CHAPTER 2

State of the Art

2.1. Historical background

Boiling is a common phenomenon which is occurs in everyday life, but still its mechanism of heat transfer is not fully understood. It is considered as the most favourable mode of efficient cooling, due to higher heat transfer coefficient. Boiling phenomenon is a complex process which is associated with the solid surface and liquid interface interaction. Modern research was initiated by Nukiyama [1], and Drew and Muller [2] who purposed a typical boiling curve, which is drawn between the heat flux and wall superheat at atmospheric pressure. It gives the first insight on, how surface temperature varies with the increase of the heat flux on a plane surface. Since then, large number of researchers studied the effect of various design parameters in pool boiling heat transfer performances. Modifying the heating surface condition is the one of the most effective approach to enhance the boiling heat transfer rate, because, it is directly linked with the active nucleation sites density distribution on the heating surface due to which trend of boiling curve can be shift remarkably [27]. However, surface modification effects, have been investigated in many ways (mathematically, numerically, and experimentally) since the last six decades to understand the boiling heat transfer performance and its enhancement mechanism.

Corty and Foust [28] first studied the surface roughness and wetting effect experimentally in a controlled environment and concluded that both parameters and contamination have influence on the boiling coefficients and on the wall superheat temperature. In a different study, Berenson [29], examined the surface finish effect on copper using pentane as working fluid and revealed HTC on rougher surface is higher. Clark et al. [30] studied the active nucleation sites on vertical surfaces of pure zinc and an aluminium alloy at atmospheric pressure using high magnification photographs. They observed, the pits (diameter between 7.62 µm and 76.6 µm) and scratches act as an active site during the experiment. Griffith and Wallis [31], Bankoff [32, 33] theoretically study the effect of cavities and scratches on the boiling heat transfer performance. Effect of surface roughness, artificial cavity, and porous layer was studied by Marto and Rohsenow [32] on a stainless steel disk in a sodium metal. It can be concluded from their investigation that surface roughness and cavity size significantly affect the ONB, boiling curve, and wall superheat. Moreover, re-entrant cavity looks more promising in comparison with other structures.

Considering surface modifications in empirical correlation based on were first proposed by Rohsenow [33]. He used different constant to express different surface, materials and a liquid combination. Later, Mikic and Rosenow [34] purposed a new correlation which also included the effect of surface characteristics on wall superheat (ΔT) for variable heat flux conditions. Cooper [35] is first who analysed surface effect quantitatively and gave a correlation of pool boiling which includes the parameter: surface roughness. Near the end of 20th century Pioro [36] evaluated the constant value of Rohsenow correlation for thirteen surface-liquid combination. Also, he reviewed the literatures to evaluate the prediction interval of Rohsenow correlation for other surface-liquids combination.

Nanofluids, which are suspensions of nanoparticles in base fluids, have attracted considerable interest from researchers in the early 21st century due to their remarkable effect on the CHF [37,38]. The significant enhancement in CHF raised the hope that nanofluids could replace conventional base fluids such as water and refrigerants in various applications. However, this hope was soon challenged by Kim et al. [39], who experimentally demonstrated that the CHF enhancement in nanofluids was mainly attributed to the formation of a nanoparticle deposition layer on the heated surface during boiling. This layer improved the surface wettability, which is a key factor for the CHF enhancement [39-41]. Since then, researchers have shifted their focus to surface modification and explored various ways to improve the boiling performance by altering the surface characteristics such as wettability and morphology.

In the recent decades with rapid growth in micro-fabrication techniques and advanced surface engineering technology, many research groups of peoples have fabricated various type of microstructures (like micro-cavity, micro-pillar, and micro porous), and nanostructures (such as nanowire, nano-cavity, nanoporous coatings) on plain surfaces to examine the boiling heat transfer performance, *particularly in the nucleate boiling regime*. Usually, the boiling performance is evaluated by three main parameters: boiling heat transfer coefficient (BHTC), onset of nucleate boiling (ONB) temperature and critical heat flux (CHF) [24]. The BHTC relates to the measurement of system efficiency and CHF with the system safety. Beyond the CHF point boiling crisis may occurs due to sudden decrease in HTC and unexpected rise in surface temperature. The unexpected rise in temperature may be a cause for the thermal failure of a system [42]. Many review article on the micro/nano structured surfaces, show that surfaces having micro or nano structures, improve the boiling heat transfer characteristics such as heat transfer coefficient, ONB, and CHF [21, 22, 43]. Bhavnani et al. [44] has presented the state-of-the-art review on boiling augmentation and its scope for different application. Kumar et al. [18] has divided surface modification into different categories like nanowire, nanoporous etc. and reviewed their effects on boiling heat transfer performance. In the recent past several types of micro and nano structures has been fabricated for the possibility to improve the pool boiling characteristics. This chapter presents a comprehensive review on various type of micro/nano structures fabrication techniques, and their effects on heat transfer performance and its mechanism, in nucleate boiling regime.

