REVIEW OF BOILING TO POOL BOILING HEAT TRANSFER USING NANOFLUID

Sudev Das*

Mukul Ray*

Biplap Debbarma*

Dr.Harinder Singh**

Dr.Swapan Bhaumik***

Abstract

Nanofluids are a new class of heat transfer fluids developed by suspending nanosized solid particles in liquids. Larger thermal conductivities of solid particles compared to the base fluids such as water, ethylene glycol, engine oil etc. significantly enhances their thermal properties. Several phenomenological models have been proposed to explain the anomalous heat transfer enhancement in nanofluids. This paper presents a systematic literature review to exploit the boiling heat transfer enhancements using different compositions of Nanofluids used experimentally also attempts are made to make systematic analysis of results in literature and try to bring out a common understanding of the results in literature.

Keyword: Boiling heat transfer, Convective heat transfer, Pool boiling, Nanofluids

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* Ph.D Scholar, National Institute of Technology Agartala, Tripura, India.

** Assistant Professor, Motilal Nehru National Institute of Technology Allahabad, India.

*** Associate Professor, National Institute of Technology Agartala, Tripura, India.

1.Introduction

Boiling is a very effective mode of heat transfer and ue to this reason it has wide applicability in various industries. Many researchers have conducted very systematic study of the basic mechanism of boiling worldwide but, its physical mechanism remains too complex to be completely understood even for a common fluid like water. It is known to depend mainly on surface heat flux, heater surface, and heater geometry. Also it is known that the inclusion of particles in a liquid alters the boiling characteristics. Various researchers investigate experimentally the pool boiling heat transfer in Nanofluids with various proportions of particle concentrations. Deterioration in heat transfer coefficient are mainly observed at higher particle concentrations (4-16% by weight) and enhancements mainly at lower particle concentrations (0.32-1.25% by weight).Moreover, the relative size of the particle with respect to the surface roughness of the heating surface seems to play an important role in understanding the boiling behavior.

2.Preparation of Nanofluids

A liquid suspended with particles of nanometer dimension is termed a nanofluid. The nanoparticles were used to produce nanofluids are: aluminum oxide (Al_2O_3), copper (Cu), copper oxide (CuO), gold (Au), silver (Ag), silica nanoparticles and carbon nanotube. The base fluids used were water, oil, acetone, decene and ethylene glycol. Nanoparticles can be produced from several processes such as gas condensation, mechanical attrition or chemical precipitation techniques. The preparation of a nanofluid begins by direct mixing of the base fluid with nanoparticles. The delicate preparation of a nanofluid is important because nanofluids need special requirements such as an even suspension, durable suspension, stable suspension, low agglomeration of particles, and no chemical change of the fluid. Methods used for stabilizing the suspensions: (1) changing the pH value of suspension, (2) using surface activators and/or dispersants, (3) using ultrasonic vibration. These methods can change the surface properties of the suspended particles and can be used to suppress the formation of particle clusters in order to obtain stable suspensions. The use of these techniques depends on the required application of the nanofluid. Selection of suitable activators and dispersants depends mainly upon the properties of the solutions and particles. Particles can fracture or agglomerate after mixing into liquid.

Transmission electron microscopy (TEM) is widely used to observe the characteristics of particles before and after dispersion in liquid. Some researchers used ultrasonic vibration techniques to disperse the particles in the base liquid. However, the ultrasonic vibration can break the agglomerates.

3.Thermal conductivity:

Thermal conductivity is one of the most important parameter for enhancing the heat transfer in fluids. Since solid metals have the higher thermal conductivity as compare to the fluids. The suspended particles are expected to be able to increase the thermal conductivity and heat transfer performance. Many researchers have reported experimental studies on the thermal conductivity of nanofluids. The transient hot wire method, temperature oscillation and the steady-state parallel plate method has been employed to measure the thermal conductivity of nanofluids. However, the transient hot wire method has been extensively used. The transient hot wire technique works by measuring the temperature/time response of the wire to an abrupt electrical pulse. The wire is used as both heater and thermometer. A derivation of Fourier's law and temperature data were used to calculate the thermal conductivity. The results from all of the available experimental studies indicated that nanofluids containing a small amount of Nanoparticles have substantially higher thermal conductivity than those of base fluids.

Most of the commonly encountered fluids have the inherent deficiency of low thermal conductivity. For example, while water has a thermal conductivity of 0.6 W/mK the value for copper is 386 W/mK. This three orders of magnitude difference between the thermal conductivity of normal liquids and metals makes one consider enhancement of thermal conductivity of liquids by suspending metal particles in them[1].Low thermal conductivity is a primary limitation in the development of energy-efficient heat transfer fluids that are required in numerous industrial sectors. Recently submicron and high aspect ratio particles (nanoparticles and nanotubes) were introduced into the heat transfer fluids to enhance the thermal conductivity of the resulting nanofluids [2].Metals in the solid form have thermal conductivity larger by orders-of magnitude than of those fluids. For example, the thermal conductivity of copper at room temperature is about 700 times larger than that of water and around 3000 times larger than that of engine oil [3].Increase in the specific surface area as well as Brownian motion are supposed to be the most significant reasons for the anomalous enhancement in thermal conductivity of nanofluids [4].The suspensions of nanoparticles in the base fluids occurred some problems like sedimentation. Various nanofluids containing mainly oxide nanoparticles (i.e., Al_2O_3, TiO_2 and CuO) and their thermo physical properties have been studied. It was confirmed that both the stability of the suspensions and their thermo physical properties strongly depend on the volume fraction, the size, shape and type of the nanoparticles, as well as the physical properties of both the nanoparticles and the base fluid. The general observations made during these measurements are that the addition of nanoparticles in the base fluid invokes an increase in thermal conductivity, viscosity and density and a decrease in heat capacity. The surface tension is not affected, unless some surfactants are used for the suspension stabilization [6].

Lee et al. [8] measured the thermal conductivity of nanofluids. The number-weighted particle diameter and the area weighted particle diameter used were 18.6 and 23.6nm for CuO, and 24.4 and 38.4nm for Al_2O_3, respectively. These particles were used with two different base fluids: water and ethylene glycol to get four combinations of nanofluids (CuO in water, CuO in ethylene glycol, Al2O3 in water and Al2O3 in ethylene glycol). The nanofluids showed substantially higher thermal conductivities than those of the same liquids without the nanoparticles. The thermal conductivity of suspended CuO in ethylene glycol showed an enhancement of more than 20% at 4% volume fraction of nanoparticles. The thermal conductivity ratios increased almost linearly with an increase in volume fraction. The experimental results revealed that the thermal conductivity of nanofluids was dependent on the thermal conductivity of both the particles and the base fluids.

