Adding solid particles of nanometer scale to fluids is one of the most important passive methods of enhancing heat transfer performance. However, this gives numerous chances to investigate new frontiers, but also raises remarkable difficulties. Nanofluids act as suspension that can be obtained by dispersing nanometer-sized nanoparticles (1-100nm) in host fluids with the aim of enhancing thermal properties. This paper is a review of recent studies on boiling heat transfer of nanofluids for pool and convective flow boiling of nanofluids. The research results, collected since 2012 to present of the recent survey are reviewed and briefly outlined. An emphasis is put on the enhancement and the deterioration of the boiling heat transfer coefficient (BHTC) and critical heat flux (CHF) of pool and convective flow boiling of nanofluids. Other important parameters affecting the boiling of nanofluids are identified and discussed in this review; while preparing future studies is greatly encouraged in order make this phenomenon well understood.

Key words: boiling heat transfer, pool boiling, convective flow boiling, critical heat flux, nanofluids.

1. Introduction

In the past decade, there has been a lot of efforts of investigators put into the research of boiling heat transfer of nanofluids, in spite of some inconsistent results on this topic, especially due to the complex mechanism of boiling of nanofluids. Attempts are still going on to understand this mechanism and detect the conflicting results. However, pool and convective flow boiling are very efficient modes in many industrial applications, such as power generation, high-tech cooling systems and chemical industrial processes, refrigeration systems, etc. While writing this review paper and collecting data from literature with special attention on the most recent period, since 2012 to present, it has become clear that there are three major groups of researchers presenting their results as regards heat transfer coefficient HTC. The first group has shown enhancement in HTC [5, 9,11, 17-20, 22, 23, 25-34, 40, 42, 44-46, 49-51, 53, 54, 56-60, 64, 65, 67-69]. The second group has dealt with deterioration in HTC [5, 10, 11, 20, 21, 23, 26-28, 30, 31, 33, 43, 49, 51, 52, 54, 55, 59, 60, 62], while the third one has shown no change in HTC [17]. Hence, these contradictions invited us to investigate this field consistently to get a better understanding of this mechanism. Moreover, researchers
interested in conducting experimental and theoretical aspects will also need to understand the effect of operating conditions on nanofluids boiling.

One of the most important passive methods for intensifying heat transfer is to use nanoscale particles with conventional fluids (water, ethylene glycol, oil engine, etc.). Nanofluids act as suspension that can be obtained by dispersing nanometer-sized particles in base fluids. Generally solid particles with high thermal conductivity are added, as additives, to the conventional fluids to increase their thermal conductivity. In this way the thermal performance of these systems will be enhanced. Nanofluids have recently attracted much attention due to their potential as high-performance heat transfer fluids improving the thermal properties of the fluids [1, 2] in many applications. Nanofluids, first reported by Choi [3] in 1995 at Argonne National Laboratory, USA, is a new class of fluids prepared by dispersing nanometer-sized solid particles (1-100nm) in the base fluids. Since 2003, nanofluids boiling has begun to draw research interest and also become an important research area of nanofluids [4] ever since. This article provides a detailed review on the HTC and CHF enhancement/deterioration of boiling heat transfer of nanofluids, with recent literature results since 2012 based on the below-mentioned parameters related to nanoparticle roles in boiling heat transfer:

- Bulk effect associated with the thermal properties of nanofluids caused by suspended nanoparticles in base fluids (e.g. Thermal conductivity, viscosity, surface tension, heat capacity and density).
- Surface effect associated with deposit nanoparticles on the heating surface (e.g. wettability, capillary wicking, and surface roughness).

Hence, this may signpost further research directions for researcher interested in this topic.

2. Boiling heat transfer

Boiling heat transfer is one of the most common phenomenon in heat transfer processes taking place in many industrial applications, and it is also a change of phases, from liquid to vapor. Boiling is a complex process and a very efficient mode of heat transfer in heat exchange systems as well as cooling in high-tech applications. Many researchers have been interested in the topic of boiling heat transfer and several studies deal with the enhancement of thermal performance of this phenomenon. When a liquid is in contact with a surface maintained at a temperature above the saturation temperature of the liquid, boiling will eventually occur in that liquid-solid interface. Conventionally, based on the relative bulk motion of the body of a liquid to the heating surface, boiling is divided into two categories; pool boiling and convective flow boiling.

