0.6% in peak heat flux (PHF) over water as base fluids for 0.3% volume concentration solutions.
Mukherjee et al. 2022 [82]	horizontal annulus test section made of a borosilicate glass tube,	water-based Al_2O_3 and CuO nanofluids	The particle size can range from 10 nm to 100 nm.	the addition of nanoparticles to base fluids, with careful consideration of the optimal nanoparticle concentration to achieve significant heat transfer enhancement.	he cooling performance of PFCs and HVs can be increased with the application of nanofluids. Bubble formation and bubble dynamics are key mechanisms of the boiling heat transfer in nanofluids.
Zolfalizadeh et al. 2023 [83]	Heat Exchanger	GNP/water nanofluid with mass fractions of nanoparticles at 0.01, 0.03, and 0.06 wt%.	The particle size of the nanofluid varies depending on the concentration of GNPs: 102.2 nm, 144.5 nm, 171.9 nm	he incorporation of graphene nanoplate (GNP) as an additive in the form of nanofluids to improve heat transfer in a shell-and-tube heat exchanger (STHE).	significant enhancement in the convective heat transfer coefficient (CVHTC) of the nanofluid with 0.06 wt.% of GNP, leading to a 22.47% increase compared to the base fluid

Calculating CHF of pool boiling experiments used nano technology

Critical heat flux for various heater surfaces can be predicted by the hydrodynamic instability theory [52] given as,

$$q" = Ch_{fg}\rho_g^{1/2}\left[\sigma g\left(\rho_f - \rho_g\right)\right]^{1/4} \quad (3)$$

C → constant
hfg→latent heat of vapourization
ρf→density of fluid
ρg→density of gas
σ → surface tension of liquid
g → accleration due to gravity

CHF happens when the rising vapor blocks the flow of fresh liquid. Vapor bubbles tend to move away from the heater surface to the liquid surface, showing a retreating effect. [84] modified the hydrodynamic instability theory to account for the surface wettability in a CHF model.

$$q_{cr}^{"} = k^{-1/2}\rho_g h_{fg}\left[\frac{\sigma\left(\rho_f - \rho_g\right)g}{\rho_g^2}\right]^{1/4} \quad (4)$$

We can observe that, the above model resembles hydrodynamic instability theory; the parameter k-1/2 is analogous to the ratio of the radius of curvature of liquid meniscus and the capillary length. The ratio is determined by,

$$k = \left(1 - \frac{\sin\theta}{2} - \frac{\frac{\pi}{2} - \theta}{2\cos\theta}\right)^{-1/2} \quad (5)$$

[85] enforced hydrodynamic instability theory by including the surface inclination factor.

$$q^{"} = h_{fg}\rho_g^{1/2}\left(\frac{1+\cos\beta}{16}\right)\left[\frac{2}{\pi} + \frac{\pi}{4}(1+\cos\beta)\cos\varphi\right]^{1/2}\left[\sigma g\left(\rho_f - \rho_g\right)\right]^{1/4} \quad (6)$$

β → receding contact angle
φ → surface inclination angle
φ = ° 0 for horizontal surface
φ = ° 90 for vertical surface

This model predicts CHF much better than hydrodynamic instability theory. These theories did not cover the heater surface properties, but many researchers still use these models for CHF prediction. Park et al. [86] predicted CHF for porous surface by modifying the macro-layer dry out theory proposed by [87] The present theory considers thickness of porous layer and the porosity of the surface.

$$\delta_{total} = r_b\left[\cos\theta - \frac{\pi}{12}\left(3\cos\theta - \cos^3\theta\right)\right] + \varepsilon\delta_{poroı} \quad (7)$$

$$q^{"} = \frac{\delta_{total}h_{fg}\rho_f}{\tau_d} \quad (8)$$

$r_b \rightarrow bubble\ radius$
$\varepsilon \rightarrow porosity$
$\delta_{porous} \rightarrow thickness\ of\ porous\ layer$
$\tau_d \rightarrow dryout\ time$

