Pool Boiling Enhancement Techniques

Subjects: Engineering, Mechanical
Contributor: José Pereira, Reinaldo Souza, Rui Lima, António Moreira, Ana Moita

Several enhancement approaches relating to the underlying fluid route and the capability to eliminate incipient boiling hysteresis, augment the nucleate boiling heat transfer coefficient, and improve the critical heat flux are assessed.

Keywords: pool boiling ; electric field ; enhanced surfaces

1. Introduction

Pool boiling is an efficient process for heat transfer, mainly because of the associated phase change. With the recent demands of meeting high heat flux dissipation of over 1 kW/cm^2 in, for instance, electronic chip cooling applications, further enhancement to pool boiling heat transfer is receiving great attention from the research community. In diverse industrial applications, nucleate boiling heat transfer is a surface phenomenon that depends on factors like the heating surface material, morphology, wettability, roughness, porosity, and thermal conductivity. Heat transport is always present in energy harvesting, use, conversion, and recovery processes. Also, the general heat transfer enhancement routes will result in certain improvements in the heat transfer system, which will be more compact and have relevant savings in pumping power and in the overall investment cost. Accordingly, any progress in the nucleate boiling heat transfer capability will entail efficiency improvements and a reduction in the cost of thermal management systems on a large scale. The advantageous feature of phase change heat transfer is its ability to transfer a large amount of energy in the form of heat. Also, the boiling process is an efficient heat transfer process due to its high latent heat and is usually applied in processes where high heat fluxes must be dissipated, including nuclear reactors [1]; desalination systems [2]; cooling of electronics [3]; and thermal management systems, including devices like heat pipes [4], heat exchangers [5], and thermosyphons [6]. Pool boiling heat transfer is associated with transient conduction, microlayer evaporation, and micro-convection. Such mechanisms are closely linked to the liquid–vapor interface around a nucleating, growing, and departing vapor bubble on the heating surface. The wettability of the liquid–vapor interface determines the shape of the interface, the motion of the contact line, and related processes. The advances related to surface energy modification of the heating surface have paved the way for enhancing the nucleate pool boiling heat transfer by altering the contact angle through the incorporation of nanostructured features and layers on the surface. These nanostructures alter the wettability and improve the critical heat flux (CHF) of the heat transfer surface. The enhancement of the nucleate boiling heat transfer behavior encompasses several goals, including initiating nucleate boiling (incipient boiling) at lower heat fluxes and wall superheats, preventing or mitigating the temperature excursion and sharp temperature drop inherent to the boiling incipience, reducing the wall superheats by increasing the number of active nucleation sites and bubble departure frequency, and delaying the CHF to higher heat fluxes. The employment of enhanced structured boiling surfaces can be a promising route to increase the available heat transfer surface area, disrupt the coalescent bubbles, and improve the CHF of the system. The pool boiling enhancement process is usually applied to achieve the following objectives: (i) initiation of the nucleate boiling at a lower boiling surface temperature; (ii) mitigation or elimination of the incipience temperature excursion; (iii) reduction in the temperature of the heat transfer surface, i.e., increase in the heat transfer coefficient (HTC) associated with nucleate boiling; and (iv) increase in the CHF value to support higher surface heat fluxes. The heat is transferred from the heat transfer surface to the operating fluid during the nucleate boiling process, and the heat transfer is carried out by convection because of the motion of the fluid. Also, the surface tension and density gradient, which produce the buoyancy force, are important parameters, together with the latent heat. The buoyancy flow and latent heat of the boiling heat transfer process result in higher heat transfer rate and coefficient when compared to single-phase convection [7]. The main beneficial features offered by a boiling enhanced curve when compared to a typical boiling curve corresponding to a heating surface without modification are the increase in CHF and the lower onset of nucleate boiling, meaning that in the enhanced curve boiling process, there is a need for lesser thermal loads to initiate nucleate boiling when compared to the loads needed in the boiling curve boiling process. In addition, it can be emphasized that thermal management heat transfer has attracted great attention from the research community dealing with the development and implementation routes for pool boiling heat transfer amelioration. One of the most commonly followed routes, like displaced heat transfer enhancement and the use of improved thermal fluids, is boiling surface modification. This approach directly deals with the inclusion in the heat transfer surface of structures at the nano/microscale [8], including porous coatings, nanoparticles [9], nanofibers, nanotubes covering, and mixed wettability characteristics [10][11]. Usually, physical [12] and chemical [13] methodologies are employed to process the intended heating surface modification, along with the exploration of a wide range of different materials, such as metals [14], metal oxides [15], ceramics [16], carbon [17], graphene, and graphene oxide [18]. The methodologies include physical vapor deposition (PVD), all types of chemical vapor deposition (CVD), electrochemical etching, spraying, magnetron sputtering, spin coating, plasma coating, and sintering, among many others. Generally, the investigation pathways require that the developed enhanced nucleate boiling heat transfer surfaces be subjected to comparison with plain, bare heating surfaces in terms of heat transfer capability, which is translated in their intrinsic parameters, like HTC and CHF. Published studies on the matter reveal that the adoption of modified enhanced boiling surfaces directly influences the nucleate HTC and CHF values at pool boiling scenarios, but normally the interpretation of the underlying mechanisms that provoke such an impact varies from researcher to researcher rather than being totally reliable and consistent [19]. For instance, different researchers have studied the vapor bubble dynamics [20][21] and deduced that the combined effect of the adhesion, buoyancy, and surface tension forces present in modified heating surfaces induced the merging of the vapor bubbles. Other authors have confirmed that the total number of vapor bubbles in a structured enhanced surface is much greater than that provided by a bare, plain boiling surface at an imposed heat flux. Moreover, other authors have stated that the heat-transfer-enhancing effect of modified porous heating surfaces come from their improved wettability character, closely linked to the capillary effect [22][23]. Moreover, it can be noted that the most commonly encountered mechanisms responsible for the enhancement of boiling heat transfer can be various, with improved surface wettability, mixed wettability, hydrodynamic instability, modified average surface roughness, and wickability action, among others, coming into play at diverse stages of the nucleate boiling process.

2. Pool Boiling Enhancement Techniques

The available techniques for nucleate boiling heat transfer improvement can be classified into active, passive, and hybrid or compound enhancement techniques, as shown in the diagram in **Figure 1**. The active techniques involve technical strategies like heating surface vibration, fluid vibration and suction, gas injection, and the application of external electric or magnetic fields for heat transfer enhancement purposes. However, the active techniques are relatively expensive and hard to apply in compact cooling enclosures, such as those used in the cooling of electronics. The passive techniques encompass various procedures of surface modification; the use of enriched working fluids and additives; and refined working conditions, like heating transfer surface orientation adjustment, pool boiling confinement, and liquid pool height. The hybrid or compound enhancement techniques involve one active technique coupled with one passive technique or, alternatively, the combined usage of two or more active enhancement techniques.

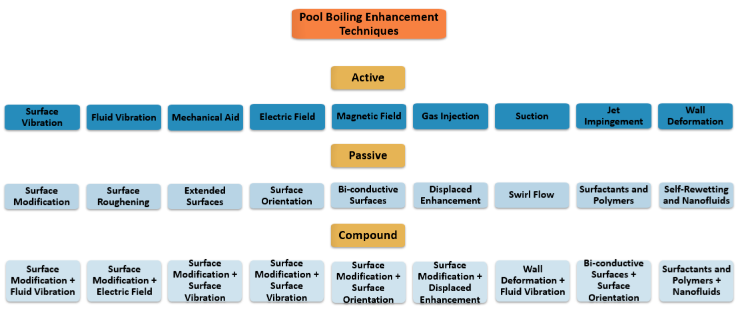

Figure 1. Main pool boiling enhancement techniques.

