CHAPTER 1

Introduction

Boiling is a rapid phase change process that mainly in engineering applications occurs at the interface of a solid surface and a liquid, when the solid surface temperature (T_w) exceeds the liquid saturation temperature. This process can produce vapour bubbles that form, grow, and detach from the solid surface, depending on the surface temperature. Boiling can be classified into two types: pool boiling and flow boiling. In pool boiling, the liquid is quiescent stage and heat transfer is driven by natural convection, and mixing induced by bubble growth and departure. In flow boiling, the liquid is forced by an external device such as a pump, and heat transfer is governed by forced convection. Boiling can also be categorized as subcooled boiling or saturated boiling, based on the bulk liquid temperature. Subcooled boiling occurs when the bulk liquid temperature is lower than the saturation temperature, while saturated boiling occurs when the bulk liquid temperature is equal to the saturation temperature.

1.1. Boiling curve and Regime of boiling

The boiling curves presented by Nukiyama [1] and Drew and Mueller [2] drawn against the heat flux verses wall superheat temperature (ΔT) are well accepted and refer as classical boiling curve. Nukiyama [1] performed the experiments on electrically heated *nichrome* wires immersed in saturated water to create temperature gradients and calculated the heat flux by measuring the supplied voltage (V) and current flow (I) accurately. The wire temperature was determined by change in electrical resistance caused by temperature variation. Initially, his arrangement was power controlled heating and few year later, Drew and Mueller [2] extended it on temperature controlled mode. A classical form of boiling curve [3] is shown in Fig. 1.1, which has four different regimes of boiling:

- Free or natural convection
- Nucleate boiling
- Transition boiling
- Film boiling

Fig. 1.1 shows the boiling curve for saturated pool boiling of water at atmospheric pressure under controlled heat flux and temperature conditions. Nukiyama [1] noticed that when wall superheat is less than the 5 °C no bubbles are generated and heat is transferred via natural convection (Fig. 1.1a).

As the wall superheat is increased beyond 5° C, vapour bubbles are generated at certain locations on the hot surface which is an indication of initial stage of nucleate boiling regime- marked as point A on Fig. 1.1. Vapour bubbles emerge from microscopic cavities or cracks on the solid surface which are popularly known as nucleation sites. When a vapour bubble gets generated at a nucleation site, it grows to a certain diameter and gets detached from the heating surface. If the excess temperature lies between the points A and B (Fig. 1.1b) where, bubbles forms and detached from the surface individually, called "isolated bubbles" region. In this region, each bubble grows and detaches from the surface without any interaction with neighbouring bubbles.

As the wall superheat increase and reaches beyond the point B the active nucleation sites increase and more bubbles are generated (Fig.1.1c) which leads to the mutual interaction between them. Due to the mutual interaction between the neighbouring bubbles vapour column and slugs are formed. During the process if heat flux further increased slightly, it attains the maximum limit, with a bubble crowding at the surface (Fig.1.1d), causes slope of the boiling curve begins to fall. The maximum value of heat flux (q''_{max}) is known as critical heat flux (CHF). The nucleate boiling regime below the CHF value is the most desirable for many industrial applications such as the advanced electronic devices [4], steam generation, and nuclear reactor design [5], because of its high heat flux at relatively lower wall superheat temperature. However, in few circumstances nucleate boiling is avoided such as in a wicked heat pipe [6].

