# BOILING HEAT TRANSFER OF NANOFLUIDS A Review of Recent Studies

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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 and critical heat flux 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

# Introduction

In the past decade, there have been many 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, 14, 15, 17-20, 22-31, 36, 37, 39, 41, 42, 45-47, 49, 50, 52-56, 59, 60, 62-64]. The second group has dealt with deterioration in HTC [5, 7, 10, 11, 14, 15, 20, 21, 23, 25-27, 29, 40, 45, 47, 48, 50, 51, 55, 56], 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

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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 solid particles with conventional fluids (water, ethylene glycol (EG), 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, Lemont, Ill., USA, are a new class of fluids prepared by dispersing nanometer-sized solid particles (1-100 nm) in the base fluids. Since 2003, nanofluids boiling have 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 critical heat fluid (CHF) enhancement/deterioration of boiling heat transfer of nanofluids, with recent literature results since 2012 based on the 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), and
- 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.

#### **Boiling heat transfer**

Boiling heat transfer is one of the most common phenomena 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.* [65].

Critical or burnout heat flux 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 HTC 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 CHF 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 [65]. The HTC in fig. 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 [66].



Figure 1. Regions of operation of the various regimes of heat transfer in terms of heat flux and quality [65] by permission of Oxford University Press

# 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 as a promising approach to improve the thermal efficiency of cooling systems and a divine choice for CHF aversion purposes. Nanosuspension 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 2. Variations of HTC with quality of various heat flux levels; note that the numbers on the curves are cross-references to the various levels indicated in fig. 1 [65] by permission of Oxford University Press

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.





mina particles ranging in size from 50 nm to  $1\mu$ m at low concentration (0.1-0.5 wt.%) observed an improvement in pool boiling heat transfer in their study. Madhusree and Dey [9] studied the effect of ZnO/EG 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.

# Recent studies on pool boiling of nanofluids

Since 2012 numerous results have been published on nanofluids pool boiling, which are summarized in tab. 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 and Maa [8], the first researchers who used the suspended alu-

Reference	Years	Nanofluids type	Concentration	HTC results	CHF results
[9]	2012	ZnO/EG	0.5-3.7 vol.%	Enhancement 22% at $\varphi = 1.6$ %	Maximum enhancement of 117% at $\varphi = 2.6$ %
[17]	2012	$\alpha$ -Al <sub>2</sub> O <sub>3</sub> -water	0.001-0.1 vol.%	Enhancement of smooth surface Unchanged of roughness surface	No data recorded
[18]	2012	TiO <sub>2</sub> -water	0.000094- 0.047 vol.%	Degraded, then improved	Enhancement about 91%
[10]	2013	H <sub>2</sub> O/LiBr+Al <sub>2</sub> O <sub>3</sub>	0-0.1 vol.% Dispersed in H <sub>2</sub> O/ LiBr solutions (3, 7, and 10 wt.% of LiBr).	Deterioration when volume friction increases	Enhanced about 48.5% with the 0.1 vol.% Al <sub>2</sub> O <sub>3</sub> in 10 wt.% LiBr aqueous solution
[19, 20]	2013	Al <sub>2</sub> O <sub>3</sub> -water-EG	0.05-1 vol.%	Enhanced about 64% at $\varphi = 0.75$ %	No data recorded
[21]	2013	Al <sub>2</sub> O <sub>3</sub> -water	0-0.1 vol.%	Reduced	Increased
[11]	2014	Al <sub>2</sub> O <sub>3</sub> /EG	0.1-0.3 wt.%	Enhanced with increase heat flux and decrease with increase concentration	No data recorded
[22]	2014	γ-Al <sub>2</sub> O <sub>3</sub> /R141b	0.001 vol.%, 0.01 vol.%, and 0.1 vol.%	Increased with concentrations of 0.001 vol.% and 0.01 vol.% With and without the sur- factant SDBS. Decreased with 0.1 vol.% concentration without the surfactant	No data recorded
[23, 20]	2014	MWCNT-water	0.01-0.1 wt.%	Enhancement for covalent nanofluids. Deterioration for non-covalent nanofluids	Enhanced about 274.2%
[12]	2014	Graphene oxide (GO)-water	0.0001, 0.0005, 0.0010, and 0.0050 wt.%	No data recorded	Increase in the CHF with increasing GO layer thickness
[24]	2015	CuO/pentane	0.005% and 0.01%	Enhancement of 20-30%. For brass surface and 15-25% at $\varphi = 0.005$ %	No data recorded
[25, 20]	2015	TiO <sub>2</sub> -water	0.0011 vol.%	Degradation	Enhancement about 220%
[26, 20]	2015	CuO-water	0.1-0.4 wt.%	Deterioration	No data recorded
[27]	2016	MWNT-water	0.1-1 wt.%	Enhancement for covalent nanofluids about 34.2% and 53.4% for MWNT-COOH and MWNT-OH Deterioration for non-covalent nanofluids.	No data recorded
[28]	2016	ZrO <sub>2</sub> -water-EG mixture (50:50)	0.025, 0.05, 0.075, and 0.1 vol.%	Enhanced up to 12% at $\varphi = 0.1$ vol. %	Increase up to 29%

