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Review Article

Advances in Nanofluid-Enhanced Pool and Flow Boiling Heat Transfer: A Comprehensive Review

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Abstract

Boiling heat transfer is an important thermal management mechanism in power generation, chemical processing, high-heat-flux electronics, refrigeration, nuclear reactors, and automotive systems because it enables large heat removal at comparatively small temperature differences. Nanofluids have emerged as promising working fluids for further improving boiling performance; however, published results remain highly scattered because critical heat flux and heat transfer coefficient depend simultaneously on nanoparticle composition, concentration, stability, surface condition, heater material, mass flux, pressure, vapor quality, and flow regime. This review addresses this gap by critically comparing experimental studies on nanofluid-enhanced pool and flow boiling and by organizing the available evidence according to working fluid, nanoparticle type, heater configuration, operating condition, HTC response, and CHF response. Al_2O_3 and TiO_2 are the most extensively investigated nanoparticles, whereas CuO, SiO_2, ZnO, Fe_3O_4, MgO, graphene oxide, carbon nanotubes, SiC, and graphite have also shown notable but condition-dependent performance. In pool boiling, reported CHF enhancements reach 200% for Al_2O_3 and TiO_2, 117% for ZnO, 100% for Al_2O_3-TiO_2 combinations, and 60% for SiO_2, while HTC improvements include 43% for Fe_3O_4, 20 to 30% for CuO, 28.7% for carbon nanotubes, and 22% for ZnO. Additional studies report study-specific pool-boiling maxima of 145 to 245% in CHF for reduced-graphene-oxide/water and 75% in HTC for Al_2O_3/water on smooth surfaces. In flow boiling, CHF enhancements of 100% for graphene oxide, 70% for Al_2O_3, 35% for SiC, and 13% for Al_2O_3 Cu are reported, whereas HTC increases reach 126% for ZnO, 86% for Al_2O_3, 30% for CuO, 27.97% for TiO_2, and 23.7% for MgO. The review shows that nanofluid boiling enhancement is governed by coupled fluid-surface-hydrodynamic interactions rather than thermal conductivity alone and identifies standardization, long-term stability, fouling, pressure-drop penalties, and predictive model validation as the principal unresolved challenges, requiring coordinated testing before reliable industrial implementation can be achieved across thermal systems and operating conditions.

Keywords

Nanofluids, Nanoparticle, Pool Boiling, Flow Boiling, Heat Transfer Enhancement, Surface Wettability, Critical Heat Flux, Nanoparticle Deposition, Surface Wettability

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1. Introduction

The analysis of heat transfer is of importance from the viewpoints of engineering and technology. According to thermodynamics, heat is the term used to describe heat energy transfer. The analysis is used to predict the potential energy transfer between material bodies as a result of a temperature difference [1]. Conduction, convection, and radiation are the three fundamental methods of heat transport, wherein conduction is the process [2] by which, through interactions between the particles of a substance, energy is transferred from the more energetic particles to the nearby, less energetic ones. On the other hand, convection is a method of transferring heat from a stationary solid surface to a moving liquid or gas nearby. In addition, the energy that matter emits as electromagnetic waves (or photons) as a result of changes to the electronic structures of atoms or molecules is known as radiation. In thermodynamics, the ratio between the heat flux and the thermodynamic force that propels the flow of heat is known as the heat transfer coefficient or film coefficient, or film efficiency, which is used to determine how much heat is transferred, usually by convection or a change in the phase between a fluid and a solid [3].

On the other hand, boiling happens at the solid-liquid interface when the surface temperature exceeds the saturation temperature, which corresponds to the liquid's pressure and causes a phase transition from liquid to vapor. The major characteristic of the boiling process is the rapid production of vapor bubbles at the solid-liquid interface. Once they reach a particular size, the vapor bubbles start to travel away from the liquid's surface and toward the free surface. Figure 1 shows the boiling curve of water [4]. In addition, boiling is a rare thermal-hydraulic phenomenon in nature compared to many others. It's caused by hot rocks or magma near the Earth's surface, subsurface volcano eruptions, or, in an extreme instance. Also, after a few opportunities to study this process in nature, humans eventually discovered boiling and began using it to prepare food for both simple and complex technical purposes [5].

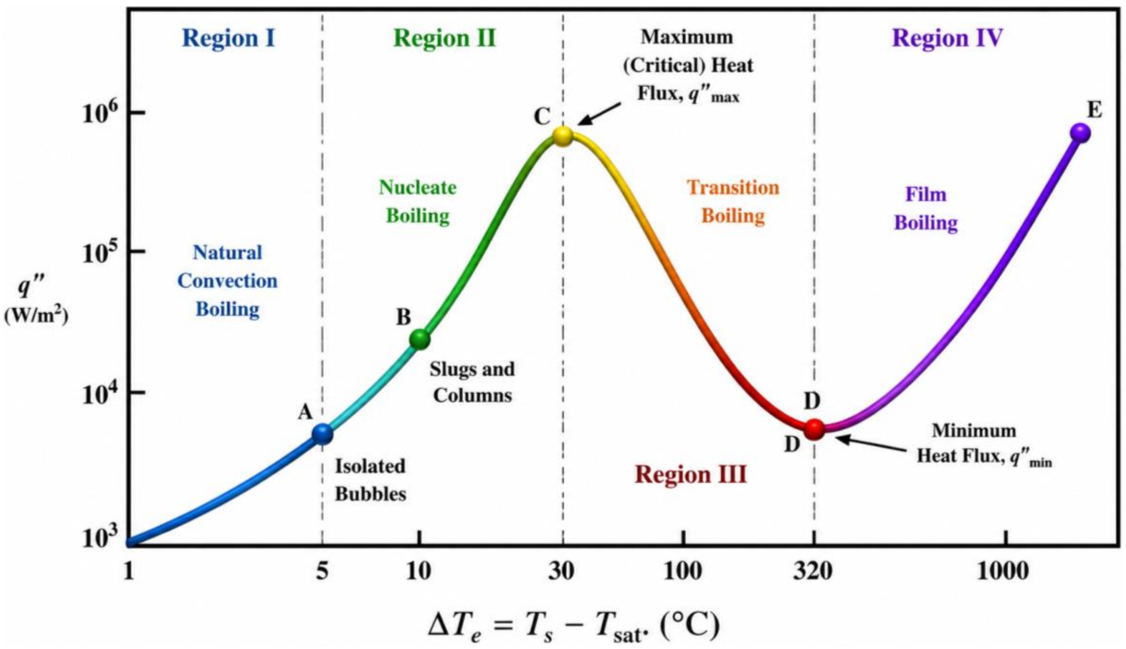


Figure 1. *Boiling curve of water showing the variation in heat flux with surface superheat, $\Delta T_e = T_s - T_{sat}$, across the natural-convection, nucleate-boiling, transition-boiling, and film-boiling regimes. The critical and minimum heat-flux points are also indicated [4].*

Nanofluids are mixtures of metal, metal-oxide, and carbon nanotube nanoparticles which ranging from 1 to 100 nm in base fluids like water, oil, and ethylene glycol. In applications, nanofluids are used in fuel cells, hybrid engines, refrigeration, heat exchangers, and coolants in nuclear reactors due to their unique features [6]. Furthermore, nanofluids are suspensions of nanoparticles with small particle sizes and lower concentrations in common or base fluids. These fluids have been identified by researchers as unique heat transfer transporters due to their thermophysical properties and a variety of potential benefits in conventional thermal engineering applications [7]. Figure 2 shows the TEM images of water-based carbonic nanofluids prepared using the one-step method (As shown in Figure 2(a)), and alumina nanofluids using the two-step method (As shown in Figure 2(b)) [8].

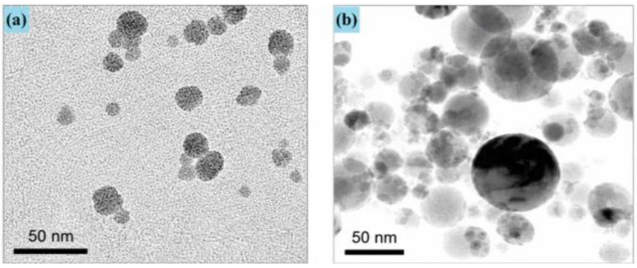


Figure 2. Transmission electron microscopy (TEM) images of water-based nanofluids prepared using different synthesis routes: (a) carbon-based nanofluid produced by the one-step method and (b) alumina nanofluid prepared by the two-step method. Scale bars: 50 nm [8].

On the other hand, phase change materials (PCMs) are used for volume fluctuations, good thermal stability, and the ability to freeze without requiring a lot of supercooling. The charging and discharging of energy in a passive energy system are provided by the temperature difference between the PCMs and the environment. PCMs also used in the manner described above have the ability to automatically store or release energy depending on the ambient temperature. Gypsum is a PCM material for use in building materials, wall partitions, and as an interior wall cladding material [9]. Microchannels are widely used in many industrial applications. To address the issues with thermal management in electronic components, it is essential to suggest a more efficient and compact device. In addition, with the advantages of superior heat transfer performance, smaller geometric size and volume per heat load, lower coolant requirement, and lower operational cost, microchannel heat sinks (MCHS) are seen to be an innovative cooling technology for electronic systems. It is acknowledged that MCHS can work in conjunction with other technologies to address the complex thermal challenges that the industry is currently facing [10].

The dimensions of the channel are of great importance in the process of flow boiling heat transfer. Depending on the size of the channel cross-section, different physical phenomena take place during the flow. The presented one of the main classifications of channels is presented, which includes two main groups: mini-channels (d_h less than 6 mm) and conventional channels (d_h greater than 6 mm) [11]. The thermal conductivity and viscosity of Al_2O_3 nanofluid based on car engine coolant were found to result in a significant enhancement of the heat transfer coefficient [12]. The analysis regarding the assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in microchannels [13]. An experimental investigation of convective heat transfer of Al_2O_3/water nanofluid in a circular tube [14]. The experimental investigation of laminar convective heat transfer and pressure drop of water-based Al_2O_3 nanofluids in a fully developed flow regime [15]. The effect of Cu/water hybrid nanofluids on heat transfer. The above discussion depicts the fundamental analysis of heat, heat transfer, boiling, nanofluids, phase change materials, and microchannels. The following section deals with boiling heat transfer in terms of pool boiling and flow boiling [16].

2. Nanofluid Boiling Heat Transfer

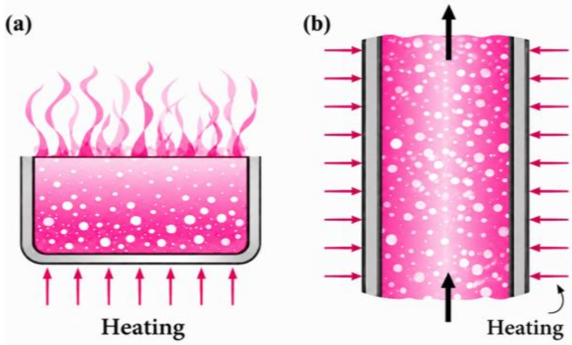


Figure 3. Schematic comparison of boiling heat-transfer configurations: (a) pool boiling, in which a stationary liquid is heated from below, and (b) flow boiling, in which the liquid flows through a heated channel [4].

Boiling heat transfer is seen to have occurred in many engineering applications such as in the cooling of nuclear reactors, the cooling of high-power electronic components, and heat exchangers. The industrialized world largely depends on the widespread use of fossil fuels to solve many undesirable issues, such as diminishing energy sources and causing global warming, which is thought to be the main driver of climate change. As a result, improving energy efficiency and environmental protection has become a must for the globe [7]. Figure 3 shows the types of pool boiling and flow boiling heat transfer [4].