Pool boiling is a mode of boiling where the fluid is stationary at the beginning with respect of the heating surface and the relative motion of the vapor produced, and the surrounding liquid near the heating surface is primarily due to the buoyancy effect of the vapor. At the same time convective flow boiling refers to boiling in a flowing stream of fluid while the heating surface may be the flow channel. Boiling and two-phase flow phenomena are generally utilized as parts of various industrial applications such as refrigeration, air-conditioning, heat pumping systems and cooling high tech-applications like electronics components [5]. Although most of the research on boiling have been dealing with pool boiling heat transfer, but the most important applications are those related to flow boiling heat transfer, such as boiler tubes, narrow rectangular channels in compact heat exchangers or longitudinal flow through a bundle of rods as in the fuel elements of a nuclear reactor, etc. [70].
Critical or burnout heat flux (CHF) is the most important parameter in terms of boiling heat transfer, and is defined as a limited point in which phase-change phenomenon acts in a way that bubble can completely cover and overwhelm the heating surface. Designing and operating heat transfer equipment, especially in high heat flux rate depending on CHF behavior, reveals the need of applying efficient cooling fluids working on the limit of CHF. Figure 1. represents the various regimes plotted in terms of relations of heat transfer regions to heat flux and also quality. Figure 2. shows the variations of heat transfer coefficient with heat flux and quality. Here the fluid temperature is defined as the saturation temperature for saturated conditions and as the mixed mean liquid temperature for subcooled conditions. In this particular diagram, the critical heat flux transition is a scheduled departure from nucleate boiling (DNB) in the region where nucleate boiling is not suppressed by the stage at which the critical phenomenon occurs [70]. The heat transfer coefficient in Figure 2. is shown as being constantly in the saturated nucleate boiling region. However, the coefficient may decline with increasing quality; a more recent flow boiling map showing detailed similar trends has been published by [71].

Figure 1. Regions of operation of the various regimes of heat transfer in terms of heat flux and quality [70] by permission of Oxford University Press.
3. Boiling heat transfer of nanofluids: recently studied

Boiling plays a vital role in any industrial application and technological areas, such as energy production. For instance subcooled boiling heat transfer can provide huge heat fluxes, and this can be befittingly engaged in the cooling of some components of fusion reactors. Furthermore, very compact heat exchangers can be manufactured with high heat transfer rate obtained by boiling heat transfer. Such improvements will be beneficial for the efficiency of the power plant cycle [6]. To get a more efficient cooling system for high heat flux systems, CHF should be prevented because it may invite the degradation of heat exchange coefficient; whereas high heat fluxes can at least harm the surface, and heat cannot be exchanged from surface to coolant. Nanofluids are designated a promising approach to improve the thermal efficiency of cooling systems and a divine choice for CHF averision purposes. Nano-suspension has higher thermal conductivity in comparison with traditional fluids, so it can be used for high heat flux applications and as productive media for cooling [7].

Figure. 3. illustrates the most recent records related to the development of annual research publications on the topics of boiling heat transfer of nanofluids. Browsing through the Web of Science, 293 publications related to boiling heat transfer using nanofluids have been found since 2012. The highest percentage of publications is 24.232% representing 293 matches in 2016.

3.1. Recent studies on pool boiling of nanofluids

Since 2012 numerous results have been published on nanofluids pool boiling, which are summarized in Table 1. In these studies, the effects of nanofluids on the most important parameters, such as HTC and CHF, in pool boiling have been investigated. Yang et al. [8], the first researchers who used the suspended alumina particles ranging in size from 50nm to 1µm at low concentration
(0.1-0.5 wt. %) observed an improvement in pool boiling heat transfer in their study. Madhusree Kole et al. [9] studied the effect of ZnO/ethylene glycol in pool boiling on HTC and CHF. The results showed that HTC enhanced with ZnO concentration and attained a maximum of 22% compared to that of the base fluid for a ZnO volume fraction of 1.6%. Also, there was an enhancement in CHF with increasing ZnO loading and displayed a maximum enhancement of 117% for nanofluids containing 2.6% volume fractions of ZnO.

Jung et al. [10] studied the CHF and pool boiling HTC of binary nanofluids (H$_2$O/LiBr+Al$_2$O$_3$) and the results concluded that the boiling heat transfer coefficient of the binary nanofluids became lower than that of the base fluid as the concentration of nanoparticles increased, while its CHF became higher. They obtained an enhanced CHF about 48.5% (compared to the base fluid) with the 0.1 vol.% Al$_2$O$_3$ in 10 wt. % LiBr aqueous solution. Sarafraz et al. [11] reported in their study that by increasing the heat flux, the pool boiling HTC of nanofluids significantly increased. In contrast, with increasing the concentration of nanoparticles, due to the deposition of nanoparticles on the surface, the average roughness of the surface and the heat transfer coefficient dramatically deteriorated, while a significant increase in fouling resistance was also reported.

Kim et al. [12] studied the effect of a graphene-oxide coating layer on critical heat flux enhancement under pool boiling phenomena, and they were reporting that nucleate boiling resulted in the deposition of the GO (Graphene-oxide) colloids onto the heated wire, whereby the GO flakes formed a smooth laminated film, and that the thickness of this layer was approximately proportional to the observed increase in the CHF. J. Ham et al. [13] carried out a theoretical analysis of pool boiling characteristics of Al$_2$O$_3$ nanofluids according to volume concentration and nanoparticle size. It was found that the nucleate site density at CHF increased from 32.97 to 30.53 sites/cm$^2$ with the increase of the volume concentration at 50 nm-nanoparticle size. However, the increase was significantly lower than that of the base fluid, which was 65.90 sites/cm$^2$.

