

Effect of Nanofluids on the Enhancement of Boiling Heat Transfer: A Review

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ABSTRACT

Boiling heat transfer can play a vital role in the two-phase flow applications. The analysis of the boiling heat transfer enhancement is of importance in such applications and the enhancement can be mostly conducted by using various active and passive techniques. One type of passive techniques is the enhancement of heat transfer by nanofluids. This article presents an extensive review on the effect of different nanofluids on the enhancement of heat transfer coefficient (HTC) and critical heat flux (CHF) for both pool as well as flow boiling. Nanoparticles addition to a working fluid is done arbitrarily to improve the thermophysical properties which in turn improves heat transfer rate. Numerous works have been done in the studies on nanofluid boiling. Among various nanoparticles, the most frequently used nanoparticles are Al_2O_3 and TiO_2 . In the case of binary nanoparticles, the most commonly used combination is Al_2O_3 and TiO_2 . After reviewing the relevant literatures, it is found that for pool boiling, the maximum HTC is increased to 138% for TiO_2 nanoparticles and the maximum CHF is increased to 274.2% for MWCNTs. Conversely, in flow boiling the maximum HTC is increased to 126% for ZnO nanoparticles and the maximum CHF increased to as 100% for GO nanoparticles. In addition, when two or more nanoparticles in succession or binary nanofluids are used the CHF in pool boiling increased up to 100% for Al_2O_3 and TiO_2 as well as the CHF in flow boiling increased up to 100% for Al_2O_3 , ZnO, and Diamond. Though the information of the coefficient of heat transfer and the critical heat flux varied for different nanofluids and vary from experiment to experiment for each of the nanofluids. This variation happens because the coefficient of heat transfer and the critical heat flux in boiling is dependent upon several factors.

Keywords: Boiling, Nanofluids, Nanoparticle, Heat transfer coefficient, Critical heat flux.

ABBREVIATIONS

HTC	Heat Transfer Coefficients
CHF	Critical Heat Flux
BHT	Boiling Heat Transfer
PBHT	Pool Boiling Heat Transfer
Nu	Nusselt Number
Re	Reynolds Number
HFP	Heat Flux Partitioning
NPs	Nanoparticles
h-BN	Hexagonal boron nitride
CNs	Carbon Nanotubes
MWCNs	Multi Walled Carbon Nanotubes
THE	Heat Transfer Enhancement
HF	Heat Flux
CMC	Carboxyl Methyl Cellulose
GO	Graphene-oxide
CFD	Computational fluid dynamics
DCM	Dichloromethane

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1 INTRODUCTION

1.1 Background

Boiling is a type of convective heat transfer characterized by high heat fluxes, which are usually experienced in many engineering applications such as cooling of nuclear reactors, cooling of high-power electronics components, heat exchangers. The industrial world essentially relies on the massive use of fossil fuels to solve many negative problems, such as decreasing energy sources and triggering global warming, which is believed to be the primary cause of climate change. As a result, the advancement of energy conservation and environmental safety have become critical criteria for the planet. The performance of numerous engineering applications, such as boilers in energy generation, cooling in refrigeration systems, and many heat exchangers for various uses, is one of the significant methods of mitigating the influence of global heating. Mostly, all of these heat exchangers are processed by boiling heat transfer. Thus, considerable study and consideration have to be given to boiling phenomena [1].

1.2 Enhancement Techniques

Enhancement techniques of boiling heat transfer are two types: passive and active enhancement techniques. Nanofluids heat transfer enhancement is one kind of passive techniques. An external source of power is not needed by passive techniques. Extended surfaces, rough surfaces, improved surfaces, gas additives, liquid additives, swirl flow devices, coiled tubes, surface tension devices, micro/nanostructured surfaces, nanofluids, magnetically actuated nanofluids, electrophoretic deposition of SiO_2 nanofluid, micro-machined porous channels and displaced enhancement devices are the examples of passive techniques. Then again, for active techniques, exterior power is essential. They include fluid vibration, electric or magnetic jet impingement fields, surface vibration, mechanical aids, injection or suction, and techniques of compounding. In this analysis, attention will be paid to the accumulation of nanofluids to the base fluid to boost the transfer of boiling heat.

1.3 Nanofluids

Nanofluids are tiny particle-size and lower concentrated nanoparticle suspensions distributed in base fluids like as water, oil, pentane, and ethylene glycol. Due to their thermophysical characteristics and a wide quantity of possible conveniences in conventional thermal engineering applications, such as energy production, transport, air conditioning, electronic devices, and cooling systems, researchers found these fluids as a special heat transfer transporter. Nanofluids are suspensions of solid particles of nanometre size and different chemistries (metals, metals, cooling systems). It can also be characterized as a mixture of solids and liquids consisting of nanoparticles and a base liquid.

Examples of such nanoparticles are Al_2O_3 , SiO_2 , TiO_2 , SiC , Bi_2O_3 , GO , CuO , CuO_2 , ZnO , Fe_3O_4 , Fe_2O_3 , ZrO_2 , Cr_2O_3 , CaO , WO_3 , and MgO . Other highly used nanoparticles are Au, CNs, MWNTs, Ceramic, Diamond, AlN and Copper. Researchers have investigated the boiling enhancement with the above nanoparticles. There is only low thermal conductivity in the traditional base fluid.

$$\boxed{\text{Nanofluids}} = \boxed{\text{Nanoparticles}} + \boxed{\text{Base fluids}}$$

1.4 Current Situation of The Study of Nanofluids

Nanofluids can be measured as heat transfer fluids of the next generation because they suggest exciting options to increase the efficiency of heat transfer as compared to pure liquids. The growth of publications on nanoparticles research is shown in figure 1. Different researchers have shown that, compared to their base fluids, nanofluids provide improved heat transfer. It can be the motivating force for research to perform and eventually replace traditional functioning fluids. It was seen that arbitrary movement (Brownian movement) of nanoparticles and thermophoresis expand the energy transport performance. However, there are major problems such as erosion, clustering, sedimentation, and precipitation related to the use of nanofluids as the operating fluid. The influence on nanoparticle stability of changes in nanoparticle surface topology has also been well documented in the literature. In various experiments, nanofluids have been used to increase heat transfer in both single and two-phase systems. The findings of the earlier experiments indubitably indicate that with forced convection, nanofluids provide excellent heat transfer enhancement. In contrast, the normal convection and boiling of nanofluids in the literature has led to some contradictory findings [2].

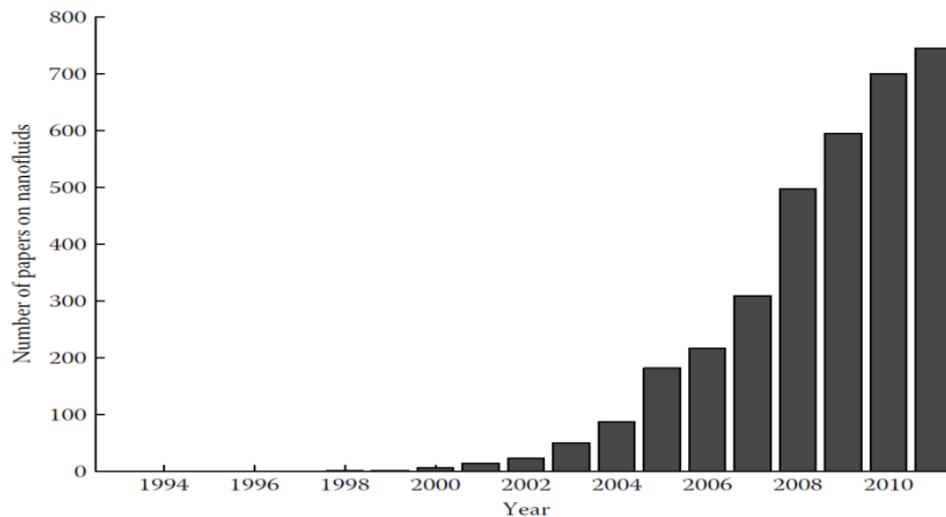


Figure 1: Growth of publications on nanofluids [3]

2 BOILING HEAT TRANSFER

A convection heat transfer process including a change in phase from liquid to vapour is referred to as boiling. It can also be defined as the change of phase from liquid to vapour at liquid vapour. Actually, boiling is a convective heat transfer process that includes phase change at a constant temperature from liquid to vapour [4]. During the boiling, the heat added to liquid for its phase change is the latent heat. Sometimes, the boiling process is also referred to as vaporization, when the latent heat of liquid is provided for its phase change such as the process of steam generation in the boiler. Boiling is also a mode of heat transfer that involves the creation of vapour bubbles at the solid-liquid boundary. The growth of vapour and its dynamics depend on temperature excess, nature of the surface and thermophysical properties of the liquid, such as its surface tension, latent heat, etc. Thus, the boiling may occur under various conditions. Based on the presence of bulk fluid motion [5], various modes of boiling are (i) pool boiling and (ii) flow boiling. Pool boiling refers to a situation of boiling in which the heated surface is immersed below the free surface of a stationary liquid and its motion adjacent the surface because of the natural convection only and the combination is made by bubble development and its separation [4]. Flow boiling refers to a situation of boiling, in which the fluid motion is induced artificially by an external means as well as by natural convection and the bubble induced mixing. This type of boiling takes place in high-pressure water tube boilers involving forced convection [5]. The schematic of the above-described types of boiling can be given by figure 2. Figure 3 shows the conventional pool boiling curve of water at atmospheric pressure and the schematic of each regime of it.

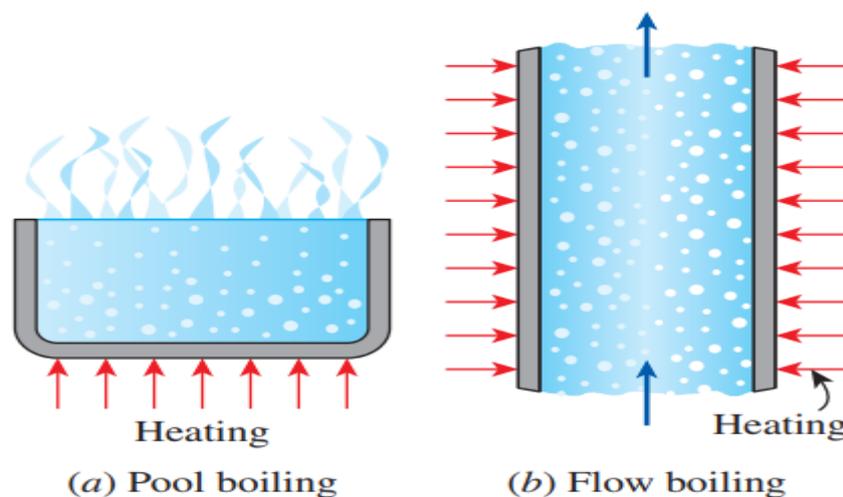


Figure 2: Types of boiling on the basis of the presence of bulk fluid motion [5].