2.2. Fabrication Methods (micro/nano textured surfaces)

Creating a uniform and stable micro/nano textured surface is a crucial and primary step in enhancement of boiling heat transfer through micro/nano textured surfaces. Researchers have used various method/fabrication techniques to prepare the different textured surfaces, which can be classified into four main categories: Micromachining and surface polishing, physical coating, chemical processing, and MEMS/NEMS. Each category includes several associated methods, as shown in the block diagram in Fig. 2.1.

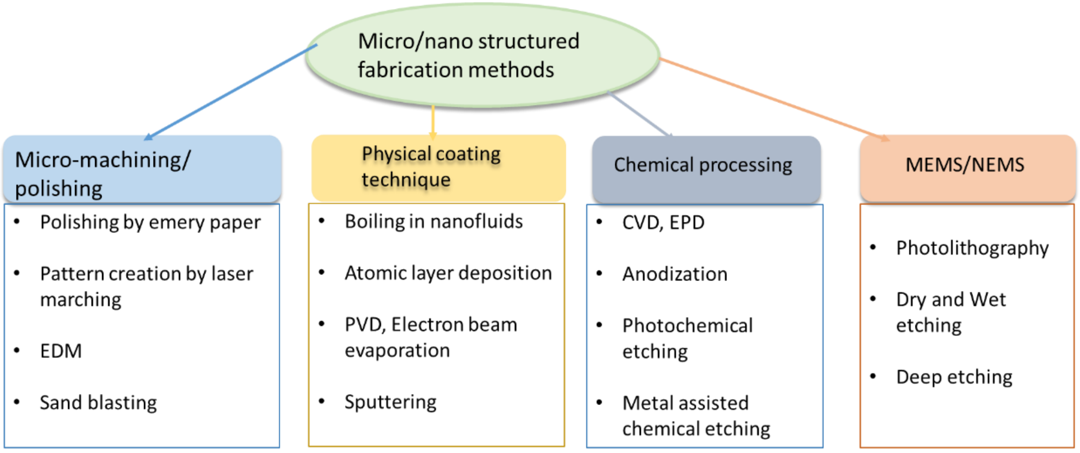

Fig. 2.1. Categorization of micro/nano textured preparation methods and its associated techniques.

2.2.1. Micromaching and Surface polishing

Machining is a very old fabrication method that can be applied to not only metal, but also polymer, wood, ceramics and composite materials. With the recent development of advanced technologies such as laser machining, 3D printing, and micro machining, it is possible to fabricate complex shapes of geometry (such as cavities and grooves) precisely with approximate sizes ranging from tens of microns to few millimetres [21]. Surface polishing using different grades of emery (sand) paper and sand blasting are also old and very useful methods to produce rough surfaces.

Benjamin and Balakrishnan [45] created rough surfaces with a roughness (R_a) range of 0.2-1.17 mm by polishing steel and aluminium with various grades of sand papers. They performed boiling experiments with different fluids, including water, and found that the enhancement in boiling heat transfer was mainly attributed to the increased nucleation sites due to the change in surface roughness. Rough steel surfaces with root mean square (RMS) roughness of 15.1 nm and 60.9 nm were produced by Kang [46] using different sand papers, and boiling experiments were conducted. The results were compared with a smooth surface, and a noticeable effect of roughness on nucleate boiling heat transfer (NBHT) was reported. Chen et al. [47] created rectangular grooved structured of size 100 micron on a Cu surface using CNC controlled precision milling machine and correlated the NBHT enhancement with the capillary effect. Jones et al. [48] conducted visualization study on different rough surfaces (R_a range 0.038-10.0 µm) which was fabricated with the help of EDM and polishing technique. Das et al. [49] prepared tunnel (100-micron width) types of structures on copper surfaces by wire EDM machining. They conducted pool boiling experiments with water and gave the hypothesis that tunnel structures can work as re-entrant cavities. Other type of microstructures such as micro indentation were created by Kandlikar [50] on the Cu surface. He investigated the boiling heat transfer on plain and structured surfaces and reported that nucleation occurs at the sharp corner of the fin base, on the structured surface and vapour and liquid pathways are separately formed, which enhanced the NBHT. Kim et al. [20] also examined the effect of surface roughness on NBHT and CHF on copper with different roughness in a pool of saturated water. The surface was prepared by polishing with different sand papers (Girt size: 80, 220, 600, 2000), and a mixture of silica oxide & alumina nanoparticles. They confirmed that surface roughness improves the number of nucleation sites and enhanced the NBHT.