Wang et al. [9] used the steady-state parallel-plate technique to measure the thermal conductivity of nanofluids containing Al_2O_3 and CuO nanoparticles. The particles were dispersed in water, ethylene glycol, vacuum pump oil and engine oil. Experimental data showed that the thermal conductivity of all nanofluids were higher than those of their base fluids. The thermal conductivity of the nanofluids increased with increasing volume fraction of the nanoparticles. For a specific volume fraction, the increase of thermal conductivity was different for each base fluid.

Xuan and Li [10] presented a study on the thermal conductivity of a nanofluid consisting of copper nanoparticles and base liquid. The measured data showed that the suspended nanoparticles obviously increased the thermal conductivity of the base liquid. Thermal conductivity of the nanofluid increased with increasing volume fraction of nanoparticles. The ratio of thermal conductivity of Cu–water to that of the base liquid increased from 1.24 to 1.78 when the volume fraction of the nanoparticles varied from 2.5 to 7.5%.

Eastman et al. [11] reported an experimental study on the thermal conductivity of ethylene glycol based nanofluids containing copper nanoparticles. The nanofluid exhibited an anomalously increased effective thermal conductivity. The thermal conductivity increased up to 40% for nanofluids consisting of 0.3% (by volume) of Cu nanoparticles of a mean diameter less than 10nm dispersed in ethylene glycol.

Xie et al. [12] measured the thermal conductivity of Al_2O_3 nanoparticle suspensions. The effects of the pH value of the suspension, the specific surface area (SSA) of the dispersed Al_2O_3 particles, the crystalline phase of the solid phase, and the thermal conductivity of the base liquid on the enhanced thermal conductivity ratio were investigated. The addition of nanoparticles into the fluid led to higher thermal conductivity. The enhanced thermal conductivity increased with an increase in the volume fraction of Al_2O_3. The enhancement increased with an increase in the difference between the pH value and isoelectric point of Al_2O_3. For the suspensions containing the same base liquid, the thermal conductivity enhancements were highly dependent on the specific surface area (SSA) of the nanoparticles. For the suspensions using the same nanoparticles, the enhanced thermal conductivity ratio decreased with increasing thermal conductivity of the base fluid. While, the crystalline phase of the nanoparticles did not appear to have any obvious effect on the thermal conductivity of the suspensions.

Das et al. [13] presented investigations on the increase of thermal conductivity with temperature of Al_2O_3 and CuO water-based nanofluids. In their study, a temperature oscillation technique was used to measure the thermal conductivity. The volume weighted average values of particle diameters was 38.4 nm for Al_2O_3 while that was 28.6nm for CuO. The experimental results showed that the thermal conductivity increased with an increase in temperature. Nanofluids containing smaller particles (CuO) showed greater enhancements of thermal conductivity with temperature than larger particles (Al_2O_3). The stochastic motion of nanoparticles could be a probable explanation of the thermal conductivity enhancement. This is because smaller particles are more easily to mobilise and bring out a higher level of stochastic motion.

Patel et al (1) measures the thermal conductivity with two types of Nanoparticles Gold (Au) and silver (Ag) with coatings Thiolate and Citrate with two different types of base fluids Toluene and water. The thermal conductivity of nanofluid used is much higher than the thermal conductivity of the base fluids. When the percentage enhancement of thermal conductivity of the nanofluid was measured with respect to the base fluid, the results at a corresponding temperature range shows the increment is polynomial with temperature and linear with particle concentrations. When the thermal conductivity of silver nanofluids were measured with the thermal conductivity of gold nanofluids, the less enhancement was measured in silver nanofluids as because of the silver particle sizes were larger than the gold particles used. Although silver have higher thermal conductivity and an order of magnitude higher concentration than gold but the results shows clearly the particle size effects. Also the thermal conductivity of nanofluid with particle coated with citrate shows higher enhancement as compare to the nanofluid with particle coated with thiolate, which shows the enhancement in heat transfer at metal surface is depend on the type of coating.

Fonseca H M (3) used the line heat source probe to measure the thermal conductivity of nanofluids of α-alumina particles dispersed in pure water at room temperature. The heating time was controlled so that the temperature rise was not higher than 4 °C, in order to reduce convective effects in the fluid. The results are compared with the base fluid pure water as well as to the values predicted with theoretical models available in the literature. With respect to the thermal conductivity at room temperature, measurements show increases of 1.6%, 2% and 5% for the nanofluids with concentrations of 1%, 1.6% and 2% vol., respectively. Such values are in accordance with those found in the literature for the same kind of nanofluid also shows significant increase of the thermal conductivity of the nanofluids for increasing concentration of nanoparticles. In addition, the theoretical predictions are in good agreement with the measured data.

Teng T P (5) investigates the thermal properties of brines containing nanoparticles using the transient hot wire method. Two nanofluids deionized water based nanofluids containing copper oxide nanoparticles and ethylene glycol based nanofluid containing copper nanoparticles are fabricated by the submerged arc nanoparticle synthesis system (SANSS) with water and ethylene glycol respectively as base solvents at different volume fractions. Traditional aqueous solutions of ethylene glycol with volume fractions ranging from 10% to 90% are mixed for comparison with brines containing nanoparticles of the same volume fractions in terms of their thermal conductivity and thermal diffusivity. The results show that the thermal conductivity of deionized water based nanofluid containing copper oxide nanoparticles is 9.8% higher than that of deionized water. Similarly, the thermal conductivity of ethylene glycol-based nanofluid containing copper nanoparticles is 5.1% higher than that of ethylene glycol. Although the thermal conductivity of copper is higher than that of the copper oxide, more copper oxide nanoparticle are added to the deionized water but due to the difference in geometrical shapes of the copper oxide nanoparticles will cause them to rotate in the fluid, this will then lead to convection like effect in some regions which attain higher thermal conductivity.

Pantzali et al (6) study the performance of nanofluid (CuO in water, 4% v/v) both experimentally and numerically in a PHE (plate heat exchanger) and compare it to that of a conventional cooling fluid (i.e., water). A commercial miniature PHE with modulated surface is employed and its performance is also compared to a respective notional heat exchanger with a flat surface.

