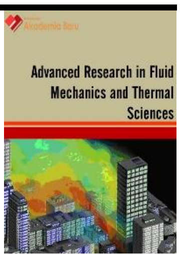
Penerbit
Akademia Baru

Journal of Advanced Research in Fluid
Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Enhancement of Boiling Heat Transfer Performance Using Nano Coating - A Review

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Ashish Mogra[1,*], Pankaj Kumar Pandey[2], Krishna Kumar Gupta[3]

[1] Department of Mechanical Engineering, MPSTME, SVKM's Narsee Monjee Institute of Management Studies (NMIMS), Shirpur Campus, Maharashtra 425405, India
[2] Department of Chemical Engineering, AMITY University Jaipur, Rajasthan 302006, India
[3] Department of Mechanical Engineering, MPSTME, SVKM's Narsee Monjee Institute of Management Studies (NMIMS), Shirpur Campus, Maharashtra 425405, India

ARTICLE INFO

Article history:
Received 29 January 2020
Received in revised form 1 March 2020
Accepted 9 March 2020
Available online 30 April 2020

Keywords:
Heat Transfer Coefficient (HTC); Critical Heat Flux (CHF); nano coating; nanoparticle; wettability

ABSTRACT

In various engineering as well as non-engineering i.e. in our daily lives boiling phenomenon is using. Boiling heat transfer is a systematic and essential mechanism for transfer of thermal energy form one surface to the relatively lower temperature surface. The phenomenon of boiling heat transfer is being applied in many industrial fields to require for maximization of the critical heat flux. Objective of this present paper is to present the effect of surface coating on heat transfer coefficient and critical heat flux in pool and flow boiling phenomenon. Present paper includes summary of existing work on heat transfer enhancement techniques using nano coating. Effect of surface wettability and nanoparticle deposition has been discussed.

1. Introduction

Some of the application in which boiling heat transfer involve are power plants for generation of energy, electronic chip cooling, refrigeration and air conditioning, food processing industries, manufacturing automobile sector, microelectromechanical and microfluidic system, atomic or fusion reactor, marine ship power generation, heat exchanger for internal combustion engine, thermal management of batteries, heat pipes, desalination and so on. Boiling is a process in which vaporization takes place at solid and liquid interface, when the temperature of heater surface exceeds the saturations temperature of liquid. Boiling phenomenon can be classified in two ways, pool boiling and flow boiling. In pool boiling process, phase change occurs from liquid to vapor when a liquid receives heat from the heated surface and converted into the form of vapor with the help of bubble. Clear understanding of the bubble dynamics including formation, growth and detachment

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[*] *Corresponding author.*
E-mail address: ashish.mogra@nmims.edu (Ashish Mogra)

https://doi.org/10.37934/arfmts.71.1.100116

mechanism of bubble from the heated surface required before applied on any engineering application.

The parameters of bubble dynamics such as bubble nucleation site density, bubble departure diameter and frequency and waiting time for bubble are need to investigate for boiling heat transfer. The boiling heat transfer can be determined from various developed correlation based on bubble dynamic parameters [1-4].

There are mainly two important parameters or factors which are directly related with boiling phenomenon known as Heat Transfer Coefficient (HTC) and Critical Heat Flux (CHF). Heat transfer coefficient indicates the performance efficiency and measure the heat transfer force. The critical heat flux represents the thermal limits of the heat flux which is available due to formation of vapor blanket over the heated surface. Critical heat flux is an important and crucial issue in boiling heat transfer. Critical heat flux is also called as a boiling crisis or dries out. In many sections such as refrigeration and air conditioning, cooling system, synthetic building and power plants heat transfer plays an important part. To make system more capable and work safely, determination and enhancement of heat transfer coefficient and critical heat flux is essential. Enhancement in heat transfer coefficient and critical heat flux significantly decreased the energy consumption [7,8].

During the flow boiling, fluid is forced to flow. In flow boiling all the phases flow simultaneously in a confined channel such as vapor and liquid in a pipe. Flow boiling occurs when convective heat transfer introduced by the help of a pump and it has flexibility of orientation. The flow boiling is an effective way for heat transfer mechanism. Although, with comparison of pool boiling the flow boiling process is affected additional by various factors such as mass flux and vapor quality of fluid. Meanwhile, the presence of pump also creates complexity in the system which leads to the loss of power due to pressure drop. In analysis of flow boiling, consideration of pumping system required which affect the cost and size of the pumping system [5,6].

Heat transfer can be defined as the thermo physical phenomenon which involved conversion of energy, its utilization in other forms and in recovery process. Enhancement of heat transfer required physical as well as chemical involvement in the system. Applying the physical improvements in the heat transfer system resulting in decrement in size and reducing the pumping power. Further developments in this area would potentially lead in to the enhancement in overall energy efficiency and reduction in size and cost of the operating system. The main advantage of boiling is the transformation of large amount of heat energy within a stipulated time and given volume through the phase change process.