The modeling of boiling heat transfer for prospects. One of the most frequent phenomena in heat transfer processes occurring in numerous industrial applications is boiling heat transfer, which also involves a phase change from liquid to vapor. In heat exchange systems and high-tech applications, boiling is both a challenging process and a highly effective way to transfer heat [5]. When a liquid comes into contact with a surface that is kept at a temperature higher than the liquid's saturation temperature, boiling eventually takes place at the liquid-solid interface. Pool boiling and convective flow boiling are the two categories into which boiling is traditionally divided based on the relative bulk motion of a liquid's body to the heating surface [17].

The boiling heat transfer properties of Al_2O_3-water nanofluids in swirl microchannels under terrestrial acceleration and gravity fields [18]. The boiling heat transfer performance and phenomena of Al_2O_3–water nanofluids from a plain surface in a pool [19]. The analysis of nanofluids and CHF through an experimental and analytical study [20]. The above discussion in this section depicts the investigation of boiling heat transfer with nanofluids, and hence, it is seen in

Figure 4 that annual publications on boiling heat transfer with nanofluids since 2003 [7].

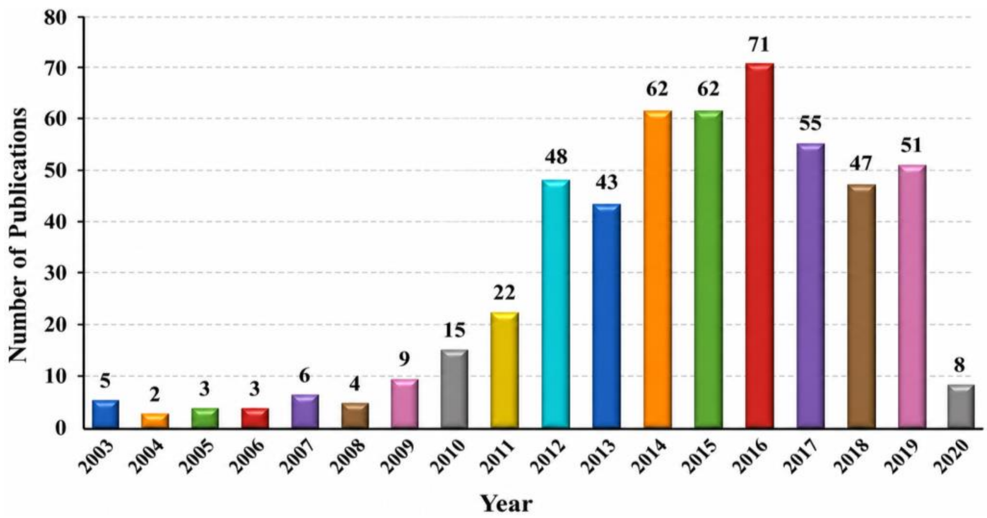


Figure 4. *Annual number of publications on boiling heat transfer using nanofluids from 2003 to 2020 [7].*

2.1. Pool Boiling Heat Transfer with Nanofluids

Pool boiling is involved in many chemical and petrochemical processes, including distillation, air separation, refrigeration, and power cycles. It is revealed that in several decades of pool boiling research, the basic mechanism remains poorly understood [21]. The commonly used particle-fluid combinations include diamond and carbon nanotubes suspended in water, ethylene glycol, ethanol, and other liquids, as well as metal nanoparticles Cu, Au, and Ag and oxide nanoparticles Al_2O_3, CuO, SiO_2, TiO_2, and CeO_2. In the presence of nanoparticles, particle-particle and particle-molecule interactions play a crucial role in improving the thermal conductivity of the nanofluids, which boosts heat transfer [22]. The experimental investigation of the pool boiling heat transfer properties of nanofluids in nucleate pool boiling was done on a horizontal, flat, square copper surface with heat fluxes ranging from 10 to 200 kW/m^2 [23]. It is seen in the study that when the particle concentration is 0.001 vol. %, the addition of the SDBS reduces the enhancement of the boiling heat transfer characteristics by nanoparticles. However, when the particle concentrations are 0.01 vol. % and 0.1 vol. %, the addition of the SDBS increases the enhancement of the boiling heat transfer characteristics by nanoparticles. An experimental design to examine how a nanofluid made of Fe_3O_4 and water, or ferrofluid, transferred heat during pool boiling under atmospheric pressure. The analysis of various volume concentrations of nanofluids showed that boiling heat transfer increased with concentration at low concentrations but decreased at high concentrations. It was determined that the boiling heat transfer coefficient increased up to 43% at a 0.1% volume concentration of nanofluid. Additionally, experimental research demonstrated that boiling heat transfer was decreased and increased, respectively, by the presence of positive and negative magnetic field gradients [24].

The pool-boiling heat transfer of non-Newtonian Al_2O_3/CMC nanofluids was investigated within the broader context of mechanical [35] and thermal engineering research [25]. The CMC solution carboxymethyl cellulose dissolved in water was mixed mechanically and ultrasonically to disperse the Al_2O_3 nanoparticles, resulting in a stable nanofluid. The effect of nanoparticles on the critical heat flux of water in pool boiling heat transfer of base fluids H_2O was studied using a Cu plate-type heater [26]. Pool boiling heat transfer to aqueous alumina nanofluids on the plain and concentric circular micro-structured (CCM) surfaces [27]. Pool boiling heat transfer experiments in silica-water nanofluids [28]. An experimental investigation into the pool boiling heat transfer of aqueous-based γ alumina nanofluids [29]. The theoretical analysis of pool boiling characteristics of Al_2O_3 nanofluid according to volume concentration and nanoparticle size [30]. The preparation and pool boiling characteristics of copper nanofluids over a flat plate heater [31]. In addition, the role of ions in pool boiling heat transfer of pure and silica nanofluids [32]. The pool boiling characteristics of nanofluid on a flat plate based on heater surface analysis [33]. The nucleate pool boiling heat transfer characteristics of TiO_2-water nanofluids at very low concentrations [34]. On the other hand, the pool boiling heat transfer of non-Newtonian nanofluids [35].

2.2. Flow Boiling Heat Transfer with Nanofluids

The analysis of flow boiling was experimentally carried out not only to measure the forced and nucleate flow boiling heat transfer coefficient of CuO/water nanofluids but also to investigate the effects of various operating conditions on the single-phase and two-phase flow-boiling of test nanofluids, including heat flux, flow rate, and dilute volumetric concentrations of test nanofluid [36]. In addition, it was seen in convective-dominated flow boiling that the heat transfer coefficient increased with increasing mass flux and vapor quality and was independent of heat flux [37]. The above discussion depicts that flow boiling has various regimes as shown in Figure 5 [38].

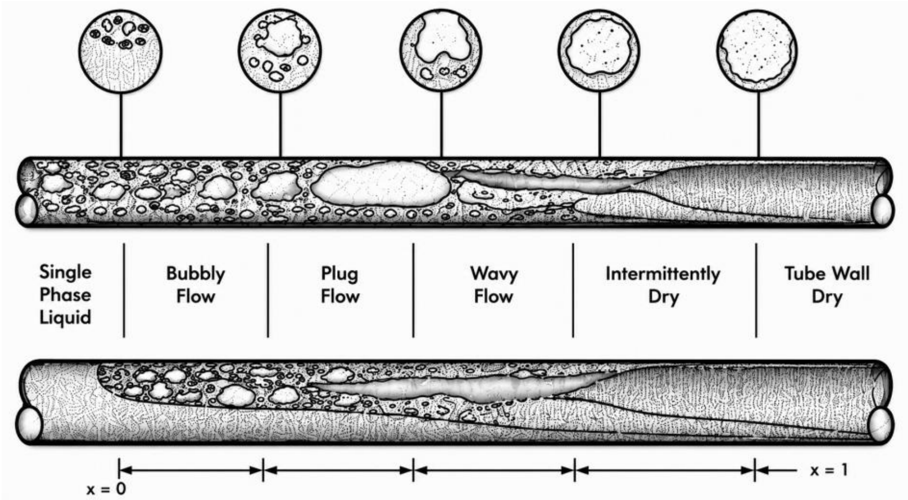


Figure 5. *Schematic illustration of flow boiling regimes in a heated channel, showing the transition from single-phase liquid to bubbly, plug, wavy, intermittently dry, and tube wall dry flow patterns along the flow direction [38].*

According to the findings of a study, at mass fluxes of 2000 to 2500 kg/m^2s, the CHF values of the nanofluids were increased by up to 40 to 50% compared to pure water, but not at 1500 kg/m^2s. The enhancement was attributed to the deposition of nanoparticles, and it appeared to be weakly dependent on nanoparticle concentration for the alumina nanofluids compared to the zinc-oxide and diamond nanofluids [39]. There is a requirement for a cooling system that offers a high HTC and high CHF due to the increase in the rate of heat dissipation in devices (CHF). The size of the devices decreases as a result of the increased energy efficiency of the boiling systems due to HTC. High CHF is also necessary to dissipate the heater's extremely high heat flux before it reaches the dry-out point. [40]. Figures 6 and 7 show the cross-sectional view of the microchannel test piece and three boiling regimes in a microchannel, case II-10, G = 330 kg/m^2s, $T_{f,\,in}$ = 92.1°C [8, 41].

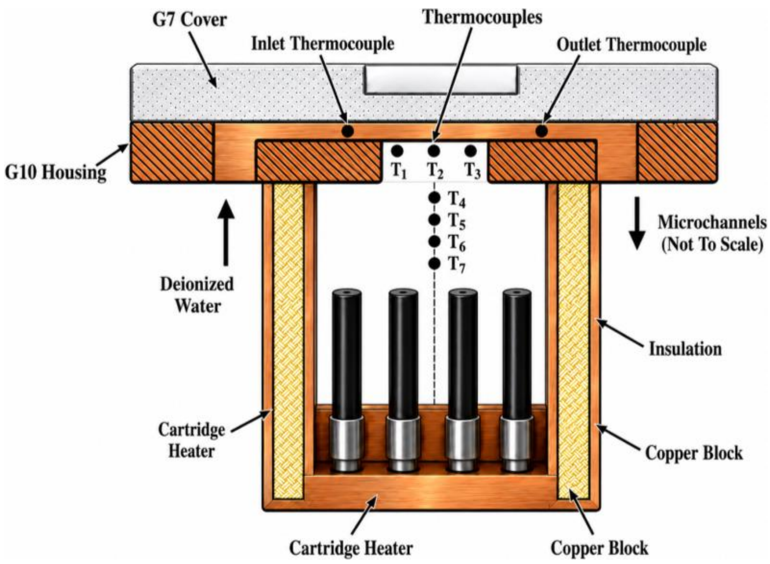


Figure 6. *Cross-sectional schematic of the microchannel flow boiling test section, illustrating the heating assembly, thermocouple arrangement, insulation, and coolant flow configuration [41].*

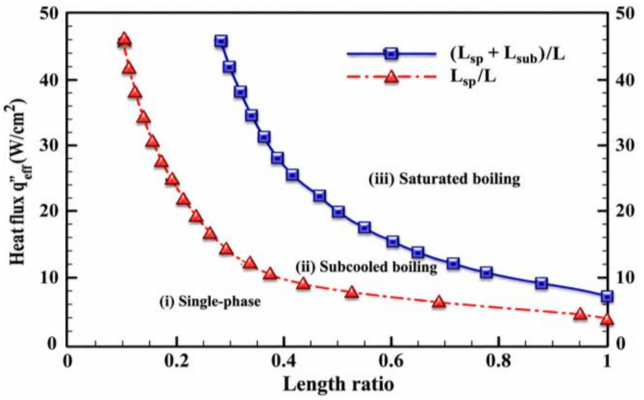


Figure 7. Heat flux distribution along a microchannel under single-phase, subcooled boiling, and saturated boiling regimes at G = 330 kg/m².s and $T_{f,in}$ = 92.1°C [8].