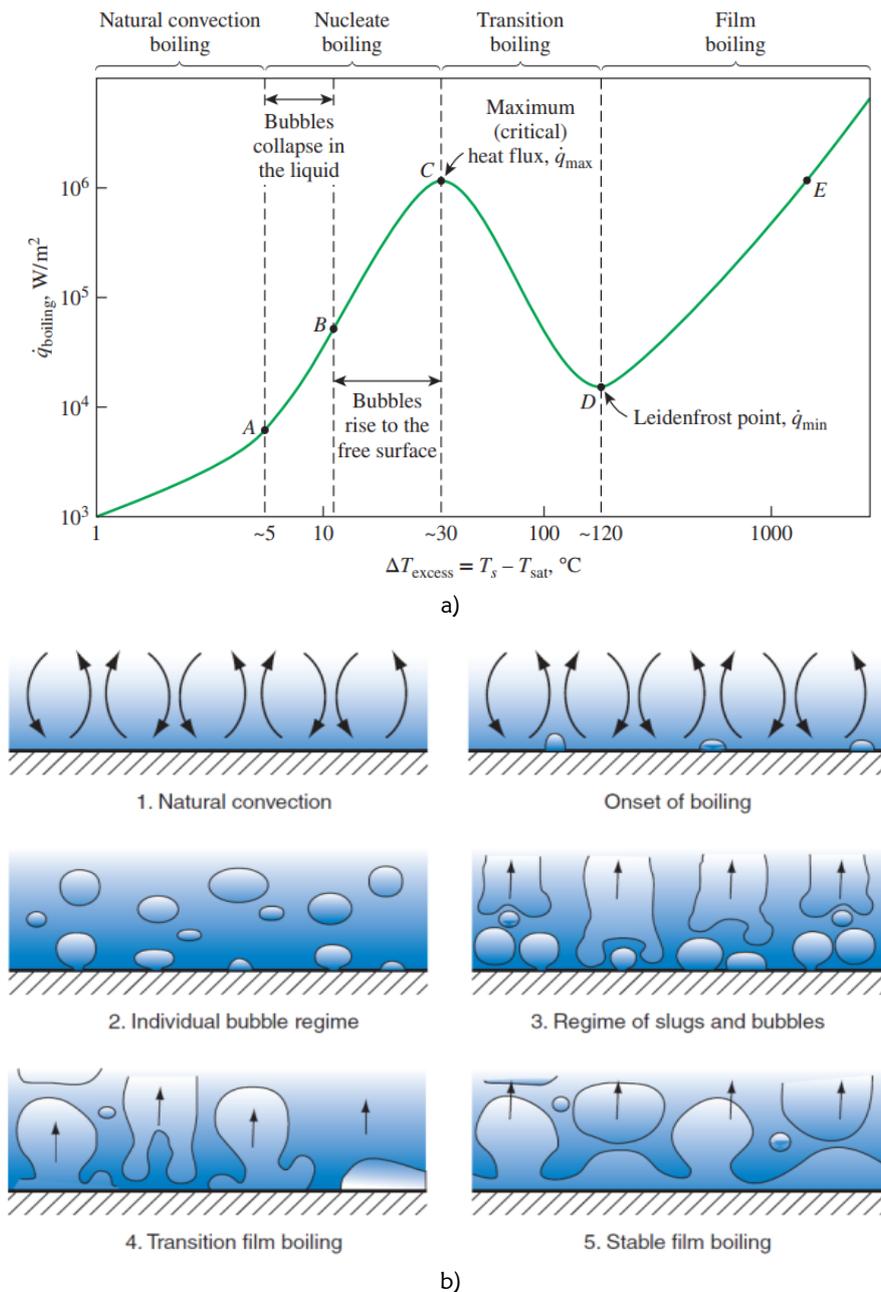


Figure 3: The a) pool boiling curve with b) schematic representation of each boiling regime [5,6]

3 MORE ABOUT NANOFUIDS

3.1 Why Nanofluids in Boiling Heat Transfer?

In recent times the experimental research has shown that nanofluids have more thermal conductivity than the base fluids. Nanofluids have many advantages of over the traditional solid-liquid suspensions. Some of them are as follows:

1. There are a greater specific surface area and greater stability of the colloidal suspension.
2. It lowered the pumping power to accomplish same heat transfer amplification compared to the base fluid.
3. It reduced particle obstruction in comparison with convention slurries, thus helping system reduction.
4. By changing particle concentrations to suit various applications, regulating properties, including thermal conductivity and surface wettability [7].
5. The properties of the fluid will differ by adjusting the concentration of the nanoparticles in order to make it suitable for various applications.
6. Nanofluids have minimum pressure drop as the particles are nanometre in size.
7. Nanofluids are also fit for fast heating and cooling systems.

8. By using nanofluids heat exchanger systems can be made smaller and lighter that will result in cost as well as energy savings.

It is notably observed that the heat transfer coefficient and critical heat flux can be increased by using nanofluids in the boiling heat transfer. This improved heat transfer coefficient and critical heat flux can be implemented in the design of heat exchangers and heat storage systems. For these reasons, nanofluids are important for boiling heat transfer research.

3.2 How Does Nanofluid Work?

Heat transfer relies on the stroll of the molecules within the substance. Temperature can be a range in which the movement energy of substance molecules is expressed in order to increase the temperature, energy from outside must be given to a substance. By altering the density and specific heat, nanofluid enhances the heat transfer characteristics of water. Despite the fact that water is generally utilized as a heat transfer medium, it is certainly not an ideal base liquid. The nanofluid heat transfer is more in contrast to the base fluid. As a result of this enhance in heat transfer nanofluid allows the heat to be transferred to the target faster and more efficiently. Nanofluid provides higher efficiency with lower energy [8].

4 PREPARATIONS OF NANOFLUID

The nanofluid generation to alter the rate of heat transfer of traditional fluids is the most significant step in the use of Nano phase particles. As a liquid-solid mixture, the nanofluid is not only stated. Nanofluids consist primarily of carbides, oxides, metals and carbon nanotubes which, with the addition of stabilizing agents, can simply be circulated into heat transfer fluids, like as hydrocarbons, water and ethylene glycol. Several processes, namely gas condensation, mechanical attribution, or chemical precipitation, may also create nanoparticles. Under cleaner conditions, these nanoparticles can also be produced and their surface can be saved from sudden coatings that can occur during the gas condensation phase [8,9]. The simple procedure of nanofluids preparation is shown in figure 4, Where nanoparticles are fixed up with base fluids in order to get the nanofluids [10]. Two key methods of preparing nanofluids are available. Single-step method and Two-step method.

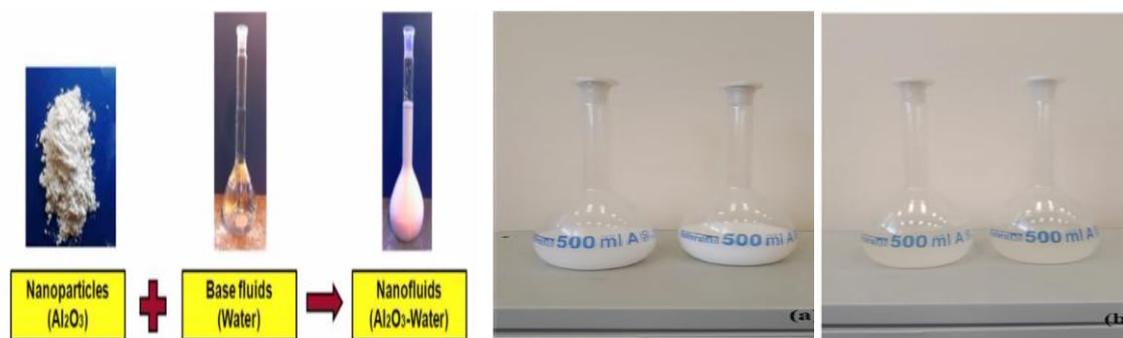


Figure 4: Simple procedure of nanofluids preparation. (a) h-BN nanofluid, (b) SiO₂ nanofluid [10]

4.1 Single-Step Method

A single-step method has been developed to decrease the synthesis of nanoparticles. Using this process, there are many ways to prepare nanofluids, including direct condensation of evaporation, condensation of chemical vapour and chemical synthesis in one step [9]. The single-step process, also known as the direct evaporation condensation method, consists of following main stages.

1. The base fluid for example water or ethylene glycol is circulated in the inner part of a cylinder so that a thin film of the fluid is regularly expelled out of the upper of the chamber.
2. Small pieces of metal evaporate using heat to form nanoparticles.
3. Finally, the fluid is allowed to cool downwards to avoid any unwanted evaporation.

4.2 Two-Step Method

Most commonly, this process is used to make nanofluids. A two-step process where nanoparticles or nanotubes are formed as a dry powder chemically or physically for the first time. In the second level, the resultant nanoparticles are dispersed in the liquid with the aid of intense magnetic energy movement, ultrasonic movement, high shear mixing, homogenization, and ball milling. As the nano powder synthesis methods have already been measured at the industrial production level, the two-step approach is the most reasonably priced approach for manufacturing nanofluids on a large scale. The two-step method for nanofluids preparation is shown in figure 5. Due to a higher surface area and surface activity, nanoparticles tend to accumulate. Using surfactants is a vital method to improve the stability of nanoparticles in liquids. Several advanced nanofluid production technologies (including the one-step process) have been developed due to the complexity of preparing stable nanofluids using the two-step method [8].

5 NANOFLUIDS ENHANCEMENT ON BOILING

Boiling has an important character in several engineering application and technological regions, for example electricity generation, nuclear reactor cooling, cooling of electronic components, etc. There are a many research and review articles regarding nanofluids; few on their expected advantages on heat transfer applications and furthermore few on their heat conductivity improvement. The usage of nanofluids for boiling enhancement is a promising zone that is as of now being explored by various researchers for pool boiling and as of late for flow boiling applications. Figure 6 shows the quick advancement of yearly research publications on nanofluids boiling heat transfer. In latest years, a sharp increase in nanofluid boiling studies have found because of the higher thermal conductivity of nanofluids. In this review article, all prevalent pool boiling and flow boiling articles using nanofluids to date have been consolidated. A summary related to pool boiling and flow boiling of nanofluid studies has been provided in the later section. It is to be hoped that this article will give a brief and reasonable record of the benefits and restrictions of nanofluids in regard to their boiling performance and application.

In Figure 7, the first number means number of articles reviewed of a nanoparticle or a series of nanoparticles and the following percentage means the corresponding percentage of that nanoparticles within the total percentage.

