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ADVANCEMENTS IN TRANSIENT POOL BOILING HEAT TRANSFER: MECHANISMS, CHALLENGES, AND INDUSTRIAL APPLICATIONS

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Abstract: *Considering larger transfer of heat coefficients than single-phase systems, boiling heat transfer is essential to many energy-related and industrial activities. Its vulnerability to the boiling crisis, however, presents serious difficulties and could harm heat exchangers. Although transient boiling circumstances have unique dynamics and important consequences for nuclear safety and metallurgical processes, they are still less studied than steady-state boiling. The boiling curve is reviewed, showing the regimes from nucleate to film boiling as well as crucial transition points including the minimal heat flux, critical heat flux (CHF), and boiling start. The role of key mechanisms to heat transmission efficiency, such as micro convection, evaporation of the micro layer, and thermal layering around bubbles, is studied. Techniques to improve the heat transfer coefficient (HTC) and reduce the coefficient of friction (CHF) are presented, with a focus on developments in computational fluid dynamics (CFD) models and empirical relationships. Pool boiling is used in many different sectors, which emphasizes how important it is for improving equipment performance and thermal control.*

Keywords: *Boiling heat transfer, pool boiling, transient boiling, heat transfer mechanisms, critical heat flux, micro convection, boiling curve, heat transfer coefficient, computational fluid dynamics (CFD), industrial applications.*

I. INTRODUCTION

Boiling heat transfer occurs frequently in energy-related and industrial operations. Although the increased heat transfer coefficient it produces compared to single-phase is generally viewed as a gain, its primary disadvantage is the boiling crisis, which can seriously damage heat exchangers. There is a plenty of material on the case of constant boiling conditions [1]–[4]. While there are notable distinctions between transient and steady boiling, transient boiling circumstances have received less research attention. A thorough knowledge and comprehension of this boiling arrangement is necessary for a number of concerns pertaining to nuclear safety or the metallurgical process. On flat plates or in cylinders, some research on transitory boiling were conducted at moderate heating rates .Auracher and Marquardt investigate the entire boiling curve from nucleate boiling to critical heat flux and film boiling, and also the rewetting process for a small flat horizontal heated surface [5]–[8].

II. POOL BOILING HEAT TRANSFER MECHANISMS

The boiling curve, illustrated in Figure 1, serves as a representation of the heat transport regimes and mechanisms involved in pool boiling. This graph illustrates the fluctuations in heat flow from the surface to a liquid pool with border superheat (wall temperature minus liquid saturated temperature). Distinguishing between the different transfers of heat regimes that emerge at different levels of wall superheat is quite effective [9]–[13]. They are comprised of

(a) The single-phase regime, corresponding to low superheats,

(b) Nucleate boiling regime, associated with bubble nucleation at the surface,

(c) Transition boiling regime: areas of the surface covered in vapor while other parts experience bubble nucleation.

(d) Film boiling regime, corresponding to high wall superheats that cause vapor blanketing over the entire surface.

These four regimes are demarcated by three important transition points:

(i) Onset of boiling (or incipient boiling) corresponding to first bubble formation on the surface,

(ii) Critical heat flux (CHF), where bubble nucleation in nucleate boiling is replaced by localized vapor blankets merging together across the surface, and

(iii) Minimal heat flux, also known as the Leiden frost point, which appears as wall superheat starts to decrease and the continual vapor blanket begins to break up in film boiling. With all nucleate boiling regime offering the highest transfer of heat factors and the film boiling regime offering the lowest, these transition points indicate significant differences in the efficiency of heat transmission between the various regimes [14]–[17].