A CFD code is also employed, and its results were found to be in very good agreement with the experimental data in terms of temperatures and pressure drop. Thus, the use of the CFD code seems suitable for the design of this type of equipment. Typical results for the effect of surface modulation on PHE performance shows that for the case of water, as expected (Kanaris et al., 2006), the heat transfer rate increases up to 60% compared to that of the flat plate PHE. However, this heat transfer enhancement is accompanied by a significant increase (up to 2.5 times) of the corresponding friction losses. The application of the nanofluid in the PHE has shown that the heat transfer rates are significantly enhanced compared to the respective values measured for water. The augmentation is higher for the lower cooling liquid flow rates tested, while at higher flow rates, where convection is the main heat transport mechanism, the nanoparticles contribution to heat transfer is relevantly lower. The results also suggest that a given heat duty can be abducted by a much lower nanofluid flow rate compared to water, and therefore the pressure drop developed is also lower, indicating that in this case less pumping power is necessary.

Kim et al (7) used the hot-wire method to measure the thermal conductivity of copper oxide nanofluid dispersed in ethylene glycol. Measured data shows that at a very low concentration of particles of about 0.001, 2.6% increase was observed in the thermal conductivity of nanofluid and the thermal conductivity enhancement was encountered when the particle concentration is less than the dilute limit which also helps the particles to move and rotate freely. The study suggests that for enhancement of heat transfer and to be an efficient nanofluid, particle should have a spherical shape to have a higher critical dilute limit and may be prolate spheroid with small aspect ratio to have both rotational and translational Brownian motion.

A Fe-nanofluid was prepared by Hong and Yang [14] with ethylene glycol; Fe nanoparticles with mean size of 10 nm were produced by a chemical vapor condensation process. They found that Fe nanofluids exhibited higher enhancement of thermal conductivity than Cu nanofluids. Their result indicated that the material with high thermal conductivity is not always the best candidate for the suspension to improve the thermal characteristics of base fluids. Also, they concluded that the thermal conductivity of nanofluids increased non-linearly with the solid volume fraction. Hong et al. (2006) also investigated the effect of the clustering of Fe nanoparticles on the thermal conductivity of nanofluids. They found that the thermal conductivity of nanofluids is directly related to the agglomeration of Fe nanoparticles, which caused the nonlinear relation between the Fe volume fraction and thermal conductivity of nanofluids due to rapid clustering of nanoparticles in condensed nanofluids.

Murshed et al. [15] investigated TiO_2 nanoparticles of rod-shape (Ø 10 × 40) and spherical shape (Ø 15) dispersed in deionized water. They observed nearly 33% and 30% enhancements of the effective thermal conductivity for TiO_2 particles of Ø10 × 40 and Ø15, respectively. Both particle size and shape influenced the thermal conductivity of nanofluids.

Xie et al. [16, 17] prepared and measured the thermal conductivities of 26 nm and 0.6 μm SiC suspensions in deionized water and EG using a transient hot-wire method. Different from the experimental results of Lee at al. (1999), they found that the nanofluids with the same solid particles in different base fluids had the same improvement in the effective thermal conductivity. Furthermore, results showed that the HC model (Hamilton and Crosser, 1962) is capable of predicting the thermal conductivity of 0.6 μm SiC suspensions, while it under-predicted that of 26 nm particles.

Zhang et al. [18] measured the effective conductivity and thermal diffusivity of Au/toluene, Al_2O_3/water, TiO_2/water, CuO/water nanofluids using the transient short-hot-wire (SHW) technique, which was developed from the conventional transient hot wire (THW) technique and is based on the numerical solution of two dimensional transient heat conduction for a short wire with the same length-to-diameter ratio and boundary conditions as those used in the actual measurements. The diameters of Au, Al_2O_3, TiO_2 and CuO spherical particles were 1.65, 20, 40 and 33 nm, respectively. The effective thermal conductivities of the nanofluids show no anomalous enhancement and can be predicted accurately by the equations of the Hamilton and Crosser model. The largest increases in thermal conductivity have been observed in suspensions of carbon nanotubes, which have a very high aspect ratio and very high thermal conductivity. The first report on the synthesis of nanotubes was conducted by Iijima (1991). Later, nanotube (multiwalled carbon nanotubes or MWNTs)-oil (olefin) mixtures were investigated by Choi et al. (2001) to measure their effective thermal conductivity. Results showed that the measured thermal conductivity was anomalously greater than the theoretical predictions and was nonlinear with nanotube loadings. As compared to other nanostructured materials discussed previously, the nanotubes achieved the highest conductivity enhancement and provided wide opportunities for effective management applications.

Xie et al. [19] also proposed a method to produce stable and homogeneous suspensions of multiwalled carbon nanotubes (CNTs) in deionized water (DW), ethylene glycol (EG), and decene (DE). They introduced oxygen-containing functional groups on CNT surfaces to form more hydrophilic surfaces. Experimental data indicated that the thermal conductivity enhancement increased with an increase in nanotube loading, but decreased with thermal conductivity increase of the base fluid.

4. Convective heat transfer

The natural convection of fluid small-particles suspensions has been used in many applications in the chemical industry, food industry and also in solar collectors [20]

Comparatively, the natural convection of suspensions is different from that of pure fluids. The natural convection of a suspension is driven by the unstable density distribution of liquid due to temperature differences and the distribution of the particle concentration due to the sedimentation [21]. A few studies have reported the natural convection of nanofluids with no, or very little, sedimentation

Madhu et al [22] investigates experimentally the phenomenon of convective heat transfer on water Al_2O_3 nanofluid flowing through a circular pipe in the laminar regime. The nanoparticle (<50nm) were dispersed in the base fluid of two different particle concentrations (0.03 vol % and 0.06 vol %) and were studied at two different flow rates in the laminar regime under the constant heat flux boundary conditions. The result shows that the enhancement in the convective heat transfer is encountered especially at the entrance region. The heat transfer coefficient of the nanofluids containing 0.06 vol % of Al_2O_3 nanoparticles was enhanced by 8% at Re=1250 and 10% at Re=1800 in comparison with pure water. This clearly indicates that the enhancement increases with an increase in the particle concentration and also with an increase in the Reynolds number.