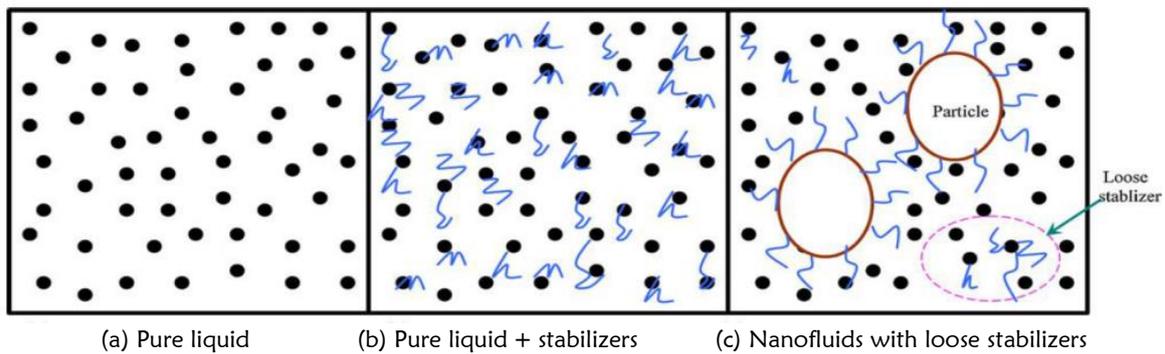


Figure 5: Two-step method for nanofluids formulation [7]

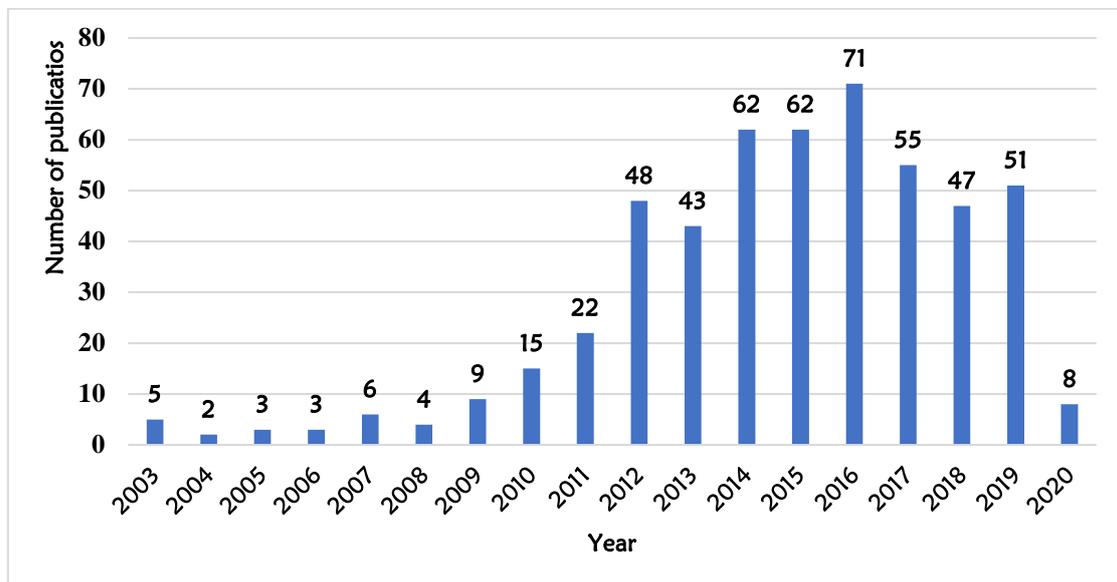


Figure 6: Annual publications on boiling heat transfer nanofluids since 2003

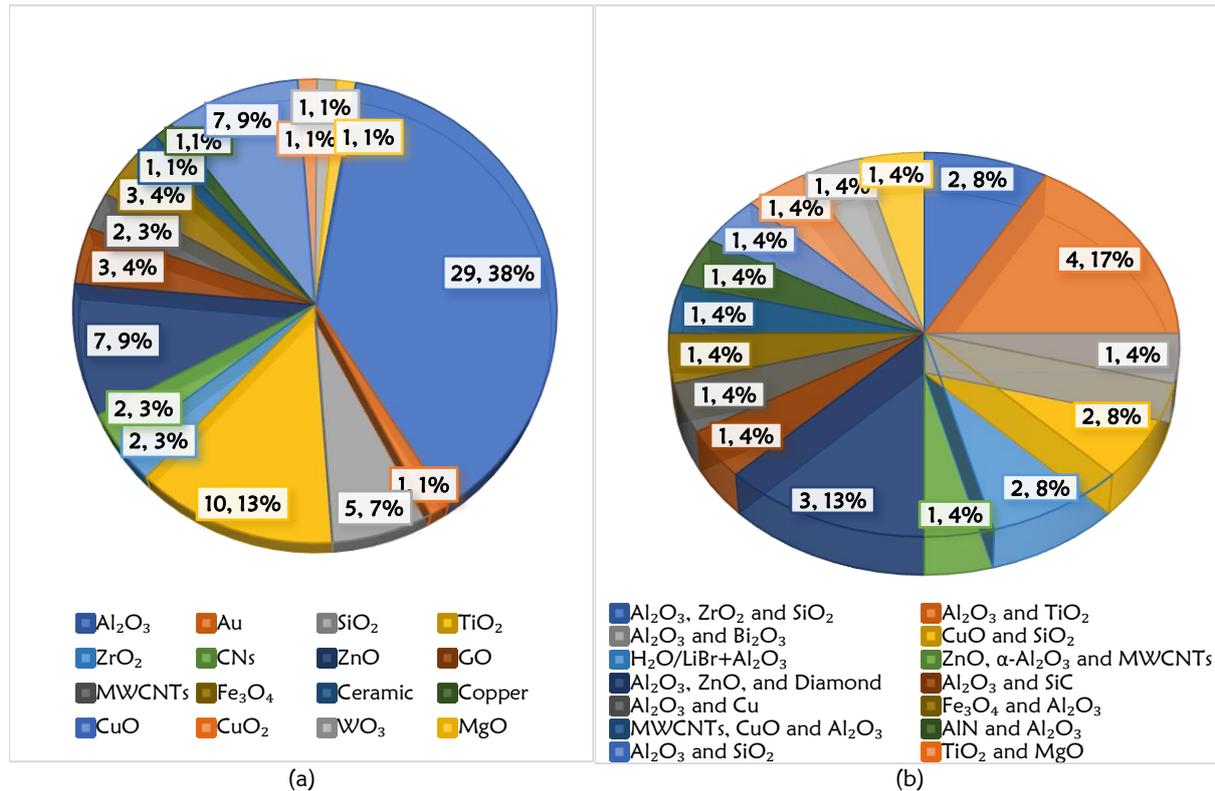


Figure 7: Number of articles reviewed with their corresponding percentage (a) nanoparticles (b) that use a series of nanoparticles or binary nanoparticles

5.1 Literature Review on Pool Boiling of Nanofluids

Since 2003, many research papers have been published on nanofluid pool boiling, that are listed in Table 1 to Table 4. In this literature review, the impacts of nanofluids on the most significant parameters, like HTC and CHF, in pool boiling is studied. The recent enhancement pool boiling heat transfer with nanofluids are discussed below.

Ciftci et al. [10] experimentally and numerically scrutinized the heat transfer enhancement in pool boiling and condensation by changing the hydrophilicity or hydrophobicity properties of the working fluid, i.e. by using nanofluid solution. In order to determine the influence of nanoparticle concentration on heat transfer properties, two separate nanofluid solutions (h-BN/DCM and SiO₂/DCM) were arranged and tested for three distinct volumetric concentrations as well as different heat flux conditions. The boiling curves for DCM, h-BN/DCM and SiO₂/DCM nanofluids under saturation and after saturation conditions at various concentration is shown in figure 8. The enhancement rate of HTC for saturation boiling, boiling after saturation, and condensation methods was found to be 27.59%, 14.44%, and 15% respectively for the experimental outcomes of h-BN/DCM nanofluid and for SiO₂/DCM nanofluid it was 20.69%, 16.67%, and 21.86%, respectively.

A theoretical analysis was carried out by J. Ham et al. [11] on pool boiling features of Al₂O₃ nanofluids based on volume concentration and nanoparticle size by using the HFP (heat flux partitioning) model with variations in the contact angle. Their result showed that the CHF base of nanofluids is higher than that of the liquid. The most critical heat flux was found to be 1,515 kW/m² under a volume density of 0.05vol.% and was gradually reduced with the density of nanofluids and the size of L₂ and L₃-nanoparticles was 50 nm and decreased gradually.

Donga et al. [12] investigated an experiment on boiling heat transfer characteristics of Al₂O₃-water nanofluid in swirl micro channels subjected to an acceleration force. They applied three test sections with dissimilar geometric parameters. The concentration (vol.) of Al₂O₃ nanoparticles (average diameter of 13 nm) was changed from 0.07% to 0.1%. The mass flow rate and vapour qualities were between 3–6 kg/h and 0.4–1.0%, respectively. Their investigational outcomes showed that the direction and width of the acceleration had an important influence on the BHT and that HTC increased with the increasing of mass flow rate and volume concentration increased and reduced with the direction ratio.

Khliyeva et al. [13] experimentally studied the impact of nanoparticle added substances to the refrigerant R141b on the pool boiling process. They observed that TiO₂ nanoparticles additives to the R141b / Span-80 solution contributed to a 2-8-fold reduction in the amount of nucleation sites. They also observed that the increase in heat flux contributes to a rise in the disparity between the nucleation site density magnitudes in R141b and R141b/Span-80 boiling. At a heat flux of 7.5 kW/m², compared to boiling on the stainless-steel surface, the amount of nucleation

sites on the Teflon surface was 2 times lesser. They also found that the form of surfaces did not affect the number of nucleation sites and the frequency of vapor bubble take-off in nanofluid boiling in the whole explored the scope of heat fluxes and the frequency of vapor bubble departure in R141b boiling and R141b/Span-80 solution on the Teflon surface 1.5-2 times lower compared to boiling on the surface of stainless steel.

An experimental study was directed by Sarafraz et al. [14] on the thermal behaviour of the ZnO nanoparticles dispersed in water-ethylene glycol (water/EG) as the base fluid under the pool boiling condition. They investigated the effects of various operational factors like as heat flux and mass concentration on HTC and thermal fouling resistance provided by heat ZnO nanofluid. Their findings showed that the HTC for ZnO/water/EG nanofluids increased with the rise in heat flux and mass concentration at a concentration of 0.5% by weight. With increasing in the nanoparticle mass concentration, the CHF point was increased because of the increase in the nanoparticle's deposition layer.

Kamel et al. [15] experimentally investigated the performance of pool boiling heat transfer by using tungsten oxide WO_3 nanomaterial-based deionized water nanofluids. They made WO_3 -based water nanofluids by using two-step process. The most important steps they observed were to achieve a stable suspension during the creation of nanofluids. Figure 9 shows the different boiling phenomena of their experiment at different volume fractions. Their experimental findings showed that at concentrations of 0.005% vol., the PBHTC ratio increased by around 6.7% and 0.01 vol.% in the high heat flux area. While there was a decrease in this ratio by about 15% at a volume concentration of 0.05% vol. in the low heat flux area.

