Review on Passive Heat Enhancement Techniques in Pool Boiling Heat Transfer

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Abstract. Improvement of pool boiling heat transfer is deeply connected to heat enhancement methods for several years. Nevertheless, the developing progress and ideas in this field make it more intensified with the recently applied methods for enhancing the CHF and HTC. This paper gives a critical analysis and thorough investigative study in the literature discussing the passive heat enhancement techniques in the pool boiling heat transfer. Heat improvement consequence within the pool boiling mainly depends on thermo-physical features of material & the working fluid, modification of surface techniques (pin-fins treated, roughness, extended, artificial cavities pattern, micro-channels), thin-film (nano-scale, micro-scale, macro-scale surfaces, and hybrid scale), coating method, working fluid (water or refrigerants) and additives for fluids. The current status of these passive heat enhancement methods for pool boiling heat transfer with various kinds, improvement potentials, future challenges, surface modification techniques, and their potential industrial and technical applications are also examined in this work.

1. Introduction

Through the years, excessive utilization of conventional energy resources has given rise to several issues like climatic variations, global warming, and depletion of energy resources. Hence, the enhancement of energy efficiency and protection of the natural environment has become an essential factor in the world. By enhancing the performance efficiency of applications of various heat exchangers, evaporators in the refrigerators, boilers in power generation plants, the impacts of global warming can be mitigated. Notably, several heat exchangers work on the boiling heat transfer technique [1]. NPBT method has been categorized into passive, active and compound methods which are given in Table 1. The passive methods need no other external power supply; another hand, the active methods need an external power input to conduct the improvement. However, on the other hand compound methods are the fusion of both passive and active methods. Passive methods have greater fidelity when contrasted to active methods, because of the lack of moving parts, it offers energy and also materials reductions supplemental energy [2].
Table 1. Different type of enhancement methods [3]

| Passive techniques                        | Compound Enhancement                                           | Active Techniques                          |
|------------------------------------------|----------------------------------------------------------------|-------------------------------------------|
| Swirl flow devices,          |                                                                      | Mechanical aids                           |
| Rough shapes and surfaces,      |                                                                      | Magnetic                                   |
| Extended and Treated surfaces |                                                                      | Electrostatic fields                      |
| Surface tension equipments      |                                                                      | Surface vibration                          |
| Displaced enhancement devices   |                                                                      | Suction or injection                       |
| Additives for fluids and gases   |                                                                      | Fluid vibration                            |
| Enhanced surfaces, Finned surface|                                                                      | Jet impingement                           |
| surface tension devices, Coiled tubes|                                                                | liquid and/or Surface rotation           |
| Displaced enhancement devices   |                                                                      | suction or injection                      |
| Micro channel structure         | Two or More active and passive techniques that are employed together. |                                           |

2. Boiling Heat Transfer

Nucleate boiling is a competent thermal process for the heat transfer mechanism. This technique is mostly employed in technical and industrial appliances due to its capability to carry considerable heat with a very less variation of temperatures. Boiling is considered to be a liquid-to-vapour phase-shifting method.

Besides this, it is essential to understand the distinction between flow boiling and pool boiling as shown in Figure 1. Pool boiling occurs in the stationary fluid. For the pool boiling, water in jar placed over heater is example of pool boiling. Pool boiling more classified forced and natural boiling. Where flow boiling takes place in flow proceed. External source is used to lift/suck water over the inside channel or heated channel. Flow boiling classified in diabatic and adiabatic boiling.

![Figure 1. Boiling Process][4]

The benefit of the pool boiling technique is, a high heat flux can be expelled passively by keeping less superheat contrasted with the natural or applied convection without the phase change. Nevertheless, heat evacuation capability is restricted by higher limits of cooling, i.e., the CHF, where the HTC reduces significantly as the boiling management has been varied from nucleate to the film boiling. Hence, the improvement of CHF is of high importance to the researchers and technicians. Investigations on the improvement of CHF by modifying the surface in a saturated pool boiling usually considered as (1) modulated or uniform porous coatings and (2) structures of different sizes established on the heated surface. In common, CHF improvement in the saturated pool boiling is a consequence of the impacts of (a) expansive surface area (i.e., metallic foams, micro fins, and porous coatings), (b) nucleation locality density (i.e. nanostructures, microcavities, and sandblasting), (c) capillary wicking, (d) wettability (i.e., hydrophobic and hydrophilic coatings), and (e) wavelength reduction on the basis of the revised hydrodynamic stability design.