S. H. Anilkumar, and Ghulam Jilani [23] investigated numerically for a complete explanation of single phase natural convective heat transfer in an enclosure with fin utilizing nano fluids for a range of Rayleigh numbers ($10^3 \leq Ra \leq 10^6$)' fin heights and aspect ratio. Nanofluid used by suspending aluminum oxide nanoparticles in ethylene glycol with various volume fractions varied between $0 \leq \varphi \leq 30\%$.The flow and temperature distributions are taken to be two dimensional and regions with the same velocity and temperature distributions are identified as symmetry of sections. One half of such a rectangular region is chosen as the computational domain taking into account the symmetry about the fin. Transport equations are modeled by a stream function vorticity formulation and are solved numerically by finite-difference schemes.

Results shows that the nanofluid heat transfer rate increases with an increase in the nanoparticles volume fraction. As Rayleigh number increases natural convection prevails, the temperature variation is restricted over a gradually diminishing region around the fin. It is also noticed that the heat affected zone becomes larger with the increasing fin height.

Wen at al [24] formulates the aqueous based nanofluids and its application under natural convective heat transfer conditions. Titanium dioxide nanoparticles are used and dispersed in distilled water through electrostatic stabilization mechanisms and with the use of high shear mixing homogenizer. Titanium dioxide/water nanofluids formulated in such a way are found very stable and are used to investigate their heat transfer behaviour under the natural convection conditions. Both transient and steady heat transfer coefficients were measured for different concentrations of nanofluids under natural convective conditions. The result shows the systematic decrease in the natural convective heat transfer coefficient with increasing particle concentration.

Li et al [25] investigated through a set of experimental measurements of the natural heat transfer characteristics of Al_2O_3-water nanofluids comprised of 47 nm size Al_2O_3 and water with volume fractions ranging from 0.5% through 6%.The temperature of the heated surface and the Nusselt number of different volume fractions of Al_2O_3-water nanofluids natural convection tests clearly demonstrated a deviation from that of pure base fluids (distilled water). In the investigation, a deterioration of the natural convection heat transfer coefficient was observed with increases of the volume fraction of the nanoparticles in the nanofluids. The deterioration phenomenon was further investigated through a visualization study on a 850nm diameter polystyrene particle-water suspension in a bottom heating rectangular enclosure. The influence of particle movements on the heat transfer and natural flow of the polystyrene particle-DI water suspension were filmed, and the temperature changes on the heating and cooling surfaces were recorded. The results were analyzed in an effort to explain the causes of the natural convection heat transfer deterioration of the 47 nm Al_2O_3/water nanofluids observed in the experiments. The visualization results confirmed the natural convective heat transfer deterioration, and further explained the causes of the deterioration of the nanofluids natural convective heat transfer.

5. Boiling heat transfer

Pool boiling of nanofluids has been a subject of many research's and investigations and incoherent results has been reported in literature. Review of literature regarding pool boiling of nanofluids shows clearly that the most experiments were conducted in nucleate pool boiling with varying parameters such as particle size, particle concentration, surface roughness etc. The following review covers the detailed study that has been done with pool boiling of nanofluids with respect to higher and lower nanoparticle concentrations.

Das et al.[26] who investigated nucleate pool boiling characteristics of Al_2O_3-H_2O nanofluids on a cylindrical stainless steel cartridge heaters of 20mm diameter and 420 V, 2.5 kW rating. They conducted experiments with high solid particle concentrations of 4-16% by weight. In this work the nanofluids were neither electro-statically stabilized nor was surfactant used to stabilize the nanofluid.

The result shows the higher the concentration the more was the sedimentation and hence the boiling performance worsened.

The reason is the nanoparticles were found to sediment on the heater, thus making it smoother and deteriorating the boiling performance. This brings out the probable cause for the deteriorating in boiling characteristics. Due to the fact that the sizes of the nanoparticles (20-50nm) are one to two orders of magnitude smaller than the roughness (0.38-1.12 µm) of the heating surface, the particles sit on the relatively uneven surface during boiling. These trapped particles change the surface characteristics making it smoother. This causes the degradation of the boiling characteristics.

Later on Das et al. [27] showed that pool boiling on nanofluids on narrow horizontal tubes (4 and 6.5mm diameter) is qualitatively different from the large diameter tubes due to difference in bubble sliding mechanism it was found that at this range of narrow tubes the deterioration in performance in boiling of nanofluids is less compared to large industrial tubes, which make it less susceptible to local overheating in convective applications. For boiling on tubes of 4mm and 6.5mm diameter there seems to be less

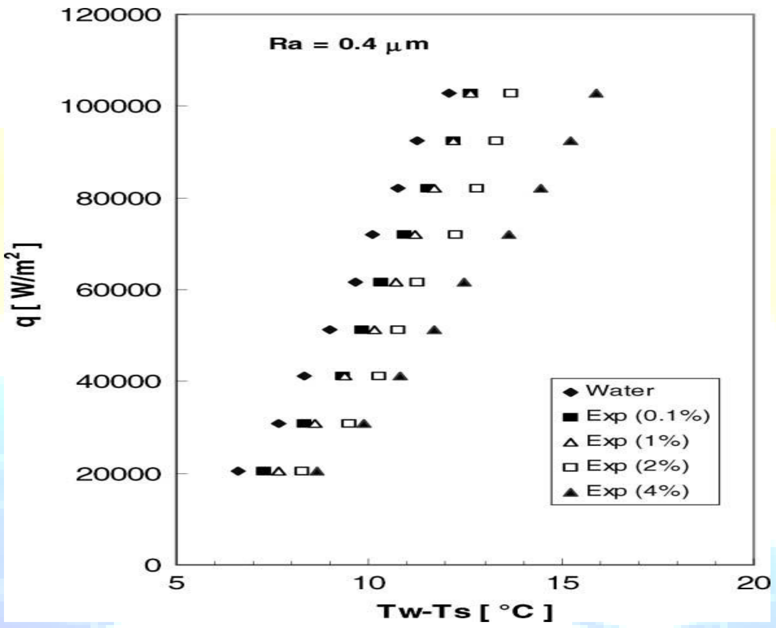

Fig.1 Result of Das et al [26] on smoother heater.