Various techniques are available in literature for enhancement of heat transfer performance that can be classified as active, passive and compound techniques as shown in Figure 1. Active techniques involve the use of various external powers for enhancement of heat transfer performance, while passive technique does not depend upon any source of power. On the other hand, compound techniques, consider as a combination of both active and passive techniques. There is no any moving part in passive technique so it showed more reliability over the active technique [11].

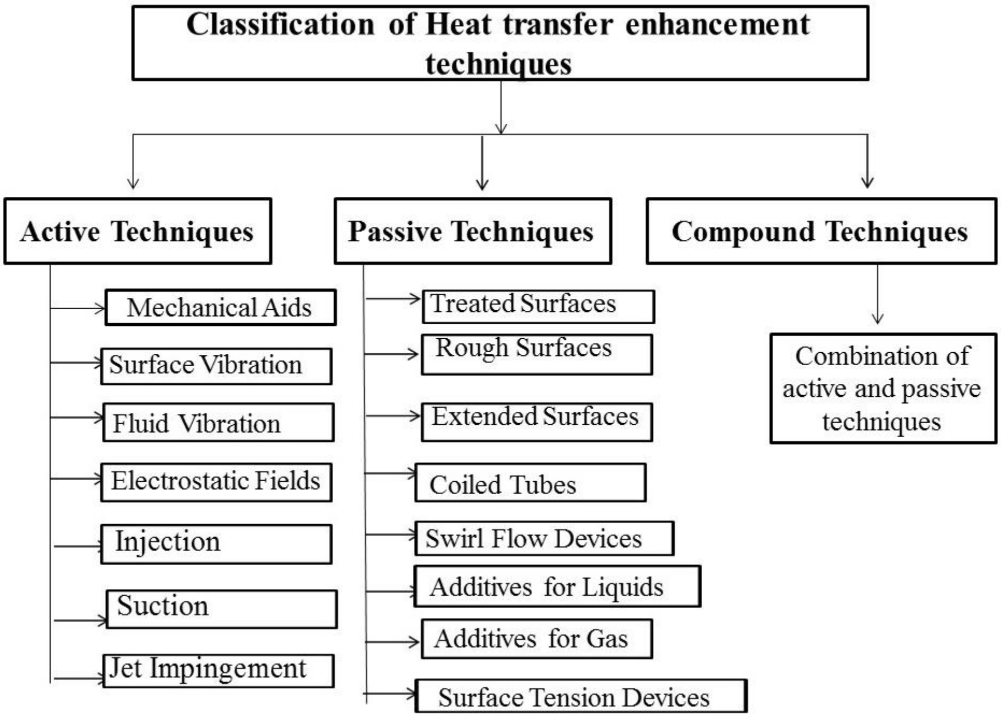

Fig. 1. Categorization of various techniques for heat transfer enhancement [16]

In Passive technique, treated surface showed more potential in recent years due to its applicability for improvement in heat transfer performance. Treated surface generally deal with modification of the surface structure or coating of various functionalized material at micro to Nano scale. However, micro-Nano scale surface modification are normally used for two phase process like boiling, condensation and freezing, but they are also found useful for single phase flow or single-phase heat transfer process [12-14].

Working fluid and solid surfaces are the two main available variables for enhancement of boiling heat transfer. Many time, modification of working fluid is not feasible due to restriction of various industrial application such as, steam power generation, water desalination etc. Therefore, modification on surface remains a key factor. So, here the modification of surface like surface roughening, surface coating comes into the picture for enhancement of heat transfer performance. In most of the industrial application, boiling is considered as a surface phenomenon, which depends upon the surface characterization. The surface characterization includes roughness, porosity, permeability and surface wettability.

In nucleate boiling phenomenon, bubble growth, nucleation site density, bubble departure diameter, bubble departure frequency is strongly influenced by topology and morphology of the surface. For specific application micro and Nano coating provides an effective solution with optimizing different surface parameters. As compared to other passive method, surface coating technique is simple, easy for selection on material and in geometry and quite functional to existing system [15,16].

2. Boiling Heat Transfer Enhancement Using Nano Coating

In this section the contributions of various researchers which are already done on relevant field have been described. Basically, the literature review is organization, arranging and critically examined the work on the relevant field of research. The main objective of this literature review is to clear everything about the existing study or to differentiate between what is known and what needs to know. This review is carried out due to rapid application of boiling phenomenon in various industrial applications, for clear understanding of the mechanism of bubble dynamics, technique for enhancement of heat transfer performance including heat transfer coefficient and critical heat flux. The scope of this research is focus on passive technique especially surface modification technique i.e. coating of material on heater in boiling phenomenon.

The present literature review is basically a collection of the experiment work that has been done on boiling phenomenon including pool and flow boiling. In present literature review the effect of surface characterization and deposition of Nanoparticle on heated surface has also been considered.