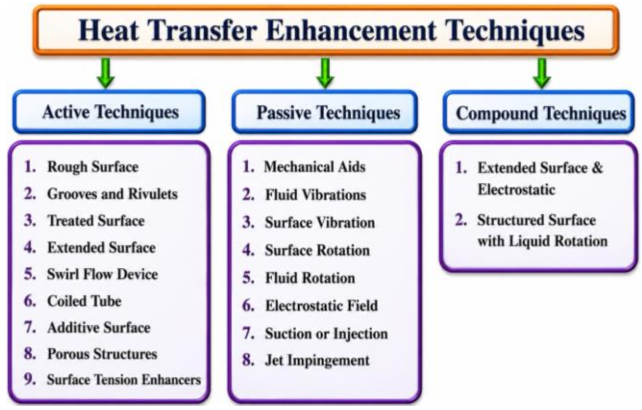


Figure 8. Classification of heat transfer enhancement techniques, including active, passive, and compound methods used to improve thermal performance [46].

The flow boiling heat transfer properties of the MgO/terminal 66 nanofluid as a potential coolant were experimentally investigated on a copper-made disc. The results showed that bubble formation caused a pressure drop inside the test section. The heat transfer coefficient improvement was at its highest at wt. % = 0.1, or 23.7%, and the maximum improvement was 16.2% and 13.3%, respectively [42]. The effects of nanoparticles on the heat transfer properties of a refrigerant-based nanofluid flowing inside a horizontal smooth tube were presented, and a correlation for forecasting the heat transfer performance of a refrigerant-based nanofluid. The results of the experiments demonstrated that the heat transfer coefficient of refrigerant-based nanofluids based on refrigerants was greater than that of pure refrigerants, with a maximum enhancement of 29.7% [43]. The experimental investigation subsequently made a comparison of subcooled flow boiling of TiO_2 nanofluid in a vertical and horizontal tube [44]. The subcooled flow boiling heat transfer of dilute alumina, zinc oxide, and diamond nanofluids at atmospheric pressure. The above discussion presents an analysis of boiling heat transfer in pool and flow boiling for various nanofluids [45]. The following section deals with boiling heat transfer enhancement in pool and flow boiling.

3. Boiling Heat Transfer Enhancement

This review article's goal is to analyze, discuss, and contrast recent research on boiling heat transfer enhancement methods. This would make it easier for the research and industry communities to decide on the best surface structure and surface manufacturing process for a specific fluid. Figure 8 shows the heat transfer enhancement techniques [46]. In Figure 8, the above discussion depicts that the heat transfer enhancement techniques can be classified as active, passive, and compound.

Two main categories of methodologies have been suggested to enhance nucleate boiling heat transfer: active and passive. The active techniques require external power, and passive techniques do not directly apply external power [47]. The nucleate boiling is an effective heat-transfer mechanism in terms of boiling regimes; it must not exceed the CHF. In addition, localized overheating at the heated surface and a reduction in the rate of heat transmission occur together with the development of CHF [48]. Islam et al. illustrated recent developments in advanced automotive-engine technology, including thermal engineering concepts [49]. Boiling phenomena and nanofluids have been investigated in various engineering and non-engineering applications. The purpose of this paper was to discuss how surface coating affected the heat transfer coefficient and critical heat flux in pools and the flow boiling phenomenon [50]. The research on improving phase change heat transfer into two categories: first, an investigation into the fluid flow or transport mechanism over a micro- or nano-structured surface, which is of utmost importance; second, actual computational and experimental methods to increase the CHF for a given surface or device [51].

Enhancing CHF was necessary to prevent boiling crises and to improve the HTC to improve the efficiency of energy conversion in the boiling process [52]. Hu et al. Efficient heat transfer mechanisms were essential for achieving high power densities and optimal system efficiency in all power generation, refrigeration, and advanced electronic systems. Additionally, improved the CHF by 112% and increased the LPT by 40K when compared to a conventional aluminum surface [53]. On the other hand, the nucleate boiling heat transfer enhancement for water and FC-72 on titanium oxide and silicon oxide surfaces [54]. In addition, the boiling of refrigerants on enhanced surfaces and the boiling of nanofluids [55].

3.1. Pool Boiling Heat Transfer Enhancement

Surface enhancements can take the shape of area or geometrical changes, changes in roughness, or changes in the material. The area or geometry is modified by mini- or micro-structures. These adjustments increase surface area without growing the footprint. Implementing nano- and porous structures on a heated surface has the power to change the surface energy, which changes the surface's wettability [56]. The CHF phenomena can lead to a substantial HTC reduction, which is followed by a notable increase in surface temperature. Therefore, HTC should be maximized to improve the boiling heat transfer, which would increase to CHF. As soon as the CHF threshold is reached, the efficiency of heat transfer abruptly decreases, leading to localized overheating of the heated surface. Maintaining CHF within a believable limit is essential for maintaining the system's safety since there is a direct correlation between the boiling limit and actual physical burnout of the heated surface. Figure 9 shows the comparison between common and ameliorated pool boiling curves [57].

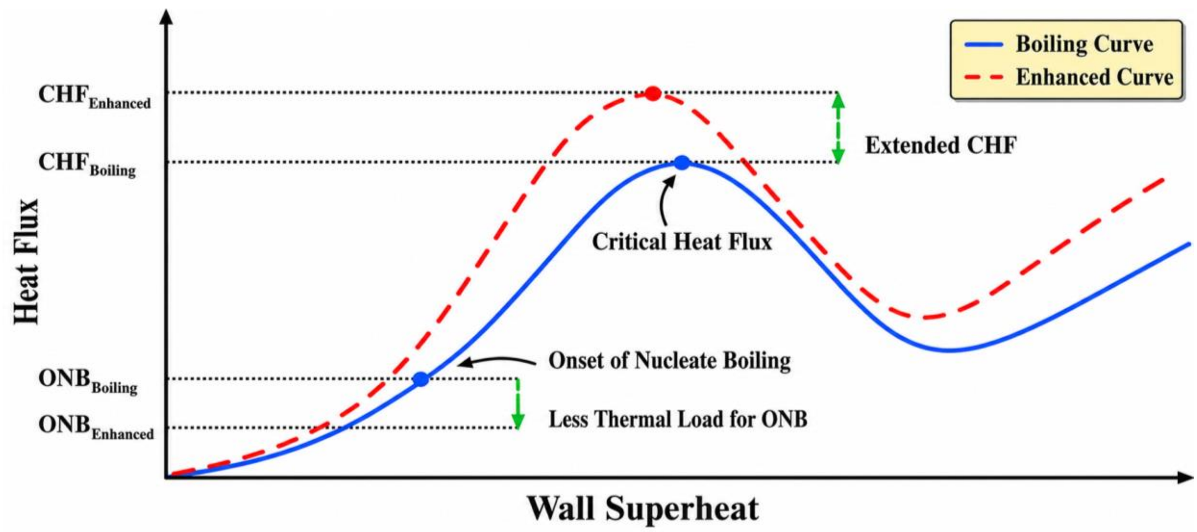


Figure 9. Comparison of conventional and enhanced pool boiling curves, illustrating reduced onset of nucleate boiling (ONB), increased critical heat flux (CHF), and improved boiling heat transfer performance achieved by surface enhancement techniques [57].

A liquid containing a colloidal dispersion of solid particles with diameters generally below 100 nm is referred to as a nanofluid. Nanoparticle-based materials and suspensions have also been considered in broader engineering and effluent-treatment applications [58]. Nanofluids commonly exhibit higher thermal conductivity than their base fluids. However, nanoparticle deposition on the heating surface can increase surface wettability, reduce the density of active nucleation sites, and consequently weaken the heat-transfer coefficient. The changes in the heating surface morphology, such as a reduction in active nucleation sites and the contact angle, are to blame for the CHF enhancement and HTC degradation caused by the use of nanofluids during pool boiling. However, for low nanofluid concentrations, the nucleation sites that are created by the deposition of nanoparticles can also help to improve the HTC [59]. Despite the consistency of the databases for the CHF, convective heat transfer coefficient, and thermal conductivity of nanofluids, the boiling HTC of alumina nanofluids is not as well standardized. To put it another way, some researchers have reported that there has been no change in the nucleate boiling regime's heat transfer, but others have reported a reduction or an increase in heat transfer [60]. The Marangoni effect on nucleate pool boiling with various working fluids. According to the experimental findings, the surface tension gradient caused Marangoni convection, which increased the CHF of the binary fluid up to 1.52 times that of water and the CHF of the self-rewetting fluid up to 1.91 times that of water [61].

The pool boiling experiments were carried out to investigate the relationship between the CHF, surface wettability, and nucleate boiling heat transfer as they relate to the boiling time in nanofluids using TiO_2-water nanofluids as the test liquid. In the experiments, the maximum CHF enhancement was found to be 91%, and a significant correlation between CHF and the contact angle was also observed. These thermal phenomena are relevant to the broader study of fire prevention and industrial safety [62]. Reduced graphene oxide (rGO) was produced from graphite using chemical reduction and the modified Hummers' method. The influence of rGO/water nanofluids on CHF enhancement during pool-boiling heat transfer was then investigated. Results showed that for the tested concentrations, CHF was increased by 145 to 245% [63]. The heat transfer coefficient for DI water and an Al_2O_3-water-based nanofluid boiling in a pool at saturation conditions. The applied heat flux ranged from 100 to 800 kW/m^2, and the average size of the nanoparticles was 10 nm. In comparison to DI water, it was found that the heat transfer coefficient for boiling nanofluid pools increased by up to 75% and 15% for smooth [62, 63] and rough surfaces, respectively [64]. The effect of nanoparticles on the CHF of water in pool boiling heat transfer [26]. On the other hand, the nucleate boiling heat transfer enhancement for water and FC-72 on titanium oxide and silicon oxide surfaces [54]. The boiling of refrigerants on enhanced surfaces and the boiling of nanofluids [55]. In addition, the pool boiling heat transfer to aqueous alumina nanofluids on the plain and concentric circular micro-structured (CCM) surfaces [27].

Pool boiling heat transfer experiments in silica-water nanofluids [28]. The experimental investigation into the pool boiling heat transfer of aqueous-based γ alumina nanofluids [29]. The thermal conductivity and viscosity of Al_2O_3 nanofluid based on car engine coolant [12]. The boiling heat transfer performance and phenomena of Al_2O_3–water nanofluids from a plain surface in a pool [19]. The theoretical analysis of pool boiling characteristics of Al_2O_3 nanofluid according to volume concentration and nanoparticle size [30]. The preparation and pool boiling characteristics of copper nanofluids over a flat plate heater [31]. Boiling time effect on CHF enhancement in pool boiling of nanofluids [65]. The role of ions in pool boiling heat transfer of pure and silica nanofluids [32]. Pool boiling characteristics of nanofluid on a flat plate based on heater surface analysis [33]. The experimental study of critical heat flux enhancement during forced convective flow boiling of nanofluid on a short heated surface [66]. The nanofluids and critical heat flux are explained in the pool boiling [20]. Figure 10 shows (a) long-term boiling performance with saturated water on an Al_2O_3 nano-porous surface at atmospheric pressure and (b) boiling curves for both enhanced and plain surfaces in water [47].

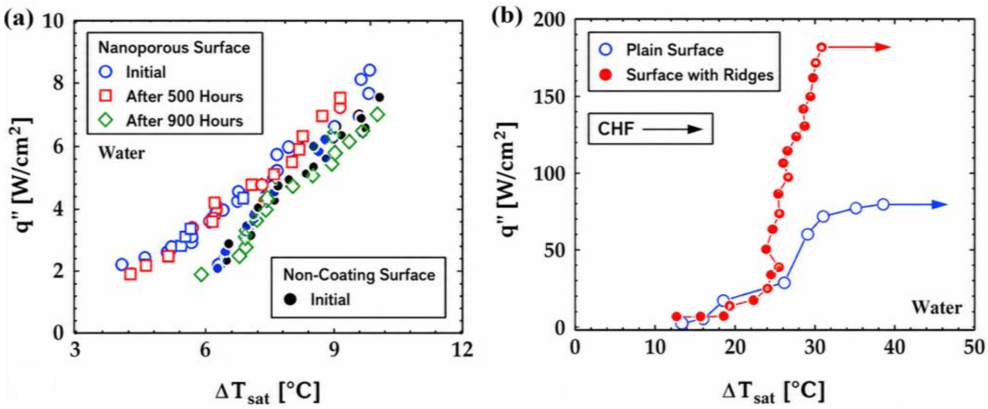


Figure 10. *Boiling performance of enhanced heat transfer surfaces: (a) Long-term pool boiling performance of saturated water on an Al_2O_3 nano-porous surface under atmospheric pressure, and (b) Comparison of boiling curves for enhanced and plain surfaces in water [47].*

Figure 11 shows the (a) boiling curves of deionized water and SiO_2 nanofluids on hydrophilic surfaces and (b) variation of boiling heat transfer coefficient versus heat flux for deionized water and SiO_2 nanofluids on hydrophilic surfaces [67].