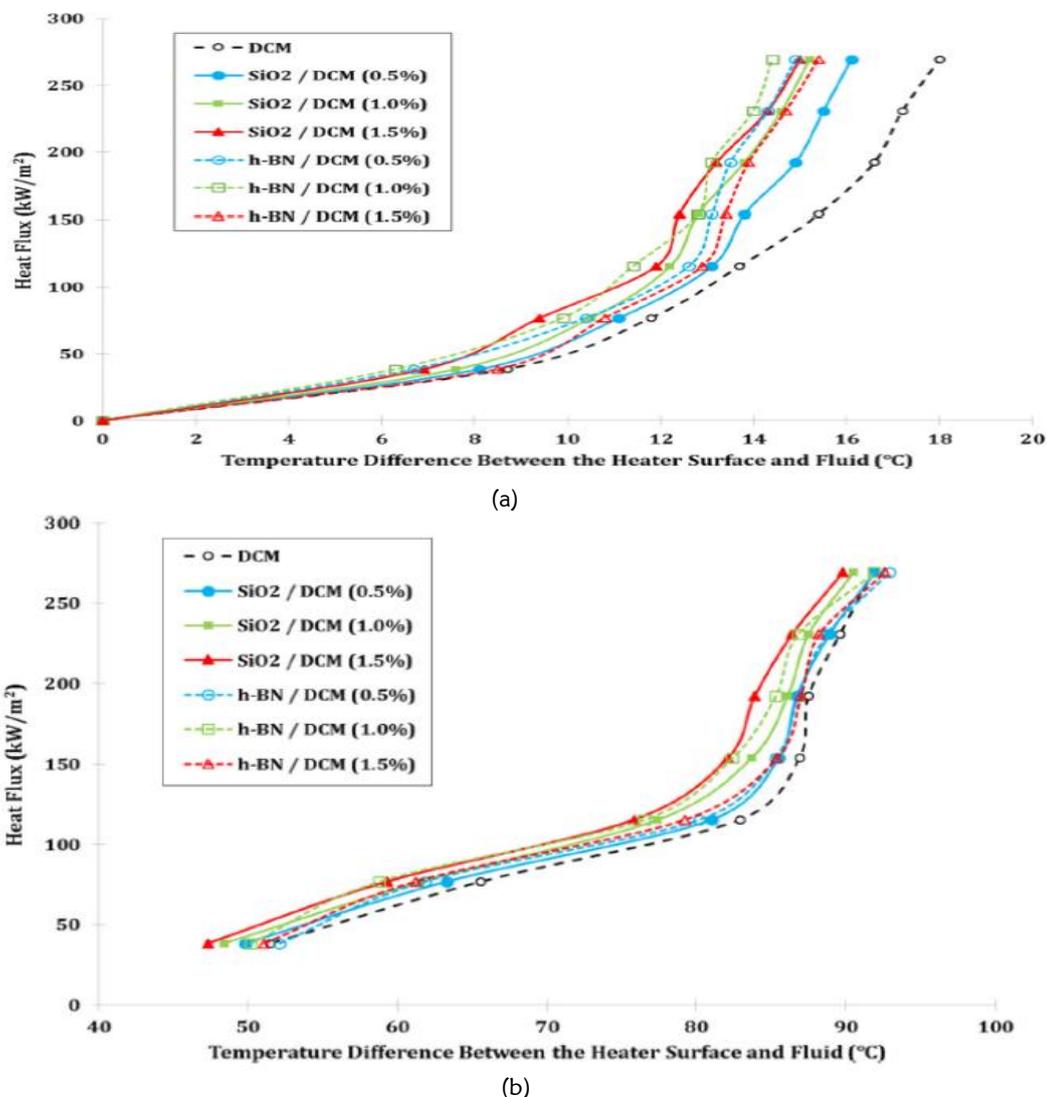


Figure 8: Boiling curves for DCM, h-BN/DCM and SiO₂/DCM nanofluids under (a) saturation (b) after saturation conditions at various concentration [10]

Yanwei et al. [16] investigated the boiling heat-transfer properties of ethylene glycol (EG) and water (H₂O) mixture based SiO₂ nanofluid under realistic conditions. They used a 0.6 vol.% EG aqueous solution as a base liquid due to the perfect frost-proofing performance of CO₂ nanofluids based on a mixture of E-glycol (EG) and water (H₂O) in realistic situations. Their results showed that the nanoparticle diameter decreased from 120 nm to 64 nm, increasing the boiling heat-transfer coefficient (HTC). Also, with increasing in the concentration of nanoparticle, initially HTC was found to be increased quickly and then showed a decrease of 0.25-1.00% in the concentration range. Also, above 0.75 vol.% nanoparticle, HTC decreased.

Shoghl et al. [17] conducted an experimental study regarding boiling performance of ZnO, α-Al₂O₃ and MWCNTs/water nanofluids. The ZnO and Al₂O₃ nanoparticles impairing heat transfer when add MWCNTs resulted in improving heat transfer. The essential effect of nanofluid which was attributed to the reference heat transfer coefficient improved by ZnO and Al₂O₃ while decreased by CNTs at the low concentrations (0.01 wt.%).

Azzat et al. [18] conducted an experiment to identify the Heat Transfer Coefficient (HTC) in saturated pool boiling of single and hybrid water-based nanofluids. They chose Al₂O₃ and SiO₂ nanoparticles and mixed into two different single nanofluids and mixed to achieve a ratio of 0:100, 25:75, 50:50, 75:25, and 100:0 % to 0.001 vol. percent final concentration. On a regular basis, they used these blends to achieve HTC standards through experimental work. They found that at the lowest concentration of Al₂O₃ nanofluids (0.00025 vol.%), HTC improved significantly but decreased for CO₂ nanofluids. Distinctly, as with hybrid nanofluids, HTCs were dramatically improved in the early stages but gradually decreased over time, especially in the case of higher proportions of SiO₂ nanofluids.

Girish Sapre et al. [19] conducted an experiment on Pool Boiling Heat Transfer using Titanium Oxide (TiO₂) and Magnesium Oxide (MgO) nanofluids. Their experimental setup consisted with a Borosil transparent glass vessel having size 130 mm diameter and 205 mm height. Due to increased thermal conductivity of nanofluid and other reasons such as presence of Brownian motion and diffusion of nanoparticles in distilled water the Critical Heat Flux of TiO₂ and MgO nanofluid are superior to the distilled water and keep on increasing with the volume fraction, both fluids show significant increment in the CHF. Their result also showed that CHF improves in the range of 10.51% to 52.42% in case of TiO₂ and 23% to 60.88% in case of MgO nanofluid with increasing in volume fraction.

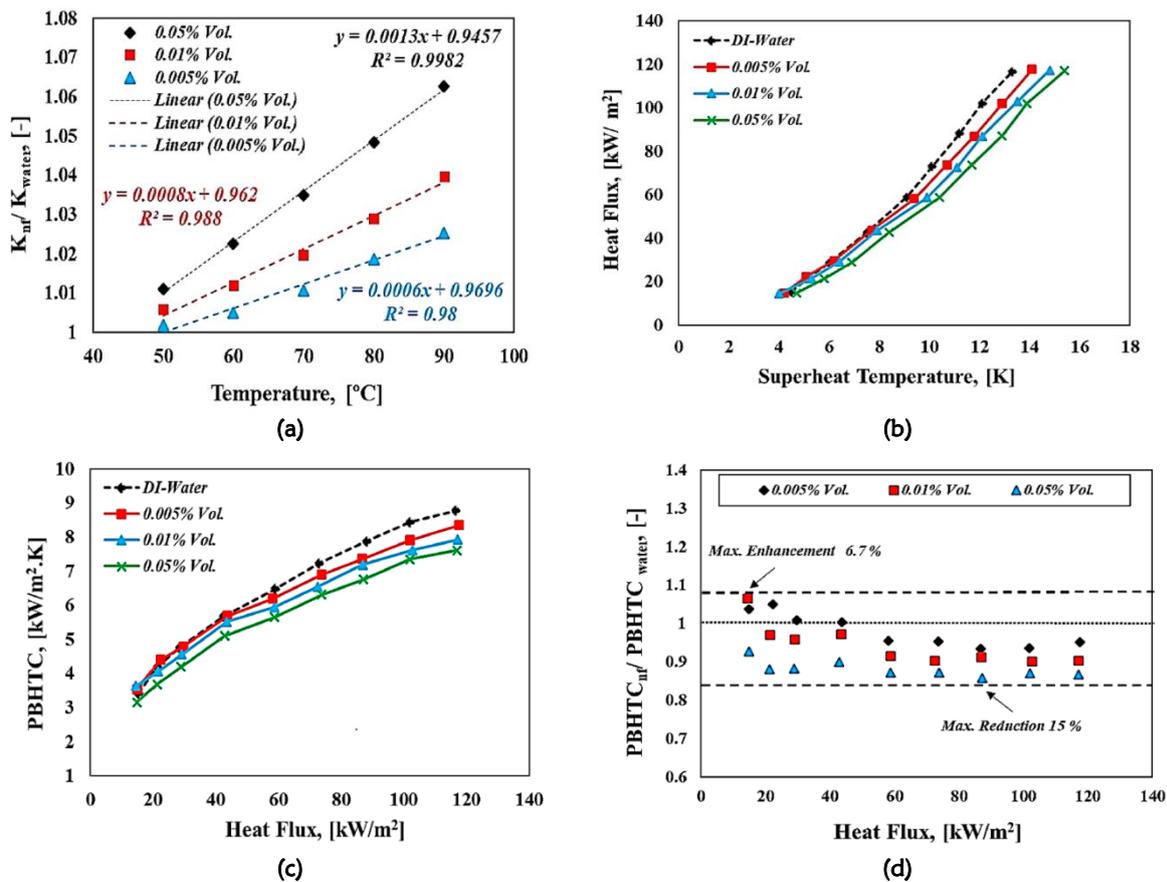


Figure 9: Different boiling phenomena for WO₃-based water nanofluids at different volume fractions [15]

5.2 Literature Review on Flow Boiling Heat Transfer of Nanofluids

A boiling heat transfer process in which an external means, as well as natural convection and bubble-induced mixing artificially causes the fluid motion is known as flow boiling. It can be used in a range of industrial applications, for example air conditioning, cooling of nuclear reactors, components of power plants (boilers), refrigeration, petroleum, and high-tech electronic cooling of components. In order to improve the efficacy of such applications in terms of heat removal or cooling systems, it is important to boost the heat transfer method of flow boiling to find a substantial decrement from the consumption of energy. The use of solid nanoscale particles with traditional cooling fluids is one of the most successful methods to enhance the flow boiling heat transfer. This solution will give new and imaginable energizing results compared to host fluids to increase thermal exchange efficiency. For certain fluids, nanofluids build a fresh fluid category and a promising next-generation. Since 2003 a lot of research paper have been published on nanofluids flow boiling, that are listed in Table 5 to Table 8. In these studies, similar to pool boiling, the influence of nanofluids on the significant factors, like as HTC and CHF, in flow boiling have been studied. The recent flow boiling heat transfer enhancement on nanofluids are discussed below.

Sudheer et al. [20] investigated an experimental studies of heat transfer and flow regimes during flow boiling of water and alumina nanofluids at different heat and mass fluxes. They investigated the flow boiling heat transfer in a vertical pipe of internal diameter 7.5mm with pure water and Al_2O_3 /water nanofluid as working fluids. For their study, they considered the particle concentrations of 0.001%, 0.005% and 0.01%. From the results, it was seen that flow boiling HTC was increased with mass flux for both water and nanofluids. It was also found that the HTC increased with particle concentration due to the altered characteristics of the heater surface and changes in the process of bubble formation. The average rise in heat transfer coefficient, in comparison with the base fluid, for the nanoparticle concentrations of 0.001%, 0.005% and 0.01% at a mass flux of 905.42 kg/s-m^2 was found to be 12.11%, 21.75% and 27.97%, respectively. The flow boiling HTC was seen to be more for the nanofluids compared to water.

