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A REVIEW OF POOL BOILING HEAT TRANSFER PROPERTIES BY NANOFLUID

M. Najmi S. A., A. Hassan*

Department of Physics and Chemistry, Faculty of Applied Science and Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Campus, 84600 Pagoh Muar, Johor, Malaysia

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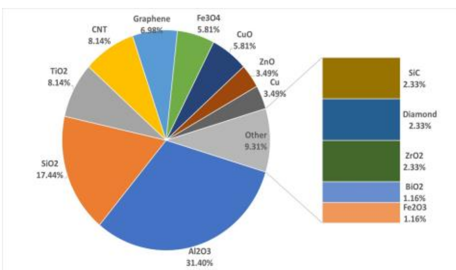
*Corresponding author
hassan@uthm.edu.my

Graphical abstract



Abstract

Boiling heat transfer has maintained a high degree of interest due to the range of its applications in the energy sector. In recent years, much research has focused on improving the nucleate pool boiling by modifying the fluid properties. In this review article, the basic properties and characteristics of Al_2O_3 nanofluids and few other nanofluids are explored and discussed through past research findings. Next, previous studies that involved pool boiling heat transfer enhancement using Al_2O_3 nanofluid and its performance in terms of critical heat flux (CHF) and heat transfer coefficient (HTC) are further highlighted. These studies have employed methods that affected the performance of CHF and HTC such as electric field and surface modification. Maximum enhancement in CHF measured is approximately 200%. On the other hand, usage of prediction models to predict enhancements are also discussed thoroughly. Regardless of boiling performance enhancements with the deployment of nanofluids, several concerns must first be addressed before it is able to be deployed for practical use.

Keywords: Pool boiling, nucleate boiling, heat transfer, nanofluid, critical heat flux, heat transfer coefficient

Abstrak

Pemindahan haba didih telah lama diberi perhatian disebabkan oleh kebolehan dan kepelbagaian aplikasinya dalam sektor tenaga. Dewasa ini, kebanyakan kajian memfokuskan kepada penambahbaikan pendidihan nukleat kolam melalui pengubahsuaian sifat bendalir. Dalam artikel ini, ciri-ciri asas dan sifat bendalir Al_2O_3 nano dan beberapa bendalir nano yang lain telah diterokai dan dibincangkan berdasarkan kepada penemuan daripada kajian-kajian terdahulu. Seterusnya, peningkatan pemindahan haba dalam pendidihan kolam melalui pendekatan bendalir nano Al_2O_3 dan prestasi dari segi fluks haba genting (CHF) dan pekali pemindahan haba (HTC) diberikan keutamaaan. Kajian-kajian terdahulu ini telah menggunakan kaedah yang boleh mempengaruhi prestasi CHF dan HTC seperti medan elektrik dan permukaan yang diubahsuai. Terdapat peningkatan maksima sebanyak 200% yang diukur dalam CHF. Di samping itu, penggunaan model ramalan untuk meramal peningkatan prestasi juga dibincangkan secara menyeluruh. Begitupun terdapat peningkatan prestasi dalam pemindahan haba didih apabila menggunakan bendalir nano, masih ada beberapa isu yang perlu ditangani sebelum bendalir nano ini digunakan secara praktikal.

Kata kunci: Pendidihan kolam, pendidihan nukleat, pemindahan haba, bendalir nano, fluks haba genting, pekali pemindahan haba

1.0 INTRODUCTION

Heat transfer processes are critical to almost every primary industry, such as system cooling, processing, or even power plants. The primary fluid used in most of these processes where heat may be gained, transported, and rejected, favouring liquids due to their remarkable thermophysical properties. This is particularly true when the liquid goes through phase changes, either via condensation or boiling, allowing for the extraction of both sensible (exchange of energy between the system and surrounding) and latent heat (transfer of energy from or to a system) [1, 2]. These phase-change processes permit the wide use of fluid in various applications.

As mentioned before, boiling is a significant phase change of the heat transfer method and the best method in terms of efficiency in transferring heat in the refrigeration and heating application. However, despite numerous technical advancements such as utilization of liquid coolers, various geometries of equipment and cooling techniques, these are still inadequate when the demands for large volumes of heat are involved, leading to the innovation of new ways to enhance transferring of heat [3–7].

Boiling operations may be carried out in several ways, including pool boiling [3, 4], micro/macro/mini-channel flow boiling [8], jet-impingement boiling [9], and spray boiling [7,10], also as a hybrid design combining two or more using these methods [11]. Pool boiling is particularly common in various industries because of its passive or pump-free operation, simplicity, and low cost [12]. However, it is essential to note that in the absence of external force to increase coolant flow velocity for greater heat transfer rate, other approaches to increase pool boiling are by altering the thermophysical traits of the liquid, increasing the boiling surface, or both [13].

Assuming that the boiling process can maintain the heated surface temperature at the desired value, the boiling curve will be obeyed. Boiling behaviours could be divided into stages of four. At the shallow wall superheat, the transfer of heat caused by natural convection will take place. As wall superheat increases, natural convection will change to nucleate boiling. When the initial bubble starts to develop, it will be marked as an onset nucleate boiling (ONB) phase. The behaviours of growth, departure and bubble nucleation are critical for heat transfer efficiency. The effectiveness of the heat transfer process can be quantified using heat transfer coefficient (HTC), which is defined as heat flux over wall superheat. It will significantly rise as wall superheat increases caused by increased intense bubble-motion-induced convection [14].