Summary and Conclusion

In the realm of pool boiling enhancement techniques, both surface geometry modifications and surface treatment using nanotechnology have shown promise. Numerous studies and review articles have explored these approaches to improve boiling heat transfer performance. The effectiveness of each method can depend on the specific application, requirements, and materials involved.
Determining which technique, surface geometry modification or surface treatment using nanofluids, results in better heat transfer depends on specific conditions, materials used, and the intended application. Both techniques have shown promise in enhancing heat transfer, but their comparative effectiveness may vary based on the context. Here are some considerations for each technique:

1. Surface Geometry Modification:
   - Pros:
     - Creates additional nucleation sites, promoting efficient boiling.
     - Enhances bubble departure from the surface.
     - May improve heat transfer in scenarios where surface roughness plays a critical role.
   - Cons:
     - Effectiveness can be application-specific.
     - May not significantly affect the thermal conductivity of the working fluid.

2. Surface Treatment Using Nanofluids:
   - Pros:
     - Improves the thermal conductivity of the working fluid, improving overall heat transfer.
     - Can be applied to various surfaces without altering their geometry.
   - Cons:
     - The choice of nanofluid and its stability can affect performance.

- May not be as effective in scenarios where surface roughness is a primary factor.

The comparative effectiveness ultimately depends on the specific requirements of the heat transfer system. Even though the results shows that the experiments used surface treatment method using nanofluids are more effective in increasing the CHF than surface modification method experiments. In some cases, a combination of both techniques may yield better results than using either one individually. Researchers often explore hybrid approaches to leverage the advantages of both surface modifications and nanofluid treatments.
Therefore, while both surface geometry modification and surface treatment using nanofluids methods have shown promise in enhancing pool boiling, further research especially in surface modification using nano fluids is needed to address their respective limitations and optimize their performance.

References:

[1] W. R. McGillis, V. P. Carey, J. S. Fitch, and W. R. Hamburgen, "Pool boiling enhancement techniques for water at low pressure," in 1991 Proceedings, Seventh IEEE Semiconductor Thermal Measurement and Management Symposium, IEEE, pp. 64–72. doi: 10.1109/STHERM.1991.152914.

[2] T. Wen, J. Luo, K. Jiao, and L. Lu, "Experimental study on the pool boiling performance of a highly self-dispersion TiO2 nanofluid on copper surface," International Journal of Thermal Sciences, vol. 184, Feb. 2023, doi: 10.1016/j.ijthermalsci.2022.107999.

[3] S. Kim, S. U. Ryu, D. J. Euh, and C. H. Song, "Experimental study on the thermal stratification in a pool boiling with a horizontal heat source," Ann Nucl Energy, vol. 106, pp. 235–246, Aug. 2017, doi: 10.1016/j.anucene.2017.03.036.

[4] A. Jalali, J. Khorshidi, Y. Bakhshan, and S. Niazi, "Numerical simulation and experimental investigation of bubble behaviour during pool boiling in the coiled wire," *Heliyon*, vol. 9, no. 11, p. e22168, Nov. 2023, doi: 10.1016/j.heliyon.2023.e22168.

[5] E S. M. A. Noori Rahim Abadi, A. Ahmadpour, and J. P. Meyer, "Numerical simulation of pool boiling on smooth, vertically aligned tandem tubes," *International Journal of Thermal Sciences*, vol. 132, pp. 628–644, Oct. 2018, doi: 10.1016/j.ijthermalsci.2018.07.005.

[6] H. Moghadasi, H. Saffari, and N. Malekian, "Experimental and semi-analytical investigation of heat transfer in nucleate pool boiling by considering surface structuring methods," *Experimental Heat Transfer*, vol. 34, no. 4, pp. 293–313, 2021, doi: 10.1080/08916152.2020.1743385.

[7] Z. Wu, Z. Cao, and B. Sundén, "Saturated pool boiling heat transfer of acetone and HFE-7200 on modified surfaces by electrophoretic and electrochemical deposition," Appl Energy, vol. 249, pp. 286–299, Sep. 2019, doi: 10.1016/j.apenergy.2019.04.160.