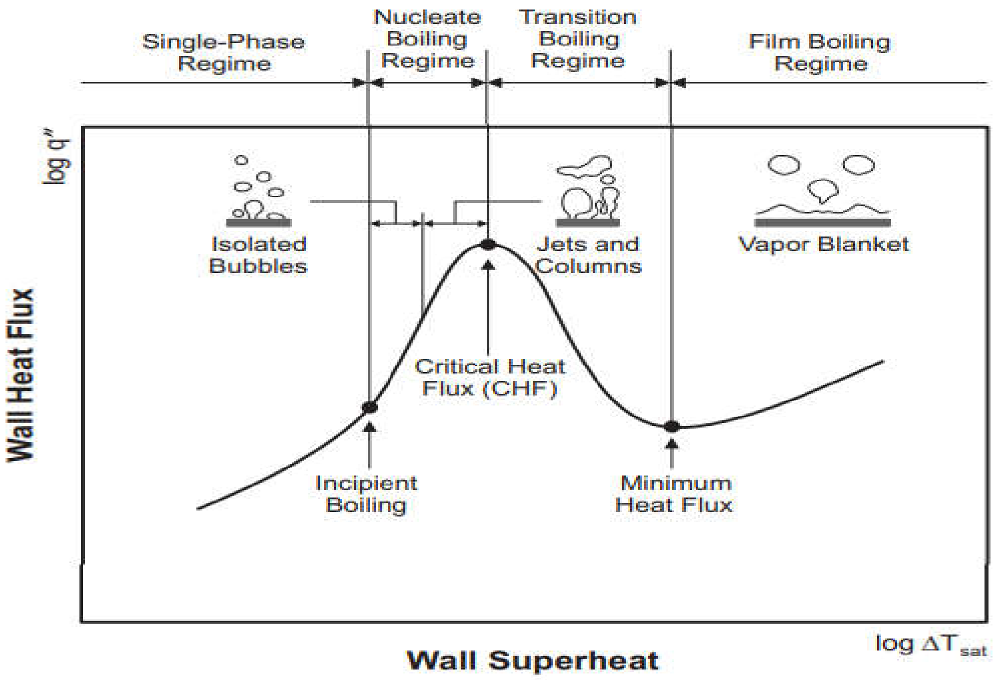


Figure 1. Pool boiling curve[5]

III. The Fundamentals and Critical Aspects of Boiling Heat Transfer

Numerous processes, such as power generation, chemical processing, and high-heat flux thermal management, include boiling heat transfer. For decades, researchers have been studying how to improve boiling heat transfer because of its importance and widespread use in various industries. Heat is transferred from a heated surface to a colder fluid during boiling via

(1) Evaporation across liquid-vapor interfaces,

(2) Transient conduction and

(3) The micro-convection generated by the nucleation, growth and departure of vapor bubbles.

The heat transfer coefficient (HTC), which is the proportion of the surface heat flux to the superheat temperature—that is, the temperature differential between the saturated fluid and the solid—quantifies the efficiency of boiling. There is a limited rate at which heat can escape from any surface during boiling. The critical heat flux (CHF) is at this maximum. CHF, also known as the boiling crisis, happens when the amount of liquid returning to the heated surface is inadequate to balance the amount of vapor produced. This causes the surface to dry out and cover the solid surface with an insulating layer of vapor. This causes the surface temperature to rise suddenly, uncontrollably, and dramatically, which can have hazardous and possibly disastrous effects like melting a nuclear reactor or destroying electronic components. Decades of research have been dedicated to comprehending and enhancing HTC and CHF in boiling systems, including the creation of several enhancement techniques[18]–[21].

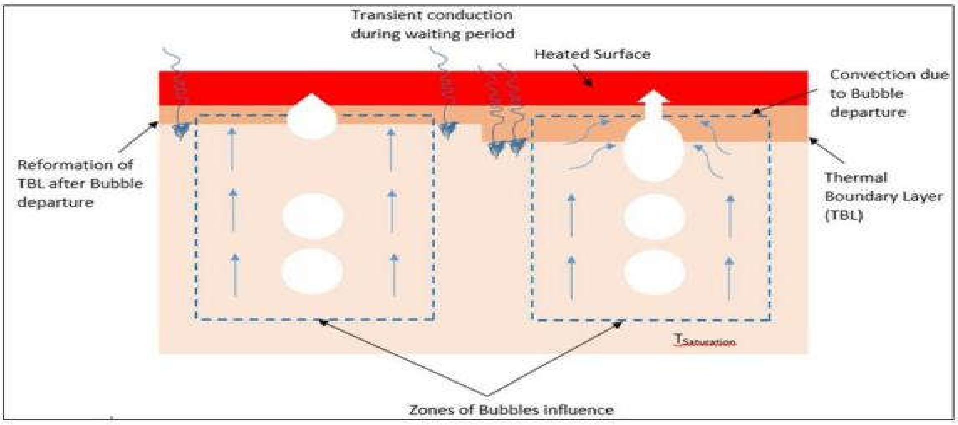
The Boiling Heat Transfer Coefficient (BHTC) and Critical Heat Flux (CHF) are the two metrics that often define boiling performance. The CHF point, or the point at which the nucleate boiling curve transfers onto the film boiling, that is defined by drying at the heat transfer surface, is when the equipment's thermal performance ends. The CHF point is characterized by an abrupt rise in surface temperature, which is followed by a sharp fall in the rate of heat transfer and surface corrosion . The performance of heat transfer is significantly reduced at the CHF because a layer of steam (a resistant layer) forms on the heated surface. Furthermore, a crucial factor pertaining to the heat's safety effectiveness is the CHFThe literature has published the CHF models for the pool boiling. The mechanisms can be summed up as follows: enhancing the surface moisture capability, active nucleation sites, heat transfer surface area, and dynamic bubble modulation, including bubble departing frequency [22]–[24].