As the heat flux increases, the frequency of the bubble increases, causing subsequent bubbles to combine and produce vapour columns. With the ensuing increase in surface superheat, additional nucleation sites will be activated, culminating in a horizontal coalescence of bubbles to produce vapour mushrooms. This could be witnessed in the fully developed nucleate boiling region. As the heat flow rises, these vapour mushrooms may create enormous vapour patches, obstructing heat transport and precipitating critical heat flux (CHF). The film boiling generated by CHF is an undesirable phenomenon because it results in total vapour coating of the surface, leading to an excessive rise in surface temperature [15]. Furthermore, if the wall superheats continue to increase, the high density of vapor bubbles combine into a vapor film, hampers the HTC because of its low thermal conductivity. As a result, nucleate boiling will quickly transition to film boiling.

Recent research has focused on improving nucleate boiling heat transfer (NBHT) and CHF [14]. While NBHT is the most efficient among the four pool boiling regimes due to its ability to remove a considerable quantity of heat flux at relatively low superheat temperatures, CHF is also crucial in the design and safety of applications that utilise heat-flux-controlled surfaces [13]. Thus, enhancements of these factors have attracted a considerable amount of attention from the researcher.

To enhance heat transfer from a boiling surface, there are two different techniques that may be categorised as active or passive [16]. Passive techniques include rough surfaces [16, 17], extended surfaces [17–19], and fluid additives [20–22], while active techniques include using an electrostatic field [22, 23] and well as surface or fluid vibrations [16]. In other words, external power is used to achieve active techniques. In contrast with the passive techniques, these active techniques are prohibitively expensive and difficult for applications requiring modest cooling systems. On the other hand, passive methods do not need external power and instead rely on changes in the fluid's traits or the surface itself (fins, shape, roughness, etc.) or both.

It is worth noting that improving pool boiling heat transfer performance with the use of nanofluids as a passive technique is significant. Nanotechnology has drawn the interest of many potential applications over the last two decades due to its better potency in boiling enhancement.

Of all types of nanofluids studied by previous researchers, the Alumina (Al_2O_3) nanofluids have piqued the author's interest. The maturity of large-scale manufacturing, reduced cost, and environmental friendliness [24] have resulted in Al_2O_3 becoming the favoured option in the preparation of nanofluids. Therefore, in this review, the authors focus on the techniques and outcomes of pool boiling heat transfer by Al_2O_3 nanofluids that has been reported in recent years.

In Section 2.0 of this article, the pool and flow boiling enhancements utilising the passive approach are summarised. Surface modification and variation of nanoparticle concentrations involved in the process are reviewed in Section 3.0, mainly for the HTC and CHF enhancement. In addition, hybrid nanofluid augmentation approaches, effect of electric field in nanofluid pool boiling and a prediction model are also considered in Sections 2.2, 4.0 and 5.0, respectively. Finally, conclusion and recommendation from this review are addressed in Section 6.0.

2.0 OVERVIEW OF NANOFLUID AND POOL BOILING

Nanofluids are a novel class of nanometer-sized artificial fluids with 1-100 nm materials (nanofibers, nanosheets, nanorods, nanoparticles, nanowires, nanotubes or droplets) scattered in base fluids. Another term for this, nanofluids are colloidal suspensions of condensed nanomaterials/ nanoparticles dispersed evenly and stably in a liquid [25]. Fundamentally, nanoparticles have the power to modify or magnify the thermal properties of the working fluid or heating surface, resulting in higher boiling heat transferability.

The use of nanofluids as a novel class of cooling liquids in pool boiling heat transfer, on the other hand, has resulted in inconsistent conclusions about the pool boiling heat transfer coefficient (PBHTC) [25, 26]. For example, on experimental data noted by Gerardi *et al*. [27], when compared to pure water, HTC for nanofluids was degraded, especially at high heat flux values. On the other hand, Akbari *et al.* [28] discovered that nanofluids have the potential to increase heat transfer coefficients. The difference in results could be explained by the type of nanofluids and thermophysical properties used in their studies, as well as the concentration of nanoparticles. Because of the discrepancy in the results, many researchers have systematically studied the pool boiling of nanofluids under various operating settings, such as the impacts of base liquid, nanoparticles, and initial surface roughness, in order to thoroughly understand the process [29].

The outcomes from nucleate pool boiling experiments utilizing nanofluid and the formation of nanoscale-sized structures on the heating surface have received much attention. Specific experimental results on the influence of nanoparticles on boiling heat transfer in terms of enhancing the base fluid's thermal conductivity have also been reported [30–32]. Most research in the open literature reported an increase in the CHF when nanofluids are used, mainly at pool boiling conditions [32,33]. Park *et al*. and Liu *et al*. also observed a significant increase in boiling heat transfer [34, 35] compared to others who reported a significant decrease in heat transfer [36–39]. Even when the nanoparticles and concentrations were the same, as well as the testing environments, these results revealed differences. Several studies have linked the differences in boiling heat transfer coefficient (HTC) to nanoparticle deposition on the heating surface [36, 39, 40].

For actual visualization purpose, Figure 2 shows Alumina nanofluid prepared by author using Two-step method while Figure 3 is SiO_2 under the boiling process. Basic setup used for pool boiling experiment is shown in Figure 4. (Figures 2, 3 and 4 are captured at UTHM laboratory).

2.1 Heat Transfer of Alumina Nanofluids

Metallic, metal oxides, diamonds, nanotubes, and glass are some examples of nanoparticles. However, it is well known that alumina oxide, Al_2O_3 is the most extensively employed type of nanoparticle in previous studies (as shown in Figure 1) due to its unique properties follows, as highly conductive thermally, forming a uniform and ongoing suspension without modifying the chemical composition of the base fluid, inexpensive cost to produce, and well-documented physical properties [41].