Table 1. Summary of nanofluids pool boiling since 2012

Reference	Years	Nanofluids type	Concentration	HTC results	CHF results
[29]	2016	Al <sub>2</sub> O <sub>3</sub> -water	0.1, 0.3 wt.%	Deteriorated and then enhanced	Intensified by increasing the mass concentration of nanofluids
[58]	2016	Reduced GO-water	0.01, 0.1, and 0.3 g/l	No data recorded	Enhancement about 145 to 245 %
[60]	2016	ZnO/EG-DI water	5.25-7.25 wt.%	Enhanced	Enhanced
[14]	2017	SiO <sub>2</sub> -water, EG	0.25–1.00 vol.%	Increased when decreasing the nanoparticle diameter and increased firstly with increasing volume fraction of nanofluids and then deteriorated for nanoparticle volume fractions above 0.75%.	No data recorded
[30]	2017	Fe <sub>3</sub> O <sub>4</sub> -water	0.1% vol.%	Increased up to 43%	No data recorded
[15]	2017	ZnO, $\alpha$ -Al <sub>2</sub> O <sub>3</sub> and MWCNT-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 <sub>2</sub> O <sub>3</sub>	ZnO and Al <sub>2</sub> O <sub>3</sub> deteriorated HTC but MWCNT improved it	No data recorded
[59]	2017	TiO <sub>2</sub> -water	12 and 15 wt.%	Enhanced with increase $\varphi$	No data recorded

Table 1. (continuation)

Jung *et al.* [10] studied the CHF and pool boiling HTC of binary nanofluids  $(H_2O/LiBr + Al_2O_3)$  and the results concluded that the boiling heat transfer coefficient (BHTC) 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.%  $Al_2O_3$  in 10 wt.% LiBr aqueous solution. Sarafraz and Hormozi [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 nanofluids, due to the deposition of nanoparticles on the surface, the average roughness of the surface and the HTC 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 CHF enhancement under pool boiling phenomena, and they were reporting that nucleate boiling resulted in the deposition of the GO 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. Ham and Cho [13] carried out a theoretical analysis of pool boiling characteristics of  $Al_2O_3$  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<sup>2</sup>. 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<sup>2</sup>.

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 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%. Shoghl *et al.* [15] reported their experimental results on the overall effect of three types of nanoparticles suspended in water. The ZnO and  $Al_2O_3$  nanoparticles were deteriorating heat transfer while adding MWCNT 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: 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 HTC. Also, the HTC 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.

# 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 have 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 few others related to flow boiling. 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 [31-33]. 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 [31, 34]. Therefore, in 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, tabs. 2 and 3, important results on HTC and CHF of flow boiling are summarized.