Effects Of Body Force On Critical Heat Flux (CHF)

Due to the significant density differences between liquid and vapor, buoyancy—which is determined by multiplying the product of gravity and density difference—can be a significant factor in vapor-liquid motion and, consequently, in the efficiency of heat transfer. One well-known heat transfer phenomenon that can show intricate variations with gravity is CHF. Since it can cause an abrupt, erratic rise in device temperature, it is especially concerning when it comes to heat-flux controlled power and electronic devices. Since most electronics are not made to survive temperature increases of this kind, the materials inside the device may melt, burn out, or sustain other irreversible damage. Predicting the exact conditions that cause CHF is crucial because it presents a difficulty when constructing a thermal management system for use in space: ensuring that the prevailing boiling heat flux remains safely below CHF. This task is particularly difficult because, due to the significant size, weight, and pumping power penalty associated with such provisions, conventional methods of improving CHF in a terrestrial environment—such as significantly increasing fluid flow rate and/or subcooling level—might not be allowed in a reduced gravity environment. Regretfully, the majority of the knowledge on two-phase flow and heat transfer that has been accumulated over almost a century of study originates from tests carried out under Earth's gravity [25] –[27].

IV.TYPES OF BOILING HEAT TRANSFER

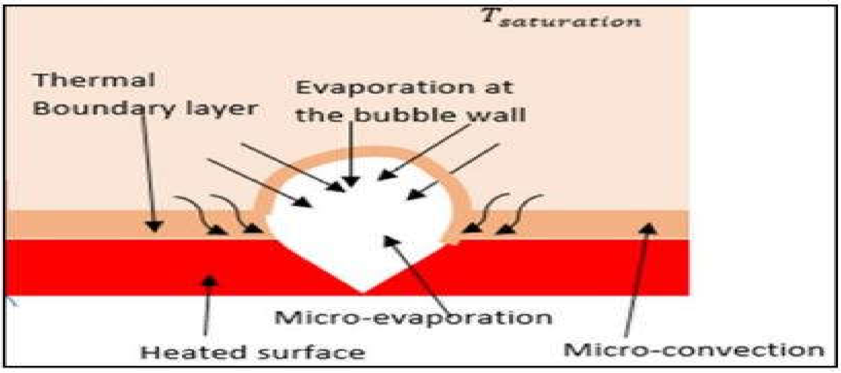
A. Pool Boiling thermal exchange: Thermal transmission during pool boiling has also been studied in recent years by researchers using computational fluid dynamics (CFD) models. The heat transfer and fluid dynamics processes involved in pool boiling are fully understood by using CFD models. For example, used CFD simulations to examine how surface wettability affected the Pool Boiling thermal transfer coefficient.



(a)

(a) Natural convection, bubble mixing, and transient conduction during thermal boundary layer rewetting and reforming.

In Figure 2 (a), Heat transmission in pool boiling happens by bubble creation, natural convection, and brief conduction when the heated surface is rewetted. Temperature differences lead to natural convection, which enhances heat transfer by displacing warmer liquid near the heated surface with cooler liquid. Localized boiling causes vapor bubbles to separate from the liquid's surface and rise through it, releasing latent heat. When a bubble breaks apart, it causes transient conduction, which lowers the surface temperature momentarily until the subsequent nucleation site forms and redistributes heat throughout the solid. Rewetting is the process of liquid returning to the surface following the departure of bubbles, reestablishing convection currents and temperature gradients. In order to avoid overheating and guarantee efficient cooling in a variety of industrial applications, these mechanisms are essential for maintaining thermal boundaries and optimizing heat transfer efficiency .



(b)

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(b) Micro convection, evaporation of the microlayer, and evaporation of the thermal layer surrounding the bubble

Figure 2. Thermal transfer during Pool Boiling can be attributed to two main mechanisms.