Wang et al. [21] investigated experimentally the study on $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ nanofluid flow boiling heat transfer under different pressures. By ultrasonic oscillation, the $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ nanofluid was prepared. The nanoparticle concentration was 0.1 and 0.5 vol. percent with diameter 20 nm. Their results indicated that the heat transfer rate of $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ nanofluid was increased in flow boiling by roughly 86% as compared to pure water. In their range of work, the rise in the average number of Nusselt nanofluids compared to deionized water was 35 percent.

Om Shankar et al. [22] studied an experiment on the flow boiling HTC by using ZnO-water nanofluids. Their 780 mm long annular test section was consisted with an electrically heated rod and a 21.8 mm internal diameter outer borosilicate glass tube. The heater was made with hollow stainless-steel rods of 12.7 mm diameter welded at both ends to solid copper rods. By using an ultrasonic vibration mixer, they prepared ZnO-water nanofluids with volume concentrations of ZnO particles ranging from 0.0001 to 0.1%. They found that, at a higher concentration of nanoparticles (0.1%), the HTC increased by 126% than the base fluid and increased surface roughness of the heater rod by 1367%, because of the deposition of ZnO/water nanofluid. Figure 10 shows the effect nanoparticle concentration on heat transfer coefficient at various heat flux.

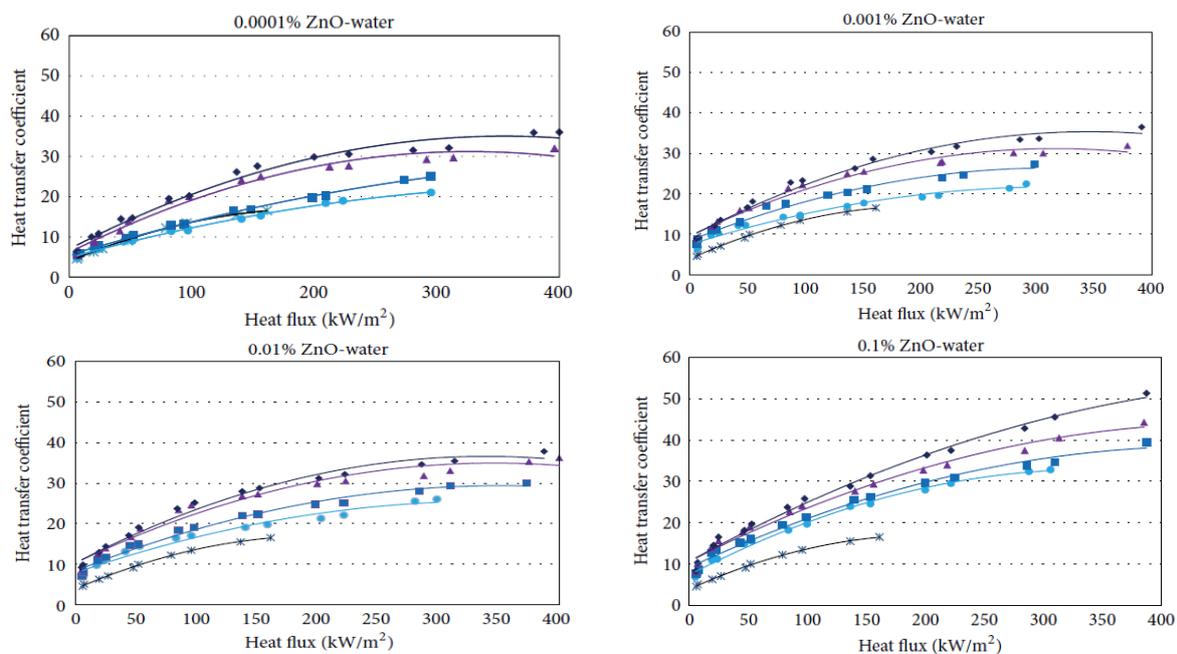


Figure 10: Variation of heat transfer coefficient, h ($\text{kW/m}^2\text{K}$), of ZnO -water nanofluid with heat flux at different ZnO nanoparticle volume fraction and $400 \text{ kg/m}^2\text{s}$ mass flowrate [22]

Sarafraz et al. [23] conducted an experiment on flow boiling heat transfer coefficients of DI-H₂O and CuO-H₂O based nanofluids at various working environments. They found that the flow boiling HTC enhanced for DI-water and CuO-water nanofluid in forced convective and nucleate boiling areas by enhancing the applied heat flux. The HTC also increased significantly in both regions by rising the flow rate of fluids. Their findings also revealed that the inlet temperature of fluids played an important character in HTC in nucleate boiling area.

Sarafraz et al. [24] performed an experimental investigation on the flow boiling heat transfer characteristics of MgO/therminol 66 nanofluid as a potential coolant on a copper-made disc. They prepared nanofluids with the help of two step method at wt.%=0.1, and wt.%=0.3. Results of their experiment showed that the existence of MgO/therminol 66 grows the flow boiling HTC as compared to the conventional base fluid. However, the coefficient of heat transfer of the nanoparticles decreased with increasing nanoparticle concentration. The HTC was also found to decrease with operating time because of the existence of nanoparticles on the boiling surface, resulting in thermal resistance on the surface being formed. The highest rise in the coefficient of heat transfer was 23.7% at wt.% of 0.1. For wt.% of 0.2 and 0.3, the greatest enhancement was found 16.2% and 13.3% respectively. Figure 12 shows the several boiling phenomena of their experiment.

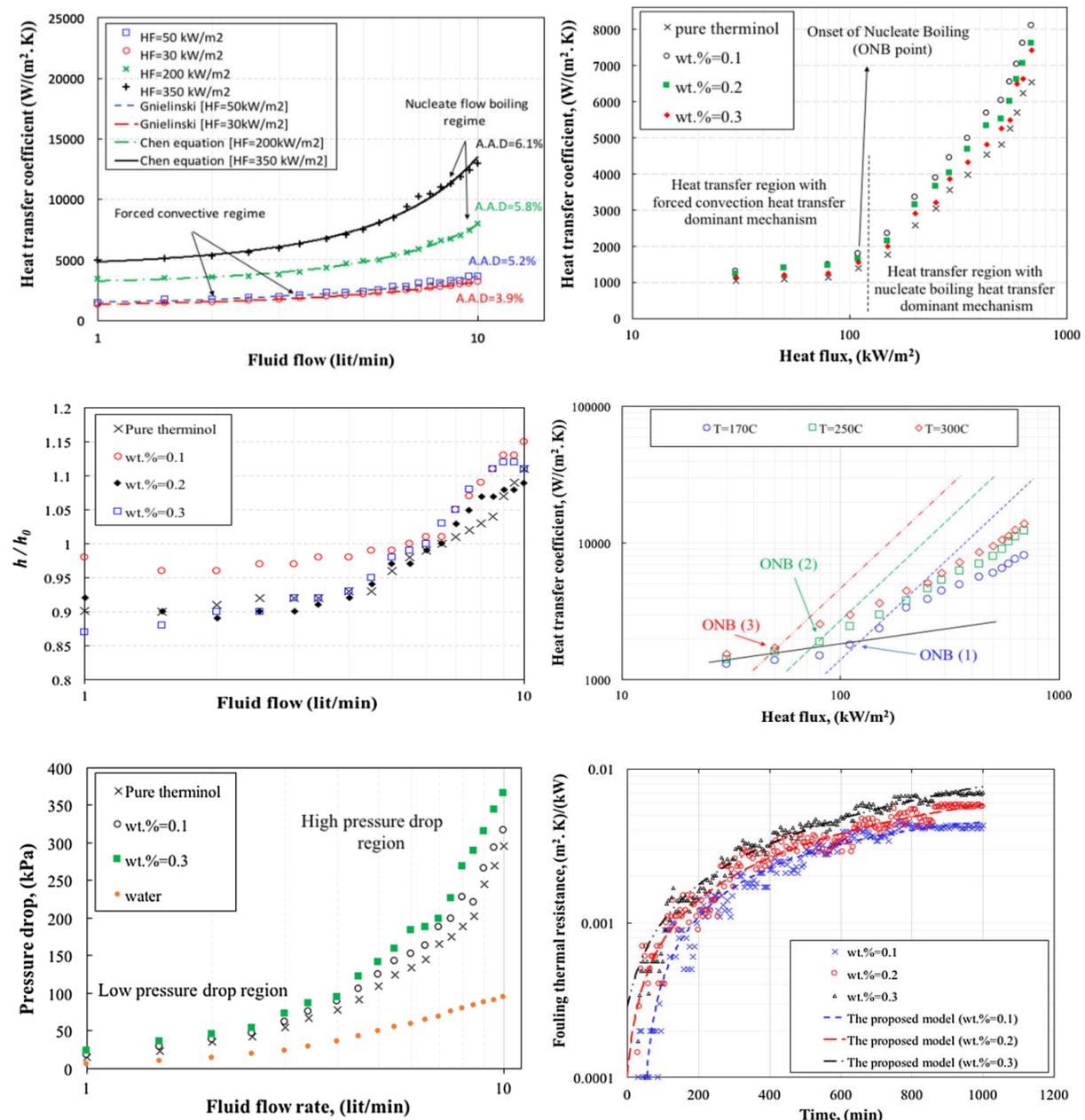


Figure 11: Some of the experimental findings [24]

Nakhjavani et al. [25] conducted flow boiling heat transfer characteristics of titanium oxide/water nanofluid ($\text{TiO}_2/\text{water}$) in an annular heat exchanger. They had seen that increasing the volume flow and the heat flux applied would increase the HTC while increasing the nanofluid weight concentration, initially improving the HTC so that the maximum increase in the HTC was 35.7% at wt. % of 0.15 and $\text{Re} = 13500$ as shown in figure 12, but over time, the nanofluid HTC decreased. Due to the rise of the IT from 333 K to 363 K, the maximum change in HTC was 4.2 percent at wt. percent = 0.15 and $\text{Re} = 13500$. The formation of the bubble was also found to be a strong function of the heat flux applied, so that the rate of bubble formation increased with the increase in the heat flux, which was also the reason behind the improvement in the HTC at larger heat fluxes applied. A persistent fouling layer of nanoparticles (NPs) was also found to be formed on the boiling surface, which induced thermal resistance against the transfer of boiling heat. The production of fouling reduced the HTC of the NF so that after 1000 minutes of the heater operation, the extreme reduction in the HTC was 21.6%.