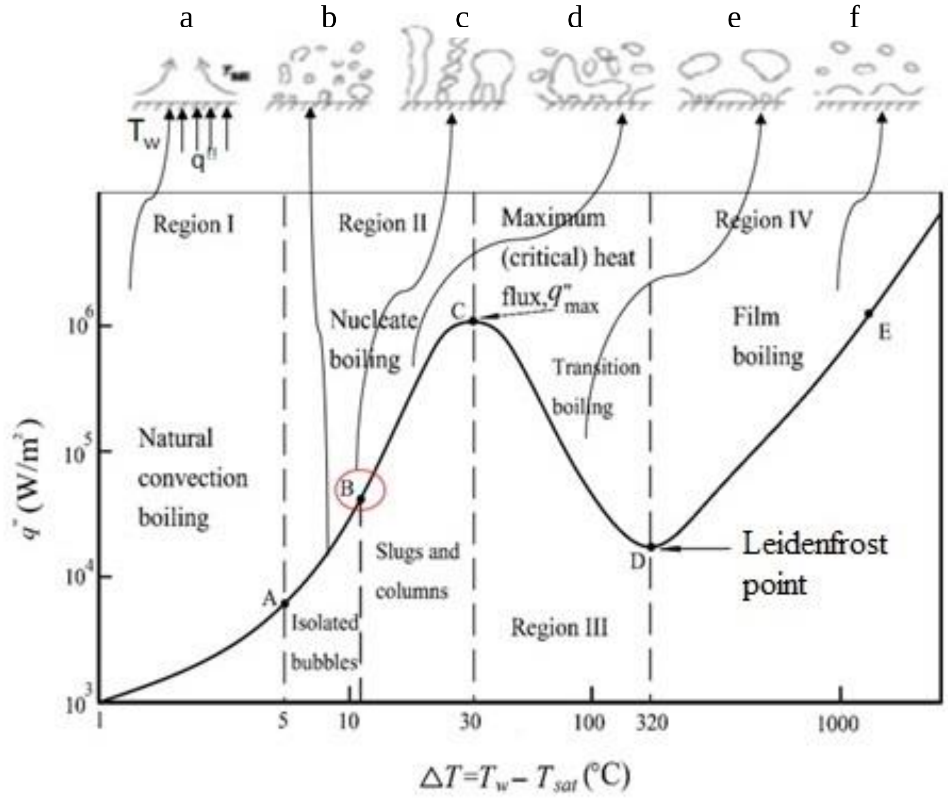

Fig 1.1. Typical pool boiling curve for saturated water at atmospheric pressure [3]

As the heat flux is increased slightly above the critical heat flux the (beyond C) boiling curve is bypassed and wall temperature suddenly jumped to the point E. In this region surface is completely covered by a vapour blanket and heat transfer occurs by conduction through vapour, subsequently heat transfer deteriorated and wall temperature increased abnormally. Sudden jump in wall superheat undesirable for most of the applications, because at that point usually temperature exceeds the melting temperature of the solid material.

The transition boiling zone is the region between point C-D on the boiling curve, where vapour film is unstable (Fig.1.1e) and the wall temperature may fluctuate rapidly. The average value of wall superheat between C and D should be considered for calculation. The heat flux is minimum when the wall superheat is high enough to form a stable vapour film, and temperature corresponding to the minimum heat flux is called the Leidenfrost temperature. Above the Leidenfrost temperature, the boiling phenomenon popularly known as film boiling (Fig.1.1f). In the film boiling regime the heat is transferred to the liquid-vapour interface by convection and mostly by radiation.

1.2. Nucleate boiling: the preferred regime

From the above discussion it is understood that the nucleate boiling regime is the most desirable for many industrial applications, as it enables high heat flux dissipation with relatively low wall superheat temperature due to rapid bubble formation and intense liquid vaporization. In this case large portion of heat energy transferred to the bulk liquid which is carried by the bubbles. Therefore, most of the researchers has focused to understand the bubble formation mechanism and scope of the heat transfer enhancement in the nucleate boiling regime. In this regime bubble nucleation, growth, and its departure mechanism, exerts major influence on the bubble dynamics and heat transfer characteristics of a system.

Various techniques have been employed to study the effect of bubble nucleation, growth, departure and augmentation of the boiling heat transfer in nucleate boiling regime. Several efforts have been made to investigate the key parameters such as fluid properties, different types of nanofluids, surface textures and roughness, which affect the boiling heat transfer performance significantly. In the past few decades, surface modification has emerged as an effective technique to significantly enhance the boiling heat transfer performances. In the recent past with the advancement and precision of manufacturing facilities, many researchers have employed different techniques to develop micro/nano structured, or porous surfaces which can be used to improve the boiling heat transfer performances.

1.3. Implication of surface modification or texturing in boiling heat transfer enhancement

Boiling heat transfer can be enhanced by developing micro/nano structures or nano coatings on the plain surfaces. A structured surface primarily affects the parameters such as nucleation sites density [7-8], bubble growth, and bubble departure frequency [9-11]. The structured surfaces also alter the surface characteristics such as porosity [9, 11-12], roughness, and wettability [13-15] which influence the boiling phenomena. One of the key advantages of using modified (Micro/Nano) textured surfaces for boiling heat transfer applications is that, they can significantly enhance the heat transfer performance without altering the fluid properties and other experimental setup accessories. However, it is to be noticed that, the use of fluid like nanofluids, the fluid property viscosity and density may increase. The increase in viscosity affects the flow phenomena and the pumping power requirement of the system, which will not a matter of concern in the case of micro/nano structured surfaces. Addition to this the nanofluid have stability and agglomeration issue in long term duration which raise a concern in any commercial applications of heat transfer enhancement.