2.2.2. Physical coating methods

To enhance boiling heat transfer, various coating techniques tried by several researcher in recent decades. Coating techniques allow surface modification without deformation and can be applied to different materials, such as metal oxides, nanoparticles, SiO_2, TiO_2, CNTs, and graphene oxide. Some of the coating methods include vapour deposition, atomic layer deposition, spray coating, nanofluid boiling, epoxy bonding, and calcination.

2.2.2.1. Boiling in nanofluids

Vassalo et al. [51] were probably the first group who observed a coating layer of silica nanoparticles on heating wire at the end of boiling experiments with silica water nanofluids. Few year later Kim et al. [52] demonstrated a significant improvement in CHF on a similar nanoparticles-coated heating wire. Afterwards, this technique has been widely adopted by many authors [53-56] to investigate the NBHT enhancement with different nanoparticles. The surface coated by this technique has stability issue and performance degrades with the time of operation.

The surfaces of nickel and stainless steel were coated with thin film silica nanoparticles by Forrest et al. [57]. They immersed the metal substrates into solutions containing silica nanoparticles and rinsed them with pure water. Then, they calcined the substrates at a temperature of approximately 500° C to form bi-layered thin film on the surface. Parker et al. [58] attached a porous graphite surface on a copper surface to investigate the BHT in FC-72 dielectric liquid.

2.2.2.2. Spray coatings

In spray coating particles are deposited when the highly accelerated coating material particles impact the surface at a very high velocity. Due to high impact, particles experience plastic deformation and thereby properly stick on the surface of the substrate. Before spraying, the coating materials may be pre-heated or melted. For example, Dewangan et al. [59] used flame spraying to coat copper particles on copper tubes and investigated pool boiling performances in refrigerants. Pialago et al. [60] applied cold spray coating to produce a coating of carbon nanotubes (CNTs)-Cu particles of various combinations on copper substrates. They explored the boiling heat transfer augmentation of composite coating in saturated R134a. Hsieh et al. [61] also conducted pool boiling experiments and achieved BHT enhancement up to 1.5-2.5 times on various coated surfaces which were immersed in saturated R -134a and R -407c. Coatings of porous aluminium were employed by flame spraying, whereas copper and molybdenum were employed by plasma spraying. Using supersonic blowing methods, Sahu et al. [62] coated polymer nanofibers on copper substrates. In this method, air is blown from the nozzle at supersonic velocity, and polyacrylonitrile (PAN) solution in DMF (dimethylformamide) is pumped from the gauge needle. The electric potential difference between the nozzle and the needle attracts the polymer particles toward the nozzle, which are deposited on the substrates. In another study [63], they investigated the effect of nanofiber coatings on pool boiling heat transfer in a dielectric liquid HFE-7300. They achieved significant enhancements in heat transfer coefficients and up to 33% increment in CHF compared to the bare surface. An et al. [64] also used a supersonic spraying technique to develop graphene oxide-coated surfaces and obtained significant improvement in CHF and boiling heat transfer coefficient relative to the bare surface. The improved surface wettability and increased number of nucleation sites of the graphene oxide-coated surfaces were attributed to the enhanced BHT performances.

2.2.2.3. Bonding with epoxy

In this method, coating of micro/nano-sized particles on a substrate is applied using an epoxy adhesive. It is an old and popular method of micro/nano textured surface fabrication, in which diamond particles are frequently applied due to superior thermal conductivity. The coated particles change the surface morphology and develop porous structures which increase the active nucleation sites on the plain surface [65]. Vemuri and Kim [66] conducted an experimental investigation of pool boiling heat transfer on a plane and nano-porous surface in saturated dielectric liquid (FC-72) at atmospheric pressure. The nano-porous surface of aluminium oxide (thickness ≈70 µm) is fixed on the plane surface by epoxy Omegabond OS 200. They reported a nearly 30% decrement in ONB temperature on the nano-porous surface over a plane surface at the similar heat flux condition. The effect of particle size on pool boiling heat transfer performance was studied by Chang and You [67]. They used diamond particles of different sizes (2-70 µm) and reported that the surface coated with 20 µm particle size gives the maximum augmentation in boiling heat transfer. In other experiments, Kim et al. [68] studied the coating effect on bubble dynamics on a wire heater, where diamond particle coating was employed. They realized that the diamond-coated wire heater produce comparatively smaller bubbles with higher frequency. But the chemical used for the binder has stability issues, particularly at higher heat flux, due to which this method is rarely used in modern research work.

2.2.3. Vapour deposition techniques

Vapour deposition technique is very popular and widely used for the fabrication of different types of engineered nanostructured surfaces. It can be divided into two main categories: physical vapour deposition (PVD) and chemical vapour deposition (CVD), and there are multiple variants within each category. PVD multi variants are electron beam physical vapour deposition (EBPVD), ion beam assisted deposition (IBAD), sputtering, etc. Like PVD, CVD also has many variants, such as LPCVD, PECVD, MOCVD, etc. Both methods are very versatile and have a wide range of applications. In the PVD method, the coating materials are evaporated and then condensed to form a thin coating layer over a substrate. Coating materials may be metals or ceramics, for example, carbides, oxides, and nitrides. All PVD processes performed under vacuum and are considered eco-friendly processes in comparison to chemical and galvanic surface treatment methods [69].

