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Pool boiling heat transfer characteristics of using nanofluids

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Abstract Every day, smaller, faster, and more potent modern technologies and systems are being created and put into use, which necessitates the advancement of the thermal fluids that are used in operation to increase the capacity for heat removal. Pool boiling is effectively used in many industrial applications such as refrigeration systems, power plants etc. Application of nanofluids in pool boiling enhances the thermal conductivity and heat transfer rates in the system. This paper highlights the pool boiling heat transfer using nanofluids and its characteristics.

Introduction

Modern heat transfer technologies demand high heat flux rates. Fluid conductivity plays a significant role for high heat flux rates. Conventional heat transfer fluids such as air, water, ethylene glycol have poor thermal properties that limit the heat transfer equipment performances. Various researches reported using nanofluids in heat transfer equipment [1-4] but very few studies reported on pool boiling heat transfer using nanofluids. Pool boiling is most effective heat transfer application for heating and cooling of systems such as refrigeration systems, power plants etc. The heat transfer coefficient and rate of heat transfer are very high thus making it a crucial component in the use of energy dissipation systems.

Various methods are employed to improve heat transfer efficiency. One technique is to add solid nanoparticles to the heat transfer fluids, also known as nanofluids, to increase their thermal conductivity. These fluids are essential for transporting a lot of heat during the nucleate pool boiling phase change process. Heat produced by large-scale functioning equipment has been released through the boiling process. When the surface temperature is raised well above liquid saturation temperature, pool boiling occurs on the hot surface immersed in a pool of liquid. The movement of the liquid is the only byproduct of the heat transfer process, with no significant external donation [5]. Physiothermal properties such surface tension, viscosity, enthalpy, specific heat, thermal conductivity as well as the structure of the surface including the roughness and homogeneity are directly related to how heat is transferred in boiling pools. It also depends on the hydrodynamic condition close to the heating surface, such as the dynamics of hot and dry areas and the frequency, diameter of bubble departures [6].

As the nanofluid boils, nanoparticles simultaneously precipitate on the heated surface. The thickness of nanoparticles layer that has been formed is very thin at lower concentrations, making heat transfer and the magnitude of the heat transfer coefficient unaffected. In this scenario, the layer is ineffective and thermal conductivity or other heat transmission processes rule within the nanofluid. On the other hand, with greater nanofluid concentrations, the layer becomes thicker and the heat transfer coefficient suffers as a result. This happens because there are fewer active nucleation sites available over the heating surface due to the layer dominating the heat transfer process, regardless of the nanofluid's capacity for heat transfer. Therefore, with nanofluid concentration, the critical heat flux remains constant and the heat transfer coefficient declines [7]. A study was conducted on pool boiling heat transfer using hybrid nanofluids with 0.01-0.1% volume concentrations. It was observed that hybrid nanofluids have a higher critical heat flux than single type nanofluids. Compared to single type nanofluids, hybrid nanofluids exhibit comparable stability and have a superior thermal conductivity. In comparison to deionized water, the maximum thermal conductivity improvement was 15.7% at ϕ = 0.1%. At ϕ = 0.01% of hybrid nanofluids and in comparison to deionized water at critical heat flux, the maximum enhancement in h_{nf} was 7.1%. Deposition of nanoparticles on heater surface, the h_{nf} declines with the increase of ϕ value [8]. This paper presents the application of nanofluids in pool boiling heat transfer characteristics.

Effect of nanofluids thermal conductivity in pool boiling

In order to optimize heat transfer performance for diverse uses pool boiling, thermal conductivity is a crucial component. The advantages of enhanced thermal conductivities of various nanofluids are higher cooling/heating rates, low power requirements for pumping, thinner and lighter cooling/heating systems, reduced inventory of heat transfer fluids, reduced friction coefficients, and enhanced wear resistance. This improved the potential for the applications of nanofluids as refrigerants, cutting and hydraulic fluids, lubricants and coolants.

Base-fluid and nanoparticle thermal conductivity have a substantial impact on the enhancement of the thermal conductivity of nanofluids [9]. With ethylene glycol nanofluids compared to base-fluids, 0.3% copper nanoparticles showed a 40% improvement [10]. With base fluids and 0.1% of copper nanoparticles, thermal conductivity was claimed to be improved by 23.8% [11]. Through observation, it has been discovered that the surface to volume ratio of nanoparticles was a key influence in the improvement of heat conductivity [12]. An enhancement in thermal conductivity has been detected of almost 150% for poly oil with 1% volume fraction MWCNT [13]. For the same oil, but with 0.35% MWCNT, a 200% gain in thermal conductivity has been observed through experimental studies [14]. Cu nanoparticles in water with a 0.3% concentration improved thermal conductivity by 70% [15]. 75% increase in thermal conductivity has been observed for ethylene glycol with 1.2% diamond nanoparticles [16]. Nevertheless, research on thermal conductivity has produced some typical results [17–20]. Temperature, volume fraction, size, and structure of nanoparticles as well as pH, surfactant addition, nanofluid stability, and other elements all affect thermal conductivity [21-24].