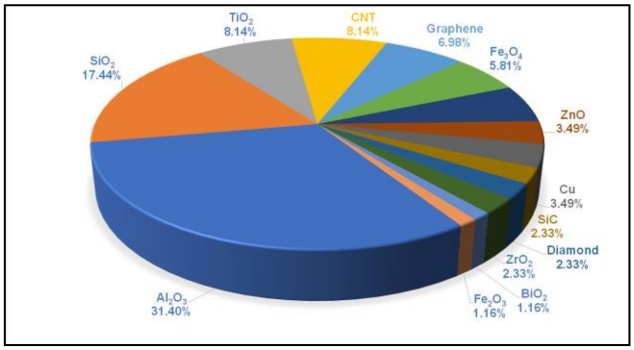


Figure 1 Percentage of nanoparticle material in the present consolidated database [42]

Table 1 presents a circumstance of experimental studies published in the last several years on nanofluid pool boiling from the works of literature. They vary in terms of working fluid, stability method and also substrates used in the investigation. These researches mostly aimed at determining the prevalence of HTC and CHF. As in the table, this review has found that the majority of the experiments for Al_2O_3 nanoparticles were carried out with copper as the heating surface.

Watanabe *et al*. [43] experimented with the nanoparticle layer's adhesion force and its impact of nanoparticle layer disassociation on boiling heat transfer properties. The heated surface used is made of copper, which is a common material, and nanoparticles used in their study are titanium-dioxide (TiO_2), alumina (Al_2O_3), and silica (SiO_2). Instead of employing nanofluid as a base fluid for boiling experiments, nanofluid is used to coat the heating surface. This allows results from the measurement of the BHT and CHF using Al_2O_3 nanoparticles to be focused in this current review. They reported that for non-damaged nanoparticle-deposited surfaces, CHF has increased to 1.92 MW/m^2. They also determined that the layer of nanoparticles that was shaped on the heating surface operated as thermal insulation and boosted the surface's wettability.

Table 1 Literature review of some nanofluid heat transfer experimental studies

No.	Authors	Circumstances	Working fluid	Stability method	Substrates	HTC effect	CHF effect	Results
1	You *et al*. [15]	Pool boiling	Al_2O_3 (alumina) nanoparticles	-	Platinum wire heater	-	Enhance	Based on the author's knowledge, nanofluid CHF enhancement cannot be explained with existing models of CHF prediction (Zuber's prediction). Therefore, further studies on nanosized particles' behaviour in liquid water and nanofluids' properties must be performed to understand this phenomenon.
2	Bang and Chang [36]	Pool boiling	Al_2O_3 nanofluid	Vibrated in an ultrasonic bath	Test plane heater	Lower than pure water	Enhance	PBHTC decreases with an increase in particle concentration. This is because nanoparticles lower the number of active nucleation sites with the surface roughness variation in NBHT. Also, roughness change causes a fouling effect with poor thermal conduction in single-phase heat transfer.
3	Watanabe *et al*. [43]	Pool boiling	Distilled water	Ultrasonic excitation (ultrasonic bath)	Copper	Deteriorate (TiO_2)	Enhance	The nanoparticle layer generated on the heated surface worked as a material for thermal insulation and enhanced surface wettability, resulting in a decrease in boiling heat transfer but an increase in critical heat flow for nanoparticle-deposited surfaces.
4	Bhambi and Agarwal [44]	Sub atmospheric Pool boiling	Al_2O_3 (alumina) nanoparticles	Magnetic stirring followed by ultrasonication	-	Enhance	-	Heat transfer is improved from the results of the behaviour of nanoparticles suspended in distilled water and the properties of the surface of the heating surface.
5	Wen and Ding [45]	Laminar flow	γ-Al_2O_3	Small amount of sodium dodecylbenzene sulfonate (SDBS)	Copper tube	Enhance	-	Nanoparticles significantly enhance convective heat transfer. This enhancement not only causes improvement of the effective thermal conductivity but the migration of the particles also is proposed to be a reason.
6	Mukherjee *et al*. [46]	Subcooled flow boiling	Al_2O_3/water nanofluid DI water	Magnetic stirring followed by ultrasonication	-	Enhance	-	The surface roughness increased as the concentration of nanofluid rose during flow. The increased roughness assisted in the rate of heat transmission. However, the accumulation of particles on the heated surface generates thermal resistance, further slowing the heat transmission rate. As a result, at a more significant concentration, HTC enhancement is hampered.
7	Sarafraz and Hormozi [47]	Flow boiling	Al_2O_3 nanofluid	Ultrasonication	Stainless steel	Enhance	-	Recommend using nanofluids for a higher rate of heat transfer rate in forced convective regions; however, the usage of nanofluid coolant in nucleate boiling region faces a decline in heat transfer coefficient.
8	Rana *et al*. [48]	Flow boiling	ZnO-water nanofluid	Ultrasonication	Stainless steel rod	Enhance	-	The heat transfer coefficient improves with heat flux. Enhanced effective thermal conductivity of nanofluid and alteration of the surface of heat transfer might be one of the possible reasons for the enhancement.
9	Prajapati and Rohatgi [49]	Flow boiling	ZnO-water nanofluid	Ultrasonication	Hollow stainless steel rod	Enhance	-	Increase in heat transfer by 126% over water with applied pressure and particle volume fraction of nanofluid within the given heat flux range adopted. Also, an increase of surface roughness of the heating surface by 1367% with an increase in the concentration of ZnO particles in the nanofluid over the water.
10	Yagnem and Venkatachalapathy [50]	Pool boiling	Al_2O_3 and CuO	Magnetic stirring followed by ultrasonication	Copper	Enhance	Enhance	CHF of hybrid nanofluids is higher compared to single-type nanofluids in pool boiling. Also, HTC will decrease with increasing volume concentrations due to the deposition of nanoparticles on the surface tested.
11	Kamel *et al*. [51]	Pool boiling	Al_2O_3 and CeO_2	Magnetic stirring followed by	Copper	Enhance	-	The present enhancement of hybrid nanofluid was about 37% for 0.05% volume concentration and initial surface roughness of