Chemical vapour deposition is a fabrication technique that involves coating a substrate usually a semiconductor with a thin film of various gaseous precursors. The precursors may consist of one or more components and they react with or decompose on the substrate surface at high pressure and temperature in an inert atmosphere. The flowing gas also removes the by-products from the reactor chamber. CVD is a very versatile method and is widely used for depositing materials such as silicon, silicon dioxide, silicon nitride, silicon–germanium, titanium nitride, tungsten, carbon-based ENM, and many others on semiconductor substrates [70], which are used in many applications like sensors, electronic device, solar cell, etc.

In the recent decade, many researchers have used both the methods (PVD/CVD) for the fabrication of micro/nano structured surfaces on various substrates and studied the pool boiling performances. Using electron beam physical vapour deposition under a vacuum pressure of 2×10^{-5} mbar, Das et al. [71] deposited SiO_2 nanoparticles of thicknesses 100 nm, 200 nm, and 300 nm over a Cu substrate. The coating enhanced the boiling heat transfer performance by creating artificial cavities, increasing wettability, and roughening the surface. The highest HTC enhancement of 58% was achieved with the 300 nm coating. In another study, Das et al. [72] created a crystalline TiO_2 thin film over a copper substrate of diameter size 9 mm. The thin film was deposited by EBPVD method at a vacuum pressure of 10^{-5} mbar. They reported that as film thickness increases, BHTC also increases. In the nuclear industry, fuel vendors apply a protected thin coating layer of Cr or ceramics over Zr-alloy fuel cladding using cold spray and PVD technology to provide additional safety under excellent corrosion/oxidation resistance [73]. Li et al. [74] fabricated Cu nanorods by oblique-angle deposition on Cu substrate with an electron-beam evaporator at very low pressure (1.33×10^{-10} bar). The average diameter of nanorod at the tip was about 40-50 nm. The average height of nanorod and spacing between the nanorod was approximately 450 nm and 50 nm, respectively. They reported significant enhancement in HTC, and low boiling incipient temperature with early CHF. In another study, vertically oriented TiO_2 NW arrays of sizes 150 nm, 300 nm, and

450 nm were fabricated by Ray et al. [7] for examining the pool boiling performance in R134a refrigerant. They produced the nanowire arrays by glancing angle deposition (GLAD) techniques using an e-beam evaporator. Their study showed that the ONB temperature reduced for modified surface and maximum reduction was 44.8% for the length of 450 nm. The BHTC also increases with the increase of NWs length and maximum enhancement was 81.3% for 450 nm length. Enhancement was better in the low heat flux zone.

Phan et al. [75] used PECVD, MOCVD, and nanofluid boiling techniques to deposit different nanoparticles on stainless steel surfaces. They fabricated different surfaces with varying wettability and conducted pool boiling experiments to explore the effects of wettability change on bubble nucleation mechanisms and consequently, on BHTC. Ahn et al. [76] used the CVD technique to deposit a uniform layer of vertically aligned multiwall CNTs of two distinct heights of 9 and 25 µm on a smooth silicon wafer. They conducted pool boiling experiments in PF-5060 liquid and revealed that heat flux is marginally affected by the height of MWCNTs, in the nucleate boiling regime, whereas in the film boiling regime, it is strongly sensitive to the MWCNTs of 25 µm height. Seo et al. [77] deposited a thin layer of graphene, single-walled carbon nanotubes (SWCNT) and a hybrid of graphene and SWCNT on indium tin oxide (ITO) to examine the pool boiling performance in FC-72. Experimental results show the enhancement in CHF and HTC of the hybrid surface is superior to the other two surfaces. This improvement can be co-related with the material properties called thermal effusivity of the surface. Dharmendra et al. [78] compared the pool boiling performance of a plane copper, sand-blasted, and CNT-deposited surface with demineralized water at 10° subcooling temperature. The CNTs were deposited over a clean copper and diamond-coated surface by the hot filament chemical vapour deposition (HFCVD) method. They observed that ONB on both surfaces occurs earlier than the plane surface, and boiling curve shifts towards the left because of the hydrophobic nature and improved relative roughness of CNTs coated surface and the sand-blasted surface, respectively. The maximum enhancement in BHTC reported for

CNT-deposited surfaces was 80%, whereas it was only 13 % for sand-blasted surfaces. Sadaghiani et al**.** [25] created a three-dimensional (3D) foamlike graphene structure over a Si surface to analyse the influence of pore size on boiling heat transfer and the underlying mechanisms. They prepared four samples with distinct coating thicknesses of 8, 12, 29, and 55 nm using the CVD technique. Their results revealed that there exists an optimal graphene thickness up to which the boiling heat transfer performance enhances. In a separate study, Ahmadi et al. [79] examined the effect of foam thickness and graphene coating on a sintered porous copper surface. They performed pool boiling experiments on three different samples: bare Cu, sintered Cu, and graphene-coated sintered porous copper surfaces. According to reported results, a thinner (0.5 mm) graphene-coated porous Cu surface gives the best HTC (161% enhancement compared to the bare surface) among the others.