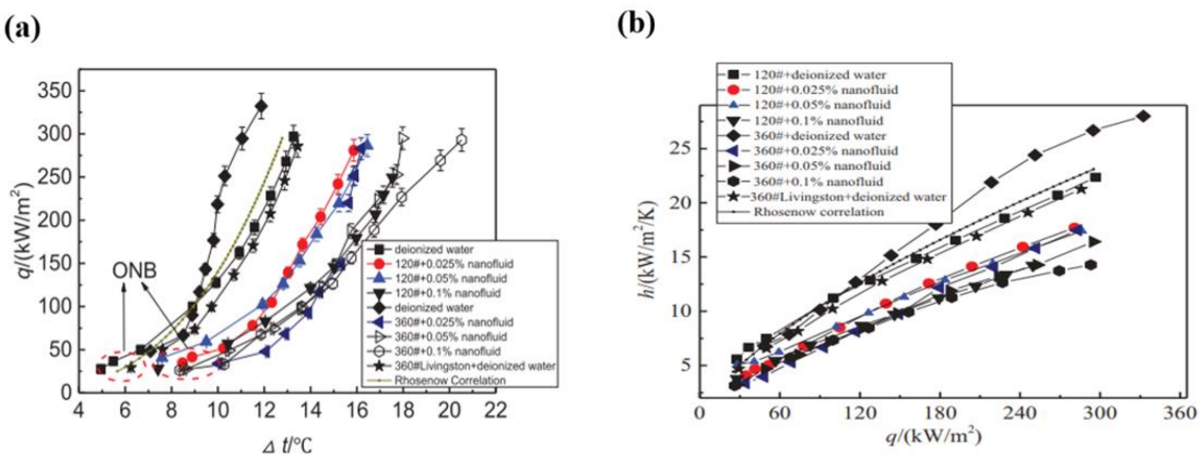


Figure 11. *Boiling characteristics of deionized water and SiO_2 nanofluids on hydrophilic surfaces: (a) Pool boiling curves at different nanoparticle concentrations, and (b) Variation of the heat transfer coefficient with heat flux [67].*

3.2. Flow Boiling Heat Transfer Enhancement

The enhancement of flow-boiling heat transfer is important in many engineering applications. Kim et al. [68] illustrated the CHF of flow boiling heat transfer for its augmentation. In this study, the CHF of Al_2O_3 nanofluids increased during flow boiling by up to 70%. At 0.01 vol. % concentrations and a mass flux of 100 kg/m^{2}s, the maximum CHF enhancement of 70.24% was observed. Figure 12 shows the flow boiling experiment [69]. In addition to nanofluid-assisted boiling enhancement, optimization of heat transfer equipment through advanced surface geometries and thermal system design has also demonstrated significant improvements in heat transfer efficiency. Louvered fin configurations can effectively enhance convective heat transfer by increasing fluid mixing and reducing thermal resistance, making them attractive for compact heat exchanger applications [70]. Furthermore, efficient thermal management remains a key consideration in high-temperature energy systems, including nuclear power plants, where enhanced boiling heat transfer contributes to improved operational safety, cooling reliability, and overall system performance [71].

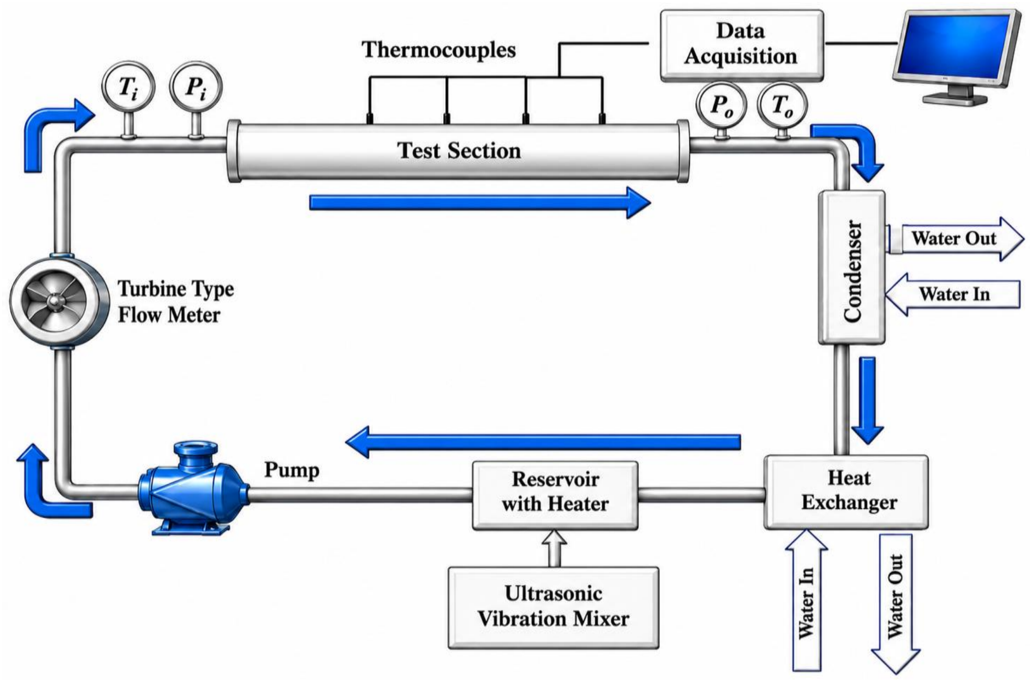


Figure 12. Schematic diagram of the experimental setup for flow boiling heat transfer using nanofluids [69].

Experimentally, the heat transfer characteristics of SiC/H_2O and Graphite/H_2O nanofluids during flow boiling. When compared to deionized water, the flow boiling heat transfer capacities of 0.1vol% SiC/H_2O nanofluid increased from −24.7% to 30.6%. Instead, it changed for 0.1 vol. % Graphite/H_2O nanofluid from −29.4% to 13.3% [72]. The use of nanofluid boiling to improve heat transfer. Figure 13 shows the two-step method for nanofluid formulation [73].

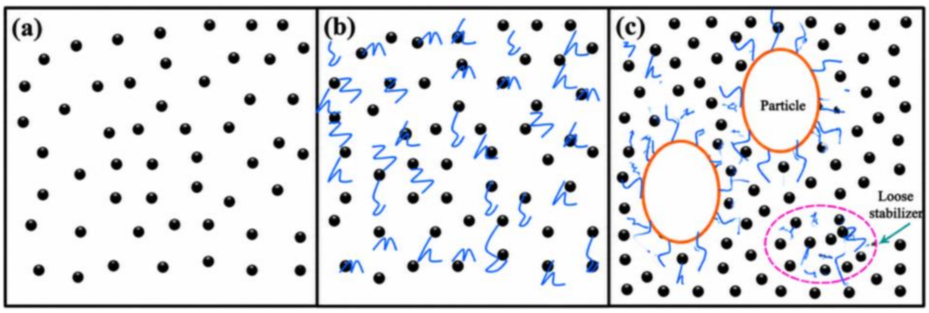


Figure 13. Schematic illustration of the two-step nanofluid preparation method: (a) pure base fluid, (b) base fluid with stabilizers, and (c) nanofluid with dispersed nanoparticles stabilized in the liquid [73].

The effects of nanoparticles on the heat transfer properties of a refrigerant-based nanofluid flowing inside a horizontal smooth tube and predicted a correlation for forecasting the heat transfer performance of a refrigerant-based nanofluid. The results of the experiments demonstrated that the heat transfer coefficient of nanofluids based on refrigerants was greater than that of pure refrigerants, with a maximum enhancement of 29.7% [43]. The improvement of thermal performance through enhanced heat transfer mechanisms is also important in various engineering systems, including steam power plants, biomass energy systems, and industrial thermal equipment. Recent studies have shown that optimizing heat transfer processes can significantly improve energy efficiency, exergy performance, and system reliability in thermal power applications [74, 75]. Moreover, advances in manufacturing technologies and material processing contribute to the development of durable heat transfer components capable of operating under severe thermal conditions [76]. Experimental investigations on engineering materials further support the importance of selecting appropriate materials with improved mechanical and thermal characteristics for reliable long-term operation of heat transfer systems [77].

A mechanism of heat transfer enhancement or deterioration of nanofluid flow boiling heat transfer [78]. The pool boiling heat transfer of non-Newtonian nanofluids. Figure 14 shows the variation of the heat transfer coefficient, h (kW/m^{2}K), of ZnO-water nanofluid with heat flux at different ZnO nanoparticle volume fractions and 400 kg/m^{2}s mass flow rate [35, 69]. Figure 14 illustrates the variation of the heat transfer coefficient (kW/m^2·K) of ZnO-water nanofluids with heat flux at different ZnO nanoparticle volume fractions and a mass flow rate of 400 kg/m^2·s [69]. Figure 15 shows the effective heat transfer coefficient of water and alumina nanofluids at G = 1500 kg/m^{2}s and G = 2000 kg/m^{2}s [45].

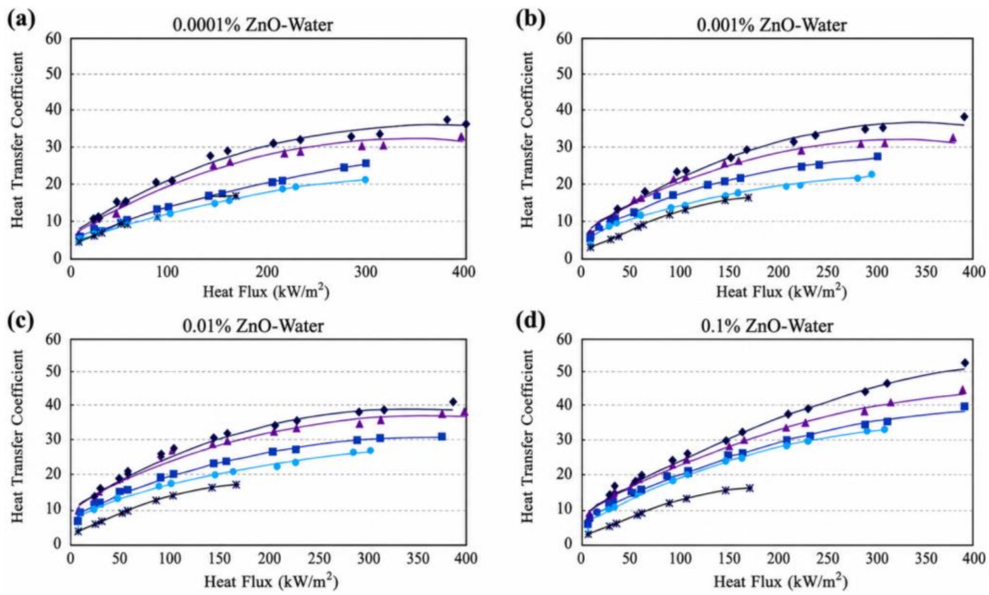


Figure 14. *Variation of the heat transfer coefficient (HTC) of ZnO water nanofluids with heat flux at a mass flow rate of 400 kg m^{-2} s^{-1} for nanoparticle volume fractions of (a) 0.0001 vol.%, (b) 0.001 vol.%, (c) 0.01 vol.%, and (d) 0.1 vol.% [69].*