No.	Authors	Circumstances	Working fluid	Stability method	Substrates	HTC effect	CHF effect	Results
				ultrasonication				382nm for the horizontal heated copper typical tube. This was a higher percentage than other hybrid nanofluids reported in the literature.
12	Manetti *et al*. [52]	Pool boiling	Al_2O_3water-based nanofluid	Ultrasonication	Copper	Enhance	-	The enhancement/deterioration of HTC is determined by changes in the morphology of the heating surface. Therefore, the authors concluded that alterations on the surface were caused by nanoparticle deposition.
13	Modi *et al*. [53]	Pool Boiling	Al_2O_3/water-based nanofluids	Ultrasonication, Sodium Dodecyl Benzene Sulphonate (SDBS)	Borofloat glass	Enhance	-	The investigations demonstrated that alumina nanoparticles, either suspended in the bulk liquid or coated on the heater substrate, improved the heat transmission performance of the single bubble-based pool boiling phenomena.
14	Chen *et al*. [54]	Pool Boiling	Al_2O_3	Polyvinyl Pyrrolidone (PVP), Magnetic stirring followed by ultrasonication	Stainless-steel needle	Enhance	Enhance	Heat transfer performance (BHTC and CHF) of resuspended nanofluid is improved owing to the coupling effect between resuspended nanofluid and electric field, which increases with voltage rise. However, there is an ideal concentration for the electric field's enhancing impact.
15	Kwark *et al*. [55]	Pool boiling	Water	-	Al_2O_3 coated heater	Enhance	Enhance	CHF enhancement because of relatively high wetting speeds. This mechanism is believed to be more prominent at lower system pressure. Later, CHF will show a decreasing trend when the inclination angle increased from 0° to 180° and when heater sizes increase.
16	Kwark *et al*. [56]	Pool boiling	Al_2O_3/water-based nanofluid	Ultrasonication	-	-	Enhance	Heater surfaces are being modified ongoingly during the process of boiling. Also, nanocoatings developed in ethanol nanofluids appear to be more uniform in comparison to water nanofluids. They also confirm the CHF enhancement dependence on surface wettability.
17	Pare and Ghosh [57]	Pool boiling	Al_2O_3-/water-based nanofluids	Magnetic stirring followed by ultrasonication	Copper block	Enhance	-	Pool boiling HTC in nanofluids has decreased with increasing particle concentrations. This is caused by an increase in heat resistance at the boiling surface caused by the deposition of particles. Furthermore, the concentration of nanofluid has a significant influence on changes in the morphology of the heater surface.
18	Shakir Majdi *et al*. [58]	Pool boiling	Al_2O_3 CuO	-	-	Enhance	-	Compared to CuO, the best nanomaterial is Al2O3, which is thought to be superior in improving the boiling process via increased speed, consequent vapour pressure, and big vapour dispersion.

Consequently, while boiling heat transfer was reduced, critical heat flux for nanoparticle-deposited surfaces increased. In addition, the incremental removal of the nanoparticle layer increased the surface contact angle while decreasing the mass of the nanoparticles deposited. As a result, as the detachment level of the nanoparticle layer increases, the boiling heat transfer declines and the intensification of critical heat decreases. Even so, significantly damaged surfaces had higher heat transfer coefficients and lowered critical heat fluxes compared to the bare heated surface.

Figure 2 Al_2O_3 nanofluid

Figure 3 SiO_2 nanofluid under boiling process

Next, Bhambi and Agarwal revealed that adding alumina nanoparticles to distilled water improves heat transfer significantly [44]. They recorded that for given heat flux, the HTC value of nanofluids is higher than distilled water. The observations are proven to be consistent with those described in You *et al*. and Wen and Ding's [15, 45] works. However, they differ from Bang and Chang [36]. They obtained that coefficients in boiling heat transfer in the nanofluids are lesser than in pure water. For work done by Wen and Ding [45], through their conducted flow boiling experiment, the result shows that adding nanoparticles can significantly enhance heat transfer. While You *et al.* [15] stated that the striking trend observed was a dramatic increase in CHF values when nanoparticles were added. In Bhambi and Agarwal's [43] work, in the case of 0.05% by volume alumina nanoparticles in distilled water, the enhancement is around 34%. The behaviour of nanoparticles dispersed in distilled water, as well as the surface features of the heating surface, can be related to these discoveries. As shown in Table 1, the results of the experiments done under various pressures were compared to those of other researchers. They arrived at the conclusion that as pressure rises, the heat transfer coefficient for a given heat flux rises as well. The most significant effect, however, is shown in surface tension. In reality, as pressure increases, the value of surface tension decreases, causing the value of the nucleation's minimum radius of curvature to decrease. As the curvature's radius of nucleation lowers, the frequency of bubble creation, growth, and departure from the heating surface rises, resulting in increased turbulence intensity. As a result, for the same heat flow at higher pressures, more significant heat transfer coefficients are discovered by Bhambi and Agarwal.