2.2.4. Chemical/Electrochemical methods

2.2.4.1. Electrochemical deposition (ECD)

Electrochemical deposition is a versatile and old technique for material synthesis, which involves applying a voltage across a conductive surface immersed in an electrolyte containing the desired ions of the materials which need to deposit. The applied potential determines the charge transfer reaction and the film growth over a substrate. The applied voltage can be fine-tuned and rapidly switched, which is responsible for precise control over the material's microstructure and properties. The main challenge in electrodeposition is to optimize the process parameters for both the quality of the material and the economic viability of the technique.

Shin and Liu [80] produced typical 3-D dendritic foam structures of copper on a copper substrate in an electrolyte of 0.4M $CuSO_4$ and 1.5M H_2SO_4 by electrochemical deposition for 20 s. Then they varied the concentration of $CuSO_4$ (0.2M, 0.6M, and 0.8M) and H_2SO_4 (0.5M-1.5M) to control the pore size and deposition thickness. They reported that both the thickness and pore size increased with the increase of copper sulphate concentration, whereas the change in sulphuric acid concentration does not affect the pore size and thickness of the 3-D foam structures. A few years later, El-Genk and Ali [81] used the same concept and fabricated different volume porosity of nano-dendrite Cu layer on a copper substrate to investigate the effect of deposition thickness and microstructures of Cu nano-dendrite layer on nucleate boiling performance in saturated dielectric liquid PF-5060. They reported that thickest (~145.6 µm) nano-dendrite copper layer performance was better than the other two layers 46.3 and 33.1 µm. In a similar study, Im et al. [82] created Cu nanowires arrayed on a thin film deposited silicon substrate with Ti, Cu, and Au metal and performed pool boiling experiments in PF-5060**.**

Yao et al. [83] fabricated copper nanowires (CuNWs) and silicon nanowires (SiNWs) to examine the effect of nanowire height on boiling heat transfer and enhancement mechanisms in a pool of water. CuNWs are directly fabricated on silicon chips by template-based electro-deposition method. Anodised alumina oxide (AAO) membranes were used as a template to form CuNWs of 200 nm diameter. Silicon nanowires were fabricated adopting metal particle-assisted electroless chemical etching in $AgNO_3$ and HF aqueous solution. They recognised that as the NW height increases density and surface cavity size increases, the resultant bubble generation is more and heat transfer enhanced. In a similar study, Shi et al. [84] also fabricated different heights of CuNWs on a polished copper substrate with the help of a PPA template by electroplating method and reported, that as NW height increases the enhancement in HTC also increases. The effect of CuNW varying diameter on pool boiling heat transfer in dielectric liquid has been studied by Kumar et al. [85]. They also synthesize CuNW on Cu substrate using a template-based electro-deposition technique. Their result indicates that as NW diameters increase, CHF and BHTC also increase and reach a maximum, & then start decreasing. The optimum value of diameter in their study was found to be ~130 nm. Wettability and micron size cavity density also improved and becomes superhydrophilic in nature. Due to the increase in micron size cavity active nucleation site density also increased which led to the significant improvement in the HTC of NWs deposited surface.

In a recent development, few of the researchers have also developed composite structures by ECM/electroplating technique and studied boiling heat transfer augmentation [86-87]. Gupta et al. [88] examined the pool boiling performance of various composite surfaces, which were made of copper sulfate pentahydrate and Titania nanoparticles by the two-step electrodeposition method. Their study on composite surfaces claimed a maximum 86% and 185%, enhancement in CHF and BHTC, respectively. Shil et al. [89] also used a similar method and fabricated superhydrophilic surfaces of Cu-Al_2O_3/Graphene coated nanocomposites. They conducted pool boiling experiments on it in distilled water and reported a maximum 122% improvement in CHF. In another study, Katarkar et al. [90] prepared composites of copper and graphene (Cu/Gr) on different pattern surfaces by a two-step electro-co-deposition technique, and showed a significant enhancement in BHTC with R-600a.

2.2.4.2. Electrophoretic deposition (EPD)

EPD is well accepted and established technique for coating various materials like polymer, ceramics, metals, composites, dyes and pigments. The development of electrophoretic coating for automotive applications started in the late 1950s, led by Dr. George E. F. Brewer and the Ford Motor Company team. The first commercial anodic automotive system was launched in 1963. Then onwards various composition and processes of EPD were recognised for many applications [91-92].