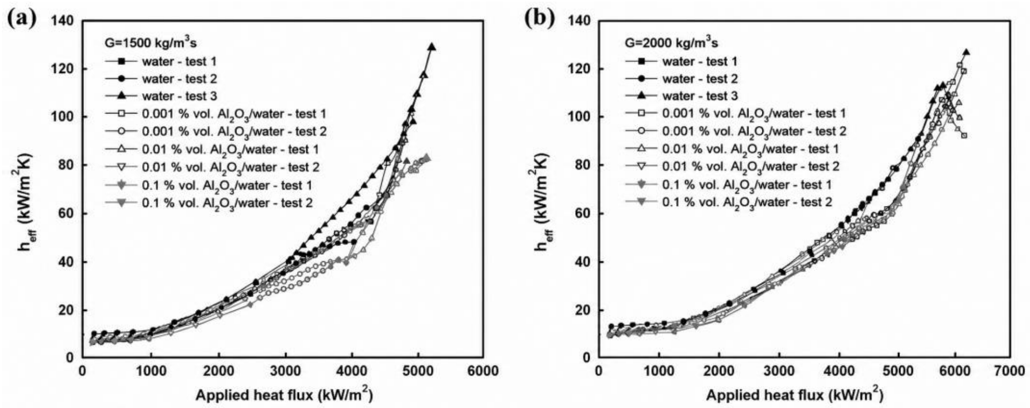


Figure 15. *Effect of Al_2O_3 Water Nanofluids on the Heat Transfer Coefficient Under Different Mass Flow Rates: (a) Heat Transfer Coefficient at G = 1500 kg/m^2·s and (b) Heat Transfer Coefficient at G = 2000 kg/m^2·s [45].*

4. Comparative Analysis of Pool and Flow Boiling Performance

The analysis of heat, heat transfer, boiling heat transfer, including pool boiling and flow boiling, and boiling heat transfer enhancement, including pool boiling and flow boiling heat transfer enhancement, is carried out in the previous section. The findings of the heat transfer enhancement in pool boiling and flow boiling are provided in the following table.

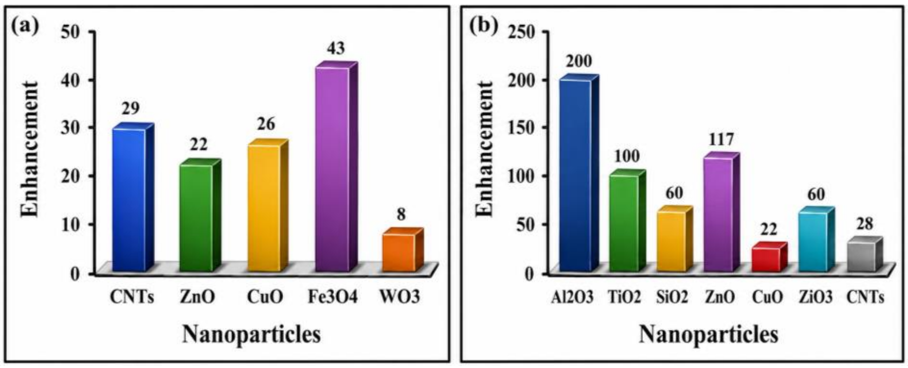


Figure 16. *Bar chart to illustrate maximum increase (%) of (a) HTC and (b) CHF in pool boiling for different nanoparticles.*

Table 1. *Summary of experimental studies on pool boiling heat transfer enhancement using various nanofluids.*

SL No.	Nanofluids		Heater Type	Observation	Ref.
	Nano-particles	Base Fluids			
01.	Al_2O_3		Copper plate	CHF enhancement reported up to approximately 200%; enhancement was not attributed solely to bulk thermal conductivity	[26]
02.	TiO_2		Copper surface	CHF increased by a maximum of 38.2%	[54]
03.	Alumina	H_2O	Copper plate	BHT enhanced between 11 and 21%. With rising particle concentration, BHT increased.	[55]
04.	Alumina		Copper plate	CHF Enhancement and HTC increased	[27]
05.	SiO_2		NiCr wire	CHF enhancement up to 60%	[28]
06.	Al_2O_3		Stainless steel plate	CHF increased by about 40%.	[29]
07.	ZiO_3	Ethylene glycol	Cu plate	CHF Enhancement and HTC increased	[12]
08.	Al_2O_3		Stainless steel	BHT decreased. CHF increased up to 50%.	[19]
09.	Al_2O_3	H_2O	0.025vol.%, 50 nm	CHF of the nanofluid increased	[30]
10.	Cu		Stainless-steel plate	CHF Enhancement and deterioration	[31]
11.	TiO_2		NiCr wire	CHF increased up to 200%	[65]
12.	SiO_2	H_2O	NiCr wire	Constant BHT. CHF increased up to 60%	[32]
13.	Alumina		Cu plate	CHF Enhancement and HTC deterioration	[33]
14.	CNTs	H_2O and R-22	Stainless steel tube	HTC was observed to increase up to 28.7% at heat fluxes of fewer than 30 kW/m^2	[63]
15.	Al_2O_3	H_2O	Cu plate	CHF Enhancement	[66]
16.	Al_2O_3 and TiO_2	H_2O	NiCr wire	CHF increased up to 100%	[20]
17.	ZnO	EG	0.5 to 3.7 vol.%	HTC increased about 22% at a concentration of 1.6 %.	[79]

SL No.	Nanofluids		Heater Type	Observation	Ref.
	Nano-particles	Base Fluids			
				Maximum enhancement of CHF was found to be 117% at φ=2.6 %	
18.	CuO	Pentane	0.005% and 0.01%	HTC increased up to 20–30% for brass surface and 15–25% at the nanoparticle concentration of 0.005%	[24]
19.	Fe_3O_4	H_2O	0.1 vol.%	HTC increased up to 43%	[28]
20.	WO_3		0.005%, 0.01% vol.	HTC ratio was increased by about 6.7%	[80]

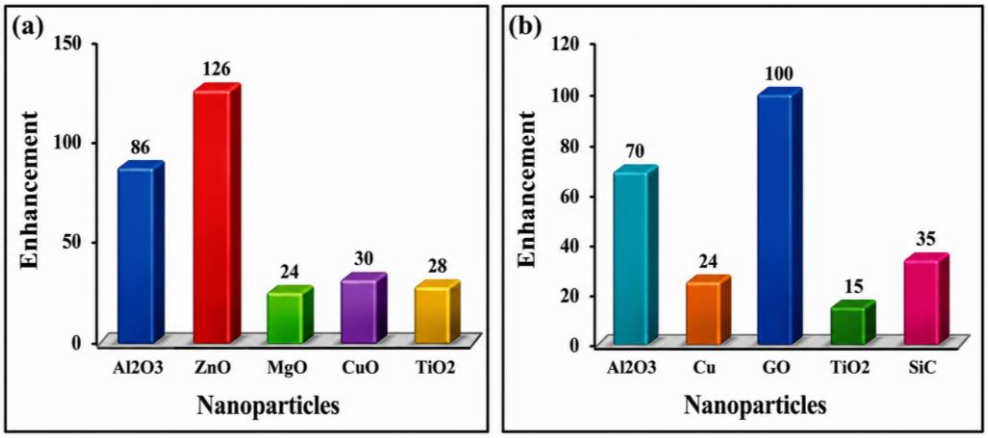


Figure 17. Comparison of the maximum enhancement in (a) heat transfer coefficient (HTC) and (b) critical heat flux (CHF) during flow boiling for different nanoparticles.

Table 2. Summary of experimental studies on flow boiling heat transfer enhancement using various nanofluids.

Sl No.	Nanofluids		Heater Type	Observation	Ref.
	Nano-particles	Base Fluids			
01.	Metal Oxide	H_2O	0.2 wt. %, NP 40nm	HTC increased by 17%	[81]
02.	Copper		50 nm parallel mini channels of dh = 800 µm.	With increasing nanoparticle concentration, BHT enhanced.	[13]
03.	Al_2O_3		Stainless steel	CHF enhancement 70%	[68]
04.	TiO_2		0.001, 0.005 and 0.01wt.%	At a given mass flux, HTC increased up to 27.97%.	[44]
05.	Al_2O_3		Cu tube	CHF enhancement	[14]
06.	TiO_2		Cu surface	Enhancement up to 15%	[34]
07.	ZnO		0.0001-0.1vol.%; NPs, D-100 (30 to 50) nm	At higher concentration, HTC increased by 126%.	[69]
08.	Al_2O_3	DI- H_2O	Cu tube	CHF enhancement 32%	[15]
09.	CuO		0.1 to 0.3 wt.%	HTC increased with the mass flow rate.	[36]
10.	GO		0.01 vol.%	CHF increased by about 100%.	[45]
11.	Al_2O_3, Cu	H_2O	Heated circular tube	CHF enhancement 13%	[16]
12.	SiC and Graphite		0.1 vol.%	At 0.1 vol.% SiC / H_2O and Graphite / H_2O	[78]

Sl No.	Nanofluids Nano-particles	Base Fluids	Heater Type	Observation	Ref.
				nanofluid, BHT increased.	
13.	CuO	R-113	Cu surface	Enhancement up to 30%	[43]
14.	Al_2O_3	H_2O	Stainless-steel heater	Enhancement up to 25%	[35]
15.	MgO	Therminol 66	0.1.0.2 and 0.3 wt.%	Maximum HTC enhancement was 23.7% at wt.% = 0.1.	[82]
16.	ZnO	H_2O	0.005 to 0.02 vol.%	Heat transfer rate of Al_2O_3/H_2O nanofluid was increased by flow boiling by roughly 86%.	[83]

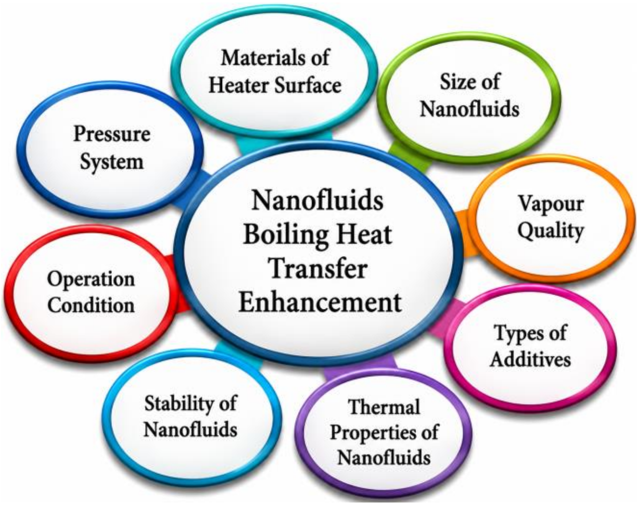


Figure 18. *Key factors influencing the enhancement of pool and flow boiling heat transfer using nanofluids.*

In the above discussion, the boiling heat transfer enhancement with nanofluids has been analyzed. The above discussion depicts that the boiling heat transfer with nanofluids can be augmented using various factors such as system pressure, materials of the heater surface, and size. Figure 16 illustrated a bar chart to illustrate the maximum increase (%) of (a) heat transfer coefficient (HTC) and (b) critical heat flux (CHF) in pool boiling for different nanoparticles. Figure 17 represented a bar chart to illustrate the maximum increase (%) (a) heat transfer coefficient (HTC) and (b) critical heat flux (CHF) in flow boiling for different nanoparticles or binary nanoparticles. Figure 18 demonstrate the factors affecting boiling heat transfer enhancement with nanofluids.

5. Discussion of Boiling Heat Transfer Performance

5.1. Cross-Study Trends and Comparative Assessment

The reviewed literature confirms that nanofluids can improve both pool- and flow-boiling performance, but the magnitude and direction of the response are controlled by the complete experimental system. As summarized in Figure 19, boiling performance (HTC and CHF) is governed by the coupled interactions among the nanofluid state, boiling-surface characteristics, and operating conditions rather than by any individual parameter. Nanoparticle material, primary particle size, agglomerate size, concentration, base-fluid composition, pH, zeta potential, surfactant type, ultrasonication history, and sedimentation stability determine the state of the suspension before boiling begins. During operation, heater material, roughness, oxidation state, wettability, orientation, pressure, heat flux, mass flux, vapor quality, channel geometry, and boiling duration further influence the measured HTC and CHF.