2.1 Surface Coating for Pool Boiling Heat Transfer Enhancement

Almost 10 years before, You *et al.,* [17] found notable enhancement in critical heat flux during the pool boiling. Working fluid was water and concentration of Al_2O_3 nano- particle less than 0.01 vol% was considered. Subsequently the research on nano particle coated surface for enhancement of boiling heat transfer was performed. Cieslinski [18] investigated the different process parameters of porous coating that affect the rate of heat transfer. It was found that surface with deposited metal particle have higher heat transfer coefficient as compared to plain surface at the same heat flux.

Li and Peterson [21] performed number of experiments to investigate the effects of geometric dimension on performance and characteristics of pool boiling. The geometric dimensions include thickness of coating, volumetric porosity, pore size and condition of porous surface coating. They find out the dependency of geometric parameters (i.e. thickness, volumetric porosity and mesh size) of the porous coating on boiling characteristics and overall performance of boiling, while pressure and size of heater held constant. Hendricks *et al.,* [22] observed higher CHF value up to 85.2 W/cm^2 when ZnO coated on Al surface as compared with bare al surface which was about 23 W/cm^2. They also found higher value of CHF up to 63.5 W/cm^2 for ZnO on Cu with flower morphology. Feng *et al.,* [23] performed experiments to enhance the critical heat flux and heat transfer coefficient on alumina coated platinum wire. It was found that CHF increased as the thickness of coating increases. The reason for enhancement in critical heat flux was super wetting property of amorphous alumina coating which increased the liquid film thickness and significantly enhanced the rewetting of the hot spot. Sakashita [24] study revealed that critical heat flux of boiling of water on coated by TiO_2 surface increased 1.8 times as compared with uncoated surface. The cause of critical heat flux enhancement was due to formation of macro layers of TiO_2 which are thicker as compared to uncoated surface.

Das and Swapan [25] found maximum heat transfer enhancement and coating thickness ranging from 29.6 to 80.3% and 100 to 300 nm respectively for TiO_2 coated surface as compared to untreated surfaces. This was due to hydrophilic surface. There was also observed the reduction of 40.3% for thickest surface i.e. 300 nm at lower heat flux. Das and Swapan [26] performed experiments on pool boiling to determine the effect of coating thickness and surface roughness. Three types of test surface are used namely, untreated, polished and Nanoparticle coated surface. They found increment of heat transfer coefficient of 60.2, 29.6 and 11.5% for TiO_2 Nano coated surface with roughness in the range of 0.289, 0.173 and 0.0338 micrometer respectively. They also concluded that heat transfer coefficient (HTC) increases as the coating thickness increased. Jun *et al.,* [27] conducted experiment and three regimes have been found namely, microporous, microporous to porous transition and porous. The nucleate boiling heat transfer and critical heat flux increased as the coating thickness increases in first regime. In second regimes the nucleate boiling heat transfer further increased at minimum heat flux but as the heat flux and coating thickness increases it gets reduced. While the critical heat flux continues increases as the thickness increased.

Table 1
Summary of pool boiling heat transfer performance with coated surface

References	Coating Material	Base Surface	Working Fluid	Orientation	Coating Thickness	Enhancement with compare to plain surface (HTC and CHF)
Chang and You [19]	Diamond	Copper	FC-72	Horizontal		HTC increases
Kim *et al.,* [20]	Diamond	Copper	FC-72	Horizontal		HTC increased
Cieśliński [18]	Al, Cu, Mo, Brass	Stainless steel	de-mineralized water	Horizontal		HTC and CHF increased
Hendricks *et al.,* [22]	ZnO	Al and Cu	De-ionized water	Horizontal		82.5 W/cm^2 (on coated)23.2 W/cm^2 (non coated)
Feng *et al.,* [23]	Amonina	platinum (Pt) micro wires	De-ionized water	Horizontal	20 nm.	HTC and CHF increased
Sakashita [24]	TiO_2 Nano particle		water	Horizontal		HTC increased 1.8 times
Das and Swapan [25]	TiO_2	copper	Distilled water	Horizontal	100, 200 and 300 Nanometer	29.6 to 80.3%
Han Seo *et al.,* [31]	graphene and silicon carbide (SiC)	indium tin oxide	FC-72	Horizontal		58% and 90%
Sung-Seek Park *et al.,* [32]	MWCNT and GO	Copper	distilled water	horizontal upward to horizontal downward	300 micrometer	HTC and CHF increased
Gwang Hyeok Seo *et al.,* [33]	SWCNT	stainless steel grade 316 (SS316)	water		290 – 1800 nm	51%
Das and Swapan [26]	TiO_2 Nano particle	Copper	water	Horizontal	300 nm	11.5%
Dharmendra [29]	CNT and intermediate layer of diamond	Copper	de-mineralized water	Vertical		38%
Seongchul Jun *et al.,* [27]	high-temperature, thermally conductive, microporous coating (HTCMC) copper	copper	Distilled water	Horizontal	49 to 283 micro meter	50%
Seunghyeon Lee *et al.,* [28]	polyethylenimine (PEI)-multi-walled carbon Nanotube (MWCNTs)	stainless steel (SS316)	Distilled water	Horizontal		47 % to 91%.
Gheitaghy *et al.,* [34]	Copper	Copper surface	water	Horizontal		Horizontal