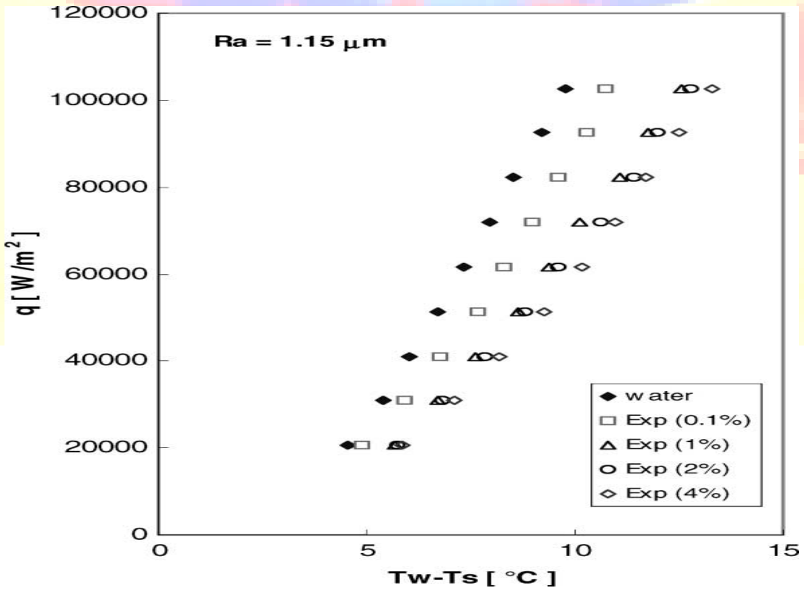

Fig.2 Result of Das et al [26] on roughened heater.

importance of sliding mechanism for larger bubbles, which are comparable to the size of bubbles of boiling on 20mm tube. This is because of the relatively small size of the tube, which produces a large curvature of the surface, which does not allow the sliding of larger bubbles but induces direct departure. However, a large number of smaller bubbles are produced in a sustainable way here and they slide but to a relatively smaller distance [26].

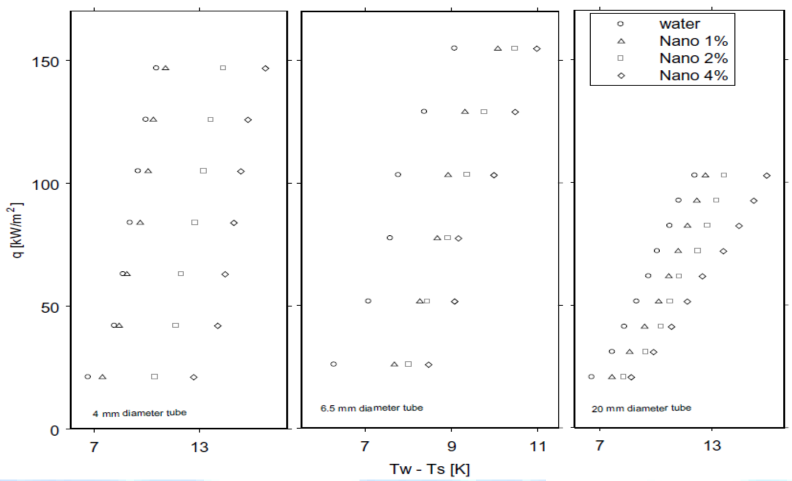

Fig.3 Results of Das et al for nanofluids on tubes of different diameters [27]

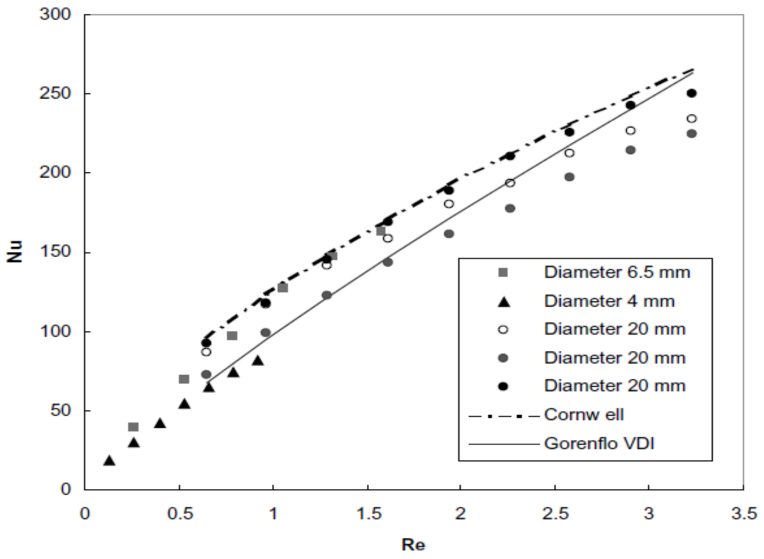

Fig.4 Dimensionless boiling characteristics of water on narrow tubes [27]

Bang and Chang [28, 29] studied pool-boiling heat transfer characteristics of Al_2O_3-H_2O nanofluids at higher heat fluxes and smoother heaters compared to Das et al. [26]. Their experiments were also with 4-16wt% nanofluids, having surface roughness ≈370 nm. They had some important observations regarding the boiling characteristics of nanofluids. Firstly they also observed deterioration of boiling with nanofluids concentration in nanofluids similar to Das et al. [26] but the rate of heat transfer was somewhat different which they attributed to the difference in geometrical features of the heaters in the two studies. They could also identify a clear natural convection regime followed by nucleate boiling. They observed that the experimental data does not conform to the Rohsenow correlation just by changing the properties of the fluid with effective nanofluid properties. They tried different variations of the same correlation like using Rohsenow correlation with changing only the effective conductivity or changing the constant C_{sf} (surface fluid combination factor) of the Rohsenow correlation. It was found that rather changing the properties of the fluid, the modification of the surface fluid combination factor, C_{sf} gives closer approximation to the experimental boiling data of nanofluids. This definitively indicates that the modification of surface characteristics during the boiling of nanofluids might hold the key in explaining the deterioration of boiling of nanofluid.