Micro convection, microlayer evaporation, and thermal layer evaporation around the bubble are the heat transmission mechanisms involved in pool boiling see in Figure 2 (b). The small-scale convective currents caused by the emergence and retreat of vapor bubbles on the heated surface are referred to as micro convection. Through convective mixing, these bubbles cause localized disruptions in the liquid that improve heat transfer. The heated surface's direct interaction with the liquid-vapor contact causes the micro layer to evaporate quickly, causing bubbles to develop as a result. Heat is transferred from the bubble's surface to the surrounding liquid during the evaporation of the thermal layer surrounding the bubble, which aids in the total dissipation of heat .

B. Nucleate Pool Boiling Heat Transfer

A bubble begins as a nucleus and expands as a result of liquid evaporating at the liquid/vapor contact (fig. 3). A small layer of liquid (the micro-layer) may be trapped by a rapidly expanding, hemispherical bubble between it the overheated wall; bubble development is encouraged by the liquid's evaporation (qml). When the micro-layer partially dries up and leaves behind a dry patch on the surface, evaporation in the 3-phase contact line (qcl) offers another way for bubbles to form. The expanding bubble can produce transfer of energy by micro convection (qmc), in addition to upsetting the surrounding liquid and the background natural convection boundary layer (qnc). As the dry patch rewets, there may be a brief conduction towards the moving liquid front (qtc). The radiant energy extracted from the micro-layer along the a 3-phase system contacting line will cause a considerable drop in temperature in the vicinity of the nucleate position.

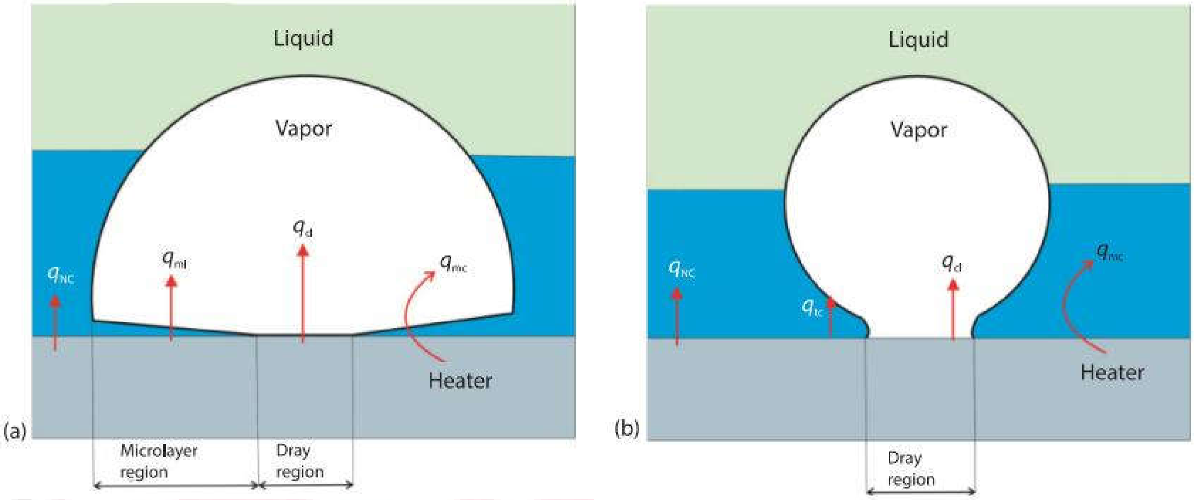

Figure 3. Physical mechanism of heat transfer during single-bubble nucleate boiling; (a) bubble growth period and (b) bubble departure period

The bubble will leave the heating surface when it reaches a certain size due to factors acting upon it, namely buoyancy in a gravitational environment. The nucleate site will go through a waiting or recovery phase once its superheat reaches the threshold of criticality and the subsequent bubble emerges. Therefore, the formation, growth, and detaching of the vapor bubbling and the rate of heat transmission thereto depend on an understanding of the parameters of bubble dynamics. The parameters pertaining to bubble dynamics are the nucleation sights density, bubble departing diameter, waiting period, growth period, and departure frequency. Alternatively empirical or semi-empirical correlations generated utilizing bubble dynamics characteristics can be used to determine the boiling HTC.

C. Transition Boiling Heat Transfer

The boiling curve across points C and D illustrates this process. From point C forward, the heat flux starts to decrease as the ΔTExcess is increased more. This is because a vapour coating has coated a sizable portion of the heated surface. This vapor sheet functions as a thermal insulator because of the relatively low thermal conductivity of the vapour. Either nucleate or film boiling partially occur in this regime. At point D, the film boiling process fully replaces the nucleate boiling, and it is advised to steer clear of the transition boiling regime are describe in figure 4.