Ray *et al.,* [30]	TiO_2	copper	R-134a	Horizontal	100 nm and 200 nm	36.91% and 44.93%
Ray and Swapan [35]	TiO_2	copper	hydro-fluorocarbon refrigerant R-134a	Horizontal	100, 200 and 300 nm thick	87.5%
Joseph *et al.,* [36]	CuO	SS 316 LN stainless steel	water	Horizontal	77-158 micro meter	30%
Kumar *et al.,* [37]	Gr/CNTs heterostructures	copper	FC-72	Horizontal		155% and 40%
Gupta and Misra [38]	Cu-TiO_2	Copper	De-ionized water	Horizontal	13 micrometer to 45 micrometer	273% and 72.5%
Meikandan *et al.,* [39]	MWCNT	Copper	water	Horizontal	2 micrometer	24.2%

In the last regime i.e. porous, when the coating thickness increases the nucleate boiling heat transfer and critical heat flux decreased. The magnitude of nucleate boiling heat transfer was found nearer to 350 kW/m^{2}K at coating thickness of 96 micrometer. The magnitude of maximum critical heat flux was close to 2.1MW/m^2 at 225 micrometer thickness. Lee *et al.,* [28] found that heat transfer coefficient depends upon the layer of coating material. It is found that 20 bi—layers of PET-MWCTs coating showed the best heat transfer performance as compared to 40 bi-layers which showed the lowest heat transfer performance. It has been concluded from the experiments that there at an optimized number of layer one can get the enhancement in heat transfer performance. CFH increased as the number of layer increases from 10 bi layers to 40 bi layers. It has been also found that CHF increased up to 147%, from 912 to 1534 kW/m^2.

Dharmendra *et al.,* [29] developed a layer of diamond between CNT coating and copper surface which provide dual benefit. Firstly, it gives the bonding strength between CNT coating and copper surface and secondly it reduces the intermediate resistance between both the materials. As the intermediate resistance decreased the rate of heat transfer increased by keeping the constant temperature between the top surface and tip of the film. Surface roughness also plays an important role for enhancement of heat transfer. As the surface roughness increases, the effective surface area increased which in turn increased the rate of heat transfer. Ray *et al.,* [30] conducted experiment to investigate the heat transfer performance for pool boiling phenomenon for environmentally friendly refrigerant R134a as a working fluid. They found highest enhancement of heat transfer coefficient for the TiO_2 coated surface of 36.91% and 44.93% on 100 nm and 200 nm respectively, over the uncoated surface. Therefore, it can be concluded that as the thickness of coating increases the heat transfer performance increased.

2.2 Surface Coating for Flow Boiling Heat Transfer Enhancement

Ammerman [40] examined the effects of flow velocity, inlet sub cooling, and surface coating on heat transfer and pressure drop. They concluded that Critical Heat Flux (CHF) increased in the range of 14 to 36% by using coating. Due to the sub cooling the vapor generated condensed quickly which showed minor impacts on pressure drop.

Khanikar *et al.,* [41] performed experiments on flow boiling phenomenon using coating of CNT on surface of copper microchannel. They used water as working fluid. They found enhancement of critical heat flux and boiling heat transfer coefficient. They developed monolithic micro/Nanofabrication process to produce the silicon nanowire coated microchannel. They conduct flow boiling heat transfer experiments for performance comparison of coated and uncoated surface of microchannel.

Khanikar *et al.,* [41] investigated the benefits of coating of CNT on bottom wall of the rectangular microchannel for enhancement of heat transfer. They observed many similarities for the bare and CNT coated surfaces which required for the boiling. It was found that boiling is always started from the downstream region of the microchannel. The critical heat flux precipitate due to backflow into the upstream, which in turn creates a dry out condition for the heated surface. Phan *et al.,* [42] performed experiments to determine the effects of surface wettability on the flow boiling heat transfer. They found significance enhancement in heat transfer coefficient up to the 85% as compared with smooth surface. They concluded that when the quality of vapor increases the heat transfer first increased and then decreased. Singh *et al.,* [43] performed experiments to compare the effect of MWCNT coated on silicon substrate with other bare silicon surface. It was concluded that the heat flux enhanced in the range of 30 to 80% during the fully developed nucleate flow boiling regime. It was also observed that the level of heat transfer enhancement was maximum at minimum values of sub cooling and flow rates.