Effect of nanofluids viscosity in pool boiling

The larger concentration of nanoparticles rises the viscosity of water-based nanofluids. As a result, the pressure drops over the cooling channel rises. Nanoparticle-water suspensions develop more viscous as the particle concentration in the suspension rises. The volume percentages of carbon nanotube are only acceptable to be less than 0.2% in real systems since the viscosity rose so quickly with higher particle loading. The particle mass fraction can therefore not be increased indefinitely. Replacing conventional fluids with nanofluids in industrial heat exchangers where significant volumes of nanofluids are required and turbulent flow is frequently created seems unfavorable [25,26]. More research studies need to be done on the effect of nanofluids viscosity in pool boiling.

Effect of nanofluids density in pool boiling

A study was conducted to observe the behavior of the density of nanofluids in pool boiling. The study's results reveal that the density of nanofluids behaves differently, and the data support the notion that this behavior is influenced by temperature. When raising the temperature, the density of the nanofluids is greater than that of its base fluid. The density falls as the volume concentration of nanoparticles rises [27]. Similar to viscosity, the density of a nano refrigerant rises as the volume fraction rises and drops as the temperature rises. To achieve efficient energy performances, an optimal particle volume fraction should be determined, considering the thermal conductivity, viscosity, and density of the nano refrigerant (as thermal conductivity rises the heat transfer coefficients, whereas viscosity and density rises the pressure drop and pumping power) [28].

Effect of nanofluids specific heat in pool boiling

According to the literature, nanofluids have a lower specific heat than base fluid. In comparison to base fluids, CuO/ethylene glycol nanofluids, SiO_2/ethylene glycol nanofluids, and Al_2O_3/ethylene glycol nanofluids all have lower specific heats. Diamond nanoparticles are sediment over time thereby lowering the specific heat of the nanofluids. Nanofluids using in pool boiling should have a greater specific heat value in order to extract more heat from the environment [29,30]. Further research studies are needed to confirm the effect of nanofluids specific heat in pool boiling.

Effect of surface roughness in pool boiling

To study the effect of surface roughness an experiment investigations were performed using Al_2O_3 nanoparticles deposition in pool boiling heat transfer. The effect of deposition on critical heat flux of R-123 was studied. When compared to the uncoated surface, it was found that the surface coated with nanoparticles increased the critical heat flow by 17% and barely changed the heat transfer coefficient [31]. In other experimental studies, the effect of surface roughness and surface material was examined using two different nanofluids in pool boiling heat transfer. The experiments were conducted at reduced pressures using cylindrical surfaces made of stainless steel, brass, and copper. It was found that at low heat fluxes, the rough surface outperformed the smooth surface in terms of boiling thermal performance. However, this tendency shifted at high heat flux. The surface material had a significant impact on the slope between the heat transfer coefficient and heat transfer, which was larger for copper and brass but lower for stainless steel [32].

Effect of surface tension in pool boiling

Increasing the effectiveness and dependability of pool boiling heat transfer through the use of nanoparticles is an innovative, creative approach that has gain a noticeable interest in the past few years. Many parameters have been studied and reviewed yet the surface tension of the nanoparticles is still a vague area. In 2008, an experimental study and numerically simulation have been done on the migration characteristics of nanoparticles in the pool boiling process of Nano refrigerant and Nano refrigerant–oil mixture. This experiment aimed to determine whether the original mass of the nanoparticles affected their migration. The findings suggested that nanoparticles can migrate from the liquid phase to the gas phase during the pool boiling process using either a single or multiple individual escaping mechanisms. However, the liquid phase surface tension prevents such escaping.Nanoparticles with sufficiently high velocities and bubbles with attached nanoparticles break through the liquid's surface tension and float away. The surface tension of Nano refrigerant–oil mixture is higher than Nano refrigerant and hence the nanoparticle migration was greater in the later one [33].

In 2015, another experiment been conducted on the Surface tension of lithium bromide (LiBr) aqueous solution/ammonia with additives and nanoparticles. In this experiment to confirm the measuring accuracy, the surface tension of a LiBr aqueous solution with 1-octanol was measured. The obtained data were then compared with those from earlier experiments. In the study, additional chemicals including cetyltrimethylammonium chloride (CTAC) and cetyltrimethylammonium bromide (CTAB) were used. The outcomes of the experiment clearly demonstrate that CTAC and CTAB can decrease the surface tension of the LiBr aqueous solution/ammonia. It was also discovered that nanoparticles are unable to significantly lower the surface tension of LiBr aqueous

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solution/ammonia. However, the surface tension of LiBr aqueous solution/ammonia can be significantly changed by the combined addition of additives and nanoparticles. In other words, additives are more crucial in lowering the surface tension of the LiBr aqueous solution/ammonia. However, nanoparticles might improve heat transmission in the process of pool boiling [34].