Wang et al. [26] conducted a mechanism of heat transfer enhancement and decrease of nanofluid flow boiling heat transfer. By considering the pressure, mass flux, and heat flux they experimentally studied the heat transfer characteristics of $\text{SiC}/\text{H}_2\text{O}$ and Graphite/ H_2O nanofluids. They found both enhancement and decrease in boiling heat transfer of nanofluids compared to based fluid. In both cases, they used 0.1vol.% the concentration of the nanofluids. The flow BHT capacities of $\text{SiC}/\text{H}_2\text{O}$ nanofluid were varied from -24.7% to 30.6% and from -29.4% to 13.3% for Graphite/ H_2O nanofluid as compared with deionized water several heat and mass flux condition. Figure 13 shows effects of mass flux and wall heat flux on Nusselt number of their experiment.

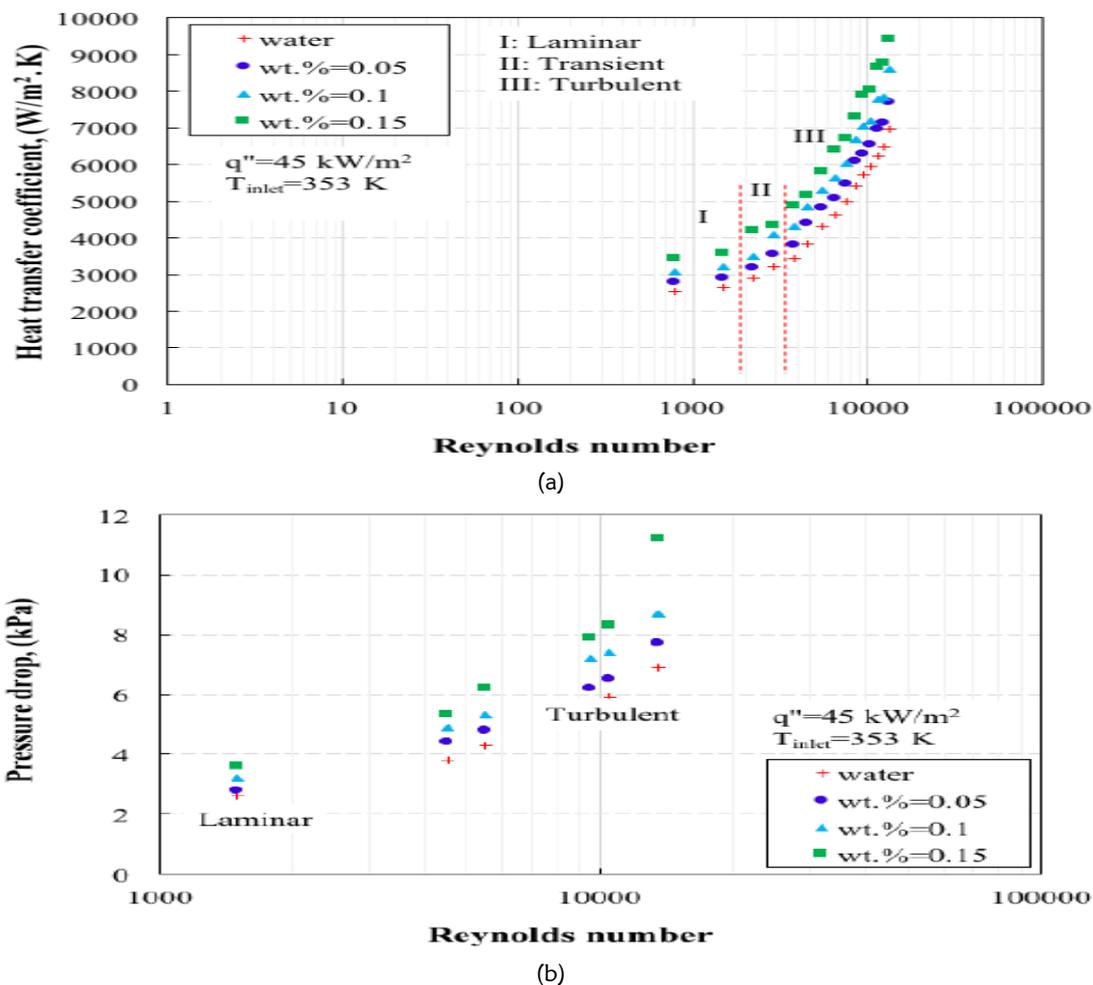


Figure 12: Effect of the Reynolds number on a) HTC b) Pressure drop [25]

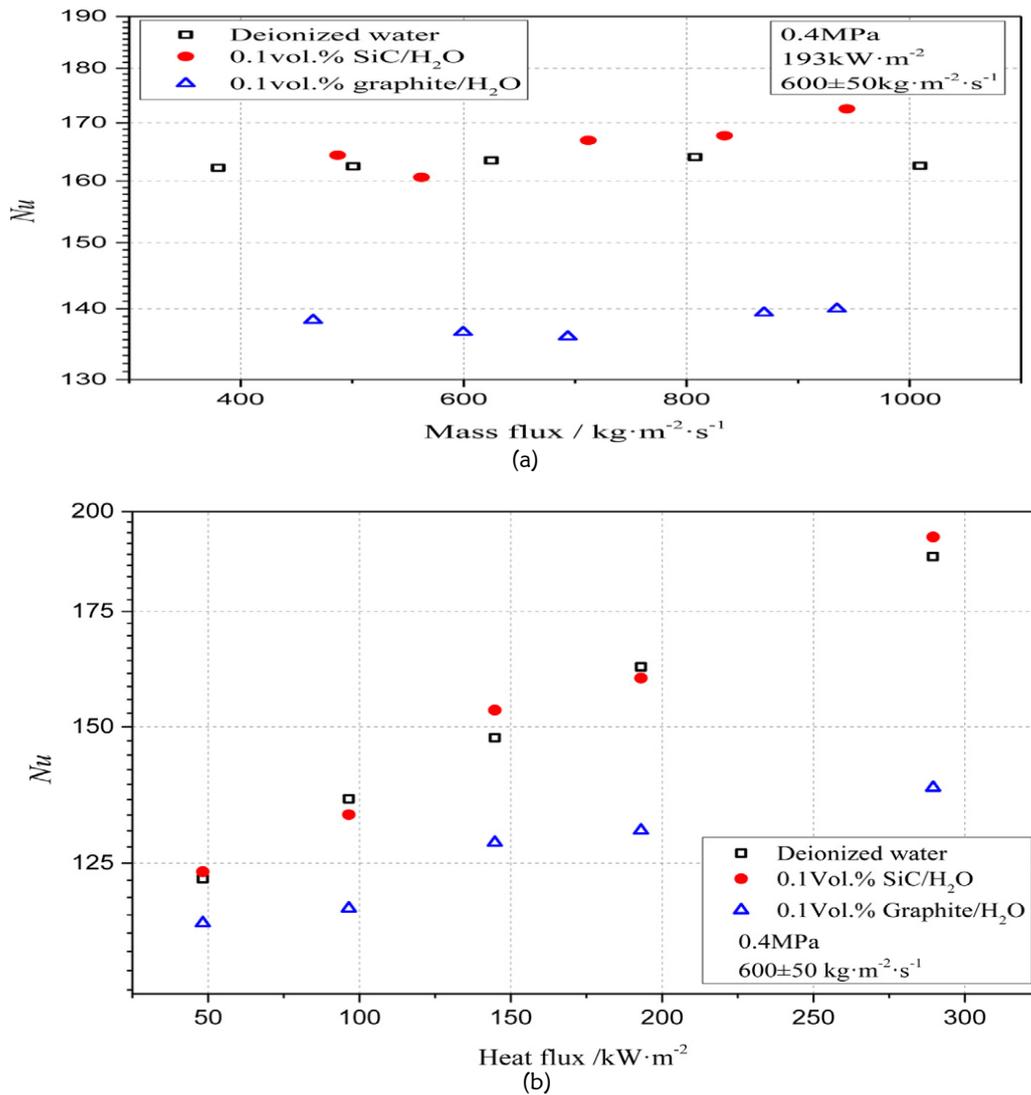


Figure 13: Effects of a) mass flux and b) wall heat flux on Nusselt number [26]

6 SUMMARY

The following tables show the summary of the pool and flow boiling since 2003. Before making the summary table the nanoparticles are classified into four broad classes namely metal, metal oxide, non-metal, and nanoparticle mixture. The available metals that used for the enhancement of boiling heat transfer are Au and Copper. H₂O is the only base fluid that used with metal to form the nanofluids. The several metal oxides that used for the enhancement of boiling heat transfer are Al₂O₃, TiO₂, Bi₂O₃, GO, CuO, CuO₂, ZnO, Fe₃O₄, ZrO₂, CuO₂, WO₃, and MgO. The several base fluids that are used with the metal oxide to produce nanofluids are H₂O, DI H₂O, ethanol, ethylene glycol, pentane, CMC solution, different refrigerants, and polyester oil. Different non-metals like ceramic, CNs, MWCNTs, and non-metallic oxide like GO, SiO₂ are used for the enhancement of boiling heat transfer. Many researchers use binary nanoparticles or a series of individual nanoparticles that are termed as nanoparticles mixture in the summary table.

Table 4 give some brief information regarding the maximum enhancement percentage of pool boiling heat transfer with different nanofluids. Some of the results are related to HTC enhancement percentage, and others are related to CHF enhancement percentage. Many of the research papers didn't mention the amount of enhancement percentage. Few results show that HTC and CHF can also be decreased even by using nanofluids. Based on the availability of the data figures 14 and 15 show the maximum enhancement percentage for different nanoparticles and binary nanoparticles. From the summary Table 1 to Table 4, the maximum increased pool boiling HTC is found as 138% for TiO₂ nanoparticles and the maximum increased critical heat flux is found as 274.2% for MWCNTs. When two or more nanoparticles in succession or binary nanofluids are used the CHF increased up to 100% for Al₂O₃ and TiO₂.

Tables 5-6 give some brief information regarding the maximum enhancement percentage of flow boiling heat transfer with different nanofluids. Some of the results are related to the HTC enhancement percentage, and others are related to the CHF enhancement percentage. Many of the research papers didn't mention the amount of enhancement percentage. Few results also show that HTC and CHF can also be decreased even by using nanofluids. This depends on some operating conditions. Based on the availability of the data, figure 16 shows the maximum enhancement percentage for different nanoparticles and binary nanoparticles. From the summary table, the maximum increased heat transfer coefficient is found as 126% for ZnO nanoparticles and the maximum increased critical heat flux is found as 100% for GO nanoparticles. When two or more nanoparticles in succession or binary nanofluids have used the flow, boiling increased up to 53% for Al₂O₃, ZnO, and Diamond.

Table 1: Summary of metal nanoparticle with base fluids for pool boiling since 2003.

Enhancement Medium	Nanofluids		Reference	Condition (Concentration/ Heater type/ NPs Size)	Observation
	Nano-particles	Base fluid			
Metal	Au	H ₂ O	[27]	0.001wt% Cu plate	BHT enhanced between 11 and 21%. Rising particle concentration, BHT increased.

Table 2: Summary of metal oxide nanoparticle with base fluids for pool boiling since 2003.