An experimental study was carried out by Yanwei et al. [14] to show the effect of nanoparticle size and concentration on boiling performance of SiO$_2$ nanoparticles based on two types of base fluids, water and EG. Results showed that the boiling heat-transfer coefficient (HTC) increased when the nanoparticle diameter was decreasing from 120 nm to 84 nm. In addition, with the increase of nanoparticle concentration, the HTC first increased rapidly and then exhibited negative growth in the concentration range 0.25-1.00%. Moreover, the HTC deteriorated nanoparticle volume fractions above 0.75%. Sina et al. [15] reported their experimental results on the overall effect of three types of nanoparticles suspended in water. The ZnO and Al$_2$O$_3$ nanoparticles were deteriorating heat transfer while adding MWCNTs resulted in improving heat transfer.

Kiyomura et al. [16] studied the effects of nanoparticles deposition on characteristics of the heating surface of pool boiling of water, and in their study, they tested several types of surfaces as follows: Smooth Surface (SS), Rough Surface (RS), Smooth Surface -Low Concentration (SS-LC), Smooth Surface - High Concentration (SS-HC), Rough Surface -High Concentration (RS-HC) and Rough Surface -Low concentration (SS-LC). Results showed that both surfaces (RS-HC and RS-LC) presented deteriorated HTC when compared with the surface without deposition.

This may be explained by the decrease of nucleation site density that may affect bubble frequency and its departure diameter, since the active sites, corresponding to larger surface cavities, are filled with nanoparticles. Consequently, cavities with a smaller mouth diameter can be formed. However, to maintain such cavities active, higher wall superheating is necessary, which is detrimental
to the heat transfer coefficient. Also, the heat transfer coefficient results of the SS-LC surface is about 20% higher than the HTC of the SS-HC and SS surfaces. This behavior seems mainly related to the fact that the roughness of the smooth surface increases with nanoparticle deposition.

Table 1. Summary of nanofluids pool boiling since 2012.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Years</th>
<th>Nanofluids type</th>
<th>Concentration</th>
<th>HTC results</th>
<th>CHF results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>2012</td>
<td>ZnO/EG</td>
<td>0.5-3.7 vol.%</td>
<td>Enhancement 22% at $\phi=1.6%$</td>
<td>Maximum enhancement of 117% at $\phi=2.6%$</td>
</tr>
<tr>
<td>[17]</td>
<td>2012</td>
<td>$\alpha$-Al$_2$O$_3$/water</td>
<td>0.001-0.1 vol.%</td>
<td>Enhancement of smooth surface Unchanged of roughness surface</td>
<td>No data recorded</td>
</tr>
<tr>
<td>[18]</td>
<td>2012</td>
<td>TiO$_2$/water</td>
<td>0.000094-0.047 vol.%</td>
<td>Degraded, then improved</td>
<td>Enhancement about 91%</td>
</tr>
<tr>
<td>[10]</td>
<td>2013</td>
<td>H$_2$O/LiBr+Al$_2$O$_3$</td>
<td>0 -0.1 vol.% Dispersed in H$_2$O/LiBr solutions (3, 7 and 10 wt. % of LiBr).</td>
<td>Deterioration when volume friction increases</td>
<td>Enhanced about 48.5% with the 0.1 vol.% Al$_2$O$_3$ in 10 wt. % LiBr aqueous solution</td>
</tr>
<tr>
<td>[19,20]</td>
<td>2013</td>
<td>Al$_2$O$_3$/water-EG</td>
<td>0.05-1 vol.%</td>
<td>Enhanced about 64% at $\phi=0.75%$</td>
<td>No data recorded</td>
</tr>
<tr>
<td>[21]</td>
<td>2013</td>
<td>Al$_2$O$_3$/water</td>
<td>0 -0.1 vol.%</td>
<td>Reduced</td>
<td>Increased</td>
</tr>
<tr>
<td>[11]</td>
<td>2014</td>
<td>Al$_2$O$_3$/EG</td>
<td>0.1-0.3 wt. %</td>
<td>Enhanced with increase heat flux and decrease with increase concentration</td>
<td>No data recorded</td>
</tr>
<tr>
<td>[22]</td>
<td>2014</td>
<td>$\gamma$-Al$_2$O$_3$/ R141b</td>
<td>0.001 vol.%, 0.01 vol.% And 0.1 vol.%</td>
<td>Increased with concentrations of 0.001 vol.% And 0.01 vol.% With and without the surfactant SDBS. Decreased with 0.1 vol. % concentration without the surfactant</td>
<td>No data recorded</td>
</tr>
<tr>
<td>[23, 20]</td>
<td>2014</td>
<td>MWCNT / water</td>
<td>0.01-0.1 wt. %</td>
<td>Enhancement for covalent nanofluids.</td>
<td>Enhanced about</td>
</tr>
<tr>
<td>Reference</td>
<td>Year</td>
<td>Nanofluid</td>
<td>Concentration</td>
<td>Effect</td>
<td>Comment</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>-----------</td>
<td>---------------</td>
<td>--------</td>
<td>---------</td>
</tr>
<tr>
<td>[24]</td>
<td>2014</td>
<td>Graphene oxide (GO)/water</td>
<td>0.0001, 0.0005, 0.0050 wt. %</td>
<td>Deterioration for non-covalent nanofluids</td>
<td>274.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increase in the CHF with increasing GO layer thickness</td>
</tr>
<tr>
<td>[25]</td>
<td>2015</td>
<td>CuO/ pentane</td>
<td>0.005% and 0.01%</td>
<td>Enhancement of 20–30%. For brass surface and 15–25% at $\phi=0.005$ %</td>
<td>No data recorded</td>
</tr>
<tr>
<td>[26, 20]</td>
<td>2015</td>
<td>TiO$_2$/water</td>
<td>0.0011 vol.%</td>
<td>Degradation</td>
<td>Enhancement about 220%</td>
</tr>
<tr>
<td>[27, 20]</td>
<td>2015</td>
<td>CuO/water</td>
<td>0.1-0.4 wt. %</td>
<td>Deterioration</td>
<td>No data recorded</td>
</tr>
<tr>
<td>[28]</td>
<td>2016</td>
<td>MWNTs/ water</td>
<td>0.1-1 wt. %</td>
<td>Enhancement for covalent nanofluids about 34.2% and 53.4% for MWNTs-COOH and MWNTs-OH</td>
<td>No data recorded</td>
</tr>
<tr>
<td>[29]</td>
<td>2016</td>
<td>ZrO$_2$ / water–ethylene glycol mixture (50:50)</td>
<td>0.025, 0.05, 0.075, and 0.1 vol. %</td>
<td>Enhanced up to 12% at $\phi=0.1$ vol. %</td>
<td>Increase up to 29%</td>
</tr>
<tr>
<td>[30]</td>
<td>2016</td>
<td>Al$_2$O$_3$/ water</td>
<td>0.1, 0.3 wt. %</td>
<td>Deteriorated and then enhanced</td>
<td>Intensified by increasing the mass concentration of nanofluids</td>
</tr>
<tr>
<td>[63]</td>
<td>2016</td>
<td>Reduced GO/water</td>
<td>0.01, 0.1, and 0.3 g/l</td>
<td>No data recorded</td>
<td>Enhancement about 145 to 245 %</td>
</tr>
<tr>
<td>[65]</td>
<td>2016</td>
<td>ZnO/ EG-DI water</td>
<td>5.25-7.25 wt. %</td>
<td>Enhanced</td>
<td>Enhanced</td>
</tr>
<tr>
<td>[31]</td>
<td>2017</td>
<td>SiO$_2$/ water, EG</td>
<td>0.25–1.00 vol.%</td>
<td>Increased when decreasing the nanoparticle diameter</td>
<td>No data recorded</td>
</tr>
</tbody>
</table>
and increased firstly with increasing volume fraction of nanofluids and then deteriorated for nanoparticle volume fractions above 0.75%.