[8] N. Gobinath, T. Venugopal, K. Palani, and A. A. Samuel, "Numerical modelling of thermophoresis in water-alumina nanofluid under pool boiling conditions," International Journal of Thermal Sciences, vol. 129, pp. 1–13, Jul. 2018, doi: 10.1016/j.ijthermalsci.2018.02.025.

[9] L. Yang and K. Du, "A comprehensive review on heat transfer characteristics of TiO2 nanofluids," Int J Heat Mass Transf, vol. 108, pp. 11–31, May 2017, doi: 10.1016/j.ijheatmasstransfer.2016.11.086.

[10] D. E. Kim, D. I. Yu, D. W. Jerng, M. H. Kim, and H. S. Ahn, "Review of boiling heat transfer enhancement on micro/nanostructured surfaces," *Exp Therm Fluid Sci*, vol. 66, pp. 173–196, Sep. 2015, doi: 10.1016/j.expthermflusci.2015.03.023.

[11] X. Fang, Y. Chen, H. Zhang, W. Chen, A. Dong, and R. Wang, "Heat transfer and critical heat flux of nanofluid boiling: A comprehensive review," Renewable and Sustainable Energy Reviews, vol. 62. Elsevier Ltd, pp. 924–940, 2016. doi: 10.1016/j.rser.2016.05.047.

[12] C. G. Jothi Prakash and R. Prasanth, "Enhanced boiling heat transfer by nano structured surfaces and nanofluids," Renewable and Sustainable Energy Reviews, vol. 82, pp. 4028–4043, Feb. 2018, doi: 10.1016/j.rser.2017.10.069.

[13] L. Duan, B. Liu, B. Qi, Y. Zhang, and J. Wei, "Pool boiling heat transfer on silicon chips with non-uniform micro-pillars," Int J Heat Mass Transf, vol. 151, Apr. 2020, doi: 10.1016/j.ijheatmasstransfer.2020.119456.

[14] E. Çiftçi and A. Sözen, "Heat transfer enhancement in pool boiling and condensation using h-BN/DCM and SiO2/DCM nanofluids: experimental and numerical comparison," Int J Numer Methods Heat Fluid Flow, vol. 31, no. 1, pp. 26–52, Jan. 2021, doi: 10.1108/HFF-02-2020-0113.

[15] G. Liang and I. Mudawar, "Review of pool boiling enhancement by surface

modification," International Journal of Heat and Mass Transfer, vol. 128. Elsevier Ltd, pp. 892–933, Jan. 01, 2019. doi: 10.1016/j.ijheatmasstransfer.2018.09.026.

[16] S. G. Liter and M. Kaviany, "Pool-boiling CHF enhancement by modulated porous-layer coating: theory and experiment," Int J Heat Mass Transf, vol. 44, no. 22, pp. 4287–4311, Nov. 2001, doi: 10.1016/S0017-9310(01)00084-9.

[17] S. Mori and Y. Utaka, "Critical heat flux enhancement by surface modification in a saturated pool boiling: A review," Int J Heat Mass Transf, vol. 108, pp. 2534–2557, May 2017, doi: 10.1016/j.ijheatmasstransfer.2017.01.090.

[18] G. Liang and I. Mudawar, "Review of pool boiling enhancement by surface modification," Int J Heat Mass Transf, vol. 128, pp. 892–933, Jan. 2019, doi: 10.1016/j.ijheatmasstransfer.2018.09.026.

[19] C. M. Patil and S. G. Kandlikar, "Pool boiling enhancement through microporous coatings selectively electrodeposited on fin tops of open microchannels," Int J Heat Mass Transf, vol. 79, pp. 816–828, Dec. 2014, doi: 10.1016/j.ijheatmasstransfer.2014.08.063.

[20] S. Mori, S. Mt Aznam, and K. Okuyama, "Enhancement of the critical heat flux in saturated pool boiling of water by nanoparticle-coating and a honeycomb porous plate," Int J Heat Mass Transf, vol. 80, pp. 1–6, Jan. 2015, doi: 10.1016/j.ijheatmasstransfer.2014.08.046.