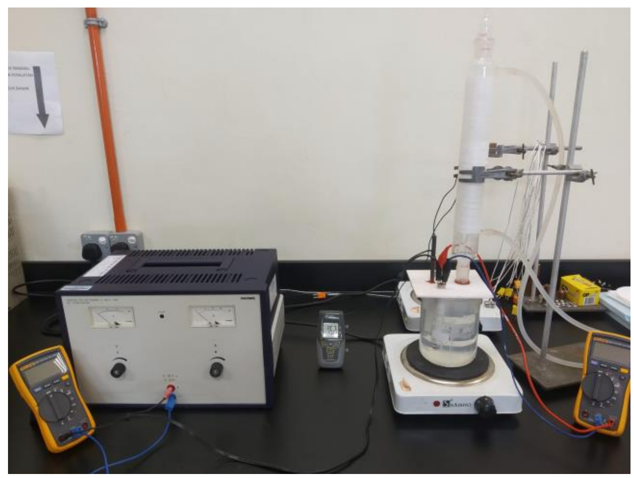


Figure 4 Simplest setup for pool boiling heat transfer process

In a study done by Mukherjee *et al*. [46], they presented an experimental work on the flow boiling heat transfer of Al_2O_3/water nanofluid. It differed from previous research in the literature in Table 1 in which others conducted experiments using pool boiling approaches. In preparation of nanofluid, they employed the two-step method as commonly used, as detailed in Figure 2. They also concluded that the results obtained are similar with Sarafraz and Hormozi [47]. With increasing the nanofluid concentration, HTC also increases compared to pure water. In the subcooled area, the HTC of nanofluids was better than that of pure water. The increase grew as the concentration of Al_2O_3 nanoparticles in water increased. With nanofluids at 0.5 wt.%, which is roughly 26%, the highest HTC augmentation was recorded.

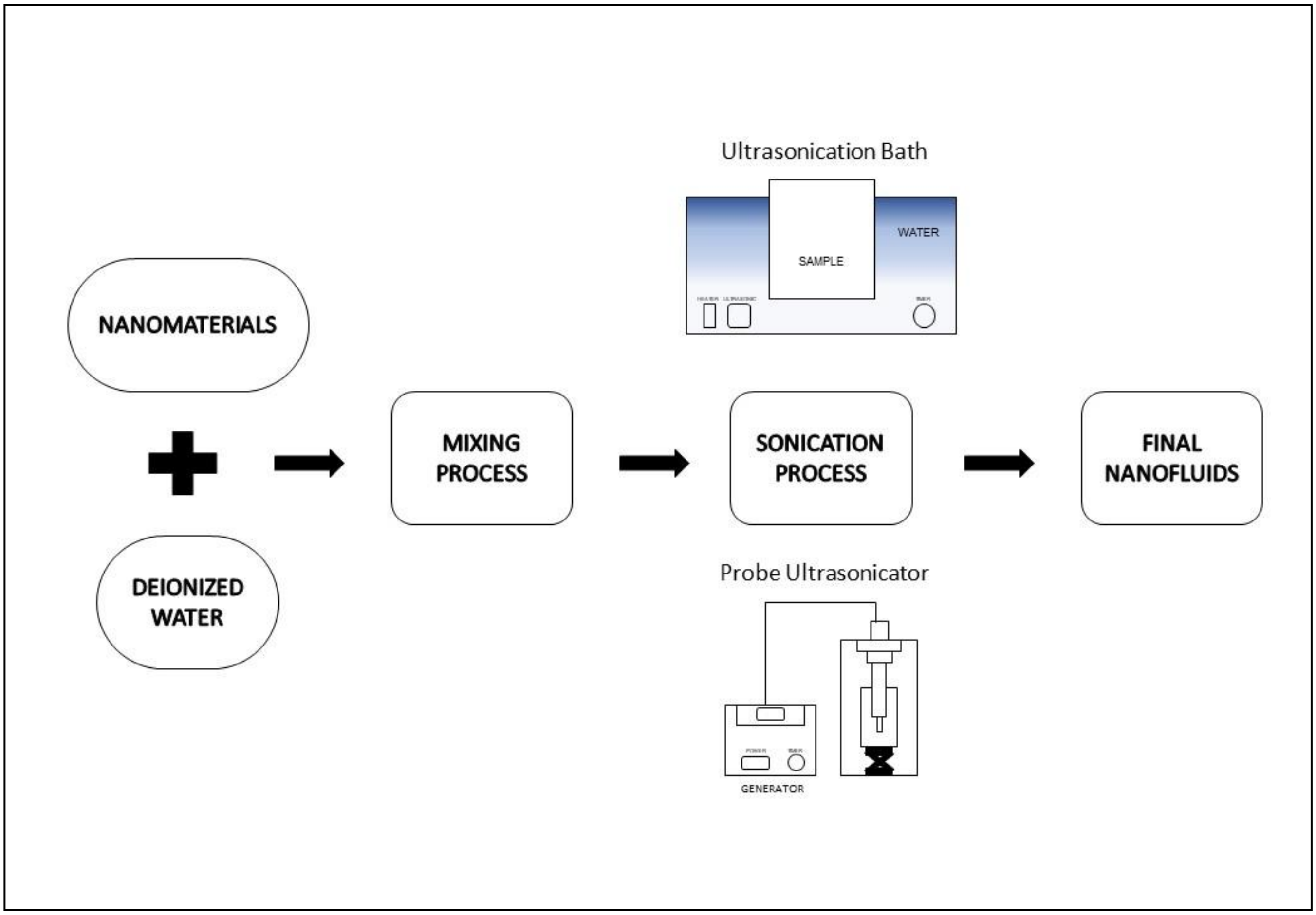


Figure 5 Two-step preparation method

They also discovered that the HTC of test fluids rose when heat flux increased for all concentrations, owing to the test fluids' energy transfer enhancement at higher heat flux. The HTC of nanofluids is higher than that of base fluids because of the presence of nanoparticles which allows for improved thermal diffusion at higher heat fluxes. These findings are claimed to be similar to previous research done by [48,49]. The main difference was that they used ZnO nanofluids instead of Al_2O_3 nanofluids. Surface roughness increased as the concentration of nanofluid rose during flow, according to Mukherjee *et al.* [46]. They also stated that the increased roughness aids heat transfer. On the other hand, particle collection on the heater surface generates thermal resistance, slowing down the heat transfer rate even more. As a result, at higher concentrations, HTC augmentation is hindered, which clearly agrees with the conclusion achieved by Watanabe *et al.* [45].