Reference/ Years	Operating conditions: D [mm]/L [mm]/G [kgm <sup>-2</sup> s <sup>-1</sup> ]/ q [kWm <sup>-2</sup> ]/outlet p [kPa]	Nanofluids; Concentration; nanoparticles diameter [nm]	HTC results
[40]/2012	10/1000/137-303/50-102/101	TiO <sub>2</sub> -water; 0.1-2.5 vol.%; 20	Deteriorated by increasing $\varphi$ in vertical and horizontal tubes
[41, 31]/ 2012, 2015	0.143/7.5/171-401/0-1000/101	Al <sub>2</sub> O <sub>3</sub> -water; 0.2 wt.%; 40	17% enhancement
[39, 42]/ 2013	5.94/1000/2500/9000/101	$Al_2O_3$ , ZnO, diamond-water; $\leq 0.1$ vol.%; 30	Enhanced with increased $\varphi$
[45]/2014	<i>D<sub>h</sub></i> = 30/300/353-1059 /19/101	Al <sub>2</sub> O <sub>3</sub> -water; 0.5-1.5 vol.%; 50	Enhanced with increasing heat flux and mass-flow rate and deteriorated in the nucleate boiling region with increasing $\varphi$
[37]/2014	$D_h = 9.1/780/400/0-400/100-250$	ZnO-water; 0.0001-0.1 vol.%; < 100 (30-50)	Increased
[47]/2014	$D_h = \frac{30}{140} \frac{353}{353} \frac{353}{353}$	CuO-water; 0.5-1.5 vol.%; 50	Enhanced with increasing heat flux and mass-flow rate and deteriorated region with increasing $\varphi$
[38]/2015	$D_h = 30/300/0-400/50-132/101$	CuO-water; 0.1-0.3 wt.%; 50	Increased with the mass-flow rate
[48]/2015	1.1/200/200-600/100-400/101	Al <sub>2</sub> O <sub>3</sub> /DI-water; 0.001-0.1 vol.%; 20-30	Decreased with increased $\varphi$
[49]/2015	$D_h = \frac{12/300}{0.5500/120}$	Al <sub>2</sub> O <sub>3</sub> -water; 0.25 vol.%; 20-30	Enhanced with surface roughness and mass-flow rate
[50]/2015	$D_h = \frac{30}{400} \frac{350-1060}{0-175}$	CuO <sub>2</sub> -water; 0.001-0.004 wt. %; 50	Increased for convective regime and deteriorated with a nucleate regime with increasing $\varphi$
[51]/2015	1.09/306/680-3100/15-406/ 120-175	Al <sub>2</sub> O <sub>3</sub> -water; 0.01-0.1 vol.%; 20-30	Degraded
[52]/2016	11.5/1500/390-1400/0-1200/100	Al <sub>2</sub> O <sub>3</sub> -water; 0.1-0.3 vol.%; ~ 26	Improved
[53]/2016	6/1100/350-1100/50- 300/200-800	ν-Al <sub>2</sub> O <sub>3</sub> -water; 0.1-0.5 vol.%; 20	Enhanced
[54]/2016	20/300/24-56/8-110/101	ZnO-water; 0.005-0.02 vol.%; *	Enhanced with the mass-flow rate and heat flux
[55]/2016	D <sub>h</sub> = 30/300/100-1200/ 2.3-210.1/101	MWCNT, CuO and Al <sub>2</sub> O <sub>3</sub> -water; 0.1-0.3 wt.%; 12-14 nm×1.5-2 μm for MWCNT and 50 nm for metal oxide particles	Enhanced for MWCNT and enhanced then deteriorated for metal oxide particles

Table 2. Summarized HTC flow boiling of nanofluids since 2012

#### Table 2. (continuation)

Reference/ Years	Operating conditions: <i>D</i> [mm]/ <i>L</i> [mm]/ <i>G</i> [kgm <sup>-2</sup> s <sup>-1</sup> ]/ <i>q</i> [kWm <sup>-2</sup> ]/outlet <i>p</i> [kPa]	Nanofluids; Concentration; nanoparticles diameter [nm]	HTC results
[5]/2016	$D_h = 30/200/0-400 / 0-175/101$	Al <sub>2</sub> O <sub>3</sub> -water; 0.5-1 vol.%; 5, 50 and 80	Enhanced in short-time study and deteriorated in the extended time – study
[62]/2016	10/1000/138-308/50-112/101	TiO <sub>2</sub> -water; 0.01-5 vol.%; 20	Augments in single-phase and degraded with a subcooled flow regime with $\varphi$
[39]/2017	6/1100/350-1100/48-289/ 200-800	AlN-water and $Al_2O_3$ -water; 0.1-0.5 vol.%; 20 for $Al_2O_3$ and 30 for ALN	Depend on some parameter according new correlation proposed
[56]/2017	10/1000/137-210/13-77/101	TiO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> and CuO-wa- ter; 0.1-2.5vol.%; 10, 20	Enhanced for single phase and degraded for subcooled regime
[7]/2017	10/1000/137-303/13-88/101	TiO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> -water; 0.1-2.5 vol.%; 20, 40	Deteriorated in both directions with increasing $\varphi$
[31, 63, 64]/2013, 2014, 2015	21.8/500/405-710/100-550/101	ZnO-water; 0.001-0.01 vol.%; 40	Enhanced with increasing $\varphi$

\* data not recorded

## Table 3. Summarized CHF flow boiling of nanofluids since 2012

Reference/ Years	Operating conditions: D [mm]/L [mm]/G [kgm <sup>-2</sup> s <sup>-1</sup> ]/ q [kWm <sup>-2</sup> ]/outlet p [kPa]	Nanofluids; concentration; nanoparticles diameter [nm]	CHF results
[35]/2012	12.7/500/100-250/75/101	Al <sub>2</sub> O <sub>3</sub> -water and SiC/water; 0.01 vol.%; Al <sub>2</sub> O <sub>3</sub> smaller than 50 and SiC larger than 50	Enhanced for both nanofluids
[39, 42]/ 2013	5.94/1000/2500/9000/101	$Al_2O_3$ , ZnO, diamond-water; $\leq 0.1$ vol.%; 30	Enhanced about 40-50%
[43]/2013	10.92/550/100-500/0-100/101	Fe <sub>3</sub> O <sub>4</sub> , Al <sub>2</sub> O <sub>3</sub> -water, 0.0001, 0.001 vol.%, 25	Enhanced for magnetic nanofluid
[57]/2013	12.7/500/100-250/ 100-3500/101	GO/water; 0.01 vol.%; *	100% enhanced
[44]/2014	10.92/550/100-500/0-100/101	Fe <sub>3</sub> O <sub>4</sub> -water, 0.0001, 0.001 vol.%, *	Enhanced for magnetic nanofluid
[46]/2014	D <sub>h</sub> = 7/750/0-150/1018/88	Fe <sub>3</sub> O <sub>4</sub> -water; 0.01, 0.1 vol.%; (15-20)	Enhancement for pure water and ferrofluids under an external magnetic field.