[21] A. Jaikumar and S. G. Kandlikar, "Enhanced pool boiling for electronics cooling using porous fin tops on open microchannels with FC-87," Appl Therm Eng, vol. 91, pp. 426–433, Dec. 2015, doi: 10.1016/j.applthermaleng.2015.08.043.

[22] Minseok Ha and S. Graham, "Pool boiling enhancement through hierarchical texturing of surfaces," in 2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, May 2016, pp. 388–394. doi: 10.1109/ITHERM.2016.7517575.

[23] R. Kaniowski, R. Pastuszko, and Ł. Nowakowski, "Effect of geometrical parameters of open microchannel surfaces on pool boiling heat transfer," EPJ Web Conf, vol. 143, p. 02049, May 2017, doi: 10.1051/epjconf/201714302049.

[24] A. M. Gheitaghy, A. Samimi, and H. Saffari, "Surface structuring with inclined minichannels for pool boiling improvement," Appl Therm Eng, vol. 126, pp. 892–902, Nov. 2017, doi: 10.1016/j.applthermaleng.2017.07.200.

[25] V. V. Nirgude and S. K. Sahu, "Enhancement of nucleate boiling heat transfer using structured surfaces," Chemical Engineering and Processing: Process Intensification, vol. 122, pp. 222–234, Dec. 2017, doi: 10.1016/j.cep.2017.10.013.

[26] M. Ha and S. Graham, "Pool boiling characteristics and critical heat flux mechanisms of microporous surfaces and enhancement through structural modification," Appl Phys Lett, vol. 111, no. 9, Aug. 2017, doi: 10.1063/1.4999158n 20 November 2023).

[27] G. Udaya Kumar, K. Soni, S. Suresh, K. Ghosh, M. R. Thansekhar, and P. Dinesh Babu, "Modified surfaces using seamless graphene/carbon nanotubes based nanostructures for enhancing pool boiling heat transfer," Exp Therm Fluid Sci, vol. 96, pp. 493–506, Sep. 2018, doi: 10.1016/j.expthermflusci.2018.03.038.

[28] B. Shen et al., "Enhanced pool boiling of ethanol on wettability-patterned surfaces," Appl Therm Eng, vol. 149, pp. 325–331, Feb. 2019, doi: 10.1016/j.applthermaleng.2018.12.049.

[29] M. Može, M. Zupančič, and I. Golobič, "Pattern geometry optimization on superbiphilic aluminum surfaces for enhanced pool boiling heat transfer," Int J Heat Mass Transf, vol. 161, p. 120265, Nov. 2020, doi: 10.1016/j.ijheatmasstransfer.2020.120265.

[30] A. Elkholy and R. Kempers, "Enhancement of pool boiling heat transfer using 3D-printed polymer fixtures," Exp Therm Fluid Sci, vol. 114, p. 110056, Jun. 2020, doi: 10.1016/j.expthermflusci.2020.110056.

[31] H. Moghadasi, H. Fathalizadeh, A. Mehdikhani, and H. Saffari, "Surface Modification Utilizing Photolithography Process for Pool Boiling Enhancement: An Experimental Study," Heat Transfer Engineering, vol. 43, no. 12, pp. 1008–1024, Jul. 2022, doi: 10.1080/01457632.2021.1932037.

[32] Y. Song et al., "Enhancement of Boiling with Scalable Sandblasted Surfaces," ACS Appl Mater Interfaces, vol. 14, no. 7, pp. 9788–9794, Feb. 2022, doi: 10.1021/acsami.1c22207.

[33] W. Li, Q. Li, H. Chang, Y. Yu, and S. Tang, "Electric field enhancement of pool boiling of dielectric fluids on pillar-structured surfaces: A lattice Boltzmann study," Physics of Fluids, vol. 34, no. 12, Dec. 2022, doi: 10.1063/5.0122145.