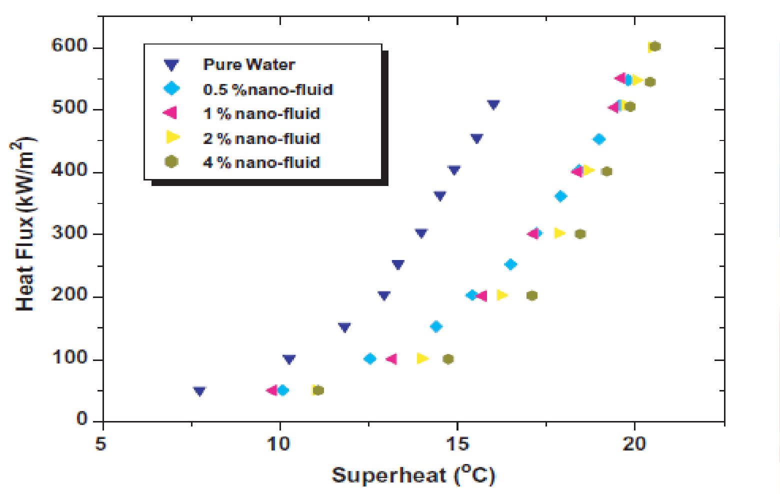

Fig.5 Boiling curve for nanofluids [28]

Zhou [40] experimentally investigated the effects of acoustical parameters, nanofluid concentration and fluid subcooling on boiling heat transfer characteristics of a copper–acetone nanofluid. The results showed that the presence of the copper nanoparticles did not affect the dependence of the heat transfer on the acoustic cavities and fluid subcooling. Without an acoustic field, the boiling heat transfer of the nanofluid was reduced. In contrast with the experimental results of Das et al. [26, 27], in this study the pool boiling heat transfer was not reduced with increasing nanofluid concentrations. With an acoustic field generated to the nanofluid, the boiling heat transfer was enhanced and the boiling hysteresis disappeared. The enhancement became obvious with increasing fluid subcooling, sound source intensity, and nanoparticle concentration.

The pool boiling of nanofluids depends on many factors, among those the particle dispersion and its concentrations is one of the most important parameter for the heat transfer enhancement. Wen and Ding [30] gave a completely different picture of boiling of nanofluids. They observed an enhancement of boiling in the presence of nanoparticles. The particles used by them were same as those used by Das et al. [26] with particle sizes 10-50nm.they stabilized the suspension by adjusting the pH value near 7, which is away from the iso-electrical point (IEP) of Alumina (about 9.1).They also used a high-speed homogenizer (~24,000 rpm) for breaking the agglomerates of Al_2O_3 powder. Even after these processes they found considerable agglomeration giving an average particle size of 167.54 nm but the nanofluid was stable. They used 2.4kw ring heater below stainless steel boiling surface.

You et al. [31] performed experiments with alumina-water nanofluids of very small solid particle concentrations (0.0001-0.005% by weight) on a 10mm square heater in sub-atmospheric conditions. They found no significant change in nucleate pool boiling

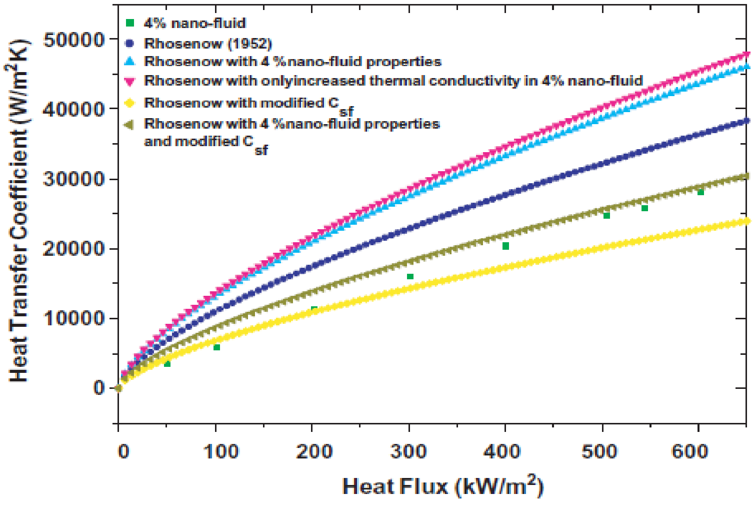

Fig.6 Boiling of 4% nanofluid and application of Rohsenow correlation [28]

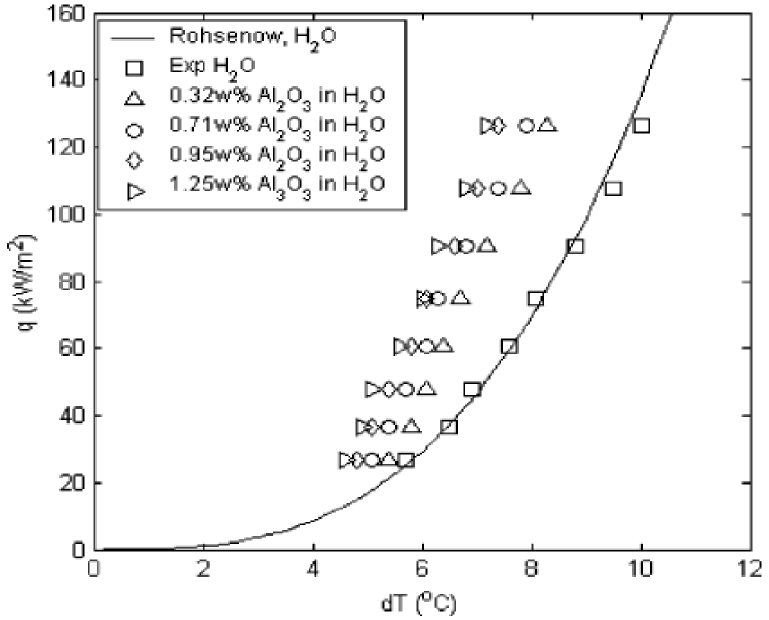

Fig.7 Comparison of Pool boiling data with Rohsenow correlation [30]

Vasallo et al. [32] conducted experiments with silica-water nanofluids (2% by weight) of different particle sizes, ranging from 15nm to 3,000 nm on a NiCr wire heater and found no significant change in the boiling performance at low and medium heat fluxes. But at heat fluxes near to CHF of water, they observed there is boiling deterioration for the 50nm nanofluid

.Witharana [33] carried out experiments using gold-water nanofluids of very low solid particle concentrations (0.001% by weight) on plate heater. An enhancement of 11-21% in heat transfer coefficient was found. With increasing particle concentration the percentage enhancement in heat transfer coefficient also increased.