Al_2O_3 and TiO_2 dominate the literature because they are comparatively available, chemically stable, and compatible with water-based systems. Their frequent use, however, should not be interpreted as evidence that they are intrinsically superior to ZnO, SiO_2, CuO, Fe_3O_4, MgO, ZrO_2, WO_3, or carbon-based nanomaterials. The relationships illustrated in Figure 19 also explain why different studies often report contrasting boiling behaviors, as variations in nanofluid preparation, surface condition, and operating parameters modify the governing boiling mechanisms. HTC reflects the rate of heat transfer at a given wall superheat and is highly sensitive to nucleation-site density, bubble departure, microlayer evaporation, and thermal resistance at the interface. CHF represents the upper heat-flux limit before persistent dryout or vapor blanketing occurs and is strongly influenced by wettability, capillary liquid supply, and vapor removal. A surface modification can therefore improve CHF while leaving HTC unchanged or even reducing it.

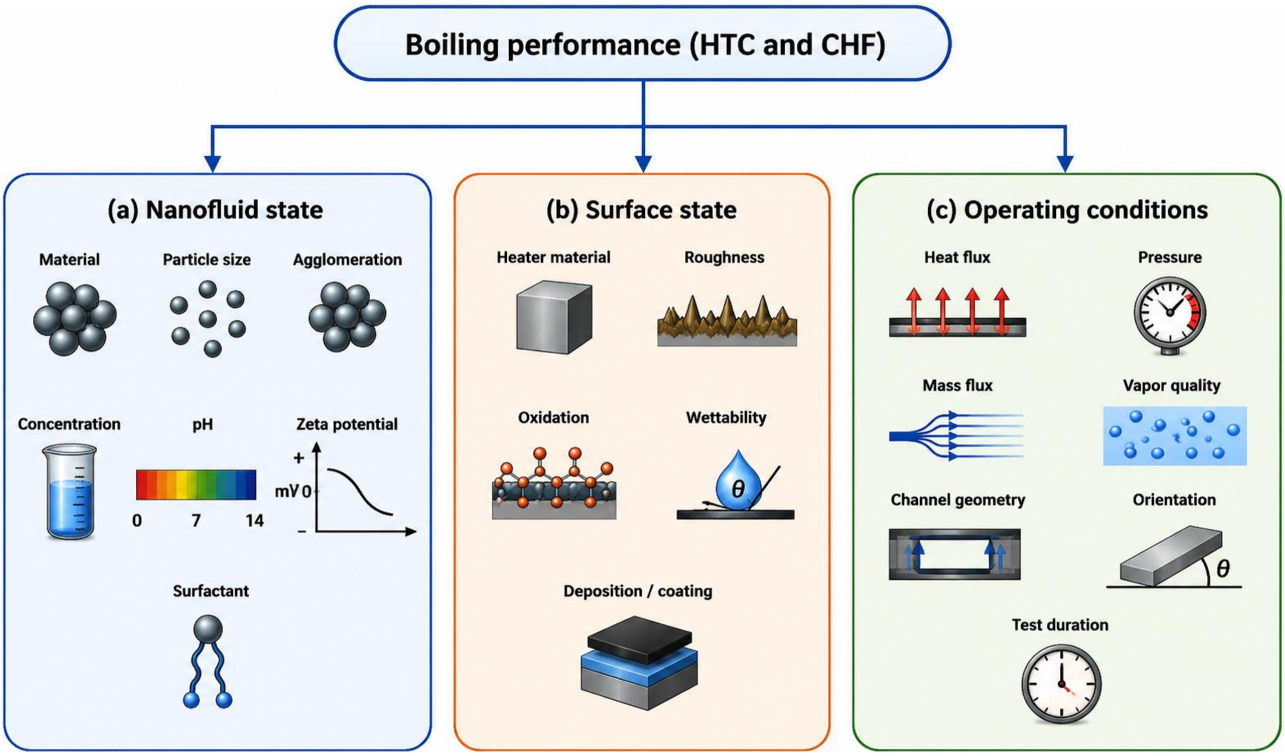
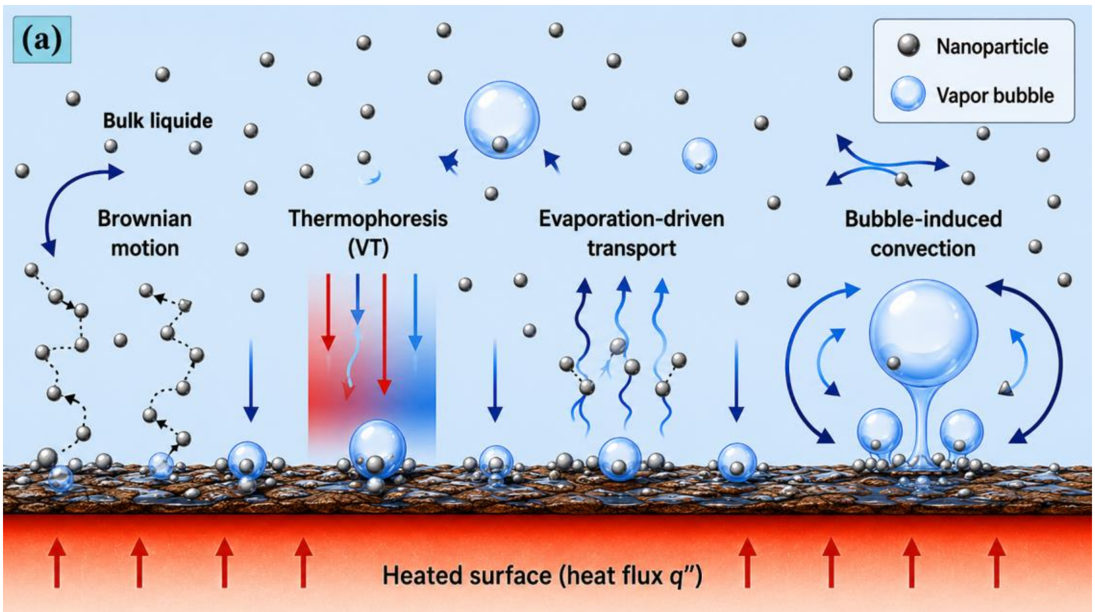


Figure 19. *Cross-study comparison of the key factors governing nanofluid boiling performance: (a) Nanofluid state, (b) Boiling surface, and (c) Operating conditions.*

5.2. Pool-Boiling Performance and Mechanisms



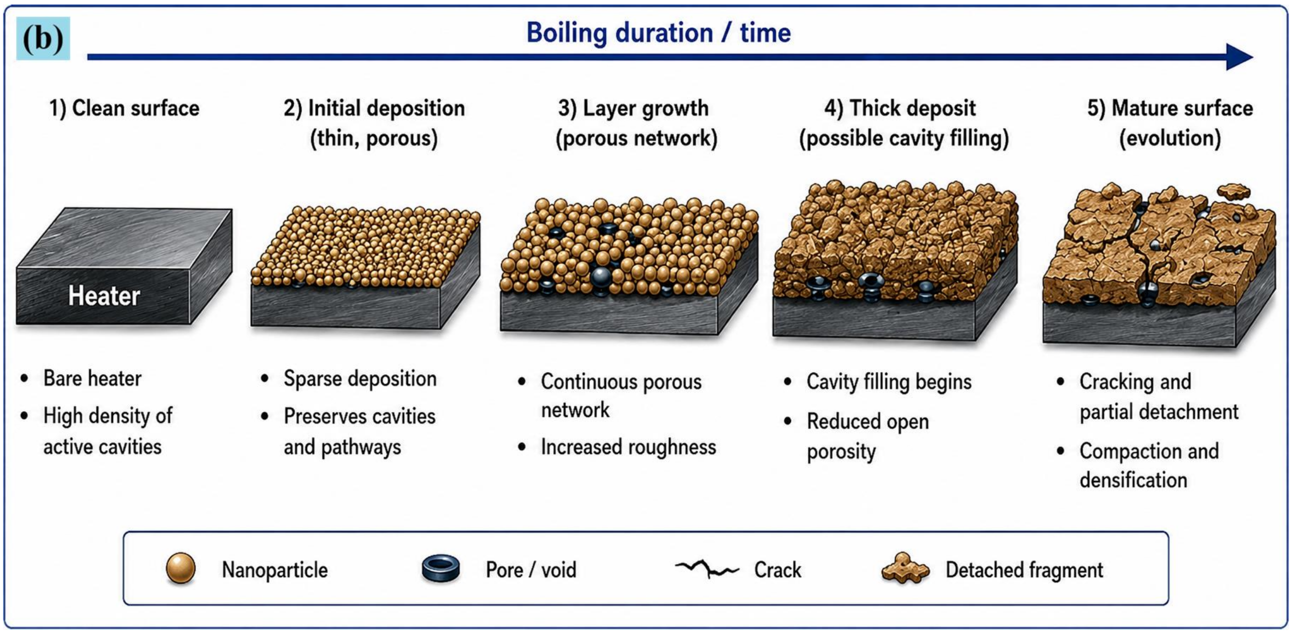


Figure 20. *Pool-boiling enhancement mechanisms: (a) Nanoparticle transport to the heated surface and (b) Surface deposition and morphology evolution.*

Pool-boiling studies show a comparatively consistent tendency toward CHF enhancement. As illustrated in Figure 20, nanoparticle transport toward the heated wall and the subsequent evolution of the deposited surface layer plays a central role in modifying nucleation characteristics and boiling performance. Selected Al_2O_3 and TiO_2-water studies report increases approaching 200%, while silica-water systems report increases of approximately 60% (Figure 21). These large values are associated primarily with changes in the heater surface rather than with the modest increase in the bulk thermal conductivity of the suspension [28, 32].

During boiling, nanoparticles are transported toward the heated wall and may form a porous or textured deposit. The sequential transport and surface-evolution mechanisms summarized in Figure 20 explain how deposition modifies wettability, capillary liquid supply, and nucleation-site density, thereby influencing both HTC and CHF. If the deposit increases wettability and capillary wicking, liquid can more readily penetrate hot or partially dry regions, delaying the formation of a stable vapor blanket and increasing CHF [19, 33].

The effect of concentration is generally non-monotonic. Increasing concentration raises the particle flux toward the wall and can accelerate favorable surface modification, but beyond an optimum range it also promotes agglomeration, sedimentation, uneven deposition, and viscosity increase. s demonstrated in Figure 21, the magnitude of CHF enhancement varies substantially among different nanoparticle materials, emphasizing that the reported performance is strongly dependent on the complete experimental conditions rather than nanoparticle composition alone. The optimum concentration is not transferable among systems because it depends on particle chemistry, base fluid, preparation method, surface material, heat flux, and test duration. For magnetic Fe_3O_4 water nanofluids, the direction and strength of a magnetic-field gradient can further redistribute particles and modify boiling behavior [24]. Several statements in the original manuscript combined numerical results with unrelated references. In particular, the rGO synthesis and 91% CHF/contact-angle claims require the correct primary publication before they can be retained. Similarly, the claimed 75% HTC improvement for Al_2O_3/water cannot be assigned to the TiO_2 synthesis paper listed as reference [64]. Removing unsupported maxima produces a more conservative but scientifically defensible synthesis.