Enhancement Medium	Nanofluids		Reference	Condition (Concentration/ Heater type/ NPs Size)	Observation
	Nano-particles	Base fluid			
Metal Oxide	Al ₂ O ₃	H ₂ O	[28]	Cu plate	HTC didn't change as the enhancement unrelated to increased thermal conductivity of nanofluids. CHF increased up to 200%.
		H ₂ O	[29]	Stainless steel plate	CHF increased about to 40%.
		H ₂ O	[30]	Stainless steel plate	BHT decreased. CHF increased up to 50%.
		H ₂ O and Ethanol	[31]	Cu and CuO, plates and plates with glass and gold coatings.	For bad wetting systems, CHF increased by up to 37%. The mechanism for CHF enhancement is the fluid's ability to increase surface wettability. Only surface modification caused in CHF improvement equivalent to nanofluids, but superheat of the lower wall at 20 ° C.
		CMC solution	[32]	Stainless steel cartridge heater	BHT decreased, more noticeable at higher concentrations of CMC. At nanoparticle concentration, BHT increased by up to 25%.
		H ₂ O-EG	[33]	0.05-1 vol.%	BHT increased about 64% at 0.75 % nanoparticle concentration.
		H ₂ O	[11]	0.025vol.%, 50 nm	CHF of the nanofluid increased.
		H ₂ O	[12]	0.07 to 0.1 vol.%, 13 nm	HTC increased with increasing the mass flow rate and the volume concentration and decreased with the aspect ratio.

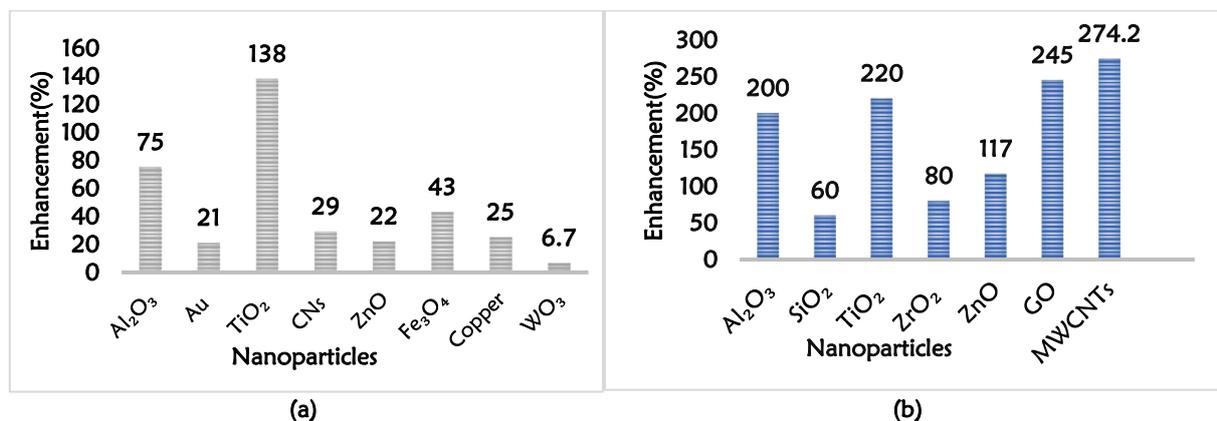
	α -Al ₂ O ₃	H ₂ O	[34]	0.001-0.1 vol.%	For smooth surface, BHT increased and constant for rough surface.
	γ - Al ₂ O ₃	R141b	[35]	0.001, 0.01 and 0.1 vol.%	BHT enhanced for nanoparticle concentrations of 0.001 vol.%, 0.01 vol.% and decreased with 0.1 vol.%.
	TiO ₂	H ₂ O	[36]	NiCr wire	CHF increased up to 200%.
		H ₂ O	[37]	0.000094-0.047 vol.%	HTC decreased, then improved. CHF increased about 91%.
		H ₂ O	[38]	0.0011 vol.%	HTC decreased. CHF increased about 220%.
		R-141b	[13]		CHF decreased.
	ZnO	EG	[39]	0.5-3.7 vol.%	HTC increased about 22% at concentration of 1.6 %. Maximum enhancement of CHF was found to be 117% at $\phi=2.6$ %.
		H ₂ O-EG	[14]	0.5 wt. %	Both HTC and CHF increased.
		H ₂ O-EG	[40]	0.025,0.05,0.075, and 0.1 vol. %	HTC increased up to 12% at concentration of 0.1 vol. %. CHF enhance about 29%.
	CuO	Pentane	[41]	0.005% and 0.01%	HTC increased up to 20–30% for brass surface and 15–25% at the nanoparticle concentration of 0.005%.
	Fe ₃ O ₄	H ₂ O	[42]	0.1 vol.%	HTC increased up to 43%.
	WO ₃	H ₂ O	[15]	0.005%,0.01% vol.	HTC ratio was increased by about 6.7%.

Table 3: Summary of non-metal or non-metallic oxide with base fluids for pool boiling since 2003.

Enhancement Medium	Nanofluids		Reference	Condition (Concentration/ Heater type/ NPs Size)	Observation
	Nano-particles	Base fluid			
Non-metal and Non-metallic Oxide	SiO ₂	H ₂ O	[43]	NiCr wire	Constant BHT. CHF increased up to 60%.
			[44]	NiCr wire	CHF enhanced greater than three times with pure water.
			[45]	NiCr wire	CHF enhanced up to 50% in SiO ₂ nanoparticles in water.
		EG and H ₂ O	[16]	0.25-1.00 vol.%	As the nanoparticle diameter decreased, the HTC increased from 84 nm to 120 nm.
	CNTs	H ₂ O and R-22	[46]	Stainless steel tube	HTC was observed to increase up to 28.7% at heat fluxes fewer than 30 kW/m ² .
		H ₂ O	[47]	0.01, 0.1, and 0.3 g/l	CHF increased about 145 to 245 %.
	MWCNTs	H ₂ O	[48]	0.01-0.1 wt. %	Depending on the types on chemical bond, HTC can either increased or decreased. CHF increased about 274.2%.
	H ₂ O	[49]	0.1-1 wt. %	HTC increased to 34.2 % for covalent nanofluids and 53.4 % for MWCNTs-COOH and MWCNTs-OH. Reduction of nanofluids that were not covalent.	

Table 4. Summary of nanoparticle mixture with base fluids for pool boiling since 2003.

Enhancement Medium	Nanofluids		Reference	Condition (Concentration/ Heater type/ NPs Size)	Observation
	Nano-particles	Base fluid			
Nano particle mixture		H ₂ O	[50]	(<0.1 vol.%) Stainless steel plate	BHT decreased. At low concentrations, CHF increased up to 80%.
	Al ₂ O ₃ and TiO ₂	H ₂ O	[51]	NiCr wire	CHF e increased up to 100%.
	Al ₂ O ₃ and Bi ₂ O ₃	H ₂ O	[52]	NiCr wire	CHF enhanced up to 50% for Al ₂ O ₃ and 33% for Bi ₂ O ₃ . With nanoparticle concentration, CHF increased for a certain heat flux value.
	LiBr and Al ₂ O ₃	H ₂ O	[53]	0-0.1 vol.% distributed in H ₂ O/LiBr solutions (3,7 and 10 wt.% of LiBr).	HTC decreased at volume friction. CHF increased about 48.5% with the 0.1 vol.% Al ₂ O ₃ in 10 wt. % LiBr aqueous solution.
	ZnO, α-Al ₂ O ₃ and MWCNTs	H ₂ O	[17]	0.01 0.02 and 0.05 wt.%	HTC decreased for both ZnO and Al ₂ O ₃ but MWCNTs improved it.
	Al ₂ O ₃ -SiO ₂	H ₂ O	[18]	0.001 vol. %	At a very low concentration HTC increased noticeably for Al ₂ O ₃ nanofluid and decreased for SiO ₂ nanofluid.
	TiO ₂ and MgO	H ₂ O	[19]	130 mm diameter and 205 mm height.	CHF increased in the range of 10.51% to 52.42% in case of TiO ₂ and 23% to 60.88% in case of MgO nanofluid with increase in volume fraction.
	h-BN and SiO ₂	DCM	[10]	1.0 vol.%	For H-BN/DCM and SiO ₂ /DCM, HTC were observed to be 27.59 %, 14.44 % and 20.69 % and 16.67 % for saturation boiling and after-saturation boiling processes.

**Figure 14:** Bar chart to illustrate maximum increased (%) of (a) HTC and (b) CHF in pool boiling for different nanoparticles.

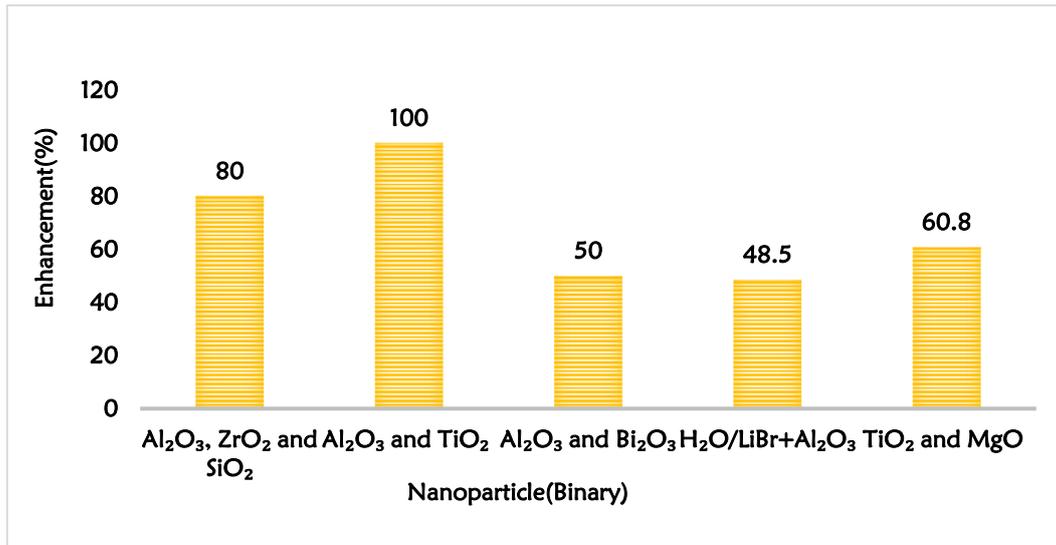


Figure 15: Bar chart to illustrate maximum increased (%) of CHF in pool boiling for different binary nanoparticle.

Table 5: Summary of metal nanoparticle with base fluids for flow boiling since 2003.

Enhancement Medium	Nanofluids		Reference	Condition (Concentration/ Heater type/Geometry (flow nature)/NPs diameter (nm))	Observation
	Nano-particles	Base fluid			
Metal	Copper	H ₂ O	[54]	50 nm parallel minichannels of dh = 800 μm.	With increasing nanoparticle concentration, BHT enhanced.

Table 6: Summary of metal oxide nanoparticle with base fluids for flow boiling since 2003.