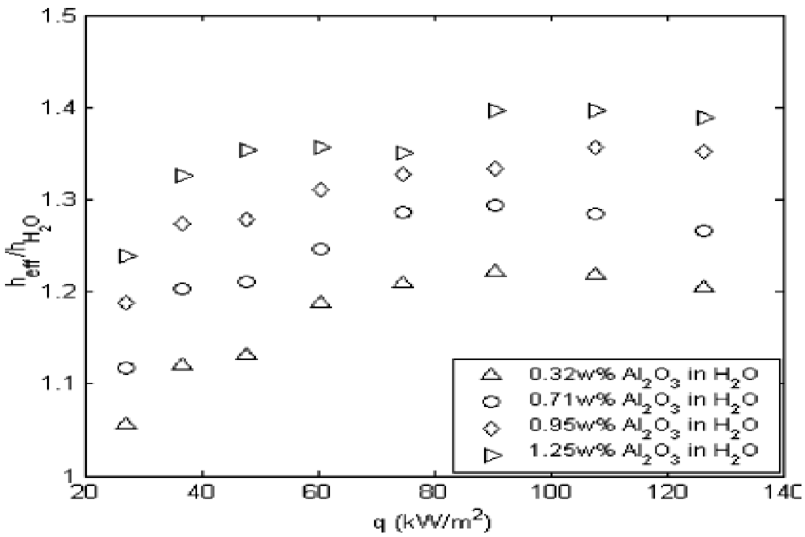

Fig.8.Heat transfer enhancement in Pool boiling[30]

Recent experiments have been carried out by Prakash et al. [34, 35] by using stable water based nanofluids containing alumina nanoparticles of various sizes with vertical tubular heaters of various surface roughnesses. He has found that when the average particle size is of the order of the surface roughness, the number of nucleation sites is greatly decreased. It was also found that when average particle size is much smaller than the heater surface roughness the number of nucleation sites is greatly increased. Here they define a new term called surface-particle interaction parameter. This is the ratio of average surface roughness Ra to average primary diameter of the particle d_p .Physically, it signifies that if it is less than 1 particle size is more than the roughness value and vice versa.

6. Boiling CHF characteristics in nanofluids

Jackson [36] conducted a set of experiments on gold nanofluids during pool-boiling. In these experiments he has found that the heat transfer decreased about 20% over the critical heat flux (CHF) was increased 2.8 times for the 3 nm sized particles on the clean surface. For 15 nm particles the CHF was increased over 3.5 times over pure water with a maximum at nearly 5 times amplification. However, a thin film was observed on the heating surface after boiling and by examining SEM images of the surface and using x-ray spectrometry it was determined that this film was deposited nanoparticles. It was then confirmed that it was this surface deposition that resulted in the adjusted boiling curves and enhanced CHF as pure water boiled on this surface performed similarly to the nanofluids. An investigation into the aspect of the surface that improved the CHF looked at its wetting characteristics. Contact angle was examined; however, the nanoparticle surface actually produced a higher apparent contact angle than the clean, polished surface. An increase in contact angle would actually serve to decrease the critical heat flux. A second look at wetting's effect on the CHF was performed by running a set of experiments using the highly wetting HFE7000 were then performed. From these tests it was found that there was no CHF enhancement when boiling HFE7000. By looking at the nucleation characteristics, it is seen that the HFE7000 has a significantly smaller bubble size than the water and that little difference is seen between the surfaces for HFE7000. It is speculated that the nanoparticle surface serves to reduce the nucleation size and increase site density which may not be seen for the HFE7000 due to its already small characteristic length.

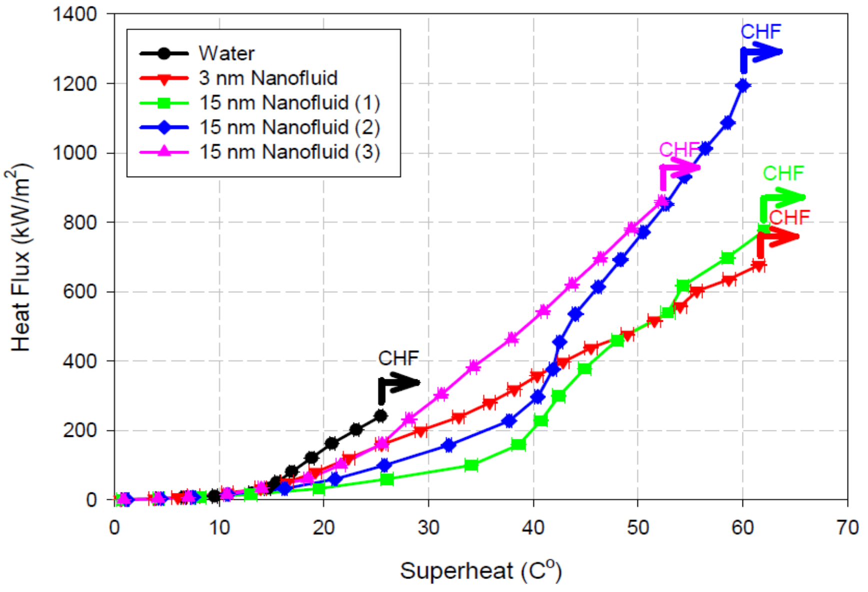

Fig.9 Boiling curve results for 3nm and 15nm trials [36].

Kim et al [37] investigated the characteristics of CHF enhancement by performing pool boiling experiments utilizing pure water and nanofluids with five different volumetric concentrations of TiO_2 nanoparticles ranging from 10^{-5} % to 10^{-1} %. In order to assess the deposition of nanoparticles on the heating surface, the heating surface was characterized with scanning electron microscope (SEM) images subsequent to the pool boiling experiment. Then, to estimate the effect of nanoparticles on the CHF of nanofluids, pool boiling CHF values were measured and compared (a) from a bare heater immersed in nanofluids, (b) from a nanoparticle-coated heater, which was prepared by deposition of suspended nanoparticles during pool boiling of nanofluids and immersed in pure water, and (c) from a nanoparticle-coated heater immersed in nanofluids. To investigate CHF enhancement using nanofluids relative to CHF of pure water, they took the experimental CHF value of pure water as a standard for subsequent CHF comparisons of nanofluids. The result shows that the pool boiling CHF of nanofluids on a bare heater was enhanced to ~200% compared to that of pure water by increasing nanoparticle concentration. SEM images of the heater surface taken after pool boiling CHF tests revealed that CHF enhancement of nanofluids was closely related to the surface microstructure and enhanced topography resulting from the deposition of nanoparticles. In this regard, pool boiling CHF of water on a nanoparticle coated heater sufficiently reproduced that of nanofluids. Moreover, in high nanoparticle concentrations of 10^{-1} % and 10^{-5} %, CHF of pure water on the nanoparticle coated heater was superior to that of nano-fluids.