[32] 2017 Fe$_3$O$_4$/water 0.1% vol.% Increased up to 43% No data recorded

[33] 2017 ZnO, α-Al$_2$O$_3$ and MWCNTs/water 0.01 wt. % CNT + 0.01 wt. % SDS and 0.02 wt. % CNT + 0.01 wt. % SDS and (0.01 and 0.05 wt.%) for ZnO, α-Al$_2$O$_3$ ZnO and Al$_2$O$_3$ deteriorated HTC but MWCNTs improved it No data recorded

[64] 2017 TiO$_2$/water 12 and 15 wt. % Enhanced with increase φ No data recorded

3.2. Recent studies on flow boiling heat transfer of nanofluids

Flow boiling heat transfer refers to boiling in a flowing stream of fluid, while the heating surface may be the channel containing the flow. It is used in many industrial applications, such as air conditioning, power plant components (boiler), refrigeration, petroleum industry, nuclear reactor cooling, and high-tech electronic component cooling. To make these applications more efficient in terms of heat removal or cooling systems, it is necessary to enhance the flow boiling heat transfer process to obtain significant detraction of energy consumption. One of the most effective methods to improve the flow boiling heat transfer is to use solid nanoscale particles with conventional cooling fluids This solution would offer new and conceivable energizing outcomes to improve thermal exchange performance compared to host fluids. Nanofluids make a new class of fluids and a promising next-generation for those fluids.

The boiling heat transfer of nanofluids has begun to draw research interest since 2003 and has become a focus of researchers’ attention in nanofluids research activities. Most of the recent studies on boiling heat transfer deal with pool boiling and some with flow boiling heat transfer. Flow boiling heat transfer has more applications in heat exchange systems than pool boiling does, and it has the potential to remarkably enhance heat transfer and thermal efficiency [34-36]. This is the reason why it should still be an essential research topic. However, research studies on flow boiling of nanofluids, in a secondary position, got into focus only in 2007. For a researcher interested in this topic there was altogether one related paper published before 2007 available [34, 37]. Therefore, in the recent years, there has been a growing interesting in flow boiling heat transfer, and some of the published papers deal with the most important parameters such as HTC, CHF and pressure drop in the testing channel.
On the other hand, bulk effects, like thermal conductivity, viscosity, and stability of nanofluids in this phenomenon, are also taken into consideration. In this section, Table 2, 3, important results on HTC and CHF of flow boiling are summarized.