[34] M. Bulut, M. Shukla, S. G. Kandlikar, and

N. Sozbir, “Experimental study of heat transfer in a microchannel with pin fins and sintered coatings,” Experimental Heat Transfer, vol. 36, no. 7, pp. 1099–1114, Nov. 2023, doi: 10.1080/08916152.2023.2176566.

[35] H. Wang, D. Guan, X. Ji, and J. Xu, “Three-dimensional mixed boiling: A strategy for critical heat flux enhancement,” Physics of Fluids, vol. 35, no. 8, Aug. 2023, doi: 10.1063/5.0161309.

[36] J. M. Kim, D. I. Yu, H. S. Park, K. Moriyama, and M. H. Kim, “Smart surface in pool boiling: Thermally-induced wetting transition,” Int J Heat Mass Transf, vol. 109, pp. 231–241, Jun. 2017, doi: 10.1016/j.ijheatmasstransfer.2017.02.009.

[37] J. M. Kim, T. Kim, D. I. Yu, M. H. Kim, K. Moriyama, and H. S. Park, “Time effect on wetting transition of smart surface and prediction of the wetting transition for critical heat flux in pool boiling,” Int J Heat Mass Transf, vol. 114, pp. 735–742, Nov. 2017, doi: 10.1016/j.ijheatmasstransfer.2017.06.114.

[38] A. Walunj and A. Sathyabhama, “Comparative study of pool boiling heat transfer from various microchannel geometries,” Appl Therm Eng, vol. 128, pp. 672–683, 2018, doi: 10.1016/j.applthermaleng.2017.08.157.

[39] D. Cooke and S. G. Kandlikar, “Effect of open microchannel geometry on pool boiling enhancement,” Int J Heat Mass Transf, vol. 55, no. 4, pp. 1004–1013, Jan. 2012, doi: 10.1016/j.ijheatmasstransfer.2011.10.010.

[40] W. R. Mcgillis, V. P. Carey, J. S. Fitch, and W. R. Hamburgen, “Pool Boiling Enhancement Techniques for Water at Low Pressure.”

[41] A. K. Sadaghiani et al., “Effects of bubble coalescence on pool boiling heat transfer and critical heat flux – A parametric study based on artificial cavity geometry and surface wettability,” Int J Heat Mass Transf, vol. 147, Feb. 2020, doi: 10.1016/j.ijheatmasstransfer.2019.118952

[42] C. Zhang, L. Zhang, H. Xu, P. Li, and B. Qian, “Performance of pool boiling with 3D grid structure manufactured by selective laser melting technique,” Int J Heat Mass Transf, vol. 128, pp. 570–580, Jan. 2019, doi: 10.1016/j.ijheatmasstransfer.2018.09.021.

[43] A. Hayes, P. A. Raghupathi, T. S. Emery, and S. G. Kandlikar, “Regulating flow of vapor to enhance pool boiling,” Appl Therm Eng, vol. 149, pp. 1044–1051, Feb. 2019, doi: 10.1016/j.applthermaleng.2018.12.091

[44] H. S. Jo et al., “Supersonically spray-coated copper meshes as textured surfaces for pool boiling,” International Journal of Thermal Sciences, vol. 132, pp. 26–33, Oct. 2018, doi: 10.1016/j.ijthermalsci.2018.05.041

[45] Y.-Q. Wang, J.-L. Luo, Y. Heng, D.-C. Mo, and S.-S. Lyu, “Wettability modification to further enhance the pool boiling performance of the micro nano bi-porous copper surface structure,” Int J Heat Mass Transf, vol. 119, pp. 333–342, Apr. 2018, doi: 10.1016/j.ijheatmasstransfer.2017.11.080

[46] H. Bian, C. Kurwitz, Z. Sun, K. Cheng, and K. Chen, “Enhanced nucleate boiling on 3D-printed micro-porous structured surface,” Appl Therm Eng, vol. 141, pp. 422–434, Aug. 2018, doi: 10.1016/j.applthermaleng.2018.05.107.