Truong et al [38] used diamond/water, zinc oxide/water and alumina/ water nanofluids to produce a thin layer of nanoparticle coating on sandblasted plate heaters via boiling deposition. The CHF enhancements obtained in this study are lower than those previously reported in the literature for untreated/smooth surfaces boiled in nanofluids. However, this study offers encouraging proof that nanoparticle coatings can further improve CHF for passive engineered surfaces, such as sandblasted plates. The CHF enhancement of diamond coated plates is about 11%, considering the measurement uncertainties this is only marginally higher than that of the bare sandblasted plate. However, zinc oxide and alumina coated plates yielded higher CHF values, approximately 35% higher than the bare sandblasted plate. Surface characterization of the plate heaters revealed that the coating patterns differ depending on the type of nanoparticles used. The metal oxide nanoparticles produced a more uniform coating, while the diamond nanoparticle coating was found to be irregular. However, the nanoparticle coating did significantly alter the wettability of the metal oxide coated heater surfaces. This change in wettability helped to enhance CHF as predicted by some existing theories/correlations relating CHF to wettability.

Kim et al [39] studied the pool boiling characteristics of dilute dispersions of alumina, zirconia and silica nanoparticles in water. Consistently with other nanofluid studies, it was found that a significant enhancement in critical heat flux (CHF) can be achieved at modest nanoparticle concentrations (<0.1% by volume). Buildup of a porous layer of nanoparticles on the heater surface occurred during nucleate boiling. This layer significantly improves the surface wettability, as shown by a reduction of the static contact angle on the nanofluid boiled surfaces compared with the pure-water-boiled surfaces. A review of the prevalent CHF theories has established the nexus between CHF enhancement and surface wettability changes caused by nanoparticle deposition. This represents a first important step towards identification of a plausible mechanism for boiling CHF enhancement in nanofluids.

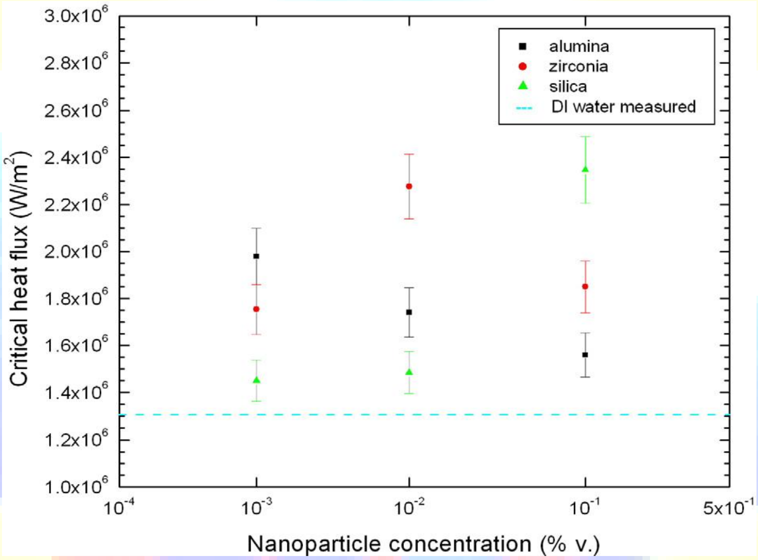

Fig.10 CHF data for pure water and alumina, zirconia and silica nanofluids [39].

Liu and Liao [41] carried out the nucleate pool boiling heat transfer experiments of water (H_2O) based and alcohol (C_2H_5OH) based nanofluids and nanoparticles suspensions on the plain heated copper surface. The study was focused on the sorption and agglutination phenomenon of nanofluids on a heated surface. The nanofluids consisted of the base liquid, the nanoparticles and the surfactant. The nanoparticles suspensions consisted of the base liquid and nanoparticles. The both liquids of water and alcohol and both nanoparticles of CuO and SiO_2 were used. The surfactant was sodium dodecyl benzene sulphate (SDBS). The experimental results of their study show that for nanofluids, the agglutination phenomenon occurred on the heated surface when the wall temperature was over 112 °C and steady nucleated boiling experiment could not be carried out. The reason was that an unsteady porous agglutination layer was formed on the heated surface. However, for nanoparticles-suspensions, no agglutination phenomenon occurred on the heating surface and the steady boiling could be carried out in the whole nucleate boiling region. For the both of alcohol based nanofluids and nano-suspensions, no agglutination phenomenon occurred on the heating surface and steady nucleate boiling experiment could be carried out in the whole nucleate boiling region whose wall temperature did not exceed 112 °C. The boiling heat transfer characteristics of the nanofluids and nanoparticles-suspensions are somewhat poor compared with that of the base fluids, since the decrease of the active nucleate cavities on the heating surface with a very thin nanoparticles sorption layer. The very thin nanoparticles sorption layer also caused a decrease in the solid–liquid contact angle on the heating surface which leaded to an increase of the critical heat flux (CHF).

Conclusion

This review presents an overview of the earlier and recent developments in the study of boiling heat transfer using nanofluids. Many important, complex and interesting phenomena involving nanofluids have been reported in the literature. The use of nanofluids in a wide range of applications appears promising, but the development of the field faces several challenges: (i) the lack of agreement between experimental results from different groups; (ii) the often poor performance of suspensions; and lack of theoretical understanding of the mechanisms. All of the research studied in this chapter reported increases in heat transfer due to the addition of nanoparticles in the base fluid. To what degree and by what mechanism is still debatable. However, the following trends were in general agreement with all researchers:

1. The heat transfer coefficient enhancement increases with increasing nanoparticle volume fraction

2. The heat transfer coefficient enhancement increases with increasing fluid temperature (more than just the base fluid alone)

3. The heat transfer coefficient enhancement increases with decreasing nanoparticle size

4. For high heat flux, the experimental results on pool boiling heat transfer indicated that the addition of nanoparticles into the base fluids did not enhance heat transfer. However, the critical heat flux of the nanofluid was dramatically increased. This revealed that nanofluids may be suitable for cooling at high heat flux applications.

5. Formation of a thin film on the boiling surface due to the deposition of nanoparticle enhances critical heat flux. Also, the nanoparticle surface produced a higher apparent contact angle than the clean surface, this increase in contact angle decreases critical heat flux.

6. Critical heat flux enhancement of nanofluids closely depends on the surface microstructure and the coating pattern on the surface of the plate purely characterizes the enhancement of the critical heat flux. It differs depending on the type of the nanoparticles used.

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