Seung et al. [38] experimentally studied the critical heat flux enhancement in flow boiling of Al$_2$O$_3$ and SiC nanofluids under low pressure and low flow conditions. Their experiment was performed in round tubes, with an inner diameter of 0.01041 m and a length of 0.5 m, under low pressure and low flow (LPLF) conditions at a fixed inlet temperature, while using water, 0.01 vol. %, Al$_2$O$_3$/water nanofluids, and SiC/ water nanofluids. It was found that the CHF of the nanofluids was significantly enhanced, and the CHF of the SiC/ water nanofluid was even more enhanced than that of the Al$_2$O$_3$/water nanofluid. Also, as seen in Figure 5, the contact angle on the inner surface of the test section after the CHF experiment using SiC/ water nanofluid (38.8°) was smaller than the one after the CHF experiment with water (60.5°), and Al$_2$O$_3$/water nanofluid (52.3°) after injecting 10 milliliters of water. These results demonstrated that the nanoparticle deposition increased the surface wettability.

Abedini et al. [39] numerically investigated the subcooled flow boiling of a nanofluid with water and Al$_2$O$_3$ by using a two-phase mixture model. Their results observed that the convective heat transfer coefficient of a nanofluid in subcooled flow boiling was higher than that of the base fluid. Heat transfer coefficient increased parallel with nanoparticles concentration increase. However, the effect of nanoparticle concentration on the heat transfer coefficient in the case of high inlet velocity was insignificant. On the other hand, in subcooled flow boiling, decreasing the inlet mass flow rate could cause either a decrease or an increase in the heat transfer coefficient, that depended on the effect of forced convection and latent heat transport on the overall heat transfer coefficient.

Om Shankar et al. [40] studied the flow boiling heat transfer enhancement by using ZnO-water nanofluids. Their loop was a closed fluid test facility. The annular test section was of 780mm long and consisted of an electrically heated rod and an outer borosilicate glass tube of 21.8mm inner diameter. The heater was manufactured of 12.7mm diameter hollow stainless steel rods welded to solid copper rods at both ends. The results indicated that heat transfer increased along with the increase of heat flux for all concentrations of ZnO/ water nanofluids due to the increased energy gained by the nanoparticles. The increase in the heat transfer coefficient was significant at 0.1% volume concentration of nanoparticles. Its reasons are as follows, at higher concentration of nanoparticles (0.1%) 120% increased thermal conductivity of ZnO/ water nanofluid, and 1367% increased surface roughness of heater rod, due to the deposition of ZnO/ water nanofluid, the nanoparticles were deposited more on the heater surface occurred. Thereby, the surface area of the heater rod was increased and thus, the heat transfer by convection was also increasing due to the increased Brownian motion, the particle driven natural convection, and the increased conduction between nanoparticles.

Sarafriz et al. [41] conducted an experimental study on flow boiling heat transfer coefficients of deionized water and copper oxide water-based nanofluids at different operating conditions in an annular space. Their results demonstrated that by increasing the applied heat flux, the flow boiling heat transfer coefficient increased for DI-water and CuO-water nanofluid at forced convective and nucleate boiling regions. In addition, by increasing the flow rate of fluids, the heat transfer coefficient dramatically increased in both regions. Also, results showed that the inlet temperature of fluids played a vital role on HTC, especially in the nucleate boiling region.

Wang et al. [42] investigated experimentally the Al$_2$O$_3$/ water and AlN/water nanofluids flow boiling heat transfer in a vertical tube under different pressure values and the influence of heat flux
and mass flow rate were also considered. Moreover, nanoparticle size and shape were observed by transmission electron microscope (TEM) to confirm that the nanoparticle had not obviously changed before and after boiling. In the experiment, new correlation for nanofluid saturated flow boiling was presented with 300 experimental points. This correlation applied to both AlN/ water nanofluid and Al₂O₃/ water nanofluid (0.1-0.5 Vol.%).

Table 2. Summarized HTC flow boiling of nanofluids since 2012.