2.1. Active Techniques

2.1.1. Surface Vibration

Several published studies have already demonstrated that applying high-frequency and high-amplitude oscillations to the boiling surface may lead to nucleate boiling heat transfer enhancement [24][25][26][27]. Also, it can be assumed that combinations of frequency and vibration amplitude of the heating surface may lead up to a 2-fold increase in the HTC value. Sufficiently intense oscillations can improve the heat transfer capability of the operating fluids by applying a surface vibration with a frequency lower than 1000 Hz. The vibration of the boiling surface through the action of an electrodynamic vibrator or motor-driven eccentric will break the boundary layer and move the nanoparticles dispersed in the fluid over to the nearby boiling surface region. Such an effect can induce forced convection in a free convection region. Additionally, the researchers Prisnyakov et al. [28] have already demonstrated that the value of heat fluxes removed from a vibrating surface strongly depends on the presence or absence of boiling on such a surface. The authors observed that in the convection region, an increase in the thermal load decreased the nucleate boiling heat transfer performance and vice versa. The authors obtained a 2-fold increase in the heat transfer coefficient with a vibrating heating surface, and that increase was directly proportional to the frequency and amplitude of the vibrations. Also, the researchers Zitko and Afgan [29] investigated the heat transfer performance of water pool boiling with a vibrating heating surface. In their experiments, the imposed heat flux varied from 0 to 85 × 10^{-4} W/m^2. The authors also varied the vibration amplitude between 0.1 and 2 mm and their frequency from 0 to 70 Hz. Based on the obtained results, the authors concluded that the HTC increased with increasing heat flux, vibration frequency, and vibration amplitude. Furthermore, the researchers Atashi et al. [30] investigated the impact of low-frequency vibrations on the boiling heat transfer capability. The authors stated that the vibrations generated turbulence and extra nucleation sites, leading to the nucleation of bubbles with smaller sizes when compared to those nucleated on a non-vibrating heating surface. The main result was achieved at a frequency of 25 Hz, where the heat transfer improved by up to 116.6% under low-frequency vibrations. In addition, the authors Sathyabhama et al. [31] investigated the effects of mechanical vibration on the pool boiling process using a smooth copper surface. The authors observed an HTC increase at low vibration frequency and amplitude conditions. On the contrary, the researchers also found that the HTC deteriorated at higher vibration amplitudes and frequencies. The HTC was found to be enhanced by up to 26% with increasing mechanical vibration intensity. Moreover, the authors Abadi et al. [32] studied water pool boiling at atmospheric pressure with the assistance of the vertical vibration of an array of heating tubes. The obtained results revealed that the vibration had considerable effect because it enhanced the HTC by up to around 90%. The researchers also observed that the effect of the vibration of the heat transfer tubes was more prominent under low imposed heat fluxes. Also, in the experimental work carried out by the authors Alangar et al. [33], the impact of the vertical vibration of a copper heating surface on its water nucleate pool boiling at atmospheric pressure was inferred. The researchers varied the vibration frequency between 0 and 25 Hz and the amplitude of vibration between 0 and 5 mm. The experimental results indicated that the surface vibration enhanced the nucleate boiling heat transfer capability of the system. It was concluded that the effect of the vertical vibration of the boiling surface was significant at low heat fluxes. The authors also observed that the heat flux that can be removed from the heating surface at a given temperature increased with the increasing intensity of the vibration. The gain in heat transfer behavior was attributed by the authors to changes in the vapor bubble parameters. The experimental data were consistent with those published for high heat fluxes. The schematic diagram of the laboratorial set-up employed in this experiment is presented in **Figure 2**. Moreover, the authors Alimoradi et al. [34] numerically investigated the pool boiling process using a silicon oxide nanofluid as operating fluid and a vibrating heat transfer surface. To consider the heat dissipation caused by the vapor bubble nucleation and departure, the authors employed the Rensselaer Polytechnic Institute (RPI) boiling method and arrived at the following main conclusions: (i) the heating surface vibration augmented the pool boiling heat transfer capability, and this effect was most remarkable at low imposed heat fluxes, regardless of the amplitude and frequency of vibration; (ii) the increase in the amplitude of vibration stimulated an increase in heat transfer rate of nearly 30.1% at an imposed heat flux of 10.9 kW/m^2 and of around 3.9% at an imposed heat flux of 265.5 kW/m^2, with Y_{wall} = 3 mm and f_{vib} = 10 Hz, compared to a non-vibrating surface; (iii) the amplitude of vibration slightly improved the heat transfer capability compared to the frequency of vibration; and (iv) the HTC increased with increasing nanofluid concentration.

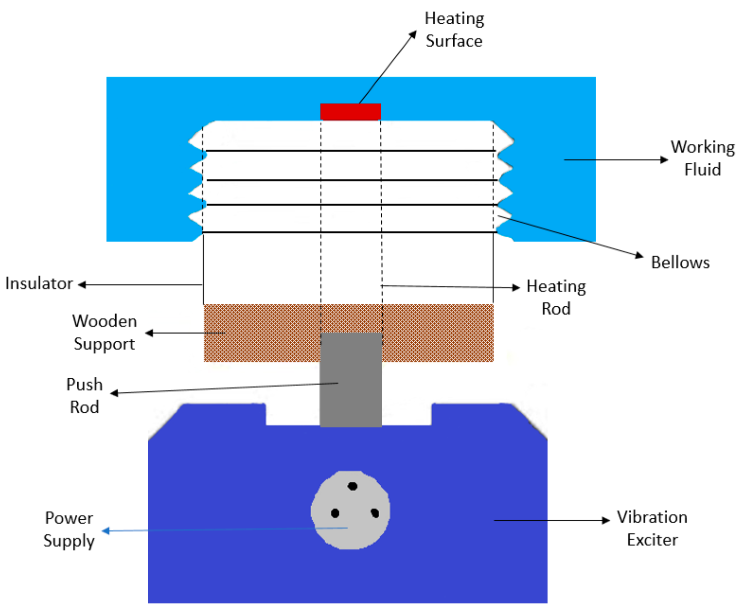

Figure 2. Schematic diagram of a surface vibration apparatus.

2.1.2. Fluid Vibration

Among the active fluid vibration heat transfer enhancement techniques, the application of an ultrasonic field in the boiling fluid has emerged as the most commonly employed fluid vibration technique for nucleate boiling heat transfer improvement, as has already been demonstrated by several researchers. The ultrasonic waves induce a force field into the boiling process, which affects the entire mechanism from nucleation to the subsequent stages of growth and collapse of the bubbles in the fluid [35]. An ultrasonic probe can create an acoustic wave field in the fluid that induces volume oscillations and surface waves on the bubbles, which facilitate their departure. Also, the bubbles tend to coalesce at higher heat fluxes, which leads to vapor film formation over the heating surface. The ultrasonic waves delay the vapor film production, leading to enhanced heat transfer capability. During the boiling process, the buoyancy force plays a prominent role in nucleate boiling by promoting the departure of the bubbles from the surface. The bubble removal is impounded in areas with an absence of gravity, and this may lead to the blanketing of the heating surface with a vapor film and deterioration of the heat transfer. Also, it should be noted that inefficient film boiling heat transfer induces high surface temperatures, leading to an eventual burnout of the boiling surface. The ultrasonic waves may provide a suitable replacement for the gravity effect to maintain stable nucleate boiling [36]. An ultrasonic field creates spatial pressure variations, and when the local pressure falls below the vapor pressure, the stretching of the fluid leads to the formation of vapor-filled cavities, usually designated as cavitation bubbles. Acoustic cavitation can be defined as the formation of bubbles due to the volumetric oscillations of pressure and their subsequent growth and collapse within the fluid. Such mechanisms stimulate the agitation of the working thermal fluid, assist in the disruption of the stagnant film at the heating surface, and, hence, lead to an improved nucleate boiling heat transfer rate. **Figure 3** illustrates the general principles of the ultrasound-assisted pool boiling process. Furthermore, the researchers Baffigi and Bartoli [37] explored 25 and 35 °C subcooling in nucleate pool boiling under the influence of an ultrasonic field with 38 kHz frequency. It was found that HTC was enhanced by 45% for subcooling of 35 °C at a heat flux of 1.4×10^5 W/m^2, whereas a nearly 26% enhancement was reported for 25 °C subcooling at a heat flux of 1.0×10^5 W/m^2 for a maximum ultrasonic power of 500 W. The obtained experimental results also exhibited a nucleate boiling heat transfer enhancement with increasing ultrasonic generator power. An increase of 114% in the HTC was reported at a power of 500 W and 25 °C subcooling, whereas the corresponding HTC enhancements for 300 and 400 W were 66% and 90%, respectively. Also, the authors interpreted the results based on the ease of bubble detachment provided by the ultrasonic field, along with the increase in subcooling degree. Furthermore, the researchers Tang et al. [38] evaluated the effect of an ultrasonic field of 20 kHz on vapor bubbles in subcooled boiling and reported an improvement in the Nusselt number and easier collapse of the bubbles under ultrasonic field action. The authors concluded that the ultrasonic field makes the thermal boundary layer unstable near the bubbles, and the formation of capillary waves stimulates the condensation of the bubbles, leading to their collapse. Additionally, the researchers Bartoli and Baffigi [39] evaluated the impact of the positioning of the heating surface on nucleate boiling heat transfer enhancement under the action of an ultrasonic field. The authors found that the ideal surface location was at a distance of 50 mm from the wall and 15 mm above the bottom of the pool boiling tank with an imposed heat flux of 1.2×10^5 W/m^2 and an ultrasound frequency adjusted to 40 kHz. Also, the authors stated that the diverse heating surface morphologies and possible dimensions had a considerable influence on the ultrasound-assisted nucleate boiling heat transfer process.