Li *et al.,* [44] found significantly enhancement in flow boiling heat transfer, including advanced onset nucleate boiling (ONB), conquer oscillating amplitude of temperature and pressure drop, and delayed in onset of flow oscillation when using coated with silicon Nanowires microchannel. Morshed *et al.,* [45] performed experiments on single and two phase flow boiling on rectangular microchannel coated with copper Nanowires. They compared the convective heat transfer performance with bare and coated surface. The enhancement of 25.2% and 23.5% for a mass velocity of 45.95 kg/m^{2}s and 143.79 kg/m^{2}s respectively was observed for coated Nanowires. Copper Nanowires significantly enhanced the boiling performance. They also found experimentally that coated copper Nanowires surface is more efficient at lower degree of sub-cooling.

Dawidowicz and Cieśliński [46] conducted experiments for determination the application of porous coating in flow boiling phenomenon using pure and mixed refrigerant as a working fluid. They found higher average heat transfer coefficient and low pressure drop for porous coated surface as compared with smooth tube with the same mass flow velocity. They also proposed a correlation for calculation of average heat transfer coefficient in flow boiling with porous coated surface.

Kousalya *et al.,* [47] demonstrated improvement of heat transfer performance in flow boiling from CNT coated copper surface which exposed to low intensity ultraviolet (UV) visible excitation. They found that as compared to non-coated surface reduction of average minimum boiling temperature up to 4.60C and enhancement of heat transfer coefficient by 41.5%. This enhancement occurs due to augmentation of hydrophilicity for exposure of UV light and possibility of Nanoscale up to thermal effects. Morshed *et al.,* [48] examined the effect of Cu-Al_2O_3 nano composites coating on heat transfer performance and its prospective use in various heat transfer equipment's which can operate in corrosive environment. They coated bottom surface of the rectangular microchannel. It has been observed that enhancement of heat transfer rate in single phase flow was higher as compared to two phase regimes. The enhancement was up to the range of 30% to 120%, with an additional pressure drop of 15%. The enhancement also depends upon the flow rate and surface temperature. Critical heat flux also has been improved by 35% to 55% for coated surface.

Sujith Kumar *et al.,* [49] investigated the effects of alumina coating on the copper surface for the flow boiling heat transfer. They observed higher enhancement of 28.3% in wall super heat flux using alumina coated as compared to the bare copper sample at a lower mass flux of 88kg/m^{2}s. This was mainly due to enhancement of area and reduction in local pumping action of the surface. Seo *et al.,*

[50] performed experiments for enhancement of heat transfer performance in flow boiling phenomenon by taking R123 refrigerant as a working fluid and Al_2O_3 nano particle. Experimental result showed that by using the nano particle coated tube critical heat flux enhanced up to 17% at a mass flux of 2400kg/m^2s as compared to bare surface. Factor that was responsible for the enhancement of heat transfer performance capillary action through porous structure, which increased the wettability of the surface.

Table 2

Summary of flow boiling heat transfer performance with coated surface

Authors	Types of coating	Coating material	Base surface	Working fluid	Orientation	Coating Thickness	Enhancement with compare to plain surface (HTC and CHF)
Ammerman [40]	Micro porous surface	Diamond	Silicon Substrate	FC-87	Horizontal		14 to 36%
Khanikar *et al.,* [41]		CNT	copper	Water	Horizontal	54 to 60 nm	HTC increased
Singh *et al.,* [43]		MWCNT	Silicon wafers	Demineralized water	Horizontal	15-30 micrometer	30 to 80%
Phan *et al.,* [42]	Nano and micro-surface treatments	Titanium and PDMS	copper	Demineralized water	Horizontal	3-4 micrometer	85%
Dawidowicz and Cieśliński [46]	porous coating	-----	Stainless steel	R22, R134a, R407C	Horizontal	55 micrometer	HTC increased
Kousalya *et al.,* [47]	Nano coating	CNT	Copper		Horizontal		41.5%.
Kumar *et al.,* [49]	porous metal oxide coatings	alumina	copper	Demineralized water	Horizontal		28.3%
Seo *et al.,* [50]	Nano coating	Al_2O_3	Stainless steel tube 316L	R1234yf	Horizontal		17%
Kumar *et al.,* [51]	composite coatings	Fe doped-Al2O3–TiO2	copper	Demineralized water	Horizontal	19.9 to 21.3 micro meter	44.11% and 52.39%
Kumar *et al.,* [52]	hydrophilic coating	ZnO-Al2O3	copper	Demineralized water	Horizontal	2.96 to 26 micrometer	44.6% and 29.7%
Mancin *et al.,* [53]	micro coating	pure Copper particle	Copper	R1234yf	Horizontal		250%
Gupta and Misra [54]	microporous coating	Cu-TiO2	copper	Distilled water	Horizontal	38 to 62 micrometer	94% and 92%

2.3 Deposition of Nanoparticle on The Surface

Form literature review it has been found that Nano particle after used deposited on the heated surface and treated as a coated surface. But higher the deposition will lead to fouling phenomenon which decreases the heat transfer coefficient and critical heat flux. Some of the research has been showed in present section.