Enhancement Medium	Nanofluids		Reference	Condition(Concentration/ Heater type/ Geometry(flow nature)/ NPs diameter (nm))	Observation
	Nano-particle	Base fluid			
Metal Oxide		H ₂ O	[55]	0.01 vol.%, Di=6.35mm D _o =12.78mm, L=0.5m Thickness=0.9mm,	CHF enhancement about to 70% at low concentration of the nanoparticle.
		H ₂ O	[56]	0.2 wt. %, NP dia=40nm	HTC increased by 17% .
		H ₂ O	[57]	0.001, 0.005 and 0.01wt.%	At a given mass flux, HTC increased up to 27.97%.
		H ₂ O	[20]	0.01-5 vol.%;	With nanoparticle concentration, HTC increased in single-phase and decreased in compressed liquid flow area.
		H ₂ O	[58]	0.15 wt.%	At 0.15 wt.% and Re = 13500, the overall increase in the HTC was 35.7%, but the HTC nanofluids decreased over time.
	ZnO	H ₂ O	[21]	0.005-0.02 vol.%	Heat transfer rate of Al ₂ O ₃ /H ₂ O nanofluid was increased by flow boiling by roughly 86%.
		H ₂ O	[22]	0.0001-0.1vol.%;NPs diameter < 100 (30-50) nm	At higher concentration HTC increased by 126%.

	CuO	R-113	[59]	Copper tube	BHT increased by 30%. Boundary layer thickness has a great impact on this improvement.
		R-113	[60]	Copper tube	Frictional pressure decreased up to 21%.
		DI-H ₂ O	[23]	0.1-0.3 wt.%	HTC increased with the mass flow rate.
	MgO	Therminol 66	[61]	0.1, 0.2 and 0.3 wt.%	Maximum HTC enhancement was 23.7% at wt.%=0.1.

Table 7: Summary of non metal and nonmetallic oxide nanoparticle with base fluids for flow boiling since 2003.

Enhancement Medium	Nanofluids		Reference	Condition (Concentration/Heater type/Geometry (flow nature)/NPs diameter (nm))	Observation
	Nano-particles	Base fluid			
Non-metal and Non-metallic Oxide	Ceramic	H ₂ O	[24]	0.1-0.5 vol.%	Modest increase in the overall nanofluid heat transfer rate.
	GO	H ₂ O	[62]	0.01 vol.%	CHF increased about 100%.

Table 8: Summary of nanoparticle mixture with base fluids for flow boiling since 2003.

Enhancement Medium	Nanofluids		Reference	Condition (Concentration/Heater type/Geometry (flow nature)/NPs diameter (nm))	Observation
	Nano-particles	Base fluid			
Nano-particle mixture	Al ₂ O ₃ and TiO ₂	H ₂ O	[25]	0.1-2.5 vol.%. NP diameter=20,40nm	Deteriorated in both directions with increasing nanoparticle concentration.
	SiC and Graphite	H ₂ O	[26]	0.1vol.%	At 0.1 vol.% SiC/H ₂ O and Graphite/H ₂ O nanofluid BHT increased.
	Al ₂ O ₃ , ZnO, and Diamond	H ₂ O	[63]	≤ 0.1 vol.%, NP dia=30nm	BHT increased marginally at low heat flux. CHF increased up to 53%.
	Al ₂ O ₃ and SiC	H ₂ O	[64]	0.01Vol. %. Al ₂ O ₃ lower than 50 nm and SiC higher than 50 nm	CHF increased for both nanofluids.
	Al ₂ O ₃ -Cu	H ₂ O	[65]	Uniformly heated tube.	CHF increased about 13%.
	Fe ₃ O ₄ and Al ₂ O ₃	H ₂ O	[66]	0.0001, 0.001 vol.%, NP diameter=25nm	CHF increased for magnetic nanofluid.
	MWCNTs, CuO and Al ₂ O ₃	H ₂ O	[67]	0.1-0.3 wt.%, 12-14nm ×1.5-2µm for MWCNT and 50nm for metal oxide	HTC increased for MWCNTs and increased then deteriorated for metal oxide particles.
	AlN and Al ₂ O ₃	H ₂ O	[68]	0.1-0.5 vol.%. NP diameter 20 nm for	HTC depends on some parameter according to new saturated flow boiling correlation proposed.

				Al ₂ O ₃ and 30 nm for AlN	
	SiO ₂ and CuO	R-134a and Polyester oil	[69]	Copper tube, L=2[m] Di=7.9[mm]	BHT decreased by 55% as compared to uncontaminated R-134a.

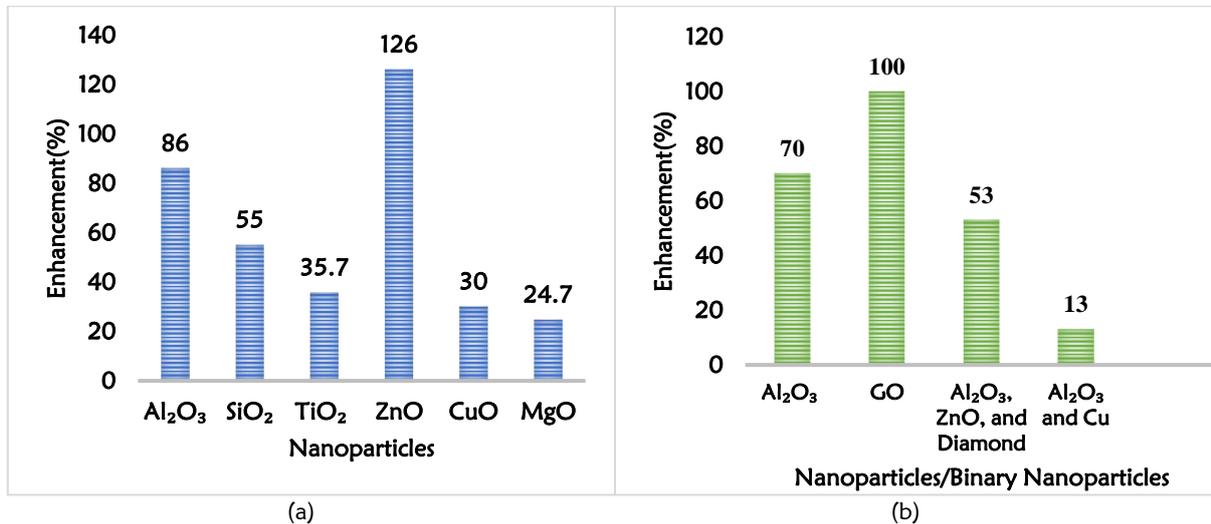


Figure 16: Bar chart to illustrate maximum increased (%) (a) HTC (b) CHF in flow boiling for different nanoparticles or binary nanoparticles.

7 RECOMMENDATION AND FUTURE DIRECTION

Many researchers are still working on detailed research on the boiling heat transfer rate of nanofluids. After reviewing several articles on nanofluids boiling heat transfer, it has been seen that the heat transfer coefficient and critical heat flux could be increased by using nanofluids in the boiling heat transfer. This improved heat transfer coefficient and critical heat flux can be implemented in the design of heat exchangers and heat storage systems. Therefore, the effects of nanofluids on the enhancement of boiling heat transfer have great importance in industrial applications such as cooling of nuclear reactors, cooling of high-power electronics components, heat exchangers. While conducting the experiment, the researchers usually varied the concentration of the nanoparticles and had found different results on both HTC and CHF. But they are unable to give any mathematical relations between nanoparticle concentration with HTC and CHF. In the future, the findings of the present research can help the researchers to concentrate on formulating the mathematical relations and can also open a door of opportunity in the field of heat transfer enhancement.

8 CONCLUSIONS

Nowadays the applications of nanoparticles in heat transfer have been increased due to its better thermophysical properties. In this paper, the authors have tried to show the progress of research on the boiling heat transfer of nanofluids. Nanofluids have large influence on the performance of pool and flow boiling heat transfer. It can either enhance or reduce the HTC and CHF. It mainly depends on several important factors. From the total summary, it can be concluded that.

1. In comparison with the base fluids, most of the nanofluids show an increased HTC and CHF and increased dramatically with rising nanoparticle concentrations. With decreasing nanoparticle size, the heat transfer coefficient increases.
2. In case of pool boiling the research papers give their results equally on HTC enhancement as well as the CHF enhancement, whereas in the case of flow boiling just a few results have been found for CHF enhancement.
3. Researchers have investigated the boiling enhancement with the various nanoparticles. Among those nanoparticles, the widely used nanoparticles are Al₂O₃ and TiO₂. Between these two, Al₂O₃ is the most widely used nanoparticles for the enhancement of pool and flow boiling heat transfer. In the case of binary nanoparticles, the most widely used combination is Al₂O₃ and TiO₂.

4. Nanofluids boiling heat transfer activity depends on different variables as shown in figure 17 which includes the thermophysical characteristics of nanofluids, mutual interactions, type of the heating surfaces, type of coatings in the plate, type of nanoparticles, the concentration of the nanoparticle (by volume and mass), size of the nanoparticle, heat and mass fluxes, pressure system, vapor quality and additives, etc.
5. In the case of pool boiling the maximum increased heat transfer coefficient is found as 138% for TiO_2 nanoparticles and the maximum increased critical heat flux is found as 274.2% for MWCNTs.
6. In the case of flow boiling the maximum increased HTC is found as 126% for ZnO nanoparticles and the maximum increased critical heat flux is found as 100% for GO nanoparticles.
7. When two or more nanoparticles in succession or binary nanofluids are used the CHF in pool boiling increased up to 100% for Al_2O_3 and TiO_2 . Also, the CHF in flow boiling increased up to 53% for Al_2O_3 , ZnO, and Diamond.
8. Binary nanofluids are superior CHF for both pool and flow boiling rather than HTC.
9. Further work will be needed in order to find more suitable nanofluids for BHT as the findings of various researchers are not constant. So, testing more and more nanoparticles are essential.
10. To make applicable nanofluids, stability is the most important thing. It should thus be examined and developed for both steady and flow conditions in nanofluids boiling.

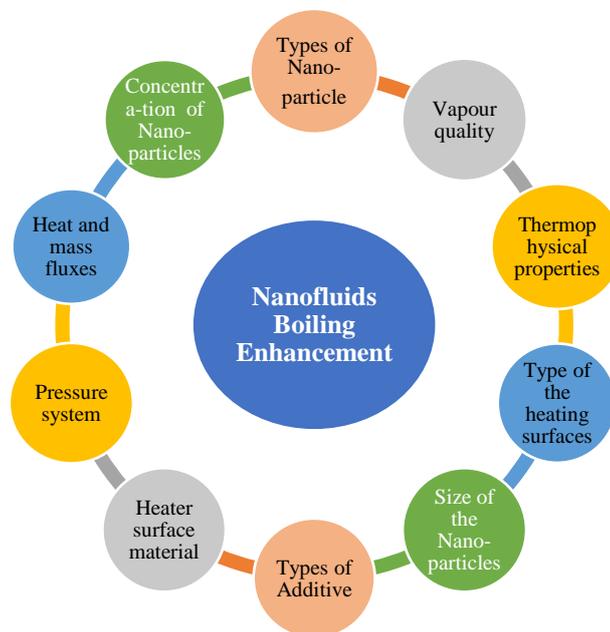


Figure 17: Factors affecting nanofluid boiling heat transfer enhancement.

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