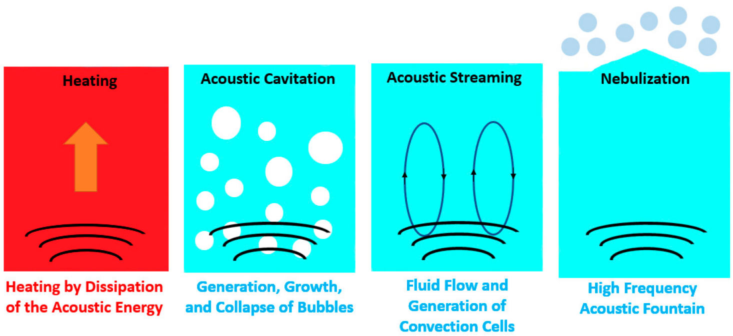

Figure 3. Schematic diagram representing the ultrasound-assisted pool-boiling-related phenomena.

Additionally, the researchers Hetsroni et al. [40] investigated the impact of the size of the heating surface on the effect of an ultrasonic field. The investigation team studied the effect of wires with sizes ranging from 20 to 250 mm and concluded that the effect of the ultrasonic field on the pool boiling process was dependent on the dimension of the heating surface. In the case of using the smallest wire with 20 mm, no improvement was observed because of the resulting less-strong vapor jets. The reduction in the wall temperature and the improvement in the boiling heat transfer capability were more pronounced in cases where larger wire sizes were employed. The maximum reduction in the wall temperature was reported using the 0.2 mm sized heating wire, whereas the HTC was enhanced by around 45%. The obtained results were interpreted by the authors based on the increased turbulence, wall shear force, and secondary acoustic streaming. The investigation of pool boiling under an ultrasonic field and different gravity conditions was introduced by the researchers Sitter et al. [41], who studied the effect of the acoustic field on the nucleate pool boiling process under terrestrial and microgravity conditions using a frequency of around 10.2 kHz and an acoustic pressure of 260 kPa. Under microgravity, the acoustic wave field force facilitated the detachment of the bubbles from the heating surface because the buoyancy force was absent. These bubbles, along with the vapor bubbles, created microagitation in the fluid and contributed to heat transfer enhancement. Additionally, Kim et al. [42] investigated the impact of the cavitation process on the natural convection and nucleate boiling regimes under the effect of an ultrasonic field. In the natural convection regime, both the mobility and density of the cavitation bubbles contributed appreciably to heat transfer augmentation. However, in the subcooled and saturated boiling regime, regardless of the reduction in the departure diameter and increase in the frequency and mobility of the vapor bubbles, the enhancement ratio of the heat transfer capability was strongly reduced. Because the ultrasonic waves are relatively low-energy waves and get easily damped, their remarkable effectiveness in assisting the boiling heat transfer process is derived only in the case of employing resonance or high generator ultrasonic power. The impact of the subcooling degree, operating pressure, boiling surface morphology, and the relative placement within the ultrasonic field should be carefully considered to infer the performance of boiling heat transfer under the action of an ultrasonic field. This need for accurate evaluation is one of the major reasons behind the only minor progress made in the research field of ultrasonic-assisted pool boiling. Nonetheless, the following conclusions can be noted: (i) The ultrasonic wave propagation in the pool boiling process affects the nucleation, growth, detachment, and motion of the vapor bubbles through the fluid. (ii) The surface modification involving structured surfaces (e.g., micro-channeled/finned surfaces) has been found to be favorable to nucleate pool boiling under the influence of an ultrasonic field. A decrease in the superheat degree and an increase in the HTC has been found for diverse enhanced boiling surfaces. (iii) The relative positioning of the heating surface in the ultrasonic field has been proved to influence the nucleate boiling heat transfer performance. (iv) Under microgravity, the bubble detachment from the heating surface becomes more difficult because of the insufficient buoyancy force, and the ultrasonic waves stimulate the displacement of the vapor bubbles. (v) Nucleate boiling heat transfer improvement under the action of an ultrasonic field is dependent on the frequency of the field, and this experimental parameter must be chosen in such a way that enables the bubble equilibrium radius to be kept near its departure radius to ensure high heat and mass transfer rates and facilitate the bubble departure stage. Nevertheless, a higher ultrasonic power has been found to foster ultrasonic pool boiling heat transfer enhancement caused by an increase in acoustic pressure. (vi) When dealing with saturated boiling cases, the ultrasonic field effect is not so effective because of the increased attenuation from the vapor bubbles at higher imposed heat fluxes. However, subcooling between 15 and 35 °C improves heat transfer behavior in the ultrasonic-assisted pool boiling process. The diverse types of surfaces, such as hydrophilic and hydrophobic types, and coatings are possible technical solutions that need to be further studied under the action of an ultrasonic field. Nonetheless, there is still a lack of rigorous numerical simulations and parametric studies, such as further investigations on the possible application of variable pressure along with different subcooling in the ultrasonic field nucleate pool boiling process. Meanwhile, it should be emphasized that it is not only ultrasonic waves that are applied in active pool boiling heat transfer enhancement techniques of fluid vibration. For instance, the numerical work performed by the researchers Mondal and Bhattacharya [43] evaluated the impact of induced vibrations in the operating fluid on the pool boiling heat transfer performance amelioration. In this direction, the authors adopted the single-component multiphase relaxation-time-based Lattice Boltzmann method (LBM) and modulated the ebullition cycles of the vapor bubbles from single and multiple nucleation sites with different nucleation densities in a pool with fluid motion provided by moving solid boundaries that periodically moved at a given frequency and amplitude values. The results provided useful insights into the nucleation, growth, and detachment stages of bubbles in stationary and fluid-motion conditions. It was found that the vibration in the fluid enhanced the growth rate and bubble departure frequency of the bubbles because of the additional forces acting on them, which facilitated their growth and detachment. Also, the surface heat flux was found to be significantly higher for the moving solid boundaries at a given boiling surface superheat value. The referred study on the motion frequency and amplitude of the solid boundaries indicated that there were ideal frequency and amplitude values that made the bubble departure frequency reach a maximum, and beyond such values, the bubble departure frequency decreased.

2.1.3. Mechanical Aid

Some researchers have been aiming to enhance the nucleate boiling heat transfer capability through the creation of strong fluid motion disturbance over the heating surface with the aid of custom-developed mechanical parts and/or devices. In this direction, the experimental work performed by the authors Suriyawong et al. [44] analyzed the nucleate pool boiling heat transfer of water with the assistance of copper rotating blades over a copper heating surface. The blades had a diameter of 30 mm, a core of 5 mm, a length of 50 mm, and a blade angle of 90°. The authors used two, three, and four blades and distances between the surface and the tip of the blades of 5, 15, and 25 mm. **Figure 4** schematically represents the four-blade rotating blade that was used in the experiments.