[47] P. Rahmati, M. Ebrahimi-Dehshali, and A. Hakkaki-Fard, “Enhancement of pool boiling heat transfer using ferromagnetic beads in a variable magnetic field,” Appl Therm Eng, vol. 164, p. 114439, Jan. 2020, doi: 10.1016/j.applthermaleng.2019.114439

[48] W. M. Rohsenow and P. G. For, “TECHNICAL REPORT NO. CORRELATION FOR BOILING OF MAXIMUM HEAT FLUX OF SATURATED LIQUIDS MASSACHUSETTS INSTITUTE OF TECHNOLOGY DIVISION OF INDUSTRIAL COOPERATION,” 1955. [Online]. Available: http://Iibraries.mit.edu/docs

[49] Y. S. N. W. Chang, “HEAT TRANSFER IN SATURATED BOILING,” Chem. Eng. Progr., vol. 56, pp. 25–28, 1960.

[50] G. Liang and I. Mudawar, “Pool boiling critical heat flux (CHF) – Part 1: Review of mechanisms, models, and correlations,” Int J Heat Mass Transf, vol. 117, pp. 1352–1367, Feb. 2018, doi: 10.1016/j.ijheatmasstransfer.2017.09.134

[51] N. Zuber, “On the Stability of Boiling Heat Transfer,” J Fluids Eng, vol. 80, no. 3, pp. 711–714, Apr. 1958, doi: 10.1115/1.4012484

[52] N. Zuber, “Hydrodynamic Aspects Of Boiling Heat Transfer (Thesis),” Oak Ridge, TN, Jun. 1959. doi: 10.2172/4175511.

[53] A. H. John Lienhard and V. K. Dhir, “EXTENDED HYDRODYNAMIC THEORY OF THE PEAK AND MINIMUM POOL BOILING HEAT FLUXES,” 1973

[54] J. H. Lienhard and V. K. Dhir, “Hydrodynamic Prediction of Peak Pool-boiling Heat Fluxes from Finite Bodies,” J

Heat Transfer, vol. 95, no. 2, pp. 152–158, May 1973, doi: 10.1115/1.3450013.

[55] Y.-P. Chang, "An analysis of the critical conditions and burnout in boiling heat transfer," University of Notre Dame, 1961.

[56] A. B.-C. A.A. Watwe, "Modeling of conduction effects on pool boiling CHF of dielectric liquids," *Proceedings of the 32nd National Heat Transfer Conference, Baltimore, USA*, 1997.

[57] Yu. A. Kirichenko and P. S. Chernyakov, "Determination of the first critical thermal flux on flat heaters," *Journal of Engineering Physics*, vol. 20, no. 6, pp. 699–703, Jun. 1971, doi: 10.1007/BF01122589.

[58] J. M. Ramilison, P. Sadasivan, and J. H. Lienhard, "Surface Factors Influencing Burnout on Flat Heaters," J Heat Transfer, vol. 114, no. 1, pp. 287–290, Feb. 1992, doi: 10.1115/1.2911261.

[59] W. Bailey, E. Young, C. Beduz, and Y. Yang, "Pool boiling study on candidature of pentane, methanol and water for near room temperature cooling," in Thermal and Thermomechanical Proceedings 10th Intersociety Conference on Phenomena in Electronics Systems, 2006. ITHERM 2006., IEEE, pp. 599–603. doi: 10.1109/ITHERM.2006.1645400.

[60] J. Kim, S. Jun, J. Lee, J. Godinez, and S. M. You, "Effect of Surface Roughness on Pool Boiling Heat Transfer of Water on a Superhydrophilic Aluminum Surface," J Heat Transfer, vol. 139, no. 10, Oct. 2017, doi: 10.1115/1.4036599.

[61] L. Wang, Y. Li, F. Zhang, F. Xie, and Y. Ma, "Correlations for calculating heat transfer of hydrogen pool boiling," Int J Hydrogen Energy, vol. 41, no. 38, pp. 17118–17131, Oct. 2016, doi: 10.1016/j.ijhydene.2016.06.254.