\* data not recorded

Lee *et al.* [38] experimentally studied the CHF enhancement in flow boiling of  $Al_2O_3$ 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 conditions at a fixed inlet temperature, while using water, 0.01 vol.%,  $Al_2O_3$ -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  $Al_2O_3$ -water nanofluid. The contact angle in the inner surface of the test section after the CHF experiment using the SiC-water nanofluid (38.8°) was smaller than that after the CHF experiment with water (60.5°) and  $Al_2O_3$ -water (52.3°) after injecting 10 milliliters of water.

Abedini *et al.* [39] numerically investigated the subcooled flow boiling of a nanofluid with water and  $Al_2O_3$  by using a two-phase mixture model. Their results observed that the convective heat transfer coefficient (CHTC) of a nanofluid in subcooled flow boiling was higher than that of the base fluid. The HTC increased parallel with nanoparticles concentration increase. However, the effect of nanoparticle concentration on the HTC 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 HTC, that depended on the effect of forced convection and latent heat transport on the overall HTC.

Om Shankar and Nirupan [37] 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 780 mm long and consisted of an electrically heated rod and an outer borosilicate glass tube of 21.8 mm inner diameter. The heater was manufactured of 12.7 mm 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 HTC was significant at 0.1 vol.% concentration of nanoparticles. Its reasons are: 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.

Sarafraz *et al.* [38] conducted an experimental study on flow BHTC of deionized water and CuO-water based nanofluids at different operating conditions in an annular space. Their results demonstrated that by increasing the applied heat flux, the flow BHTC 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 HTC 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.* [39] investigated experimentally the  $Al_2O_3$ -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 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  $Al_2O_3$ -water nanofluid (0.1-0.5 vol.%).

# Recent studies in other parameter effect

Although there are many researchers shown wide interest in BHTC and CHF using nanofluids [7-57]. 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. Yu *et al.* [51], for instance, conducted an experimental study

on forced convective flow boiling and two-phase flow of  $Al_2O_3$ -water nanofluids through a mini-channel. 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.* [40] 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 HTC degraded, (see also [61]).

Wang and Wu [62] numerically studied the growth and departure of a single bubble behavior in  $Al_2O_3$ -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  $Al_2O_3$ -water grew faster and the bubble departure frequency of  $Al_2O_3$ -water was greater than that in pure water. The effects of nanoparticle concentrations and diameters of  $Al_2O_3$ -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 (20-38 nm) should be beneficial to enhance flow boiling heat transfer of  $Al_2O_3$ -water.

Rana *et al.* [63] preformed an experimental visualization study on subcooled flow boiling of ZnO-water nanofluids with different low particle concentrations ( $\leq 0.01$  vol.%) 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.

#### **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 nano-

fluid 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 CHF, of nanofluid can be found in data



Figure 4. Factors affecting nanofluid boiling enhancement

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 efforts should be made to find a reliable nanofluid database with worldwide co-operation 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 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, fossil fuel 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

- $D_h$ - hydraulic diameter, [mm]
- $D_{in}$ - inner diameter, [mm]
- mass flux, [kg m<sup>-2</sup>s<sup>-1</sup> G
- heat transfer coefficient, [kWm<sup>-2</sup>K<sup>-1</sup>] h
- length of tube, [mm] L
- atmospheric pressure, [kPa]
   heat flux, [kWm<sup>-2</sup>] р
- q

#### Greek symbols

- alpha α
- gamma γ
- concentration, volume friction, [%] Ø

Acronyms

AIN	<ul> <li>aluminum nitride nanparticles</li> </ul>
BHTC	<ul> <li>boiling heat transfer coefficient</li> </ul>
CHTC	- convective heat transfer coefficient
CHF	<ul> <li>critical heat flux</li> </ul>
DNB	<ul> <li>departure from nucleate boiling</li> </ul>
EG	<ul> <li>ethylene glycol</li> </ul>
GO	<ul> <li>graphene oxide</li> </ul>
HTC	<ul> <li>heat transfer coefficient</li> </ul>
LPLF	<ul> <li>low pressure, low flow</li> </ul>
MWCN	T– multi-wall carbon nanotubes
MWNT	<ul> <li>multi-wall nanotubes</li> </ul>
SDBS	<ul> <li>sodium dodecyl benzene sulfonate</li> </ul>

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