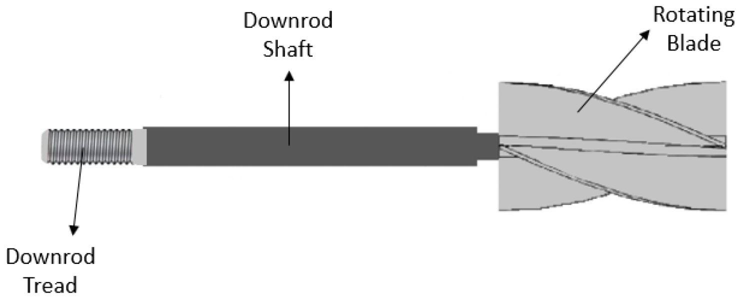

Figure 4. Scheme of a four-blade rotating blade.

The obtained results indicated that a decrease in the distance between the surface and the tip of the blades enhanced the HTC. It was also found that the technical solution employing four blades placed at 5, 15, and 25 mm from the heating surface yielded the highest HTC enhancements of nearly 29.7%, 18.6%, and 12.4%, respectively. The fact that the 5 mm distance promoted the highest HTC enhancement was explained by the authors as being the result of the increased likelihood of vapor bubbles striking the rotating blades in the shortest distance, creating more fluid motion disturbance over the boiling surface. Additionally, the results also revealed that increasing the number of employed blades promoted HTC enhancement. For instance, at 5 mm from the surface, the HTC improvement with two, three, and four blades was around 13%, 19.8%, and 29.7%, respectively. The authors interpreted these results based on the fact that the added blades increased the area that received the strike force from the bubbles, and as a result, the rotating blades created more disturbance in the working fluid motion over the boiling surface. **Figure 5** presents the schematic diagram of the set-up of the experiments.

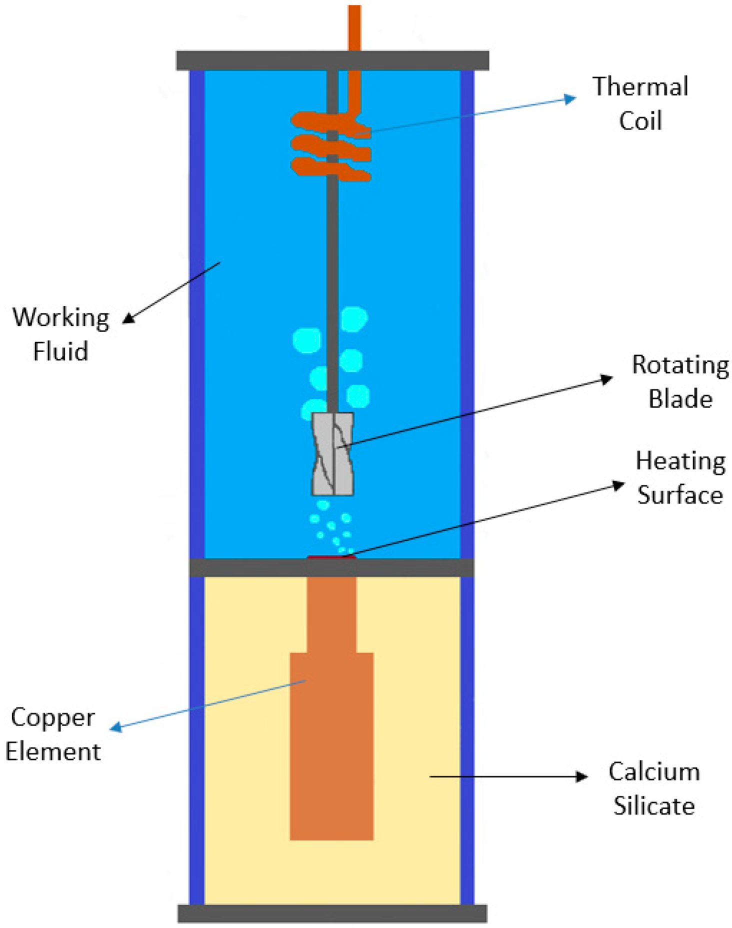

Figure 5. Schematic diagram of the set-up with a four-blade rotating blade.

Another case of a practical methodology that generates fluid disturbance is the one proposed by the researchers Ashouri et al. [45], who placed an inner corrugated hollow conical frustum (ICHCF) above the heat transfer surface to improve the thermal performance of the pool boiling process. The authors evaluated the behavior of various ICHCFs in both stationary and rotating cases, and the impact of various factors, including the height and thread depth of the ICHCF, distance between the ICHCF and the boiling surface, rotational velocity of the ICHCF, and temperature increase, were investigated. In view of the obtained results, the authors arrived at the following main conclusions: (i) the increase in the height of the ICHCF enhanced the HTC in both rotating and stationary modes; (ii) the study found an ideal imposed heat flux in the rotating mode at which the maximum HTC value was achieved; (iii) for both rotating and stationary modes, the excess temperature decreased with increasing ICHCF height; (iv) the rotating ICHCF enhanced the HTC regardless of its height and imposed heat flux; (v) the rotational speed increase in the ICHCF augmented the HTC, but after a certain speed value, the enhancement decreased with increasing speed; (vi) the smaller pitches and higher thread depths improved the HTC; and (vii) HTC enhancements of up to 19.8% and 1302% were obtained in the stationary and rotating modes, respectively, compared to those obtained using a plain surface.

2.1.4. Electric Field

The application of an external electric field has already been demonstrated to be a very suitable methodology to enhance the nucleate boiling heat transfer performance, especially by breaking the bubbles and preventing dry-out. In this sense, the researchers Zaghdoudi and Lallemand [46] studied pool boiling heat transfer enhancement by a DC electric field for n-pentane, R-113, and R-123. The authors found that high DC electric field promoted HTC and CHF enhancements and prevented hysteresis. The level of enhancement of the HTC and CHF through the action of the electric field varied with different working fluids employed in the experiments. Accordingly, the authors Hristov et al. [47] observed a similar phenomenon through the nucleate pool boiling process of the R-123 thermal fluid under an electric field. The authors also found that their results were not consistent with the published ones from similar experiments but under different surface conditions and different wire mesh electrode configurations. Additionally, the authors Di Marco and Grassi [48] studied the enhancement in nucleate pool boiling induced by the electric field under both terrestrial and microgravity conditions. It is well known that there is an additional force acting on the vapor bubbles under the influence of an electrostatic field, given that the electric permittivity of the vapor is different from that of the fluids. Moreover, other researchers have investigated the effect of the electric field acting together with different types of structures. This was the case with the authors Darabi and Ekula [49], who developed a chip-integrated microcooling device by combining electrohydrodynamic (EHD) pumping to form a thin film and used its evaporation to dissipate heat. The fundamental EHD interactions are summarized in the schematic diagram in **Figure 6**.

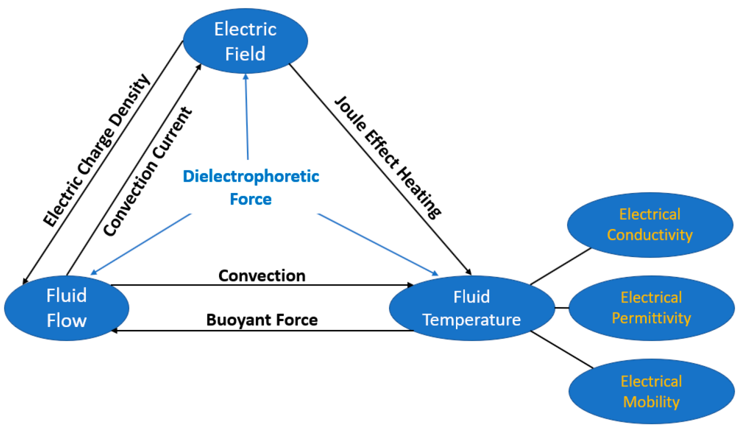

Figure 6. Schematic diagram of the electrohydrodynamic (EHD) interactions.