[62] M. A. K. R.I. Soziev, "Calculating critical heat flux density with pool boiling," Therm. Eng. 37, 1989.

[63] V.M. Borishanskii, "On the Problem of Generalizing Experimental Data on the Cessation of Bubble Boiling in Large Volume of Liquids," Report No. Ts. K.I.T 28, Soviet Union, 1955.

[64] J. A. Eastman, "Enhancing thermal conductivity of fluids with nanoparticles." [Online]. Available: https://www.researchgate.net/publication/236353373.

[65] J. T. Cieśliński and K. Krygier, "Augmentation of the Critical Heat Flux in Water-Al 2 O 3 , Water-TiO 2 and Water-Cu Nanofluids," MATEC Web of Conferences, vol. 18, p. 01012, Dec. 2014, doi: 10.1051/matecconf/20141801012.

[66] S. B. White, A. J. Shih, and K. P. Pipe, "Boiling surface enhancement by electrophoretic deposition of particles from a nanofluid," Int J Heat Mass Transf, vol. 54, no. 19–20, pp. 4370–4375, Sep. 2011, doi: 10.1016/j.ijheatmasstransfer.2011.05.008.

[67] Y.-W. Lu and S. G. Kandlikar, "Nanoscale Surface Modification Techniques for Pool Boiling Enhancement: A Critical Review and Future Directions," in ASME 2010 8th International Conference on Nanochannels, Microchannels, and Minichannels: Parts A and B, ASMEDC, Jan. 2010, pp. 1365–1376. doi: 10.1115/FEDSM-ICNMM2010-30170.

[68] M. M. Sarafraz and F. Hormozi, "Pool boiling heat transfer to dilute copper oxide aqueous nanofluids," International Journal of Thermal Sciences, vol. 90, pp. 224–237, Apr. 2015, doi: 10.1016/j.ijthermalsci.2014.12.014.

[69] O. Ahmed and M. S. Hamed, "Experimental investigation of the effect of particle deposition on pool boiling of nanofluids," Int J Heat Mass Transf, vol. 55, no. 13–14, pp. 3423–3436, Jun. 2012, doi: 10.1016/j.ijheatmasstransfer.2012.02.021.

[70] M. S. Kamel and F. Lezsovits, "Enhancement of pool boiling heat transfer performance using dilute cerium oxide/water nanofluid: An experimental investigation," International Communications in Heat and Mass Transfer, vol. 114, p. 104587, May 2020, doi: 10.1016/j.icheatmasstransfer.2020.104587

[71] M. S. Kamel and F. Lezsovits, "Experimental investigation on pool boiling heat transfer performance using tungsten oxide WO3 nanomaterial-basedwater nanofluids," Materials, vol. 13, no. 8, Apr. 2020, doi: 10.3390/MA13081922

[72] X. Tang, Y.-H. Zhao, and Y. Diao, "Experimental investigation of the nucleate pool boiling heat transfer characteristics of δ-Al2O3-R141b nanofluids on a horizontal plate," Exp Therm Fluid Sci, vol. 52, pp. 88–96, Jan. 2014, doi: 10.1016/j.expthermflusci.2013.08.025.

[73] L. L. Manetti, M. T. Stephen, P. A. Beck, and E. M. Cardoso, "Evaluation of the heat transfer enhancement during pool boiling using low concentrations of Al2O3-water based nanofluid," *Exp Therm Fluid Sci*, vol. 87, pp. 191–200, Oct. 2017, doi: 10.1016/j.expthermflusci.2017.04.018.

[74] M. Karimzadehkhouei, M. Shojaeian, K. Şendur, M. P. Mengüç, and A. Koşar, "The effect of nanoparticle type and nanoparticle

mass fraction on heat transfer enhancement in pool boiling," Int J Heat Mass Transf, vol. 109, pp. 157–166, Jun. 2017, doi: 10.1016/j.ijheatmasstransfer.2017.01.116.

[75] E. Abedini, T. Zarei, M. Afrand, and S. Wongwises, "Experimental study of transition flow from single phase to two phase flow boiling in nanofluids," J Mol Liq, vol. 231, pp. 11–19, Apr. 2017, doi: 10.1016/j.molliq.2017.01.049.