1.4. Motivation

Due to sustainable and economic growth of many developing country, high power capacity, energy efficient, and compact devices are preferable over less energy efficient devices. Day by day the demand of high-power capacity and compact system are increasing worldwide. These devices generate large amount of heat during operation. To utilise maximum capacity and longer life an efficient cooling mechanism is required. The thermal management of the system should dissipate the generated heat out of the system, so that temperature of the device maintained under the limiting operating condition. Adequate heat removal from a heating surface is one of the serious concerns in some of the applications like cooling of nuclear reactor, space craft, microelectronic circuit, and battery management system of electric vehicles. Phase change heat transfer techniques, particularly nucleate boiling as already mentioned is most desirable for dissipating high heat flux at relatively low temperature differences (ΔT). Boiling heat transfer (BHT) is used in many industrial applications, such as power electronic cooling, integrated chip cooling of large server and data centre, chemical processing industries, space craft thermal management system, steam generator, and refrigeration systems. In order to reduce the energy utilization or consumption, enhance the capacity, and improve the efficiency, the boiling heat transfer process should be upgraded/modified.

Nucleate boiling is a highly efficient heat transfer mechanism that involves rapid bubble formation and intense liquid vaporization at the solid-liquid interface [16]. The vaporization phenomenon is mainly influenced by two factors: surface wettability [17-19] and surface roughness [18, 20], which are interrelated and depend on the surface morphology. Various surface modification techniques, such as thin film coating and micro/nano texturing [21, 18, 22], have been employed to alter the surface wettability and topography and to enhance the boiling heat transfer performance. Several studies have reported significant improvements in boiling heat transfer coefficient (BHTC), onset of nucleate boiling (ONB) temperature, and critical heat flux (CHF) on these modified surfaces. For example, Lee et al. [23] achieved higher BHTC on nanoporous surfaces produced by anodization; Betz et al. [24] demonstrated that reduced wettability facilitates early nucleation on superhydrophobic and superhydrophilic surfaces; Sadaghiani et al. [25] obtained enhanced BHTC on nanoporous surfaces coated by CVD; Song et al. [9] observed a 76.9 % increase in BHTC on Al_2O_3 coated surfaces; and Sun et al. [26] reported 1.55 times and 1.87 times improvements in CHF and BHTC, respectively, on novel microstructures with spatially-controlled mixed wettability. These studies provide motivation and inspiration for further research on surface modification to improve the heat transfer performance, which can meet the future demand of compact and efficient thermal management systems.

1.5. Thesis structure

The present work has presented in six main chapter excluding the final concluding remarks. The whole thesis, is divided into seven different chapters. Chapter 1 focuses on the introduction of boiling and different regimes of boiling. It also describes various techniques/methods used to enhance the pool boiling performances, followed by the motivation,

Chapter 2 includes a literature review of various types of microstructures and their effects on pool boiling performance characteristics. It also reviews the mechanism of heat transfer, characterization techniques and influence of wettability on bubble dynamics and heat transfer performance. In the last part research gap and work objective have been also presented. Chapter 3 presents the details of the material, surface preparation and characterization techniques which are used in the present work.

Chapter 4 provides a detailed description of the experimental setup facility, its major components, experimental procedure and uncertainty analysis. It also explains the data reduction method used to calculate the supplied heat flux, surface temperature, and heat transfer coefficient. Chapter 5 presents the experimental results of polished surface and modified surface with Milli-Q water. It also analyses and compares the boiling performance characteristics such as pool boiling curve and heat transfer performance curve (HTC) with those of polished surface under similar conditions.

Chapter 6 focused on the bubble visualization and few dynamics parameters analysis. The bubble dynamics parameters such as departure diameter, departure frequency has studied estimated with the help of latest proposed model. It also compares the results of the new model with the previous models. Last but not the least the thesis ends with chapter 7, which summarizes the major findings of the present work and suggests the scope of future work.

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