EPD is a type of electrochemical methods which is occurs between two electrode cells. In this process charged particle dispersed in a suitable liquid, move towards the oppositely charged conductive electrode (substrate which is to be coated) due to an applied (DC) electric filed. Because of continuous accumulation of charge particles a relatively compact homogeneous and thin film is developed at the oppositely charge electrode (substrate) [93].

Several studies reported nanoparticle coatings such as alumina [94], TiO_2 [95], and ZnO [96] on a surface using nanofluid. However, Kwark et al. [94] recognised very early a marginal improvement in CHF on a coated surface made by the EPD process with a very low concentration of alumina nanofluid. In a subsequent study, White et al. [97] used a higher concentrated nanofluid for dense and better deposition and investigated pool boiling heat transfer on ZnO deposited surfaces in DI water. They achieved a 200 % enhancement in HTC for a 10 minute deposition. This study work as a turning point for EPD where it was recognised as a most general tool for enhancing boiling performances. Joung and Buie [98] produced a novel hybrid surface with varying wettability. They first fabricated a superhydrophilic surface by breaking down the anodization (BDA) process, and then hydrophobic nanoparticles were coated over superhydrophilic surface by EPD to achieve high CHF and low boiling inception temperature (BIT).

Song et al. [9] used alumina nanoparticles to fabricate a nanoporous coating on a SS304 surface using EPD process. They prepared three surface by varying the concentration (0.5 %, 1%, and 2 wt. %) of alumina dispersed nanofluid and investigated pool boiling heat transfer performance with SES36 fluid. Their experimental results show that the nanoporous coated surface significantly enhances the HTC, and the maximum gain in HTC is reported for those surface which were fabricated in a 2 wt. % nanofluid concentration. The remarkable improvement in HTC is mainly due to an increase in active nucleation sites on the deposited surface. Liu et al. [15] developed composite micro/nanostructured surfaces on a copper substrate. First, microstructures were created on a polished copper surface by femtosecond laser processing, and then the processed surface was further modified by EPD of Cu nanoparticles. The experimental results showed that, all modified surfaces had a lower wall superheat and significant higher boiling HTC, compared to the plain surface. Because, modified surfaces had more heat transfer area and more nucleation sites. The best composite micro/nanostructured surface improved CHF by over 60% and HTC by over 300% if compared with a polished one. Rahimian et al. [99] reported decrease in HTC, and an increase in CHF with increase in coating thickness up to 90 nm. Their group created hydrophilic thin film coating using anodic EPD process in SiO_2 nanofluids and examined BHT and CHF in water. Significant enhancement in CHF, (58% for nanocoated and 60% for sintered surface) was reported for both surfaces. In a different study, Cao et al. [16] investigated boiling heat transfer and bubble dynamics on a Cu-Zn alloy nanoparticles coated surface in HFE-7200 liquid. They realised that the reduction in boiling incipient temperature (BIT) and enhancement in HTC was remarkable, but the improvement in CHF was negligible. The enhancement in HTC was mainly due to an increase in active nucleation sites, decrease in bubble departure diameter, and increase in bubble frequency.

2.2.5. MEMS/NEMS Technologies

Micro electromechanical systems or nanoelectromechanical systems (MEMS/NEMS) have a wide range of applications in various fields, such as microfluidics, biotechnology, medicine, electronics, microchips, and sensor development. They enable the fabrication of small structures with sizes ranging from a few nanometres to 100 microns on different materials, such as silicon, polymers, metals, and ceramics. MEMS/NEMS techniques include chemical etching, lithography, wafer bonding, and thin film deposition for micro/nano patterning on silicon chips. In recent years, MEMS/NEMS technologies become very popular for forming different patterns (micro or nano size) on semiconductor and microelectronic devices to explore the scope of nucleate boiling heat transfer enhancement.

Near the beginning of the 21st century, Honda et al. [100] used dry etching to create micro-pin-fin structures on silicon wafers. The micro-pin-fins (MPFs) are square in shape with cross-sections of 50×60 μm and roughness is in the submicron range. Pool boiling experiments on these surfaces were conducted by Wei and Honda [101] in FC-72 liquid by varying the size and arrangement of micro-pin fins. There was a noticeable enhancement in