<table>
<thead>
<tr>
<th>Reference/ Years</th>
<th>Operating conditions: D (mm)/L (mm)/G (kg m⁻² s⁻¹)/q (kW m⁻²)/ outlet p (kPa)</th>
<th>Nanofluids; Concentration; nanoparticles diameter (nm)</th>
<th>HTC results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[43]/ 2012</td>
<td>10/ 1000/ 137-303/ 50-102/ 101</td>
<td>TiO₂/water; 0.1-2.5 vol.%; 20</td>
<td>Deteriorated by increasing φ in vertical and horizontal tubes</td>
</tr>
<tr>
<td>[44, 45]/ 2012</td>
<td>0.143/ 7.5/ 171-401/ 0-1000/ 101</td>
<td>Al₂O₃/water; 0.2 wt.%; 40</td>
<td>17% enhancement</td>
</tr>
<tr>
<td>[46]/ 2013</td>
<td>5.94/ 1000/ 2500/9000/ 101</td>
<td>Al₂O₃, ZnO, diamond/water; ≤ 0.1 vol.%; 30</td>
<td>Enhanced with increased φ</td>
</tr>
<tr>
<td>[47]/ 2014</td>
<td>Dₚ= 30/ 300/ 353-1059 / 19/ 101</td>
<td>Al₂O₃ / water; 0.5-1.5 vol.%; 50</td>
<td>Enhanced with increasing heat flux and mass flow rate and deteriorated in the nucleate boiling region with increasing φ</td>
</tr>
<tr>
<td>[48]/ 2014</td>
<td>Dₚ= 9.1/ 780/ 400/ 0-400/ 100-250</td>
<td>ZnO/ water; 0.0001-0.1 vol.%; &lt; 100 (30-50)</td>
<td>Increased</td>
</tr>
<tr>
<td>[49]/ 2014</td>
<td>Dₚ= 30/ 140/353-1059 / 0-190/ 101</td>
<td>CuO/ water; 0.5-1.5 vol.%; 50</td>
<td>Enhanced with increasing heat flux and mass flow rate and deteriorated region with increasing φ</td>
</tr>
<tr>
<td>[50]/ 2015</td>
<td>Dₚ= 30/ 300/ 0-400 / 50-132/ 101</td>
<td>CuO/ water; 0.1-0.3 wt.%; 50</td>
<td>Increased with the mass flow rate</td>
</tr>
<tr>
<td>[51]/ 2015</td>
<td>1.1/ 200/ 200-600/ 100-400/ 101</td>
<td>Al₂O₃/ DI-water; 0.001-0.1 vol.%; 20-30</td>
<td>Decreased with increased φ</td>
</tr>
<tr>
<td>[52]/ 2015</td>
<td>Dₚ= 12/ 300 / 490-880 / 0-5500/ 120</td>
<td>Al₂O₃ / water; 0.25 vol.%; 20-30</td>
<td>Enhanced with surface roughness and mass flow rate</td>
</tr>
<tr>
<td>[53]/ 2015</td>
<td>Dₚ= 30/ 400/350-1060 / 0-175/ 101</td>
<td>CuO₂/ water; 0.001-0.004 wt. %; 50</td>
<td>Increased for convective regime and deteriorated with a nucleate regime with increasing φ</td>
</tr>
<tr>
<td>[54]/ 2015</td>
<td>Dₚ= 1.09/ 306/ 680-3100/ 15-406/ 120-175</td>
<td>Al₂O₃ / water; 0.01-0.1 vol.%; 20-30</td>
<td>Degraded</td>
</tr>
<tr>
<td>[55]/ 2016</td>
<td>11.5/ 1500 / 390-1400/ 0-1200/ 100</td>
<td>Al₂O₃ / water; 0.1-0.3 vol.%; &lt; 26</td>
<td>Improved</td>
</tr>
<tr>
<td>[56]/ 2016</td>
<td>6/ 1100/ 350-1100/ 50-300/ 200-800</td>
<td>γ-Al₂O₃/water; 0.1-0.5 vol.%; 20</td>
<td>Enhanced</td>
</tr>
<tr>
<td>[57]/ 2016</td>
<td>20/ 300/ 24-56/ 8-110/ 101</td>
<td>ZnO/ water; 0.005-0.02 vol.%; *</td>
<td>Enhanced with the mass flow rate and heat flux</td>
</tr>
<tr>
<td>[58]/ 2016</td>
<td>Dₚ= 30/ 300/100-1200 / 2.3-210.1/ 101</td>
<td>MWCNT, CuO and Al₂O₃/ water; 0.1-0.3 wt.%; 12-14nmx1.5-2μm for MWCNT and 50nm for metal oxide particles</td>
<td>Enhanced for MWCNT and enhanced then deteriorated for metal oxide particles</td>
</tr>
<tr>
<td>[59]/ 2016</td>
<td>Dₚ= 30/ 300/100-1200 / 2.3-210.1/ 101</td>
<td>MWCNT, CuO and Al₂O₃/ water; 0.1-0.3 wt.%; 12-14nmx1.5-2μm for MWCNT and 50nm for metal oxide particles</td>
<td>Enhanced for MWCNT and enhanced then deteriorated for metal oxide particles</td>
</tr>
</tbody>
</table>
### Table 3. Summarized CHF flow boiling of nanofluids since 2012.