2.1.5. Magnetic Field

Magnetic fields have already been applied to enhance boiling heat transfer. These fields improve the heat transfer from the boiling surface to the fluid by creating external forces. Boiling heat transfer enhancement under the influence of a magnetic field is derived mainly from the effect of the magnetic field on the vapor bubbles. When a non-uniform magnetic field is applied, the magnetic thermal fluids will be under the action of the magnetic body force, which is directly proportional to the magnetization magnitude. The magnetization of a magnetic fluid decreases with its increasing temperature, and hence, it is larger in the lower temperature layer where the magnetic body force is stronger. The magnetic fluids can be attracted by the magnetic body force in the high magnetic field strength region, while the bubbles in the magnetic fluid are transferred from the strong magnetic force regions to the weak magnetic force regions. The force pointing toward the low magnetic field strength is called magnetic levitation force and acts on the vapor bubbles. At the departure stage of the bubbles from the heating surface and without the magnetic field activation, the buoyancy force can be balanced by the surface tension. In cases where magnetic field is applied, the magnetic levitation force acting on the bubble gains importance. In cases where the magnet is placed at the bottom of the pool boiling vessel, there exists an equilibrium of forces on the bubble, that is, the upward magnetic levitation force results in a smaller bubble departure diameter. Furthermore, under an applied magnetic field, a force will act at the center of the vapor bubbles, making them elongated and aligned with the direction of the magnetic field. The heat is transmitted from the heating surface to the bubbles by the evaporation of the superheated layer between the bottom of the bubbles and the surface. Also, the magnetization in the temperature difference layer is weaker than in the bulk liquid, resulting in a weaker magnetic force so that the elongated bubble deforms further as its bottom spreads out on the heating surface. Thus, the bubble becomes slender in the middle and broader at the bottom, and this new shape increases the area of the temperature difference layer beneath the bottom of the bubble and causes faster growth of the bubbles by the evaporation of the microlayer and a higher lift-off speed. Though the bubbles exhibit smaller departure diameters, faster growth, and higher velocities in the presence of a magnetic field, the lower number of bubbles generated stimulates only a minor improvement in the nucleate boiling heat transfer performance at low heat fluxes, where the natural convection boiling surface area is larger. At high heat fluxes, the nucleate boiling surface area also increases with the presence of more bubbles on the surface, and the influence of the magnetic field on the bubbles in the boiling heat transfer becomes stronger and, consequently, the boiling heat transfer enhancement increases remarkably. An example of a published work on the matter is that of Ozdemir et al. [50], who enhanced nucleate boiling heat transfer by nearly 42% using magnetic nanoparticles dispersed in water as operating fluid and with the assistance of a magnetic field. The authors reported that in cases where nanoparticles with higher mass ratios were suspended and with no application of the magnetic field, more vapor bubbles gathered on the heating surface, diminishing the heat transfer capability. The researchers interpreted this fact based on the increase in fluid drag caused by the rising bubbles due to the mass fraction of the magnetic nanoparticles. Nevertheless, under the effect of the magnetic field and because of the improved mixing of nanoparticles, the influence of the mass fraction on the nucleate boiling heat transfer performance became negligible. The authors Rahmati et al. [51] investigated water nucleate boiling using a copper heating surface covered by a mixture of magnetic and non-magnetic beads under the action of an alternating magnetic field. The forces acting on the beads and the principles of actuation of the beads for heat transfer performance enhancement are presented schematically in **Figure 7**. The number of beads was selected in such a way that they would cover 1/3, 1/2, and 2/3 of the heating surface. The magnetic field was adjusted through the coil's input voltage. It was found that the beads increased the number of nucleation sites as they extended the available heat transfer surface and improved the mixing because of the random movement of the beads on the surface. Also, when the magnetic field was applied, the movement of the beads became more organized, and the bubble detachment rate suddenly increased because of the stronger force generated from the beads. In view of the obtained experimental results, the authors arrived at the following conclusions: (i) There was an optimum number of beads that maximized the HTC. An excessive number of beads hindered their movement and eliminated the influence of the applied magnetic field. An insufficient number of beads reduced the available heat transfer area and collisions between the beads. (ii) In cases where the magnetic field was not applied, the HTC value did not vary appreciably with the different number of beads. Nonetheless, in cases where the magnetic field was applied, the HTC increased, which was caused by the vigorous mixing promoted by the motion of the beads and the consequent turbulence. In these last cases, the nucleate HTC was enhanced with increasing field strength, with the highest enhancement reported for the application of a magnetic field of 90 V, where the HTC value was 22% higher than that obtained without magnetic field action. (iii) The nucleate boiling heat transfer performance was ameliorated with increasing magnetic field cut-off frequency.

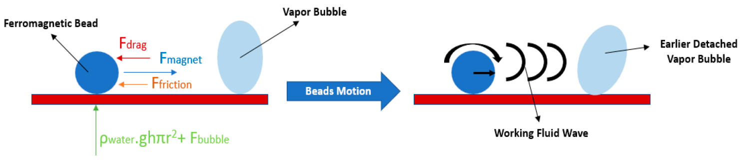

Figure 7. Schematic diagram of the actuating forces and principle of actuation of the beads.

2.1.6. Gas Injection

Another active nucleate boiling enhancement technique that has been employed is the inclusion of dissolved inert gas in the working thermal fluids. Employing this enhancement technique, Kandlikar investigated the impact of the inclusion of dissolved inert gas in the FC-72 coolant. The researcher concluded that the dissolved inert gas provoked an appreciable reduction in the incipience temperature caused by the partial filling of the cavities of the heating surface with gas embryos. Nonetheless, because of the eventual removal of the dissolved gas from the surface cavities, the nucleate boiling heat transfer behavior at high heat fluxes was found to be like the one verified with the degassed FC-72 refrigerant. Accordingly, the researchers O'Connor et al. [52] and You et al. [53] arrived at similar conclusions and highlighted that the boiling incipience for the FC-72 refrigerant was sensitive to the dissolved inert gas at concentrations superior to 0.005 mol/mole. In the experimental work carried out by the authors Sarafraz et al. [54], the effects of SO_2 gas injection on the water nucleate pool boiling heat transfer performance were studied. In this direction, the effects of different operating parameters, including the mole fractions of SO_2 dissolved in water and different imposed heat fluxes up to 114 kW/m^2, on the nucleate pool boiling HTC, nucleation site density, and bubble departure diameter were experimentally examined. The researchers found that the incorporation of SO_2 in the vapor inside the bubbles, especially near the heat transfer surface, enhanced the nucleate pool boiling HTC. The investigation team also found that the nucleation site density could be described by an exponential function of the imposed heat flux and proposed a new prediction correlation for the nucleation site density that was able to estimate the mean bubble diameters and the local disturbance caused by the bubble frequency rate. In view of the experimental results, the authors stated that the HTC considerably increased with increasing gas rates dissolved in the water because of the higher mass transfer driving force between the SO_2 captured inside the bubbles and the bulk of the solution and due to the increased local disturbance provoked by the gas injection. The researchers also concluded that the number of active nucleation sites, bubble nucleation, and diameter appreciably increased with an increasing SO_2 injection rate. Nonetheless, the bubbles may have been generated due to the injection process and local disturbance due to the interaction of SO_2 bubbles.