HTC, and CHF was reported for the structured surface. Using the same process, Cao et al. [102] fabricated two different configurations, staggered pin fins and aligned pin fins with empty areas. Both surfaces were further modified by depositing FeMn oxide nanoparticles to study the pool boiling heat transfer in FC-72 liquid. Their experimental results showed that HTC was significantly increased on MPF-structured surfaces. To understand the enhancement mechanism, bubble behaviour was captured by a high-speed camera. The bubbles had smaller departure diameters and higher departure frequencies on the micro-pin-fin-structured surfaces with and without nanoparticle deposition at low and moderate heat fluxes. At higher heat flux near the CHF, a vapour blanket formed on the smooth surface, while flame-like bubble clusters appeared on the MPF surfaces, which could break and leave the surface. In a similar study, Zhang et al. [103] studied the pitch and different configuration effects of MPFs in FC-72 at subcooling 15, 25, and 35K. They observed that a change in fin configuration gives much better enhancement than a change in fin pitch. The liquid flow in the gap between MPF is driven by a strong capillary pumping force, which enhances liquid replenishment and prevents the drying out of the heating surface. A higher area ratio implies a smaller gap and a stronger capillary pumping effect. However, it also increases the flow resistance and impedes liquid replenishment, which reduces the CHF enhancement effect. Liu et al. [104] created a cylindrical micro cavity on each MPF top surface, and prepared five different surfaces by varying the cavity number (1, 4, 9, 16, and 25). The MPF with cylindrical micro-cavity, known as composite micro-structured. All surfaces were prepare using deep etching technology. They studied the effect of cavity number on pool boiling performance in HFE-7100 Liquid. Experimental results showed that in the low heat flux region, HTC increases with cavity number; however, throughout the nucleate boiling region, composite structures with 16 cavities perform among the best. In another study, Liu et al. [105] modified micro–pin–fin (MPF) by creating nano structures at different positions of micro-pin-fins. Nanostructures formed at the top corner of MPF, at the top edge of MPF, and on micro-nano composite surfaces with nano forest at the top and bottom of MPF. All MPF surfaces are made of phosphorous-doped silicon of the same size using the normal etching technique, whereas nanostructures form on MPF at different positions using deep etching technology. They analysed boiling heat transfer in FC-72 liquid. The highest HTC was observed for MPF-top edge nanostructure surfaces, whereas micro-nano composite surfaces with nano-forests at the top and bottom have the lowest wall superheat at ONB. Kim et al. [106] prepared hierarchical micro-nano hybrids structured in two-step silicon etching for boiling heat transfer enhancement. They used deep reactive ion etching (DRIE) to create microstructures on Si wafers and then immersed the microstructures into 0.02 M $AgNO_3$ and 5 M HF solutions to form Si nanowires. Yao et al. [107] created a microchannel on a silicon nanowire and examined pool boiling performances with water. Dong et al. [108] investigated the effect of micro and nano-sized structures on HTC, bubble nucleation, and departure characteristics in ethanol. They used dry etching and wet etching for fabricating micro-pillars, micro-cavities, nanowires, and nano-cavities on a silicon wafer.

2.3. Wettability effects on boiling heat transfer and bubble dynamics

After the extensive literature survey, it was realized that micro/nano structures alter surface wettability and morphology, which affects boiling performance and bubble dynamics. Wettability is a liquid's ability to spread on a solid surface, as measured by the contact angle formed by a liquid droplet at the solid-liquid interface. Many researchers have demonstrated that wettability affects nucleation site densities, bubble growth, and departure frequency. For example, Wang and Dhir [109] discovered that higher wettability results in a lower fraction of nucleation cavities, whereas Kolev [110] concluded that contact angle is most effective factor which influences the nucleation site density and heat transfer.

Li et al. [74] investigated the effect of surface roughness on wettability by using nanorod surfaces with different roughness levels. They found that increased surface roughness enhanced wettability, which in turn increased nucleation site density and bubble departure frequency while decreasing bubble departure diameter. Betz et al. [24] created surfaces that were either superhydrophobic or superhydrophilic and observed that lower wettability caused earlier nucleation and shifted the boiling curve to the left. Similarly, Bourdon et al. [111] compared surfaces with different wettability but similar roughness and found that hydrophobic surfaces had earlier ONB and higher heat flux than hydrophilic surfaces. For hydrophobic graphene-coated surfaces, Sadaghiani et al. [25] showed that as the contact angle increased, bubble departure diameter decreased and departure frequency increased, which led to a higher heat transfer coefficient. In a recent study, pool boiling heat transfer and bubble dynamics behaviour on copper foam with modified wettability in DI water were examined by Shi et al. [112]. Their results showed that in the low heat flux region ($q'' < 0.2$ MW/m^2), copper foam with superhydrophobic surface heat transfer performance was better, while in the medium to high heat flux region ($q'' > 0.2$ MW/m^2), superhydrophilic copper foam performance was superior. With the help of bubble visualisation, they concluded that in the overall region of heat flux, bubbles easily leave the superhydrophilic copper foam surface.