[76] S. K. Gupta and R. D. Misra, "Experimental study of pool boiling heat transfer on copper surfaces with Cu-Al2O3 nanocomposite coatings," International Communications in Heat and Mass Transfer, vol. 97, pp. 47–55, Oct. 2018, doi: 10.1016/j.icheatmasstransfer.2018.07.004.

[77] F. R. Dareh, M. Haghshenasfard, M. Nasr Esfahany, and H. Reza Salimi Jazi, "An experimental investigation of pool boiling characteristics of alumina-water nanofluid over micro-/nanostructured surfaces," Heat Transfer Engineering, vol. 40, no. 20, pp. 1691–1708, Dec. 2019, doi: 10.1080/01457632.2018.1496980.

[78] M. Modi, P. Kangude, and A. Srivastava, "Performance evaluation of alumina nanofluids and nanoparticles-deposited surface on nucleate pool boiling phenomena," Int J Heat Mass Transf, vol. 146, p. 118833, Jan. 2020, doi: 10.1016/j.ijheatmasstransfer.2019.118833.

[79] A. Pare and S. K. Ghosh, "Surface qualitative analysis and ANN modelling for pool boiling heat transfer using Al2O3-water based nanofluids," Colloids Surf A Physicochem Eng Asp, vol. 610, p. 125926, Feb. 2021, doi: 10.1016/j.colsurfa.2020.125926.

[80] T. Le Ba *et al.*, "Experimental Study of Halloysite Nanofluids in Pool Boiling Heat Transfer," *Molecules*, vol. 27, no. 3, p. 729, Jan. 2022, doi: 10.3390/molecules27030729.

[81] Y. Kumaravelu et al., "Influence of Aluminum Silicate and Cerium (IV) Oxide Nanofluid on Pool Boiling Characteristics," International Journal of Photoenergy, vol. 2022, pp. 1–11, Feb. 2022, doi: 10.1155/2022/5357053.

[82] S. Mukherjee, S. Ebrahim, P. C. Mishra, N. Ali, and P. Chaudhuri, "A Review on Pool and Flow Boiling Enhancement Using Nanofluids: Nuclear Reactor Application," Processes, vol. 10, no. 1, p. 177, Jan. 2022, doi: 10.3390/pr10010177.

[83] M. Zolfalizadeh, S. Zeinali Heris, H. Pourpasha, M. Mohammadpourfard, and J. P. Meyer, "Experimental Investigation of the Effect of Graphene/Water Nanofluid on the Heat Transfer of a Shell-and-Tube Heat Exchanger," Int J Energy Res, vol. 2023, pp. 1–16, Mar. 2023, doi: 10.1155/2023/3477673.

[84] T. G. Theofanous and T. N. Dinh, "HIGH HEAT FLUX BOILING AND BURNOUT AS MICROPHYSICAL PHENOMENA: MOUNTING EVIDENCE AND OPPORTUNITIES," *Multiphase Science and Technology*, vol. 18, no. 3, pp. 251–276, 2006, doi: 10.1615/MultScienTechn.v18.i3.30.

[85] S. G. Kandlikar, "A Theoretical Model to Predict Pool Boiling CHF Incorporating Effects of Contact Angle and Orientation," J Heat Transfer, vol. 123, no. 6, pp. 1071–1079, Dec. 2001, doi: 10.1115/1.1409265.

[86] S. D. Park et al., "Effects of nanofluids containing graphene/graphene-oxide nanosheets on critical heat flux," Appl Phys Lett, vol. 97, no. 2, Jul. 2010, doi: 10.1063/1.3459971.

[87] P. Sadasivan, P. R. Chappidi, C. Unal, and R. A. Nelson, "Possible mechanisms of macrolayer formation," International Communications in Heat and Mass Transfer, vol. 19, no. 6, pp. 801–815, Nov. 1992, doi: 10.1016/0735-1933(92)90016-B.