Experimental studies on nanofluids pool boiling

Pool boiling is a well spread topic and there are research studies since 1962 but the research studies on application of nanofluids in pool boiling started recently. In 2020, Experimental research was done on the pool boiling heat transfer performance of deionized water and deionized water with magnesium-oxide nanoparticles. The nanofluids were generated at different volume concentrations and the pool boing heat transfer performance was tested under various heat flux and at atmospheric pressure. Using ultra sonication procedures, the stability of the created nanofluids was examined and was found to be reasonably good at least for the duration of the experiment. The obtained results showed that for volume concentrations of 0.001, 0.004, and 0.007 Vol%, the pool boiling heat transfer coefficient enhancement ratio was improved. The maximal enhancement ratio was 1.22 for 0.004 vol%. This ratio declined at the values of 0.01 and 0.04 vol% [35].

The tests were run with various heat flux and nanofluid concentrations for approximately 12 hours of boiling time. With various nanofluid concentrations and low and medium heat flow, the surface temperatures remained largely constant. For low, medium, and high concentration nanofluids, the high heat flow studies showed constant, oscillatory & incremental, and abrupt temperature spikes. With increasing heat flow, nanofluid concentrations, and boiling times, it was shown that the rate of heat transfer decreased by up to 90% and that the deposition of nanoparticles increased by 50% to 300%. Qualitative examinations of the microscopic pictures demonstrated the evolution of nucleation sites and deposition patterns over a range of trends as shown in Fig.1 [36].

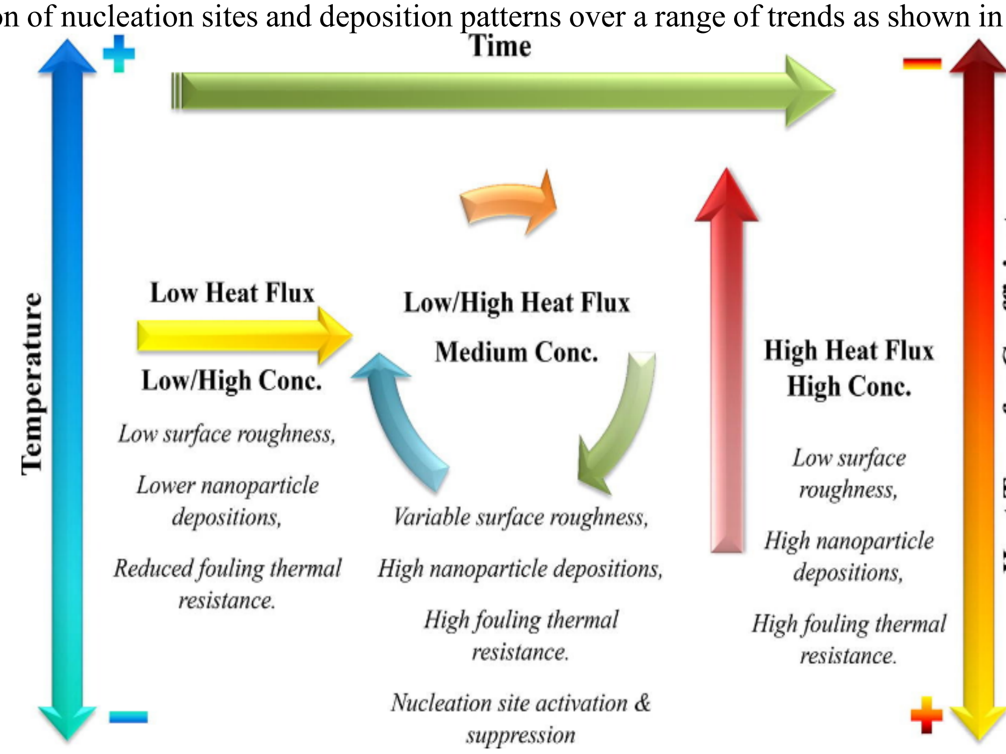

Figure 1. *Nucleation sites and deposition patterns evolve throughout a range of trends [36]*

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In 2022, Experimental research was done on the pool boiling heat transfer of the Fe_3O_4/deionized water nanofluid while using mechanical vibration. The findings from the study of concentration also demonstrated that, at low concentrations, boiling heat transmission is increased while at high concentrations, it is decreased. As a result, at a concentration of 0.1 vol%, the boiling heat transfer coefficient was determined to be at its best for the nanofluid. When mechanical vibration is applied at all vibrational frequencies, it improves the boiling process' heat transmission. The maximum increase in the boiling heat transfer coefficient was found to be 87.3% when mechanical vibration was applied at the ideal concentration and vibrational frequency of 33 Hz [37].