Hegde *et al.,* [55] performed experiments to investigate the effect of Nano coated surface on enhancement of critical heat flux in pool boiling. They conducted experiments with CuO Nanofluid and observed the enhancement of critical heat flux by 35.83 and 41.68% respectively at the concentration of 0.1 and 0.5 g/l respectively as compared to bare surface. After performing rigorous experiments on boiling in nano-fluid, the nanoparticle deposited surface was again tested with pure water. In this way they observed the effect of deposition of nanoparticle, which was treated as a surface coating. The critical heat flux was found increased by 29.38 and 37.53% at a concentration of 0.1 and 0.5 g/l respectively. It can be concluded that higher Nanoparticle concentration can increased the critical heat flux with Nano coated surface as compared with uncoated surface. Hyungdae Kim *et al.,* [56] carried out experiments to identify the effect of nanoparticle deposited on heater surface during the pool boiling. They used titanium (TiO_2) nanoparticle in their research. They analyzed different parameters which are responsible for deposition of nano particle including surface wettability. They found that critical heat flux increased due to deposition of nano particle which act as a nano coating. The enhancement in critical heat flux happened because as the nanoparticle deposited on surface in the form of layer, the coating thickness increased which significantly induce capillary flow of liquid toward to the dry area. During this process the condition of local dry out could be delayed.

Hassan *et al.,* [57] performed experiments to determine the effect of nanoparticle deposition after several use on heat pipe surface. These deposited nano particles behave like wick porous in nature. The aggregation of nanoparticle developed a serious capillary and thermal resistance which result in effect of performance of heat pipes. They found about 50% enhancement of heat pipe performance of nanoparticle deposited surface as compared with plain surface.

Mori *et al.,* [58] conducted experiments in order to enhance heat transfer performance during saturated pool boiling of water a honeycomb porous plate and nano fluid was used. However, it was known that as the size of heater increased the critical heat flux decreased in case of Nanoparticle deposition on heater surface. The nano fluid was deposited on heater surface by continues using of nano particle on heated surface and then liquid which containing the nano particle was removed so like that nano coating have been prepared. The critical heat flux of honeycomb porous surface coated with nanoparticle deposition surface increased up to 3.1, 2.3 and 2.2 MW/m^2 for 10 mm, 30 mm and 50 mm diameter respectively. So, by using the combination of honeycomb porous plate and Nano fluid one can get the maximum heat performance on larger heater size.

Hu *et al.,* [59] discussed the influence of heat flux and nanoparticle mass fraction on pool boiling heat transfer performance. They used ethylene glycol aqueous solution which is mixture of ethylene glycol (EG) and deionized water (DW) in the volume fraction of 60:40 respectively. By adding graphene nanosheets (GNs) in aqueous solution increased heat transfer performance as the surface wettability increased due to deposition of Nano particles on heated surface. however, is has been found that increasing the concentration of graphene nanosheet boiling heat transfer get reduced due to sedimentation of GNs and subsequently blockage of nucleation sites. Ji Min Kim *et al.,* [60] performed experiments to investigate the effect of water based Graphene Oxide (GO) on colloidal suspension on silicon dioxide surface for enhancing the pool boiling heat transfer performance. They found enhancement of CHF value by 94%, 139% and 105% for the concentration of GO as 1mg/l, 5 mg/l and 10 mg/l respectively as compared with bare surface and DI water. Zhen Cao *et al.,* [61] performed pool boiling heat transfer experiments using dielectric fluid through modified micro pin fin silicon surfaces and by deposition of nano particles. Firstly, they performed experiments on modified pin fin surface using nano particles and then investigate the performance using nano particle deposited on surfaces. They observed high heat transfer coefficient for pin fin surfaces as compared with plain surfaces. The wickability of the surface has been measured and found main reason for enhancement of critical heat flux. A nearly 100% critical heat flux increased when Fe-Mn oxide nano particle deposited on surfaces. Higher the bubble departure frequency and lower the departure diameter found on micro pin fin surfaces with and without nanoparticle at low and moderate heat flux.

Modi *et al.,* [62] performed experiments on plain copper surface and nanoparticle deposited surfaces. They consider water and alumina nanoparticles for their analysis in nucleate pool boiling phenomenon. The result of experiments revealed that the alumina nanoparticles in liquid form, suspended form or in the deposited form on heater surface increased heat transfer performance.

2.4 Effect of Wettability on Heat Transfer Performance

Surface wettability plays a crucial role for enhancement of heat transfer performance. Wettability can be defined as the contact angle made by solid surface and fluid. A surface can be classified as hydrophobic and hydrophilic depending upon the contact angle. If the contact angle made by surface and liquid is greater than 90^o, then the surface treated as hydrophobic surface, on the other hand if the contact angle is less than 90^o, surface is called as hydrophilic in nature. The literature review showed that research has been also done on development of super hydrophobic and super hydrophilic surface. It means when the contact angle is greater that 150^o surface is known as super hydrophobic, while when contact angle close to 0^o it termed as super hydrophilic surface. Recent development focused on development of smart surface which behave hydrophilic as well as hydrophobic in nature. This surface can be developed by doing composite coating on the surface. Present literature review focused some of the work that carried out by researchers.