Overall, many recent studies have shown improvements in the HTC and CHF with nanofluids compared to the performance of heat transfer using conventional base fluid. Morphology changes on the heating surface, surface wettability increases, surface tension, and behaviour of suspended nanoparticles in the base fluid are some of the enhancing mechanisms.

2.2 Hybrid Nanofluids

Hybrid nanofluids can be described as a number of types (two or more) nano-additives suspended in a base fluid [21]. As nanofluids can enhance heat transfer performance, Yagnem and Venkatachalapathy [50] mixed two different nanofluids, Al_2O_3 and CuO, to study whether hybrid nanofluids could further improve CHF and HTC in pool boiling as listed in Table 1. These nanofluids were prepared by the two-step method separately and then combined in equal volumes. They conducted a pool boiling experiment using a mixture of deionized water (DI) water and the hybrid nanofluids with a volume concentration of 0.01-0.1% to observe enhancement at various concentrations. The augmentation of CHF was 19.33, 27.29, 34.39, 45.35, and 49.84%, respectively, at 0.01, 0.03, 0.05, 0.08, and 0.1% volume concentrations. At critical heat flux, the largest enhancement in HTC was 7.1% at 0.01% volume concentration of hybrid nanofluids compared to DI water. HTC was shown to be reduced when volume concentrations increased due to nanoparticle deposition on the test surface. They concluded that in pool boiling, hybrid nanofluids have a higher CHF compared to single type nanofluids. The boiling curves of hybrid nanofluids were shifted to the left when compared to DI water. As concentration grew, the curves shifted to the right due to particle deposition, resulting in stronger capillary action. Hybrid nanofluids are also more thermally conductive and stable than single-type nanofluids.

Kamel *et al*. [51] used a two-step approach to generate a hybrid nanofluid with a 50:50 mixing ratio with DI water as base fluid. However, they combined Al_2O_3 with Cerium Oxide, CeO_2. Intending to evaluate the performance of the PBHTC from a horizontal copper tube, their findings revealed that employing this sort of hybrid nanofluids improved pool boiling heat transfer performance. They developed pool boiling curves for nanofluids, and the result was that the curve shifted to the left side by for a given heat flux for all volume concentrations compared to the DI water pool boiling curve. They discovered that hybrid nanofluids with a volume concentration of 0.05% Vol. had a more significant PBHTC enhancement percentage of 37% at moderate heat flux. This was a larger percentage than reported by Yagnem and Venkatachalapathy [50] previously. They concluded that the deposition of nanoparticles with different particle diameters on the initial surface roughness of the heating element was a main reason for these enhancements.

From both studies, it can be concluded that hybrid nanofluid could be a promising working fluid through boiling application by utilizing optimum conditions related to the heater type, topology and orientation, and this is due to the interaction of both nanomaterials with a surface roughness of the heater during the deposition of nanoparticles.

3.0 EFFECT OF SURFACE MODIFICATION ON BOILING PHENOMENA

As listed in Table 1, according to Manetti *et al*. [52], the morphological changes on the heating surface also determine the enhancement or deterioration of HTC. Furthermore, modifications on the surface caused by nanoparticle deposition only increase HTC at low nanoparticle concentrations, and notably when the surface-interaction parameter (SIP) (defined as the ratio between the surface roughness and the particle size) is less than one. Therefore, as their studies were aimed to clarify the effects of nanoparticle deposition and nanofluid concentration on the pool boiling heat transfer, they conducted an experiment with a low and high concentration of nanofluid with a smooth and rough surface of heater where the smooth surface was created mechanically by polishing the copper surface with an aluminium-oxide abrasive compound. In contrast, the rough surface was created manually by polishing the copper surface with #600 emery paper. Based on their findings, they acquired up to a 75% improvement in HTC for a low concentration Al_2O_3 water-based nanofluid on a smooth surface heated copper and a 15% enhancement for a rough surface heated copper for a low concentration Al_2O_3 nanofluid. On the other hand, when the nanofluid concentration rose, the HTC deterioration was shown as wall superheating, ΔT increased, regardless of the baseline surface roughness.

Since there has never been a parametric investigation of pool boiling of water using a nanoparticle-coated flat heater, Kwark *et al*. [55] conducted the study with a flat square heater since it is more adaptive for a fundamental pool boiling study. The nanoparticle-coated heater is constructed using the same basic square copper block heater. Using the same method reported in their previous study [56], the nanocoating is created by boiling a 1g/l concentration of Al_2O_3-ethanol nanofluid. They investigated the impacts of particle size of the nanocoating system pressure, heater size, and heater orientation on the boiling performance of pure water in their study.