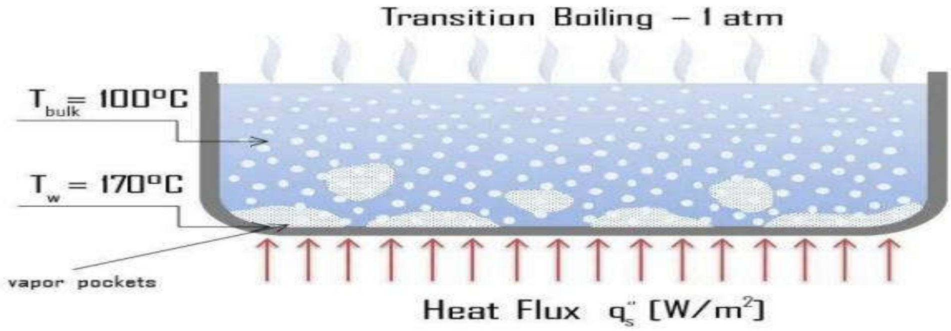

Figure 4.Transition boiling

V. APPLICATION OF POOL BOILING

The capacity to extract significant amounts of heat from the heating surface while maintaining a smaller temperature differential makes pool boiling features extremely useful for heat transfer. By improving the functionality of equipment used in numerous industries, including process industries, power plants, refrigeration, and air conditioning, among others, this results in a smaller heat exchanger.Among the noteworthy applications are:

- **Power Generation**: Power stations make considerable use of pool boiling for cooling purposes. By effectively removing heat from the system, it aids in the cooling of steam generators, nuclear reactors, and other vital parts.

- **Chemical Processing**: Pool boiling is used in the chemical industry for both heating and cooling procedures. Reactors, distillation columns, and other pieces of equipment where exact temperature control is necessary for chemical reactions and final products depend on it heavily.

- **Refrigeration and Air Conditioning**: To evaporate refrigerants in refrigeration cycles, a pool must boil. Heat transfer from the surrounding air to the refrigerant, used cools air conditioners, freezers, and chillers, is facilitated by it.

- **Industrial Heat Exchangers**: Pool boiling is employed in various industrial heat exchangers to transfer heat between fluids efficiently. It helps in maintaining optimal operating temperatures in equipment used in manufacturing processes, food processing, and HVAC systems.Boiling heat transfer is used in a number of industrial applications, such as server cooling, cryogenic applications, and nuclear power plants, to remove excessive heat flux . High heat removal in server cooling is absolutely necessary to preserve the computer's performance by keeping the junction temperature under the permitted threshold. Up to 10% less performance is achieved with every 2 °C increase in temperature.

- **Aerospace and Defense:** Aircraft engines, military uses, and spacecraft cooling systems all use pool boiling. In order to preserve operational safety and dependability, it makes sure that heat is removed from crucial components effectively.

- **High-Heat Flux Thermal Management:** Pool boiling is essential in applications requiring high-heat flux dissipation, such as electronic cooling systems, where maintaining low operating temperatures is crucial for device performance and longevity. The effectiveness of boiling heat transfer as a cooling technique has been established. Because of the bubble's erratic mobility, it has a high heat transfer coefficient. The single-phase liquid's inherent convection is aided in cooling by surface rewetting and bubble evaporation, which raises the heat transfer coefficient. As of late, it has been possible to increase the heat transfer coefficient within a boiling system by up to 2 MW/m2√°C, which is 10 times more than forced convection using dielectric liquids.

VI. CONCLUSION

Boiling heat transfer offers opportunities and challenges because it is crucial for many industrial applications, such as chemical processing and power production. Comprehending the complexities of transient boiling, in addition to mechanisms such as micro convection and evaporation processes, is crucial in order to maximize the effectiveness of heat transmission and avert disastrous consequences like the boiling crisis. The performance and dependability of heat exchange systems can be improved by increasing the heat transfer coefficient (HTC) and controlling the critical heat flux (CHF) thanks to developments in computer simulation and empirical correlations. We will be able to harness the advantages of boiling transferring heat while reducing its inherent hazards with more research into these areas.This well-organized review offers a thorough analysis of boiling heat transfer methods, regimes, and real-world applications while also providing insights into present and potential future paths for the field's research.

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