<table>
<thead>
<tr>
<th>Reference/ Years</th>
<th>Operating conditions: (D (\text{mm})/L (\text{mm})/G (\text{kg m}^{-2} \text{s}^{-1})/q (\text{kW m}^{-2})/\text{outlet } p (\text{kPa}))</th>
<th>Nanofluids; Concentration; nanoparticles diameter (nm)</th>
<th>CHF results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[38]/ 2012</td>
<td>12.7/ 500/ 100-250/ 75/ 101</td>
<td>(\text{Al}_2\text{O}_3/\text{water and SiC/water}; 0.01\text{Vol. }%; \text{Al}_2\text{O}_3 \text{smaller than 50 and SiC larger than 50} )</td>
<td>Enhanced for both nanofluids</td>
</tr>
<tr>
<td>[45, 46]/ 2013</td>
<td>5.94/ 1000/ 2500/9000/ 101</td>
<td>(\text{Al}_2\text{O}_3, \text{ZnO, diamond/water}; \leq 0.1 \text{vol. }%; 30 )</td>
<td>Enhanced about 40-50%</td>
</tr>
<tr>
<td>[47]/ 2013</td>
<td>10.92/ 550/ 100-500/ 0-100/ 101</td>
<td>(\text{Fe}_3\text{O}_4, \text{Al}_2\text{O}_3/\text{water, 0.0001, 0.001 vol. }%; 25 )</td>
<td>Enhanced for magnetic nanofluid</td>
</tr>
<tr>
<td>[61]/ 2013</td>
<td>12.7/ 500/ 100-250/ 100-3500/ 101</td>
<td>(\text{GO/water; 0.01 vol. }%; * )</td>
<td>100% enhanced</td>
</tr>
<tr>
<td>[48]/ 2014</td>
<td>10.92/ 550/ 100-500/ 0-100/ 101</td>
<td>(\text{Fe}_3\text{O}_4/\text{water, 0.0001, 0.001 vol. }%; * )</td>
<td>Enhanced for magnetic nanofluid</td>
</tr>
<tr>
<td>[50]/ 2014</td>
<td>(D_h= 7/ 750/ 0-150/ 1018/ 88 )</td>
<td>(\text{Fe}_3\text{O}_4/\text{water; 0.01, 0.1 vol. }%; (15-20) )</td>
<td>Enhancement for pure water and ferrofluids under an external magnetic field.</td>
</tr>
</tbody>
</table>

* data not recorded

### 3.3. Recent studies in other parameter effect

Although there are many researchers shown wide interest in boiling heat transfer coefficient and critical heat flux using nanofluids [8-62], yet, there are a group of researchers interested in presenting other sub-phenomena, such as flow boiling instabilities, bubble formation and flow patterns regarding flow boiling heat transfer of nanofluids. Leyuan Yu et al. [55], for instance, conducted an experimental study on forced convective flow boiling and two-phase flow of \(\text{Al}_2\text{O}_3/\text{water} \) nanofluids through a minichannel. They were studying the effects of nanofluids on the onset of nucleate boiling
(ONB) and two-phase flow instabilities with an emphasis on the transition boundaries of onset of flow instabilities (OFI). It was found that the presence of nanoparticles delayed ONB and suppressed OFI, and the extent of delay/suppression was proportional to the nanoparticle concentration. These effects were attributed to the changes in available nucleation sites and surface wettability, as well as thinning of thermal boundary layers in nanofluid flow.

Abedini et al. [43] experimentally investigated the subcooled flow boiling of TiO$_2$/ water. Their results showed that the increase of heating surface wettability due to TiO$_2$ nanoparticles deposition on the surface increased the departure size of bubbles and decreased their frequency. This made the heat transfer coefficient degraded.

Wang et al. [67] numerically studied the growth and departure of a single bubble behavior in Al$_2$O$_3$/ water and pure water flow boiling processes by an improved Moving Particle Semi-implicit method in different flow boiling conditions. They concluded that the bubble in Al$_2$O$_3$/ water grew faster and the bubble departure frequency of Al$_2$O$_3$/ water was greater than that in pure water. The effects of nanoparticle concentrations and diameters of Al$_2$O$_3$/ water on the bubble behavior were also investigated and compared under the same flow conditions. It was found that the increase of nanoparticle volume concentration might increase the bubble departure frequency and departure diameter, while the increase rates of departure frequency and departure diameter were lessened with the increase of nanoparticle volume concentration. The intriguing finding was that in the same nanoparticle volume concentration condition, the bubble departure frequency for the nanofluid with a nanoparticle diameter of 29 nm showed a maximum value. Increasing nanoparticle diameter lead to the decrease of bubble departure diameter. It is a brave prediction to say, however, that an optimal nanoparticle diameter range between (20-38nm) should be beneficial to enhance flow boiling heat transfer of Al$_2$O$_3$/ water.

Rana et al. [68] preformed an experimental visualization study on subcooled flow boiling of ZnO/water nanofluids with different low particle concentrations (≤0.01 volume %) in horizontal annulus. The results showed that heat flux increase lead to the increase in bubble diameter. Adding nanoparticles into the base fluid enhanced the maximum bubble diameter and decreased bubble density. Both bubble diameter and bubble density decreased in both water and nanofluids with the increase of flow rate.