2.1.7. Suction

The suction of the operating fluid in a nucleate pool boiling system can considerably improve the heat transfer behavior of the system. The improvement in the nucleate boiling heat transfer performance that can be accomplished through the active suction enhancement technique can be attributed to the enhancement of the fluid supplement and the increased bubble departure velocity caused by the local low pressure and shear lift force induced by the suction process. It should be stated that, for most active boiling heat transfer enhancement techniques, the detachment of the coalesced bubbles from the heating surface and the flow status of the working fluid have a great influence on the heat transfer behavior. On the one hand, when the fluid flow velocity increases, the thickness of the heat transfer boundary layer may be reduced, causing a delay in the onset of nucleate boiling. On the other hand, the heating surface will be covered by a vapor film at high heat fluxes, which will make liquid replenishing difficult, and the heat transfer performance will therefore deteriorate. Hence, the suction of the fluid and the bubbles perpendicular to the heating surface is one of the suitable active methods to enhance the pool boiling heat transfer performance. The method has therefore attracted more attention from the research community to fully understand its underlying mechanisms. A representative published work is the study carried out by the authors Zhang et al. [55], in which a smooth silicon chip was immersed in the subcooled FC-72 coolant to infer the nucleate pool boiling heat transfer behavior. The authors developed an apparatus incorporating a suction tube with different inner diameters of 2.2, 5.5, and 9.6 mm and tested the distances from the tube inlet to the chip heating surface of 1, 3, and 5 mm. For comparison purposes, the researchers also performed an experiment without suction on the same heating surface. In view of the obtained results, the authors deduced the following conclusions: (i) The suction pool boiling considerably improved the pool boiling heat transfer performance when compared to the result achieved without the suction process. The suction process enhanced the shear lift force of the vapor bubbles on the surface, increased the turbulent kinetic energy of the bubbles departing from the heating surface, increased the velocity of the two-phase motion, and facilitated fluid replenishing. (ii) The various distances between the suction tube inlet and the heating surface and the distinct tube diameters impacted the nucleate pool boiling heat transfer performance. For the same distance between the suction tube inlet and the heating surface, there was an ideal inner tube diameter that provided the highest CHF value and also possessed the highest HTC at high heat fluxes. For the same tube diameter, a shorter distance between the suction tube inlet and the heating surface promoted better heat transfer capability. Hence, the suction distance order for improving the heat transfer was 1 mm > 3 mm > 5 mm, and the suction tube inner diameter order for improving the heat transfer was 5.5 mm > 9.6 mm > 2.2 mm. (iii) The pool boiling process with suction presented higher CHF and HTC values than those obtained for pool boiling without suction. On the one hand, considering a tube diameter of 5.5 mm and 1 mm distance between the suction tube inlet and the chip heat transfer surface, the CHF increased by nearly 39.2% when compared to the value achieved with pool boiling without the suction process, having a maximum value of 33.4 $W \cdot cm^{-2}$. On the other hand, the HTC was enhanced by around 79.8% compared to that with the pool boiling process without suction, achieving a value of 1.093 $W \cdot cm^{-2} \cdot K^{-1}$.

2.1.8. Local Jet Impingement

The combined usage of boiling and jet impingement procedures is a relevant contributor to the development of effective and compact thermal management systems that deal with high heat flux dissipation requirements in applications such as computers, power electronics, and gas turbines. The impact of the geometric and working parameters on the single-phase jet impingement process that facilitates the achievement of the optimal pressure drop, flow rate, temperature uniformity, and heat dissipation capability is already known. The phase change heat transfer, together with the very high HTC achieved with the single-phase jet impingement, can enhance the heat removal capability and, at the same time, improve the temperature uniformity. Additionally, the sweeping of vapor from the heating surface through the action of the liquid jet greatly increases the CHF, especially when compared to that obtained with pure pool boiling [56]. Moreover, the researchers Ma and Bergles [57] investigated nucleate boiling using jet impingement for R113 with varying velocities, subcooling degrees, flow directions, and surface conditions. The authors employed jet diameters of 1.07 and 1.81 mm and two heaters of 5 × 5 mm^2 and 3 × 3 mm^2 dimensions. The authors confirmed that the temperature overshoot decreased with increasing jet velocity, which was attributed to the increase in the HTC with increasing velocity. Additionally, the surface status was also found to appreciably affect the fully developed boiling regime, with the boiling curves shifting because of the surface aging effect. Additionally, the authors Wolf et al. [58] studied the local free-surface planar water jet impingement boiling heat transfer characteristics with the aim of revealing the major factors impacting boiling heat transfer. The authors concluded that the heat transfer in the fully developed boiling regime was not influenced by the velocity of the jet but was instead determined by the evaporation and vigorous mixing provoked by the detachment of the bubbles. Nonetheless, in the single-phase and partial boiling regimes, the velocity of the jet had an appreciable impact on the HTC because of the convective heat transfer present in these regimes. The streamwise distance from the stagnation point showed a relative influence on the single-phase HTC but had no impact on the fully developed regime. Also, to ameliorate the thermal performance of the jet impingement process, the incorporation of enhanced nanostructures on the impinged surface has already been proposed [59]. Generally, the following concluding points concerning jet impingement heat transfer enhancement techniques can be listed: (i) In fully developed boiling regimes, the boiling curves for free circular or plan configurations are independent of the velocity and diameter of the jet and subcooling degree. Therefore, it can be inferred that the jet impingement boiling curve can be extrapolated from the pool boiling correlations. Nonetheless, the overshot temperature and CHF are influenced by the referred parameters. (ii) Conflicting findings and results have been published regarding submerged and confined jet impingement configurations in fully developed boiling regimes. Some researchers have found that the velocity of the jet and the degree of subcooling does not affect the boiling curve, whereas other authors have stated that these parameters strongly affect the nucleate pool boiling heat transfer behavior. Nonetheless, it can be argued that in the submerged configuration, the variation of the far-field temperature in the operating fluid greatly affects the effectiveness of the nucleate boiling heat transfer process, while in the confined configuration, the mixing of the vapor bubbles and the impinging jet is strongly promoted. (iii) The roughness of the heating surface has been found to be critical to jet impingement boiling heat transfer. (iv) The jet impingement boiling heat transfer has been found to be independent of the wettability (contact angle characterization) of the boiling surface in the single-phase convection, while it is affected by the mentioned wettability in boiling heat transfer. (v) In cases where the area of the heating surface is larger than the jet diameter and the thermal boundary condition is close to the wall heat flux, the existence of the single-phase convection at the stagnation zone and boiling at the far-field on the heating surface is likely. The diagram in **Figure 8** shows the typical range of the heat transfer coefficients associated with the mechanisms involved in local jet impingement pool boiling heat transfer enhancement.

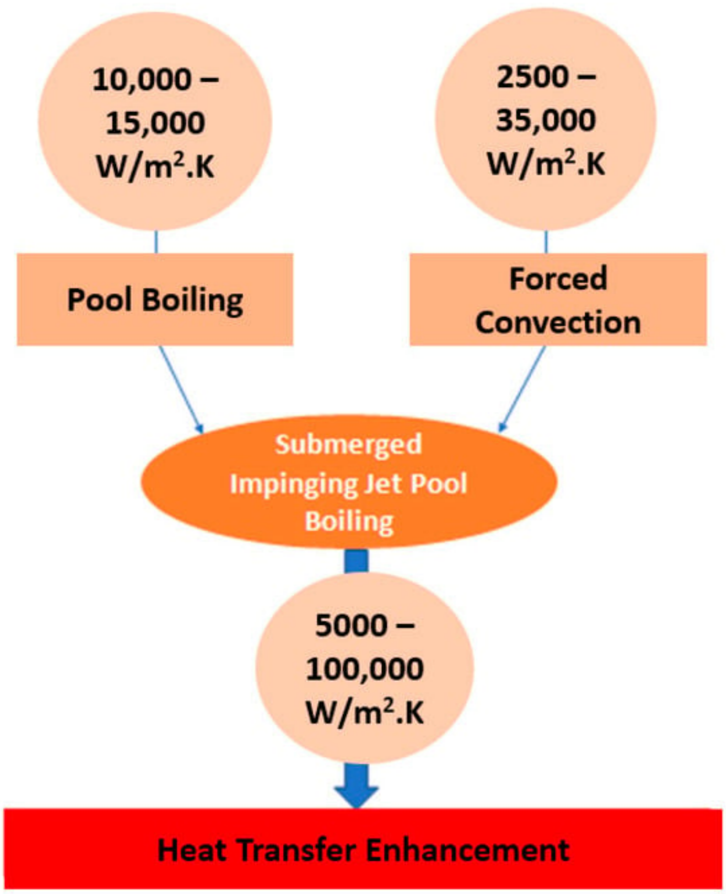

Figure 8. Schematic diagram showing the typical ranges of the heat transfer coefficients of the mechanisms involved in submerged impinging jet pool boiling.