Yuan-Yang Li *et al.,* [63] conducted pool boiling experiments on plain nickel surface, nickel-based chemical treated surface and nickel based electrochemical treated surface with nano cone array structure. They measured effect of the surface characteristics parameters such as solid-liquid contact angle, nano scale surface roughness on heat transfer coefficient. They proposed a correlation for predicting the heat transfer behavior on convex structure by considering the effect of effective heat transfer area ratio, r. They also investigated and compared the bubble dynamic behavior on nano cone array surface as well as on chemically treated surface by taking the same contact angle between solid and liquid.

The compared data showed that bubble departure diameter (Db) and bubble departure volume (Vb) of nano cone array surface was 0.75 and 0.42 times of the chemically treated plain surface. The nano cone array surface creates hydrophilic surface and found more active nucleation site on nano structured surface, therefore heat transfer coefficient increased.

Kim *et al.,* [64] modified the heating surface characteristics by applying atmospheric pressure plasma (AP-Plasma) technique for investigation of critical heat flux through surface wettability. By applying the AP-Plasma technique the static angle was reduced from 80 degree on original treated surface to 15 degree with treated surface. As the contact angle reduced the enhancement of critical heat flux of 18% achieved under flow boiling conditions on treated surface. Seo *et al.,* [65] performed substantial experiments on pool boiling heat performance to verify the effect of Fe-Cr-Al layer as promising coating material for safety of various thermal heaters. They found maximum enhancement of CHF up to 60% for sputter deposited layer on a substrate for at least 1hr at a temperature of 150°C. This was the first kind of study which showed the enhancement of CRH for Fe-Cr-Al material. Jo *et al.,* [66] investigated new coating material known accident tolerant fuel (ATF) treated as a cladding and Cr and Fe-Cr-Al coating on zirconium alloys substrate to determine the potential effect in Critical Heat Flux (CHF). The characterized various surface parameters such as surface roughness, surface contact angle and morphology which directly affect the CHF in pool boiling phenomenon. They used spray coating technology for preparation of heater surface. They found influence on CHF due to sub-millimeter cladding thickness of ATF. Their investigation showed that after determining the thermo physical properties of ATF it can be used as cladding or coating material for all types of boiling phenomenon.

Moon *et al.,* [67] performed experiments for determination the effect on droplet dynamics wetting for different micro structured surfaces including Micro sized pillars (MP), Micro holes (MH), Nano size wires on pillars (MN-P) and Nano size holes (MN-H). They found Wenzel or mixed as well as Cassie-Baxter wetting behavior on MH, MN-P, MN-H and MP surface respectively. They observed surface energy enhanced for Nano wire. Critical Heat Flux (CHF) increased for the tested surface in the order of MH < Bare < MN-H < MP < MN-P. Lowest value of CHF received at micro hole (MH) surface due to activation of extremely nucleation site on the surface. The highest value of CHF occurs at MN-P surface because of capillary pressure gradient inducted and due to presence pf nanowire structure surface energy increased which enhanced the liquid supply on heater surface and delay the CHF. Sarafraz *et al.,* [68] conducted experiments on functionalized and non-functionalized carbon nano tube under pool boiling heat transfer phenomenon. Result showed that functionalized carbon Nano tube (FCNT) enhanced heat transfer coefficient and critical heat flux and could be a promising option for pool boiling condition. The major outcome was effect of contact angle characteristics on heater surfaces. It has been found that contact angle for FCNT Nano particle slightly decreased and it showed the hydrophilic surface characteristics. On the other hand, CNT Nano particle showed the hydrophobic characteristics. Therefore, the heat transfer coefficient and critical heat flux increased for hydrophilic surface due to surface capillary wicking action.

Yang *et al.,* [69] presented a novel Plasma Immersion Ion Implantation (PIII) method to produce Black Silicon (BSi) which gained attention due to its Nanostructure structure. The surface characterization showed the roughness and contact angle of the BSi surface become larger than that of silicon, which create more nucleation sites. Although, due to higher possibility of bubble coalescence, increased diameter of bubble departure and decreased the bubble frequency. Using this approach critical heat flux enhanced as compared to plain silicon surface. Doretti *et al.,* [70] carried out experimental measurement in flow boiling condition by taking R134a as a working fluid on a carbon/carbon surface. The objective of this study was to explore the capabilities of carbon/carbon surface such as low density and high thermal conductivity as compared with copper in boiling process with the refrigerants. They proposed a new model that can validate the estimation of the heat transfer coefficient for refrigerant on carbon /carbon surface. They also observed the wettability characteristics on carbon/carbon surface which can be linked in to heat transfer performance. HangJin Jo *et al.,* [71] performed experimental investigation on mixed hydrophobic-hydrophilic surface for single bubble dynamics with distilled water as a working fluid. They consider the hydrophobic dot diameters in the range from 50 micrometer to 6 mm. They found that the homogeneity could affect the interfacial bubble dynamics which caused pinning phenomenon. During this the contact angle of bubble decreased and as the contact angle decreased to receding contact angle of bare hydrophilic surface, the triple line moves outwards which is known as slip behavior. After that point the nucleate bubble elongated vertically and started to depart from the surface. By using the bubble dynamics behavior on heterogeneously patterned surface the boiling heat transfer coefficient increased 2.1 times as compared to bare hydrophilic surface.