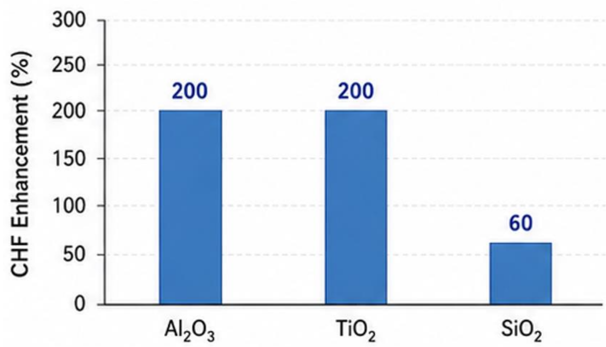


Figure 21. *Representative CHF enhancement of selected nanofluids under pool-boiling conditions.*

5.3. Flow-Boiling Performance and Hydrodynamic Effects

low boiling exhibits greater cross-study variability because the nanofluid interacts with an evolving two-phase flow. As illustrated in Figure 22, the transition from bubbly flow to slug, churn/annular, dispersed flow, and local dryout continuously changes the dominant heat-transfer mechanisms, causing the contribution of nanofluids to vary throughout the flow path. The relative contribution of forced convection, nucleate boiling, thin-film evaporation, and intermittent dryout vary with mass flux and vapor quality. Pressure changes, saturation temperature, density ratio, bubble size, and latent heat; channel size controls bubble confinement; and orientation changes the balance between buoyancy and imposed flow. Figure 24 further demonstrates that the final boiling performance depends on the coupled interaction among the operating regime, bubble confinement, particle deposition, and local particle concentration rather than on any single parameter.

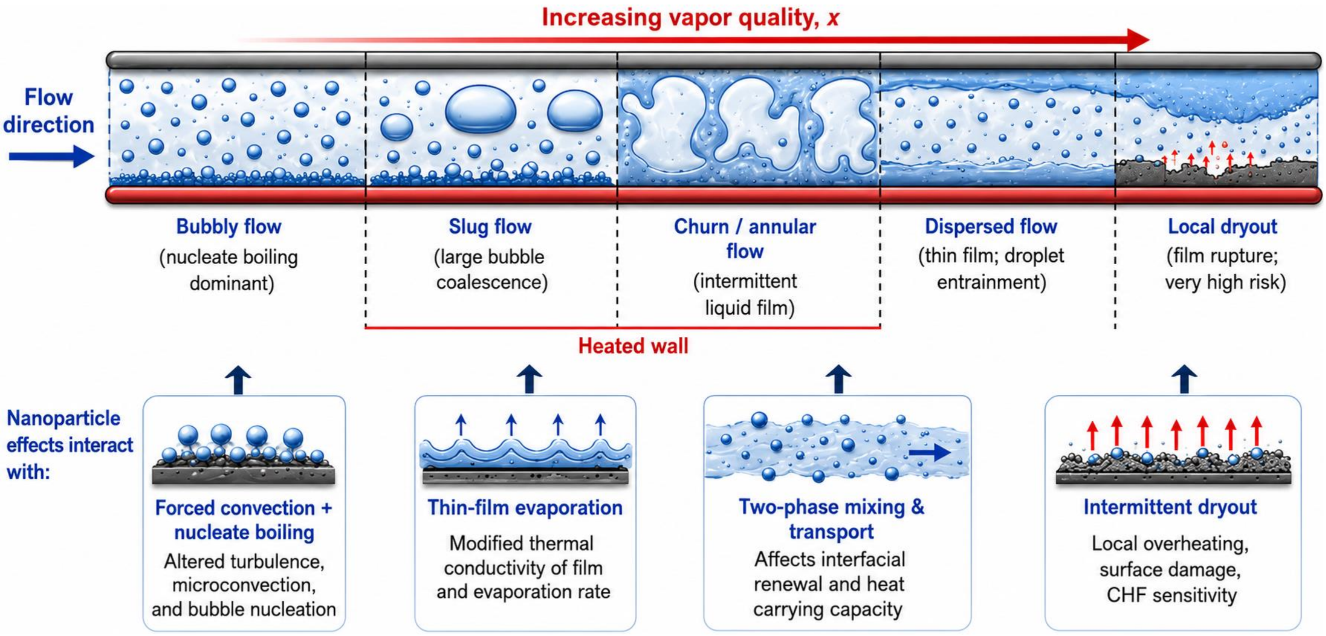


Figure 22. *Flow-boiling hydrodynamics and nanofluid interactions across two-phase flow regimes.*

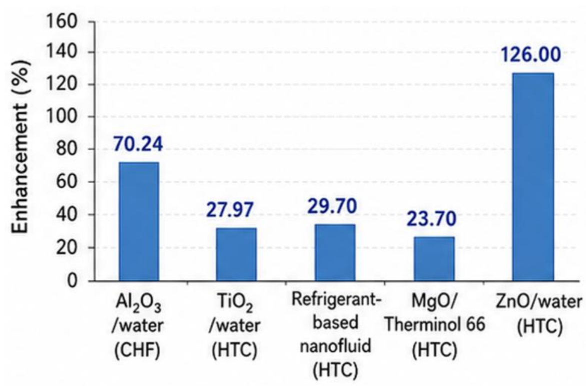


Figure 23. *Representative HTC and CHF enhancement of selected nanofluids under flow-boiling conditions.*

Representative findings include a maximum CHF enhancement of approximately 70.24% for Al_2O_3-water at 0.01 vol.% and a mass flux of 100 kg m^{-2} s^{-1}, HTC enhancement up to approximately 27.97% for TiO_2-water, approximately 29.7% for a refrigerant-based nanofluid, approximately 23.7% for MgO Therminol 66, and up to approximately 126% for ZnO-water under the reported conditions (Figure 23) [42]. As summarized in Figure 23, these reported enhancements differ substantially among nanofluid systems because boiling performance is governed by the combined effects of nanoparticle properties, flow regime, heat flux, mass flux, vapor quality, and channel geometry rather than by nanoparticle composition alone [69]. The large ZnO value should be interpreted cautiously because a single maximum does not establish reproducibility across different channels, heat-flux ranges, or stability conditions.

The SiC water and graphite-water results illustrate the importance of operating conditions: the same nominal concentration produced The SiC/water and graphite/water results illustrate the importance of operating conditions: the same nominal concentration produced deterioration in some regimes and enhancement in others. As summarized in Figure 24, nanofluids can either enhance or deteriorate boiling performance depending on the combined effects of local flow regime, bubble confinement, deposition characteristics, particle concentration, and flow-pattern transition. Such behavior may arise from changes in bubble confinement, local particle concentration, deposition, or flow-pattern transition. It also shows why a single average HTC enhancement can conceal important local behavior. Axial wall-temperature measurements, flow visualization, local vapor quality, and pressure-fluctuation data are needed to identify the mechanisms responsible for the observed response. Figure 24 further emphasizes that both thermal enhancement and hydrodynamic penalties should be evaluated simultaneously, since improved HTC or CHF may be accompanied by increased pressure drop, fouling, erosion, or flow instability.

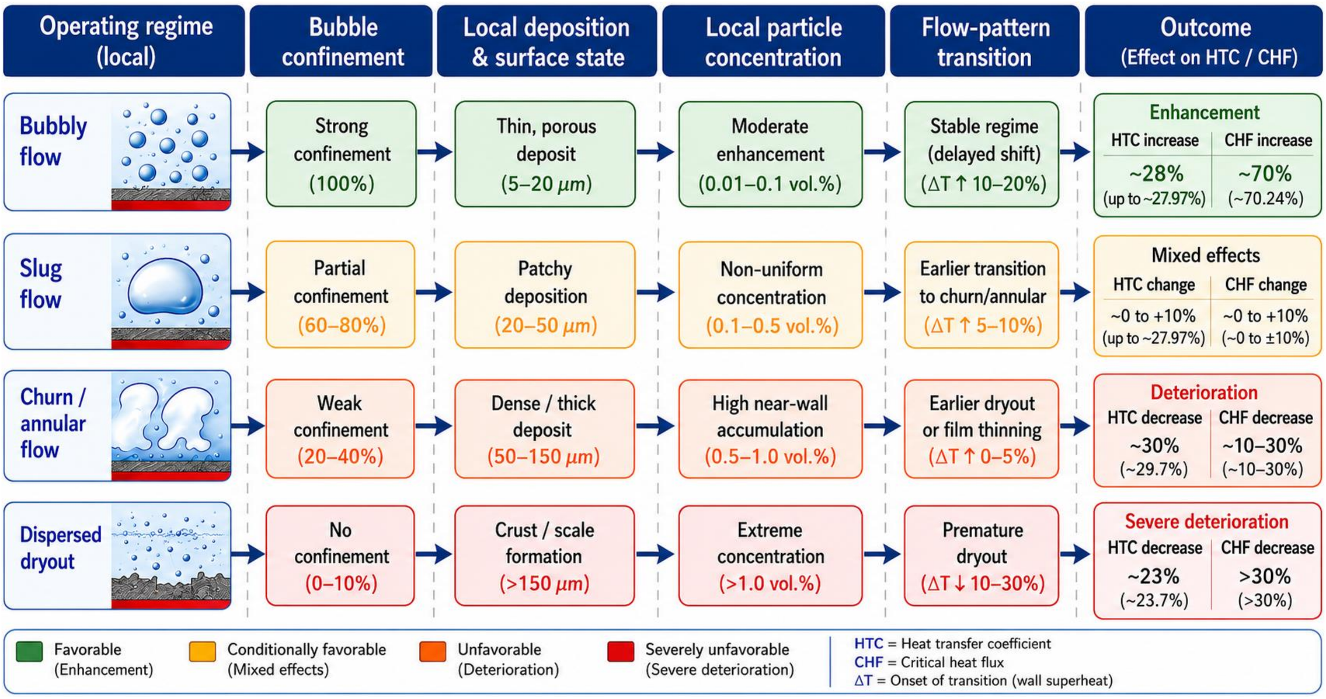


Figure 24*. Conceptual framework illustrating the conditions leading to enhancement or deterioration of flow-boiling performance in nanofluids.*

5.4. Integrated Mechanisms Governing Boiling Enhancement

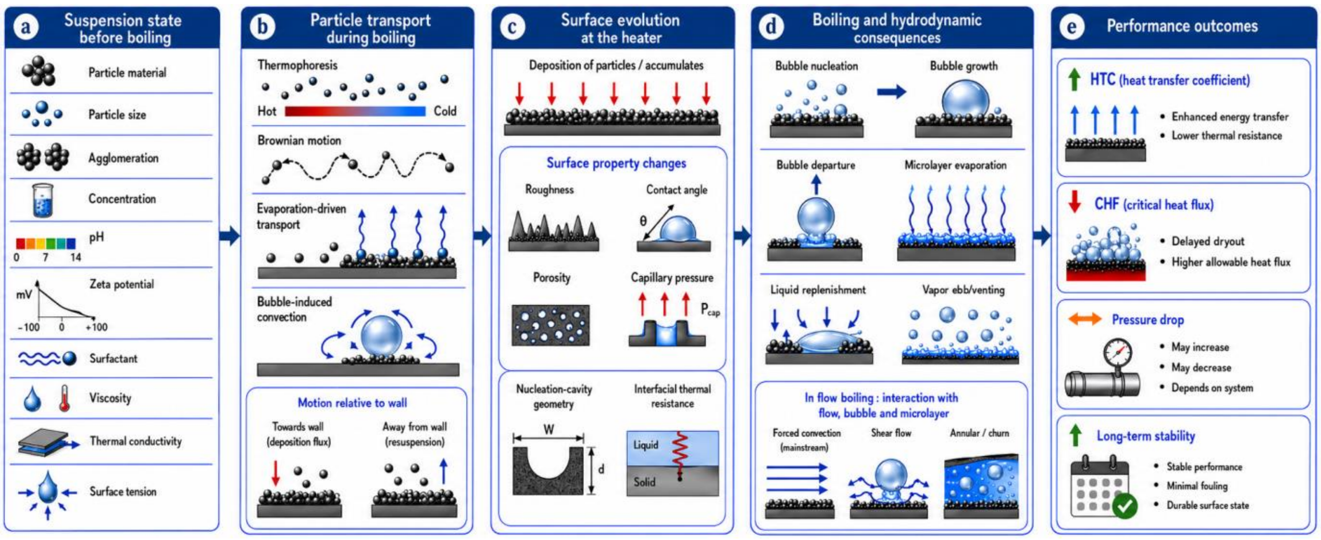


Figure 25*. Integrated mechanisms governing nanofluid boiling enhancement: (a) Suspension state, (b) Particle transport, (c) Surface evolution, (d) Flow-boiling hydrodynamics, and (e) Performance outcomes.*

The available evidence supports a unified interpretation in which nanofluid boiling is governed by coupled fluid, surface, and hydrodynamic processes. As illustrated in Figure 25, boiling enhancement is a multistage process that begins with the suspension state, progresses through nanoparticle transport and surface evolution, and culminates in hydrodynamic interactions that determine the overall thermal-hydraulic performance. Before boiling, the suspension state determines viscosity, thermal conductivity, surface tension, and particle mobility. During boiling, thermophoresis, Brownian motion, evaporation-driven transport, and bubble-induced convection carry particles toward or away from the wall. Figure 25 further highlights that these coupled mechanisms collectively regulate nucleation behavior, liquid replenishment, vapor removal, and ultimately the measured HTC and CHF.