3. Surface Coating Techniques

In the present scenario, numerous technologies are being employed for decreasing the size of the material into micro and nano-thicknesses. By reducing the material to nano-size, it has led to the
development of novel and unusual performances of those materials in the areas of applications like optoelectronics, electro-optics, dielectrics, and so on. Micro and nano surface coatings methods are employed as inventive methods to enhance the performance of heat transfer to hold periodic dry out. Thin films perform a major function in the advancement and investigation of the materials with unique and novel characteristics. A thin layer of nano-micron material on the surface is termed as a thin film, where the material thickness is in the range of a few nanometers to the number of micrometers. By these thin films, a layer-by-layer (LbL) method is one of the promising techniques of fabricating multi-layer coatings, composition, accurately regulated design architecture, and nanometer thickness level. The thin films have a prominent influence on recent technology. These films can be manufactured by adopting physical and chemical depositions.

3.1. Chemical Vapor Deposition (CVD)
CVD is a method in which the substrate is exhibited to volatile antecedents, which decay and/or react on the surface of the substrate in order to form a deposit of thin films. This process is a chemical process which is employed to deliver efficient, good-performance, better-quality materials. Some of the examples are Chemical bath deposition, Electroplating technique, Sol-gel technique, etc.

![Figure 2. Diagram CVD Processes](image1)

![Figure 3. Diagram of PVD Processes](image2)

3.2. Physical Vapor Deposition (PVD)
PVD is defined as a kind of vacuum ousting methods that are employed to create coatings and thin films. In PVD, the transition of material takes place from a condensed to vapour state and later reverse to the condensed state. Some of the examples are Evaporation techniques like Ion plating, Molecular beam, Vacuum thermal, Electron beam, Laser beam, and Sputtering techniques like RF and DC sputtering.

4. Heat Enhancement Techniques
In general, improving the performance of heat transfer is accomplished by just modifying the characteristics of the surfaces like modifying the coating, roughness, wettability and contact angle (CA) or by enhancing the area of the surface for heat exchanging like enlarged surfaces, coiled tubes, tube inserts, metallic foams, micro fins and porous coatings. Other improvement methods summon for the inclusion of supplements in working fluid like nanofluids and surfactants. The above-suggested methods come under passive heat transfer enhancement methods [5]. Many published reports are present in the literature, which discusses the enhancement of boiling heat transfer employing the modification of surfaces technique. All these reports either discuss the improvement of pool boiling, accompanying with additional heat transfer methods are applied solely to the enhancement of pool boiling techniques.

4.1. Macro-finned surfaces
Manufacturing various quadrilateral or squared fins on the heating surface is a prevailing way to increase the heat transfer. Whereas the apparent advantage of this method is increasing the area of heat transfer, the main complication in this is reducing the size and spacing of the fins in the view of the best performance of cooling.
Rainey and You [6] summarized that the performance of NBHT for FC-72 with the surface thickness of 1-mm wide and 1-mm spacing fins was tremendously improved with the growing height of the fins up to approximately 5 mm, over which the tip of the fins temperature has dropped to a very low value to sustain the boiling, which decreased the ‘efficient’ surface area of boiling with no extra heat transfer improvement.

4.2. Porous mesh and Porous foam attachments

4.2.1. Porous mesh
Earlier investigations concerning to employment of porous mesh over the heat-diffusing surface point to various NBHT advantages, involving plainness, an enhanced quantity of effective nucleation localities, and the breakup of huge vapour bubbles, as well as detachment of paths of liquid and vapour for the betterment of fitter surface liquid replenishment.

They also Melendez and Reyes [7] discovered that the porous metal coating of the surface has enhanced the boiling HTC for the binary ethanol-water compounds.

4.2.2 Porous foam
In recent days, a high porosity metallic foam has captivated important consideration due to its mixed advantages of heat transfer improvement and lightweight. Yang et al. [8] discovered that welding of the copper foam over surface heating has decreased the initial superheat for H₂O. They gained the greatest improvement with a PPI of sixty and further showed that the performance efficiency of boiling was affected by PPI as well as the foam cover thickness.