They found out that CHF significantly improved comparability, implying no significant dependency on nucleate BHT and CHF over the nanoparticle size range. They also concluded that when pressure is applied, the CHF improvement for nanocoated surfaces is inversed when compared to untreated surfaces. As a result, CHF enhancement in nanocoating is greatest at low pressure and declines with increasing pressure. Since the nanocoating is hydrophilic, the faster wetting speeds allow for increased effective rewetting beneath the expanding bubbles. This is the process behind CHF enhancement on nanocoated surfaces. This CHF improvement mechanism is anticipated to be of higher prevalent at lower system pressures, where bigger bubble departure diameters are produced.

As the inclination angle increased from 0° to 180°, both surfaces (uncoated and nanocoated) showed a similar declining trend in CHF for inclination further than 90° (135° and 180°) in this study. The nanocoated surface, substantially in comparison to the uncoated heater, increased CHF significantly in all tested orientations. The largest improvement is generated when the orientation is turned downward (180°). The duration of bubbles residing in this direction is substantially longer, producing a significantly faster local dry-out and a significant reduction in CHF. The nanocoating's relatively fast rewetting speed, on the other hand, is projected to be enough to provide liquid to the bases of departing bubbles, resulting in an improvement in CHF at all orientations, downward-facing included.

Finally, as the heater size increases, the CHF decreases for both coated and uncoated surfaces. This drop-in CHF could be attributed to a colder bulk fluid having a longer resistive path as heater size increases. On the other hand, the nanocoating's wettability is projected to reduce route resistance while considerably increasing CHF (by 90%) compared to the uncoated surface.

Next, Modi *et al*. [53] modify the surface heater by depositing nanoparticles from boiling experiments of 0.01% Al_2O_3 nanofluid with a plain surface as the heated substrate. Their work aimed to evaluate Al_2O_3/water-based nanofluids and Al_2O_3 nanoparticles-deposited heated substrates in the context of nucleate pool boiling heat transfer and its dependency on the dynamics of a single vapour bubble. Single vapour bubble nucleate pool boiling experiments were conducted with varying volume concentrations of Al_2O_3/water-based dilute nanofluids (with a plain surface as the heated substrate) and water-based boiling experiments were conducted on nanoparticle-deposited heated substrates for a direct comparison.

With the Rainbow Schlieren Diagnostic technique with optical configuration adopted from [59], qualitative and quantitative single bubble-based nucleate pool boiling events were described. Bubble dynamics characteristics and heat transfer rates for water on the nano-deposited surface were comparable with plain surface nanofluids. 1) Nanofluids affect bubble dynamics dramatically, 2) cycle time comparison showed that the growth time dominates the cycle for the water case, whereas the wait time constitutes a significant portion of the ebullition cycle for nanofluids. Furthermore, the overall cycle time was found to decrease significantly for the nanofluids case, thereby leading to an increased departure frequency which supported by works done by [60, 61]. Which during single bubble-based pool boiling studies, it was discovered that the roughness of the substrate surface caused by nanoparticle deposition rises with increasing nanofluid concentration and on rough surfaces, bubble departure frequencies were greater. 3) Nanofluids weaken natural convection at any concentration due to superheat layer is more stretched. The stretching of the superheat layer in the presence of suspended nanoparticles has been ascribed to the random movement of the suspended nanoparticles under the impact of temperature gradients in the superheat layer [62, 63]. Lastly, 4) overall BHTC of nanofluids showed an improvement over the case of water owing to the observed substantial changes in the bubble dynamics parameters. In the end, experiments showed that alumina nanoparticles, either suspended in bulk liquid or deposited on heater substrate, improved single bubble-based pool boiling heat transfer.

4.0 NANOFLUID POOL BOILING IN ELECTRIC FIELD

Although many researchers have worked on improving pure working fluid in pool boiling by an electric field [64–67], few have focused on enhancing nanofluids pool boiling by an electric field.

Chen *et al*. [54] investigate the nanoparticle resuspension behaviour, the quantitative analysis of heat transfer performance for various nanofluid concentrations with the coupling effect between electric field and nanofluid, and the model for pool boiling heat transfer change under the electric field. By adopting the two-step method, hydrophilic Al_2O_3 and deionized water were selected to produce nanofluids and PVP was dispersed in the mixture to guarantee suspension stability.

Their results clearly illustrate that the deposited layer grows thinner as the voltage increases. This is because the leftover nanoparticles on the heat transfer contact at high voltage become very thin. Furthermore, when voltage increases, the turbidity of the boiling fluid increases, which is attributed to the resuspension of nanoparticles by the electric field and bubbles.

Next, it is worth mentioning that at a heat flux of 344.0 kW/m^2, the influence of the electric field on the BHTC of nanofluid is considerably reduced. The BHTC is almost constant. However, for the other heat flow in this location, the improved heat transfer impact of the electric field outperforms the effect of no electric field.

Lastly, they concluded that the model's predicted curves which proposed by Ganapathy *et al*. [68] which alter by introducing the influence of electric field are accord well with the experimental data. However, the model's prediction impact is not applied to the 0.075 vol% nanofluids. This is because the nanoparticles agglomerate significantly as concentration increases; therefore, the heat transmitted by the particles in an electric field is not proportional to concentration.

5.0 MODEL ANALYSIS OF POOL BOILING HEAT TRANSFER USING ALUMINA NANOFLUIDS

In recent times, there have been researchers who have established models that could perform qualitative analysis or empirical approaches for pool boiling heat transfer characteristics of nanofluids. In 2018, Hassanpour *et al*. [69] designed an intelligent model based on artificial neural networks (ANN) to predict accurately the pool boiling heat transfer coefficient of Alumina water-based nanofluids. They employed sixteen distinct previous experimental studies addressing the pool boiling heat transfer coefficient of alumina water-based nanofluid by changing the parameters of the AI techniques under consideration to construct this model. As a result of correlation matrix research, the most relevant parameters for pool boiling HTC prediction were discovered to be excess temperature, pressure, nanoparticle diameter, and weight percent in water. After a trial-and-error procedure and statistical accuracy study, a two-layer multi-layer perceptron (MLP) model with twelve hidden neurons was determined to be the best model for the purpose. With an absolute average relative deviation percent (AARD) of 9.53, a mean square error (MSE) of 4.17, a root mean square error (RMSE) of 2.042, and an R2 = 0.9929, the proposed MLP network can predict the complete experimental dataset.