Yim *et al.,* [72] explained the influence of surface wettability on heat transfer performance in nucleate pool boiling by coating the layer of titanium oxide (TiO_2) on a cylindrical plain aluminum 6061 surface and make it hydrophilic. The result explored that nucleate pool boiling performance enhanced up to 64.1% of TiO_2 coated surface as compared to plain surface. These surfaces also depict the mechanism for more nucleation site and bubble departure frequency on TiO_2 coated surface.

Li *et al.,* [73] investigated the effect of wetting surface and their wicking phenomenon in boiling heat transfer during the quenching process. They fabricate both hydrophilic and super hydrophilic surface using the deposition of nanoparticle and chemical etching technique respectively on stainless steel spheres. They found that while performing the quenching operation, the transitional heat flux (THF), which separate the transitional film boiling sub regime and nucleate boiling sub regime was significantly enhanced by enhancing the surface wickability. Maximum enhancement of about 656% in THF was found for wickable surface as compared with bare non treated surface. A new linear correlation between enhancement ratio of THF and modified Weber number has been proposed based on hydrodynamic instability model.

Pialago *et al.,* [74] conducted experiments for enhancement in capillary assisted water evaporation in semi-flooded evaporator they used ternary external composite surface coating of copper-carbon nanotube-titanium dioxide on copper tube. The composite coating made by electrostatic spraying and combining by sintering in electric furnace using ball milled composite powder. The characterization showed that ternary coating i.e. Cu-CNT-TiO_2 composites coating had a higher hydrophilic surface as compared the only pure copper coated surface. Figure 2 showed the apparent static contact angles between both the surfaces. They found enhancement in evaporation heat transfer coefficient in the ratio of 3.15, as compared to pure copper coated surface to ternary composite coated surface.

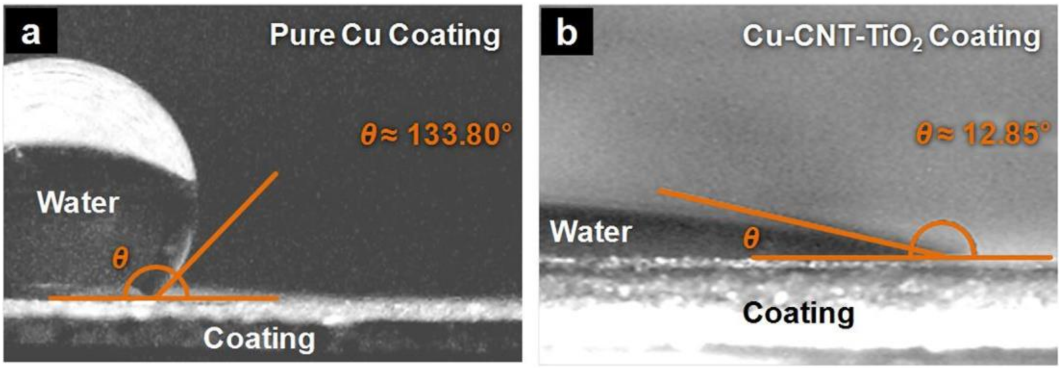

Fig. 2. Apparent static contact angles (h) between water droplets and coating surfaces: (a) pure Cu coating and (b) Cu-CNT-TiO2 coating [71]

3. Conclusion and Future Scope

The outcome of literature review showed that enhancement of heat transfer coefficient and critical heat flux are necessary requirements for any device used in boiling condition. In future, experiments will perform for analysis of data. Some of the following point has been found for future studies.

i. By conducting the extensive literature review it has been found that more research has been done on coating of single layer of material but less work on composite coating in boiling phenomenon.

ii. It has been found that appropriate technique for fabrication of coating on all kind of surface for boiling heat transfer enhancement required further attention towards the development of surface modification.
iii. It has been found that most of the researches done for pool boiling condition on porous or coated surface less work have been performed on flow boiling condition.
iv. For prediction of boiling phenomenon most of researches have been focused on experimental investigation less work has been done on numerical or mathematical modelling for prediction of boiling phenomenon.
v. It has been found from the literature review that complete set of experimental data on critical heat flux for different types of fluid and surface and comprehensible quantification of various surface parameters i.e. porosity and the diameter of porous particle is still not researched yet.

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