Most recent experiment published in 2023, was experimental research done to examine and compare the pool boiling performance of a highly self-dispersion TiO_2 nanofluid with mass concentrations ranging from 0.0001 to 0.1%. Tests for repeatability, wettability, and macro/micro morphology were used to examine the impact of the boiling-induced deposition layer. The results showed that distilled water's critical heat flux (CHF) was only slightly increased by nanofluid, and that the CHF enhancement was caused by a super-hydrophilic micro-porous deposition layer that formed on the boiling surface of the nanofluid. Rising nanofluid concentration caused the deposition on the surface to occasionally come off, which complex and unpredictable boiling performance. Type and concentration of nanofluids had a minimal impact on CHF. The boiling curves of 0.0001% TiO_2 and Al_2O_3 nanofluids were comparable, although ZnO nanofluid had a lower heat transfer coefficient [38].

When nanoparticle and base fluid are combined, they are regarded as a single-phase mixture with stable qualities (mixed properties between the nanoparticle and base fluid properties). Given that the flow of a nanofluid may be thought of as a single-phase, incompressible flow, the simplest method for addressing the single-phase assumption is to use the governing equations for the flow of a pure fluid without taking the thermophysical characteristics of the nanofluid into account [39]. In investigating the “Linear stability theory of single phase nanofluids” it was concluded that the resulting eigen space of nano disturbances is constructed on the equivalent pure flow eigen space of perturbations, and that when the nanoparticles are added, the mean flow of nanofluids is somewhat modified [40].

Nanofluids/nanoparticles have been investigated heavily in the past two decades. It is known that nanoparticles increase the heat transfer rate. In recent study it has been shown that the boiling process increases vaporization velocity and has an impact on pressure and flow velocity as nanomaterial concentrations rise [41]. And recently based on experimental calculations it has been concluded that the heat transmission coefficient grows as the volumetric concentration of nanoparticles increases. When a result, as the heat flux increases, the boiling curve's slope decreases to lower superheat temperatures. The heat transfer coefficient increases by 49.35% by raising the volumetric concentration of nanoparticles to 0.1% when the heat flow is q = 341.8 kWm^{-2}. Additionally, the density of nucleation sites is inversely related to the quantity of nanoparticles. The diameter of the bubble leaving the zone with lower heat fluxes increases as the nanofluid concentration decreases. But as the nanofluid concentration drops at the high-flux zone, it gets smaller [42]. Therefore, we may infer that nanofluids can affect heat transfer boils in either a positive or negative way depending on their hydrophilicity and hydrophobicity.

To study the effect of hybrid nano fluids, an experiment has been done investigating TiO_2 and SiO_2 nanoparticles' effects on the nanofluid's heat transfer coefficient (HTC) during pool boiling. According to the findings, the HTC of TiO_2-SiO_2-water hybrid nanofluids is significantly higher than that of TiO_2 water and SiO_2 water single nanofluid systems. According to experimental data, the hybrid nanofluid is present at a concentration of 0.05% when the heat flux and HTC are at their greatest values [43].

There are many factors affecting pool boiling the most important ones are porosity, coating thickness, particle concentration, and surface roughness. An experimental study has been done in

2020 it studied the use of porous and the coating thickness, this experiment found that the use of porous heating surfaces enhances heat transfer efficiency and prevents temperature overshoot because of their linked porous structure, which increases wetted area and active nucleation site density. The outcomes also demonstrated that whereas low heat fluxes are best served by high thickness, high heat fluxes are best served by low thickness [44].

The surface roughness rises along with the nanofluid concentration, and the lower the nanofluid concentration, the smaller the contact angle of water with the coated surface. thus, increasing the diameter of the nanoparticles enhances the boiling heat transfer coefficient of nanofluids. The number of active bubble-generating sites is decreased when the size of the nanoparticles is decreased, filling smaller and more areas on the boiling surface. On the other hand, as nanoparticle diameter grows, more unoccupied places on the boiling surface of the copper block become accessible. Additionally, when nanoparticles build up, the boiling surface becomes rougher, creating potential new locations for the production of water vapor bubbles [45,46].

Conclusions

Pool boiling heat transfer is widely used in various industrial applications such as refrigeration systems, heating and cooling systems, power systems etc. Pool boiling with conventional fluids has limitations in heat transfer rates due to their Physiothermal properties. In the recent past, nanofluids with high thermal conductivity nanoparticles are widely applied for heat transfer applications. Researches are reported using nanofluids for pool boiling and it was observed the enhancement of heat transfer rates. However, there is a lot scope for further research studies on application of nanofluids in pool boiling, its heat transfer performance and effect of various Physiothermal properties.

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