Pare and Ghosh [57] conducted a pool boiling experiment and then further proceeded with qualitative analysis and development ANN model. They noticed that using nanofluids caused a considerable rise in HTC. The outcome of the experiment stated that as the concentration of the nanoparticles increased, heat transfer rates dropped due to particle deposition on the boiling surface, increasing thermal resistance. This observation was recorded to be similar with the observation reported by Das *et al*. [38]. It was established that the addition of nanoparticles increased the thermophysical parameters of the boiling fluid, resulting in the improvement in boiling heat transfer for Al_2O_3-water nanofluids when in comparison to distilled water. The usage of nanofluids improved thermal conductivity and decreased specific heat capacity, allowing for faster heat evacuation via natural convection. Following that, an ANN model was created to estimate the pool boiling heat transfer coefficient while taking into consideration the parameter variation seen in the previous experiment. Thermal conductivity, surface temperature, nanoparticle concentration, heat flux, contact angle, and roughness of the surface are among the key experimental characteristics used as input values for the neural network. An optimal model is created using a multi-layer perceptron (MLP) feed forward ANN architecture. The transfer functions, learning algorithms, number of hidden layers, and number of neurons in each hidden layer are all changed to achieve the lowest number of errors. As a result, the model can help to evaluate the effect of various input parameters on the final output, as well as to remove noisy and poor results from the experimental dataset. Five learning techniques were used to teach the neural network model: BFGS quasi-Newton backpropagation (BFG), Bayesian regularisation backpropagation (BR), Levenberg-Marquardt backpropagation (LM), Resilient backpropagation (RP), and Scaled conjugate gradient backpropagation (SCGB) (SCG). When statistical parameters and the quantity of epochs were considered, the LM method produced the best ANN model. It was also revealed that the single-layered ANN model based on the Levenberg-Marquardt backpropagation (LM) method produced considerably less variance in MSEs than the dual-layered ANN model as the quantity of neurons increases. The construction of a suitable ANN architecture might be accomplished by incorporating quantitative and qualitative properties, notably for pool boiling of nanofluids, and optimising the model using several ANN training techniques. This allows for smaller mistakes and greater correlation coefficient values. As a consequence, the model correctly predicts HTC values by including the effects of physical components affecting the boiling surface.

Other than using the ANN model, researchers use the CFD program, which is developed to address difficulties related to thermal-hydraulic safety, such as determining the critical heat flux [70]. The convective flow boiling of refrigerant R-113 in a vertical annular channel was simulated using the CFD model CFX. There was a strong qualitative agreement with experimental data [71]. Previously, boiling water under high-pressure conditions, which are critical in nuclear power reactors, was modelled similarly. It has been proved that various tests may be simulated using a single set of model parameters under certain circumstances [72]. The computational model employed combines heat flux partitioning with the Euler/Euler two-phase flow description. Previously, very similar modelling was used to mimic the boiling of water under high-pressure conditions, which is critical in nuclear power plants [73]. The influence of nanomaterials and various forms of fins on the boiling process was researched, and it was determined which nanoparticles are better by understanding the vapour speed and volume fraction.

Shakir Majdi [57] studied the effect of microfins on boiling and the impact of nanoparticle ratio and nanoparticles type on the boiling process using the CFD program. It turns out that the pressure value in the circular fin is larger than the pressure value in the other geometric forms studied, with the square fin having the lowest pressure value. As a result, they determine that the best fin is square. In their conclusion, It is known that increasing the concentration of nanoparticles enhances the efficacy and improves the boiling process, as it was shown that the optimal concentration is the largest, where the concentration of nanomaterials 1% is superior compared to the other concentrations. Compared to CuO, the best nanomaterial is Al_2O_3, which is thought to improve the boiling process via increased speed, consequent vapour pressure, and big vapour dispersion.

6.0 CONCLUSION

The pool boiling and flow boiling enhancements employing Al_2O_3 nanofluids are summarised in this paper. Nanofluid, surface modification, and hybrid nanofluid techniques for these previous years are explored. The development of model analysis using ANN is also discussed. The following are the review's conclusions: Overall, nanofluid has significantly improved CHF. Al_2O_3 has been shown to significantly enhance CHF by improving surface wettability after nanoparticle deposition on the surface. However, HTC has received some unfavourable feedback. The degradation impact is affected by several parameters, which are the size and concentration of the nanoparticles. The roughness of the boiling surface must also be addressed. More gaps on the boiling surface can be filled with nanoparticles as their size decreases, leading to a drop in the number of active bubble nucleation sites and a decrease in HTC. In terms of hybrid nanofluids, research has indicated that there is a high potential to improve CHF.

With the success of improving pool boiling performance whether enhancement of heat transfer in nucleate region or enhancement of CHF, various technical challenges must be explored before nanofluid can be used in real application. It is generally recognised that nanoparticle deposition may improve boiling performance. Still, it can also cause nanoparticle clumping, sedimentation, precipitation, complex design clogging, erosion of the heating surface, and temporal variations in cooling performance. Lastly, because most of the studies regarding the pool boiling with nanofluid experimentation are transient, time dependent boiling performance should be addressed for future works.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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