2.1.9. Wall Deformation

It has already been found that one possible way to relieve the high temperature needs required for the onset of the nucleate boiling process is to increase the operating fluid stability by temporarily decreasing the pressure of the fluid. Accordingly, under confinement conditions, the low-amplitude dynamic deformation of the wall may change the liquid pressure, and hence, the morphing of the wall appears to be a promising attempt to control the onset of nucleate boiling and to reach boiling incipience at lower temperatures. The innovative active heat transfer enhancement technique that can be designated by wall deformation was proposed in the work performed by the authors Leal et al. [60]. The aim of the technique is to decrease the pool boiling incipience point through the dynamic deformation of the confinement wall in a narrow horizontal space. Such dynamic deformation generates pressure alterations that increases the fluid's metastability. It was developed as an in-house-built experimental apparatus to measure the boiling incipience temperature, and the obtained results were compared with the those offered by the available theoretical hydrodynamic/nucleation models. The main experimental parameters were 625 μm maximum distance between the heat transfer aluminum cylinder and the confinement plate, a maximum deformation amplitude of 210 μm, and a frequency varying between 0 and 100 Hz, which were employed for determining the impact of frequency on the nucleate boiling incipience. The experimental results revealed a nearly linear decrease in the boiling incipience overheating with increasing frequency, which was interpreted by the authors as being the result of the liquid pressure variation. Also, the researchers noted that the dynamic deformation frequency increase increased the fluid pressure variation over time. During the liquid pressure reduction process, the overheating of the operating fluid increased due to reduction in the saturation temperature, and this increase may be enough for the onset of nucleate boiling. Additionally, for a better understanding of the impact of the deformation of the wall on boiling incipience superheating, the authors also proposed two different models: one hydrodynamic model and one nucleation model. In this sense, when using the nucleation model, the investigation team considered the pool boiling incipience as being independent of the level of confinement of the boiling heat transfer system. Finally, the boiling incipience temperature decreased when the deformation frequency of the wall was raised. Also, when wall deformation did not occur, the pool boiling incipience temperatures were consistent with the those given by the nucleation model. However, in cases where wall deformation was employed, the theoretical and experimental results differed considerably. For instance, within the range of frequencies considered, the decrease in the wall superheating was around only 2 K according to the nucleation model, while it was experimentally measured as being near 20 K. These discrepancies may reveal that the incipience temperature reduction was not provoked only by the reduction in fluid pressure. Indeed, other mechanisms should be considered to clarify the origin of these differences, like the transient and convection phenomena, and further experimental and numerical studies are required to better understand the decrease in the incipience point. The fundamental conclusion of the referred work was that the pool boiling incipience temperatures were reduced by the dynamic deformation of the wall effect. It also should be emphasized that for a deformation amplitude of 210 μm, a confinement distance of 625 μm, and a frequency of 100 Hz, the wall superheating at boiling incipience almost disappeared.

References

1. Kerlin, T.W.; Upadhyaya, B.R. Chapter 13—Boiling water reactors. In Dynamics and Control of Nuclear Reactors; Academic Press: Cambridge, MA, USA, 2019; pp. 167–189.
2. Singh, T.; Atieh, M.A.; Al-Ansari, T.; Mohammad, A.W.; Mckay, G. The Role of Nanofluids and Renewable Energy in the Development of Sustainable Desalination Systems: A Review. Water 2020, 12, 2002.
3. Moita, A.; Moreira, A.; Pereira, J. Nanofluids for the Next Generation Thermal Management of Electronics: A Review. Symmetry 2021, 13, 1362.
4. Sureshkumar, R.; Mohideen, S.T.; Nethaji, N. Heat transfer characteristics of nanofluids in heat pipes: A review. Renew. Sustain. Energy Rev. 2013, 20, 397–410.
5. Dixit, T.; Ghosh, I. Review of micro- and mini-channel heat sinks and heat exchangers for single phase fluids. Renew. Sustain. Energy Rev. 2015, 41, 1298–1311.
6. Zhang, K.-I.; Liu, Z.-H.; Zheng, B.-C. A new 3D chip cooling technology using micro-channels thermosyphon with super-moist fluids and nanofluids. Energy Convers. Manag. 2016, 128, 44–56.
7. Bergman, T.L.; Incropera, F.P.; DeWitt, D.P.; Lavine, A.S. Fundamentals of Heat and Mass Transfer; John Wiley & Sons: Hoboken, NJ, USA, 2011.
8. Khan, S.A.; Atieh, M.A.; Koç, M. Micro-Nano Scale Surface Coating for Nucleate Boiling Heat Transfer: A Critical Review. Energies 2018, 11, 3189.
9. Hsu, C.-C.; Chen, P.-H. Surface wettability effects on critical heat flux of boiling heat transfer using nanoparticle coatings. Int. J. Heat Mass Transf. 2012, 55, 3713–3719.

10. Motezakker, A.R.; Sadaghiani, A.K.; Çelik, S.; Larsen, T.; Villanueva, L.G.; Kosar, A. Optimum ratio of hydrophobic to hydrophilic areas of biphilic surfaces in thermal fluid systems involving boiling. Int. J. Heat Mass Transf. 2019, 135, 164–174.
11. Shen, B.; Mine, T.; Iwata, N.; Hidaka, S.; Takahashi, K.; Takata, Y. Deterioration of boiling heat transfer on biphilic surfaces under very low pressures. Exp. Therm. Fluid Sci. 2020, 113, 110026.
12. Kim, D.E.; Yu, D.I.; Jerng, D.W.; Kim, M.H.; Ahn, H.S. Review of boiling heat transfer enhancement on micro/nanostructured surfaces. Exp. Therm. Fluid Sci. 2015, 66, 173–196.
13. Kalita, S.; Sen, P.; Sen, D.; Das, S.; Das, A.K.; Saha, B.B. Experimental study of nucleate pool boiling heat transfer on microporous structured by chemical etching method. Therm. Sci. Eng. Prog. 2021, 26, 101114.
14. Mudhafar, M.A.H.; Zheng-hao, W. Optimization of Pool Boiling Heat Transfer on microporous metal coating surfaces with FC-72 as a working fluid. Heat Mass Transf. 2022, 58, 1963–1977.
15. Moghadasi, H.; Malekian, N.; Saffari, H.; Gheitaghy, A.M.; Zhang, G.Q. Recent Advances in the Critical Heat Flux Amelioration of Pool Boiling Surfaces Using Metal Oxide Nanoparticle Deposition. Energies 2020, 13, 4026.
16. Zhao, H.; Dash, S.; Dhillon, N.S.; Kim, S.; Lettiere, B.; Varanasi, K.K.; Hart, A.J. Microstructured Ceramic-Coated Carbon Nanotube Surfaces for High Heat Flux Pool Boiling. ACS Appl. Nano Mater. 2019, 2, 5538–5545.
17. Lee, S.; Seo, G.H.; Lee, S.; Jeong, U.; Lee, S.J.; Kim, S.J.; Choi, W. Layer-by-layer carbon nanotube coatings for enhanced pool boiling heat transfer on metal surfaces. Carbon 2016, 107, 607–618.
18. Mao, L.; Zhou, W.; Hu, X.; He, Y.; Zhang, G.; Zhang, L.; Fu, R. Pool boiling performance and bubble dynamics on graphene oxide nanocoating surface. Int. J. Therm. Sci. 2020, 147, 106514.
19. Liang, G.; Mudawar, I. Review of pool boiling enhancement by surface modification. Int. J. Heat Mass Transf. 2019, 128, 892–933.
20. Cho, H.J.; Wang, E.N. Bubble nucleation, growth, and departure: A new, dynamic understanding. Int. J. Heat Mass Transf. 2019, 145, 118803.
21. Liu, J.; Orejon, D.; Zhang, N.; Terry, J.G.; Walton, A.J.; Sefiane, K. Bubble Coalescence During Pool Boiling with Different Surface Characteristics. Heat Transf. Eng. 2024, 45, 360–380.
22. Wang, X.; Fadda, D.; Godinez, J.; Lee, J.; You, S.M. Effect of wettability on pool boiling heat transfer with copper microporous coated surface. Int. J. Heat Mass Transf. 2022, 194, 123059.
23. Xu, N.; Liu, Z.; Yu, X.; Gao, J.; Chu, H. Processes, models and the influencing factors for enhanced boiling heat transfer in porous structures. Renew. Sustain. Energy Rev. 2024, 192, 114244.
24. Bergles, A.E. The Influence of Heated-Surface Vibration on Pool Boiling. J. Heat Transfer. 1969, 91, 152–154.
25. Hosseinian, A.; Isfahani, A.H.M.; Shirani, E. Experimental investigation of surface vibration effects on increasing the stability and heat transfer coefficient of MWCNTs-water nanofluid in a flexible double pipe heat exchanger. Exp. Therm. Fluid Sci. 2018, 90, 275–285.
26. Unno, N.; Yuki, K.; Taniguchi, J.; Satake, S. Boiling heat transfer enhancement by self-excited vibration. Int. J. Heat Mass Transf. 2020, 153, 119588.
27. Zhang, B.; Gong, S.; Dong, S.; Xiong, Z.; Guo, Q. Experimental investigation on vibration characteristics of subcooled and saturated pool boiling. Appl. Therm. Eng. 2023, 218, 119297.
28. Prisnyakov, V.F.; Navruzov, Y.V.; Mamotov, P.V.; Stoichev, A.V. Characteristics of heat emission from a vibrating heat source in a vessel with liquid. Teplofiz. Vysok. Temp. 1992, 30, 105–110.
29. Zitko, V.; Afgan, N. Boiling Heat Transfer from Oscillating Surface. J. Enhanc. Heat Transf. 1994, 1, 191–196.
30. Atashi, H.; Alaei, A.; Kafshgari, M.H.; Aeinehvand, R.; Rahimi, S.K. New Pool Boiling Heat Transfer in the Presence of Low-Frequency Vibrations Into a Vertical Cylindrical Heat Source. Exp. Heat Transf. 2014, 27, 428–437.
31. Sathyabhama, A.; Prashanth, S.P. Enhancement of Boiling Heat Transfer Using Surface Vibration. Heat Transf. 2017, 46, 49–60.
32. Abadi, S.M.A.N.R.; Ahmadpour, A.; Meyer, J.P. Effects of vibration on pool boiling heat transfer from a vertically aligned array of heated tubes. Int. J. Multiph. Flow 2019, 118, 97–112.
33. Alangar, S. Effect of boiling surface vibration on heat transfer. Heat Mass Transf. 2017, 53, 73–79.
34. Alimoradi, H.; Zaboli, S.; Shams, M. Numerical simulation of surface vibration effects on improvement of pool boiling heat transfer characteristics of nanofluid. Korean J. Chem. Eng. 2022, 39, 69–85.
35. Brennen, C.E. Cavitation and Bubble Dynamics; Cambridge University Press: New York, NY, USA, 2014.