2.4. Summary and research gap

The summary points of the state-of-the-art review are presented below: -

- Nucleate boiling is the most effective and efficient mode of cooling for generating high heat flux devices where extension of the heat transfer area is not an option. However, this phenomenon is very complex due to the presence of various interlinked parameters that affect the boiling heat transfer significantly.
- Some of the important parameters that affect the boiling heat transfer phenomenon are: heating surface shape and size, orientation of the surface, type of micro/nano structures, surface roughness, and morphology of the heating surface. Liquid properties like surface tension, latent heat of vaporization, thermal conductivity, and

specific heat capacity. Solid and liquid interface properties such as wettability, adsorption, etc.

- In the existing literature, most studies have focused either on copper or silicon surfaces. Because copper uses in various engineering applications, such as: condenser tubes, electronics circuit boards (PCBs), electronic chip cooling, immersion heating, and chemical processing industries. Whereas silicon widely used in electronic chip and semiconductor industries.
- There are several techniques that have been used by various researchers, such as metal assisted chemical etching (MaCE), atomic layer deposition, physical vapour deposition, chemical vapour deposition, pulse laser deposition, electroless etching, electrophoretic deposition, sputtering, photolithography, boiling in nanofluids, etc. But some of the techniques require high energy, a skilled operator, a high initial cost, and safety precautions, because of higher temperatures, complex controlling and monitoring parameters, a longer fabrication time, and hazardous chemical mediums. On the other hand, methods like boiling in nanofluid, dipping in nanofluid has stability issues. Binding with epoxy has the stability issue of a chemical binder at higher heat fluxes. MEMS/NEMS techniques are limited to semiconductor materials like Si, Si wafers, etc.
- As per literature, electrophoretic deposition (EPD) offers several benefits, such as high material efficiency, low energy consumption, easy application over complex shapes, minimal waste generation, a modest capital cost, and easy scalability over other methods. Using this method, thickness can be produced from 1 -100 µm by adjusting voltage, solution concentration, and coating duration over a conductive material. EPD requires simple apparatus and has the ability to produce a good range of uniform coatings on complex geometries as well.

- Addition to the higher boiling heat transfer performance, chemical resistance and water repellent are prime requirements of modern devices. Therefore, a hydrophobic surface with micro/nano structures may meet these requirements.
- It has been observed that very less literature is available related to the boiling heat transfer on a hydrophobic surface. Also, hydrophobic surface performs better within the low heat flux region, and poorly in the medium to high heat flux region [24, 9, 111, 11]. Therefore, more effort and research are required to develop a hydrophobic surface that can also perform well in the medium to high heat flux range.
- According to literature, oxide micro/nano coatings are more stable than metal nanowires, metal porous coatings, and CNTs. However, the boiling heat transfer performance of these oxide coatings is pitiful.
- The topic of composite coating and its effects on boiling performance is relatively new and less investigated. Most researchers have considered either hydrophilic [88] or superhydrophilic [89] nanocomposite coatings. To the best of the authors' knowledge, the exploration of hydrophobic nanocomposite coatings and their effects on pool boiling performance are very limited.
- The effects of surface morphology, wettability, and surface roughness on boiling heat transfer has investigated by many researchers, but specific effect of coating thickness rarely pointed in literature.
- Hydrophobic surfaces exhibit specific functional properties such as anti-fogging, corrosion resistance, and low wettability [113]. Low wettability and micro/nano structured surfaces can enhance the BHTC in the low heat flux region by promoting bubble nucleation [86]. Considerably less experimental work conducted with water, compared to the refrigerants on the textured surfaces.

Therefore, an effort has made in the present study to address these issue and challenges related with the oxide composite coatings and hydrophobic surfaces with demineralized water.

2.5. Aim and objectives

The main purpose of this research is to develop composite hydrophobic coatings on copper substrates using oxide nanoparticles. These coatings are expected to enhance heat transfer performance in low to medium heat flux conditions. The electrophoretic deposition (EPD) method was selected for thin film coating, which allows easy control over film thickness and morphology by adjusting deposition time and applied voltage.

To achieve the aim work has divided into various parts which may consider as the thesis objectives. The objectives of the work are:

- Development of micro/nano textured of hydrophobic composites coatings on Cu substrate using EPD technique in binary oxide nanofluids.
- Characterization of developed composites textured using various characterization techniques such as SEM/FESEM image analysis, surface roughness measurement, contact angle measurements, and determination of coating layer thickness.
- Development of pool boiling test facility and its validation in pure water with literature as well as Rohsenow's correlation for polished Cu surface.
- Investigation of coating effects on pool boiling performance on various micro/nano composite textured surfaces in demineralised water at atmospheric pressure and nearly saturation temperature.
- Investigation of coating layer thickness, and surface morphology role in boiling heat transfer performance.
- Study of bubble visualization and estimation of few bubble dynamics parameters such as bubble departure diameter, and departure frequency using recent developed semi-analytical model.

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