4. Conclusion and recommendations

Recent progress in researching on boiling heat transfer of nanofluids has been reported and reviewed in the present paper. Figure 4. illustrates pictorially the main factors affecting nanofluid boiling enhancement. It has been shown by researchers that there are several factors that individually, or in combination, can play an important role in enhancing nanofluid boiling, especially for HTC and CHF. The possibilities to develop a cooling effectiveness system, on the ground of nanofluid coolants application, have received interesting efforts from many researchers. However, the inconsistent results that related to convective and boiling heat transfer coefficient CHTC, BHTC, and critical heat flux, CHF, of nanofluid can be found in data published in literature. There is no hypothesis or theory that clarifies the mechanism of heat transfer process in nanofluids, especially for boiling process. So, work and unremitting efforts need to be made to accelerate the engineering applications of nanofluids related to the boiling of nanofluids, especially on matters below.
A determined effort should be made to find a reliable nanofluid database with worldwide cooperation of researchers for thermal transport properties including more details of nanoparticle types, size, concentration, stabilizing additives (if used), and appropriate preparation methods giving more understanding to promising nanofluid calculation, modeling and analysis.

More effort is needed to find some suitable nanofluids for different engineering systems. From this point of view, we need to test more types of nanoparticles.

Stability is very important to make nanofluids applicable so, it should be tested and improved in boiling nanofluids for both stationary and flow conditions.

There are numerous chances to investigate new frontiers by preparing hybrid (composite) nanoparticles. Hybrid nanoparticles are defined as nanoparticles composed of two or more different materials of nanometer size with an aim to improve thermal conductivity of nanoparticles for hybrid nanofluids.

Nanoparticles composed by two or more different materials of nanometer size.

The major roles of nanoparticles affected by nanofluid boiling heat transfer should be well understood including the bulk effect associated with suspended nanoparticles of the fluid and their thermal properties (thermal conductivity, viscosity, heat capacity and density). The surface effect associated with deposit nanoparticles, which modified the characteristics of heating surface (wettability, homogeneity, roughness and solid surface tension, etc.). That will be achieved by careful experimental observations and numerical simulations.

Boiling sub-phenomena such as bubble formation with suspended nanoparticles, stabilizer (if used) and nanoparticles allocation should be studied numerically and experimentally to provide more details about the enhancement of HTC and CHF.

More effort on numerical analysis and theoretical studies regarding boiling of nanofluid, especially flow boiling of nanofluid, should be made because these types of analyses play an important role in developing new CFD models for CHF.

The mixed convection flow of nanofluids (combined forced and natural convection) in tubes, especially in inclined tubes, is significant in many industrial applications of flow boiling using nanofluid, such as solar energy collectors, supercritical boilers, and nuclear reactors. So, further studies are needed to develop the different single- and two-phase CFD models for analyzing the nanofluid heat transfer during mixed convection.

In some special applications, systems of managing emergency core cooling (ECC) for both pressurized-water reactor, and boiling-water reactor, boiling heat transfer of nanofluids should be studied carefully with consideration of other practice factors, such as orientation of heating surface, material composition, and other physical conditions related to the environment.

In the view of these impediments, nanofluids are not commercialized in numerous industrial applications, for example, nuclear reactors, boilers, spray cooling, and high-tech hardware cooling. Once the key issues tend to, it will give trust to doing experiments with thermal engineering systems.
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Nomenclature

\[ h \text{ [kW m}^{-2}\text{K}^{-1}] \quad \text{Heat transfer coefficient} \quad \text{HTC} \quad \text{Heat transfer coefficient} \]
\[ q'' \text{ [kW m}^{-2}\] \quad \text{Heat flux} \quad \text{BHTC} \quad \text{Boiling heat transfer coefficient} \]
\[ G \text{ [kg m}^{-2}\text{s}^{-1}] \quad \text{Mass flux} \quad \text{CHF} \quad \text{Critical heat flux} \]
\[ D_{in} \text{ [mm]} \quad \text{Inner diameter} \quad \text{LPLF} \quad \text{Low pressure, low flow} \]
\[ L \text{ [mm]} \quad \text{Length of tube} \quad \text{EG} \quad \text{Ethylene glycol} \]
\[ P \text{ [KPa]} \quad \text{Atmospheric pressure} \quad \text{EO} \quad \text{Engine oil} \]
\[ D_h \text{ [mm]} \quad \text{Hydraulic diameter} \quad \text{GO} \quad \text{Graphene oxide} \]

Greek symbols

\[ \alpha \quad \text{Alpha} \quad \text{SDBS} \quad \text{Sodium dodecyl benzene sulfonate} \]
\[ \gamma \quad \text{Gamma} \quad \text{CFD} \quad \text{Computational fluid dynamics} \]
\[ \varphi \quad \text{Concentration, volume friction} \quad \text{ECC} \quad \text{Emergency core cooling} \text{[\%]} \]
Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNB</td>
<td>Departure from nucleate boiling</td>
</tr>
<tr>
<td>BHT</td>
<td>Boiling heat transfer</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission electron microscope</td>
</tr>
</tbody>
</table>

References


[38] Lee, S., et al., Critical heat flux enhancement in flow boiling of Al$_2$O$_3$ and SiC nanofluids under low pressure and low flow conditions, *Nuclear Engineering And Technology*, 44 (2012), 4.