This interpretation explains why thermal conductivity alone cannot predict boiling performance. As summarized in Figure 25, improvements in boiling performance arise from the synergistic interaction between nanofluid properties, surface modification, and two-phase flow dynamics rather than from any single enhancement mechanism. An increase in effective conductivity may improve single-phase convection, but boiling is controlled by interfacial events occurring over multiple length and time scales.

5.5. Standardization, Reproducibility and Industrial Scale-up

A quantitative meta-analysis is not presently justified because the available studies employ widely different particle sizes, particle-size distributions, concentrations, preparation methods, heater materials, surface conditions, pressures, geometries, heat-flux ranges, and data-reduction procedures. As summarized in Figure 26, improving the reproducibility of nanofluid boiling research requires standardized protocols covering nanofluid preparation, surface characterization, experimental reporting, uncertainty analysis, long-term testing, and industrial evaluation. Several studies also provide incomplete information regarding measurement uncertainty, nanofluid stability, surface characteristics, and deposited-layer properties. Figure 26 further emphasizes that consistent documentation of these variables is essential for meaningful comparison among independent studies and for reliable technology translation.

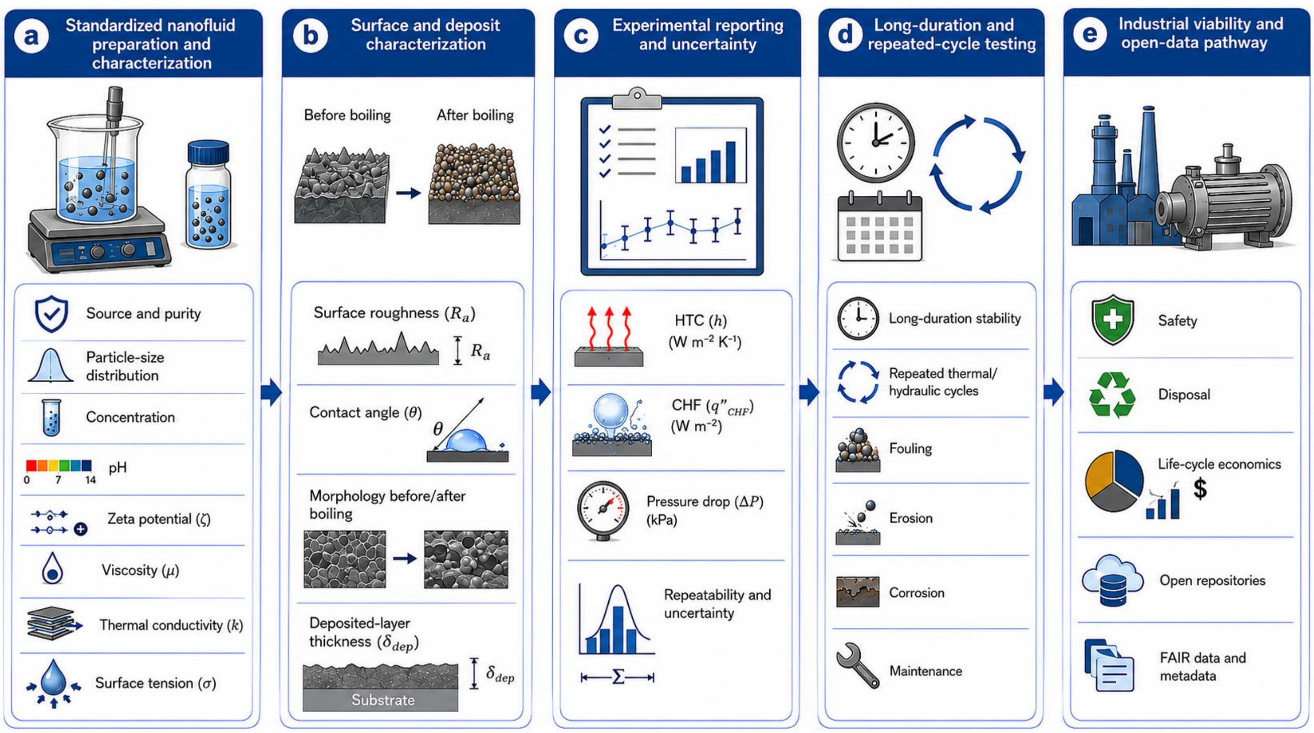


Figure 26. *Framework for standardization and industrial implementation: (a) Nanofluid preparation and characterization, (b) Surface and deposit characterization, (c) Experimental reporting and uncertainty, (d) Long-term testing, and (e) Industrial viability and open-data practices.*

Long-duration and repeated-cycle experiments are required to quantify particle sedimentation, agglomeration, fouling, erosion, corrosion, and the persistence of HTC and CHF enhancement. As illustrated in Figure 26, long-term stability testing, uncertainty quantification, and standardized reporting are equally important as thermal-performance measurements for evaluating the practical viability of nanofluid boiling systems. These experiments should include start-stop cycles, standby periods, and post-test inspection of pumps, valves, channels, and heat-transfer surfaces. Future mechanistic models should connect nanoparticle transport and deposition with surface evolution, nucleation-site activation, bubble growth and departure, capillary liquid replenishment, flow-regime transitions, HTC, CHF, and pressure loss. Figure 26 highlights that future progress toward industrial deployment will require integrating mechanistic understanding with standardized experimental protocols, transparent data reporting, uncertainty-qualified datasets, and open-access repositories. Physics-informed machine-learning approaches may assist prediction, but they should be trained using transparent, uncertainty-qualified datasets and validated against independent experiments.

6. Conclusions

This review critically assessed nanofluid-enhanced pool and flow boiling, with emphasis on the effects of nanoparticle properties, fluid stability, heater-surface condition, operating parameters, and two-phase hydrodynamics on the heat transfer coefficient and critical heat flux. The principal conclusions and recommendations are as follows:

1) Nanofluid boiling enhancement is a system-level response. It cannot be predicted from nanoparticle thermal conductivity or composition alone because the fluid, heated surface, boiling regime, and operating condition interact continuously.
2) Al_2O_3 and TiO_2 are the most frequently studied materials, but the current evidence does not establish a universally optimal nanoparticle. ZnO, SiO_2, Fe_3O_4, MgO, ZrO_2, WO_3, and carbon-based materials also show potential under selected conditions.
3) Pool boiling generally produces more consistent CHF improvement than HTC improvement. Representative Al_2O_3- and TiO_2-water studies report CHF increases approaching 200%, while silica-water systems report increases of approximately 60%; these values are specific to the tested fluids, surfaces, and procedures.
4) Flow boiling is more sensitive to hydrodynamic conditions. Selected studies report CHF enhancement of approximately 70.24% for Al_2O_3-water and HTC enhancement up to approximately 126% for ZnO-water, but the response changes with mass flux, vapor quality, pressure, channel geometry, orientation, and flow regime.
5) Nanoparticle deposition is the central mechanism linking the fluid to the surface. Increased wettability, porosity, and capillary wicking can improve liquid replenishment and delay vapor blanketing, thereby increasing CHF. Excessive or compact deposition can block nucleation cavities and add thermal resistance, reducing HTC.
6) An optimum concentration and a controlled deposited-layer state are more important than high particle loading. Excessive concentration can increase agglomeration, sedimentation, viscosity, pressure drop, fouling, and pumping-power demand.
7) Surface aging must be treated as a time-dependent design variable. Long-duration, repeated-cycle, and start-stop testing is necessary because short-term HTC or CHF enhancement may not persist after deposition, erosion, corrosion, or sedimentation.
8) Thermal and hydraulic performance should be evaluated simultaneously. Future flow-boiling studies should report HTC, CHF, pressure drop, pumping power, flow instability, and dryout using a common thermal-hydraulic performance metric.
9) The present literature does not support ranking nanoparticles solely by reported maximum percentage enhancement. Standard benchmark fluids, surfaces, geometries, operating conditions, preparation protocols, data-reduction methods, and uncertainty reporting are required for meaningful comparison.
10) Characterize both the nanofluid and the heater surface before and after boiling. Essential measurements include particle-size distribution, zeta potential, pH, viscosity, thermal conductivity, sedimentation stability, surface roughness, contact angle, deposit thickness, and surface morphology.
11) Predictive models should couple particle transport, deposition, surface evolution, bubble dynamics, liquid replenishment, flow-regime transition, HTC, CHF, and pressure loss. Data-driven models should be validated using independent and uncertainty-qualified experiments.
12) Industrial implementation requires assessment of material compatibility, corrosion and erosion, particle recovery, occupational and environmental safety, maintenance, filtration, scale-up reliability, and techno-economic performance.
13) Nanofluid-assisted boiling remains a promising approach for high-heat-flux thermal management, but reliable deployment will depend on coordinated optimization of fluid formulation, surface engineering, and system design rather than on short-duration laboratory enhancement values alone.

Abbreviations

BHTE	Boiling Heat Transfer Enhancement
BC	Boiling Curve
CHF	Critical Heat Flux
COP	Coefficient Of Performance
DI	Deionized
PBHT	Pool Boiling Heat Transfer
FBHT	Flow Boiling Heat Transfer
FBHTE	Flow Boiling Heat Transfer Enhancement
GO	Graphene Oxide
HT	Heat Transfer
HTC	Heat Transfer Coefficient
HTE	Heat Transfer Enhancement

PCM	Phase Change Materials
LPT	Leidenfrost Point Temperature
MCHS	Microchannel Heat Sinks
MWCNTs	Multi-Wall Carbon Nanotubes
NB	Nanofluids Boiling
PBHTE	Pool Boiling Heat Transfer Enhancement
SDBS	Sodium Dodecylbenzene Sulfonate
TEM	Transmission Electron Microscopy
A	Area (m^2)
C_{pl}	Liquid Specific Heat (J/kg · K)
K	Thermal Conductivity (W/m · K)
G	Mass Flux (kg m^{-2} s^{-1})
h	Heat Transfer Coefficient (W m^{-2} K^{-1})
q″	Heat Flux (W m^{-2})
T	Temperature (°C or K)
ΔT_e	Wall Superheat, $T_s - T_{sat}$ (K)
φ	Nanoparticle Volume Fraction

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Author Contributions

Md. Rezaul Karim Sikder: Conceptualization, Methodology, Writing – original draft

Mohammad Zoynal Abedin: Funding acquisition, Supervision, Writing – review & editing

Samsul Islam: Methodology, Writing – original draft

Md. Jakir Hossen: Project administration, Resources

Jahirul Islam: Visualization, Writing – review & editing

Ruman Uddin: Formal Analysis, Investigation

Abdul Ahad: Data curation, Software

Md. Shah Mamunur Rashid: Validation, Visualization

Nurul Hoda Sanid: Resources, Investigation

Mohammad Monirul Kabir Mridha: Formal Analysis, Resources

Conflicts of Interest

The authors declare no conflicts of interest.

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