36. Quintana-Buil, G.; González-Cinca, R. Acoustic effects on heat transfer on the ground and in microgravity conditions. Int. J. Heat Mass Transf. 2021, 178, 121627.

37. Baffigi, F.; Bartoli, C. Heat transfer enhancement from a circular cylinder to distilled water by ultrasonic waves in subcooled boiling conditions. In Interdisciplinary Transport Phenomena VI: Fluid, Thermal, Biological, Materials and Space Sciences; Wiley: Volterra, Italy, 2009.

38. Tang, J.; Sun, L.; Wu, D.; Du, M.; Xie, G.; Yang, K. Effects of ultrasonic waves on subcooled pool boiling on a small plain heating surface. Chem. Eng. Sci. 2019, 201, 274–287.

39. Bartoli, C.; Baffigi, F. Use of ultrasonic waves in sub-cooled boiling. Appl. Therm. Eng. 2012, 47, 95–110.

40. Hetsroni, G.; Moldavsky, L.; Fichman, M.; Pogrebnyak, E.; Mosyak, A. Ultrasonic enhancement of subcooled pool boiling of freely oscillated wires. Int. J. Multiph. Flow 2014, 67, 13–21.

41. Sitter, J.S.; Snyder, T.J.; Chung, J.N.; Marston, P.L. Acoustic field interaction with a boiling system under terrestrial gravity and microgravity. J. Acoust. Soc. Am. 1998, 104, 2561–2569.

42. Kim, H.-Y.; Kim, Y.G.; Kang, B.H. Enhancement of natural convection and pool boiling heat transfer via ultrasonic vibration. Int. J. Heat Mass Transf. 2004, 47, 2831–2840.

43. Mondal, K.; Bhattacharya, A. Pool boiling enhancement through induced vibrations in the liquid pool due to moving solid bodies—A numerical study using the lattice Boltzmann method (LBM). Phys. Fluids 2021, 33, 093310.

44. Suriyawong, A.; Saisorn, S.; Wongwises, S. Pool boiling heat transfer enhancement of distilled water with passive rotating blades installed above the heating surface. Exp. Therm. Fluid Sci. 2017, 87, 109–116.

45. Ashouri, M.; Rahmati, P.; Hakkaki-Fard, A. On the effect of corrugated conical frustum on pool boiling heat transfer. Exp. Therm. Fluid Sci. 2022, 130, 110494.

46. Zaghdoudi, C.; Lallemand, M. Pool Boiling Heat Transfer Enhancement by Means of High DC Electric Field. Arab. J. Sci. Eng. 2005, 30, 189–212.

47. Hristov, Y.; Zhao, D.; Kenning, D.B.R.; Sefiane, K.; Karayiannis, T.G. A study of nucleate boiling and critical heat flux with EHD enhancement. Heat Mass Transf. 2009, 45, 999–1017.

48. Di Marco, P.; Grassi, W. Effects of external electric field on pool boiling: Comparison of terrestrial and microgravity data in the ARIEL experiment. Exp. Therm. Fluid Sci. 2011, 35, 780–787.

49. Darabi, J.; Ekula, K. Development of a chip-integrated micro cooling device. Microelectron. J. 2003, 34, 1067–1074.

50. Ozdemir, M.R.; Sadaghiani, A.K.; Motezakker, A.R.; Parapari, S.S.; Park, H.S.; Acar, H.Y.; Kosar, A. Experimental studies on ferrofluid pool boiling in the presence of external magnetic force. Appl. Therm. Eng. 2018, 139, 598–608.

51. Rhamati, P.; Ebrahimi-Dehshali, M.; Hakkaki-Fard, A. Enhancement of pool boiling heat transfer using ferromagnetic beads in a variable magnetic field. Appl. Therm. Eng. 2020, 164, 114439.

52. O'Connor, J.P.; You, S.M.; Chang, J.Y. Gas-Saturated Pool Boiling Heat Transfer from Smooth and Microporous Surfaces in FC-72. J. Heat Transf. 1996, 118, 662–667.

53. You, S.M.; Simon, T.W.; Bar-Cohen, A. Experiments on nucleate boiling heat transfer with a highly-wetting dielectric fluid. In Effects of Pressure, Subcooling and Dissolved Gas Content; American Society of Mechanical Engineers, Heat Transfer Division: Minnesota, MN, USA, 1990; pp. 45–142.

54. Sarafraz, M.M.; Peyghambarzadeh, S.M.; Fazel, S.A.A. Enhancement of the pool boiling heat transfer coefficient using the gas injection into the water. Pol. J. Chem. Technol. 2012, 14, 100–109.

55. Zhang, Y.; Liu, W.; Liu, B.; Yu, X.; Wei, J. Experimental Study of Enhanced Boiling Heat Transfer with Suction. Microgravity Sci. Technol. 2021, 33, 39.

56. Mitsutake, Y.; Monde, M. Ultra High Critical Heat Flux During Forced Flow Boiling Heat Transfer with an Impingement Jet. ASME J. Heat Transf. 2003, 125, 1038–1045.

57. Ma, C.-F.; Bergles, A.E. Jet impingement nucleate boiling. Int. J. Heat Mass Transf. 1986, 29, 1095–1101.

58. Wolf, D.H.; Incropera, F.P.; Viskanta, R. Local jet impingement boiling heat transfer. Int. J. Heat Mass Transf. 1996, 39, 1395–1406.

59. Ndao, S.; Peles, Y.; Jensen, M.K. Experimental investigation of flow boiling heat transfer of jet impingement on smooth and micro structured surfaces. Int. J. Heat Mass Transf. 2012, 55, 5093–5101.

60. Leal, L.; Lavieille, P.; Miscevic, M.; Pigache, F.; Tadrist, L. Control of pool boiling incipience in confined space: Dynamic morphing of the wall effect. In Proceedings of the 3rd Micro and Nano Flows Conference, Thessaloniki, Greece, 22–24 August 2011.