Yang et al. [9] observed that with the copper foam, the orientation of varying surfaces from parallel upward-facing to the perpendicular facing has only a trivial influence on the boiling performance.

4.3. Microscale surface modification

4.3.1. Surface roughening
The growing coarseness of the heat-dissipating surface, accomplished by sandblasting, developing various small artificial cavities or by mechanical roughing, are successful methods for enhancing the performance efficiency of nucleate boiling. Figure 4 show the cross section of rough surface.

Marto and Rohsenow [10] observed that for sodium, the roughness of the surface is highly influenced by the nucleate boiling HTC as well as the boiling incipience. Jones et al. [11] observed that the improvement of the roughness of the surface was mainly reliant on fluid.

![Figure 4. Cross section of rough surface](image)

Increasing the roughness of the heat-dissipating surface, gained by sandblasting, by developing various small synthetic holes, mechanical hardening, or by chemical etching is a traditional technique for improving the nucleate boiling performance [12].

4.3.2. Micro-fin surfaces
Modeling micro-fins over the surface of heating enhances the area of heat transfer and additionally takes benefit of effected capillary discharge plus aids in segregating the ways of escaping replenishment fluid and vapor. Those supplemented advantages need a precise configuration of micro-fin design and also reducing the width of the fin, spacing, and length [13]. The surfaces of the micro-
fin are available in different types of molds, like parallel inclined fins that are aimed to catch vapor embryos, rectangular cross-sectional parallel vertical fins which are likewise known as open micro-channels, cylindrical fins as given in Figure 5.

![Diagram of parallel horizontal fins, parallel vertical fins, and cylindrical fins](image)

**Figure 5.** Models of the patterns of micro-fins employed for boiling improvement.

Mitrovic and Hartmann [14] increased a unique composition of micro-fin composing of circular fins with orbicular points using an electro-coating process. By R-141b, they demonstrated that the superheat from the wall continued fairly constant with increasing heat flux.

4.3.3. Tunnel surfaces and reentrant holes

Ramaswamy et al. [15] analysed the boiling method over the surface of microporous material for FC-72 with a design lightly similarly to [16]. Nevertheless, the surface design prepared by wafer dicing and wet etching, driving in an interrelated tiny micro-channel system.

4.4. Nano Enhancement (Nanotubes, Nanowires, Nanofibers)

4.4.1. Nanotubes

With the advantage of good mechanical and high thermal conductivity properties, carbon nanotubes (CNTs) are utilized for boiling enhancement from a decade. CNTs are very thin carbon graphite tubes with lengths ranging from 1 to 50 μm and diameters from 1 to 100 nm. Also, CNTs are said to increase the boiling performance by generating TiO2 nanotubes on substrate. In [17], authors have examined a copper surface with CNTs coating and included a layer of diamond between the copper surface and CNTs for adhesion improvement. They also obtained initiation of boiling when compared to copper surface that is bare; this is attributed to increased roughness and high hydrophobicity.

4.4.2. Nanowires

Nanoscale rod with some diameter of few nanometers, a large ratio of diameter to length is called a nanowire. Lu et al. [18] studied wafer-scale electroless etching in which saturated water pool boiling on plain surfaces of silicon coated with few thicker arrays of a silicon nanowire. An increase in CHF has been observed, resulting in enhanced liquid spread ability on the surface of the nanowire. Assuming that the vapor jet's critical Helmholtz wavelength emitting normal to the surface persisted unchanged compared to that of a bare surface, but by changing ratio of surface area covered by jets to the surface area in total, they gave the good agreement of their CHF data with hydrodynamic instability model of Liang and Mudawar [19].

4.4.3. Nanofibers

Nanofiber is one kind of fiber created of polymers having diameters smaller than 100 nm. Jun et al. [20] examined electrosprun copper nanofibers boiling performance. They estimated BHTC for ethanol and water 3-8 times those from these bare exterior but witnessed no improvement in CHF. They
It is recommended that heat transfer enhancement during nucleate boiling was the outcome of this technique’s ability to improve the average temperature of surrounding liquid bubbles, through fostering more efficient bubble growth.

4.5. Nano coating
4.5.1. Nano film coating
Many studies have suggested that the inclusion of a coating of heat transfer surfaces with few nanoscale-thickness layers to improve boiling performance by enhancing surface wettability. In [21], authors manufactured a polymer nanoparticle membrane coating on a nickel substrate employing a layer by layer technique. They obtained excellent surface adhesion along with adsorption of the following layers over the surface. Their experiments revealed more than 100% improvements in both CHF for water and NBHTC, which were associated with enhanced nucleation and improved wettability.

4.5.2 Nanoporous coating
Tang et al. [22] developed nanoporous copper surfaces possessing 50–200 nm pores upon a copper substrate, by which they managed to achieve a 63.3% decline in incipience superheat, including a 172.7% rise in nucleate BHTC for water. But a change in porosity and the three-dimensional structure were observed.

Jones et al. [23] used molecular dynamics simulations to introduce one mechanism for maintaining superheated liquid inside hydrophilic pores to water with giving a new pathway during wetting by vapor condensation inside surface textures. This idea remained to be efficient for minute spacing, notably in the nanoscale.

4.6. Nanofluid
Nanofluids hold suspended nanoparticles that have particles with volumes tinier than 100 nm. Nanofluids are stable when compared to the milli- and micro fluids, because they experience less gravitational and erosion ousting over more extended periods. The boiling of these nanofluids became an exciting topic over the last decade. Several researchers examined the deposition of nanoparticles on the heated surface. This increases wettability and surface roughness. CHF is also observed to be improved significantly. Nonetheless, questionable results were achieved for HTC.

Narayan et al. [24] described boiling of nanofluids over the aspired surface can change out to become a novel coating technique. For that, one must be able to handle the thickness of the deposition.

4.7 Structure of Micro Channel
Micro channel surface produced by chemical etching is a traditional technique for improving the nucleate boiling performance as shows in Figure 6.

![Figure 6](image)

**Figure 6.** Different structure of micro channel surface.

Hao et al. [25] applied titanium nickel which is a part of shape memory alloy to manufacture a distorted compounded structure of micro-channel, the form of which can be changed while the process of boiling; this method produced the best performance of nucleate boiling in ethanol compared to the closed as well as open micro channel-structures produced the best performance of nucleate boiling in
ethanol compared to the closed as well as open micro channel-structures. Many innovative designs have been created on the channel walls to improve the thermal efficiency of mini- and micro-channels [26].

5. Conclusion
This paper reviewed thoroughly the issues reported and discussed by other researchers about the passive heat enhancement techniques in PBHT. This paper captures the glimpses of the involved techniques used for coating, structured surfaces, nano-scale, micro-scale and macro-scale surfaces, the structure of micro-channel, and nanofluid methods. Besides this, the study also points out difficulties associated with the execution of experimentation techniques and its probable solutions. Important conclusions from this study are compiled as given below:
1. Improvement of Macroscale methods involves the application of expansive surfaces, porous foam and mesh. They render different levels of improvement of CHF as well as NBHTC, simultaneously with the exclusion of the superheat.
2. Microscale improvement methods comprise roughening of the surface and application of the open micro-channels, micro-fins, sintered and graphite particle coats, brazed coats, tunnels with re-entrant holes and structures of dendritic microporous. The main advantage of these methods is the improved density of nucleation site, that improves the NBHTC, however their influence on CHF changes.
3. Nano-scale improvement methods include surface coating with nanofibers, nanowires, nanotubes, layers of nanofilms and nanoparticle as well as nanoporous deposition by nanofluid boiling. The essential advantage of surface improvement at this range is boiling improvement by the capillary wicking inside the nano-structures.
4. In spite of the important advances in the performance of NPBHT essentially through recently formed micro-nano coating materials and methods, the technical utilization is not yet feasible. New fabrication methods are required to be scrutinized to guarantee the less cost of surfaces and nano-coatings.
5. The smooth surfaces explicate more limited heat improvement contrasted to micro-structured surfaces. Particularly, utilizing the heavily-wetted structure surface, the occasional dry out is increased, i.e. the quality of the critical vapour increases.

Nomenclature

| Symbol | Definition |
|--------|------------|
| A      | surface area (m²) |
| h      | heat transfer coefficient (W/m² K) |
| q      | heat flux(W/m²) |

Abbreviation

| Abbreviation | Description |
|--------------|-------------|
| CHF          | Critical Heat Flux |
| HTC          | Heat transfer coefficient |
| LbL          | layer-by-layer |
| NBHTC        | Nucleate boiling heat transfer coefficient |
| R            | Refrigerant |

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