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Experimental studies of flow boiling heat transfer by using nanofluids

A critical recent review

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Abstract

Flow boiling heat transfer widely utilized in numerous industrial applications such as boiler tubes, evaporators and cooling of reactors in a nuclear power plant. Nanofluids are a new category of thermal fluids, made by dispersing a nanometer solid particle which is usually less than 100 nm into conventional liquids such as water, oil engine and ethylene glycol with the intent to enhance the thermal properties of the base fluids. This work reviews the recent experimental studies focusing on the flow boiling heat transfer using nanofluids. The latest results associated with this subject are presented and outlined to account the influence of several parameters, which are related to operating conditions and nanoparticles morphology on the heat transfer coefficient and the critical heat flux. Besides, the effects of nanoparticles on other related sub-phenomenon of the flow boiling by using nanofluids were discussed. Moreover, the latest review papers of the related topic were presented and briefly discussed. Finally, suggestions for future research activities related to this field were also concisely listed.

Keywords Experimental studies · Flow boiling · Nanofluids · Two-phase flow · Heat transfer coefficient (HTC)

List of symbols

HTC	Heat transfer coefficient
CHF	Critical heat flux
TEM	Transmission electron microscope
DLS	Dynamic light scattering
MWCNT	Multi-walled carbon nanotubes
DW	Deionized water
GA	Gum Arabic
SDBS	Sodium dodecylbenzene sulfonate
PVP	Polyvinyl pyrrolidone
SDS	Sodium dodecyl sulfate
CTAB	Cetyl trimethyl ammonium bromide
CNC	Computer or/computerized numerical control
ONB	Onset of nucleate boiling
DNB	Departure from nucleate boiling
OFI	Onset of flow instabilities
OBE	Onset of bubble elongation
G	Mass flux (kg m^{-2} s^{-1})
q''	Heat flux (kW m^{-2})
P	Pressure system (kPa)
D_h	Hydraulic diameter (mm)
T_in	Inlet temperature in degree Celsius (°C)
L	Length of channel (mm)
U	Velocity of fluid (m s^{-1})
$\overset{\circ}{m}$	Mass flow rate (kg s^{-1})
ρ_l	Density of liquid (kg m^{-3})
ρ_g	Density of vapor (kg m^{-3})
C_p	Heat capacity (J kg^{-1} K^{-1})
F_ht	Nanoparticle impact factor on heat transfer coefficient
Re	Reynolds number
Gr	Grashof number
Bo	Bond number
Mo	Morton number
Ja	Jacob number

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Ku	Kutateladze number
x	Vapor quality
φ_V	Volume fraction (%)
σ	Surface tension (N m^{-1})

Greek letters

γ	Gamma
φ	Phi (volume friction) (%)
μ	Mu (viscosity) (Ps a)

Subscripts

nf	Nanofluids
bf	Base fluids
chf	Critical heat flux
sub	Subcooling
in	Inlet
V	Volume
l	liquid
v	Vapor

Introduction

Boiling heat transfer and two-phase flow play a vital role in heat transfer processes in many industrial heat exchange systems. Boiling is an efficient heat transfer phenomenon compared with others, and it occurs with a change in phase from the liquid state to a vapor one. Flow boiling is classified as a type of boiling mode, and it can be referred to boiling of moving stream inside the channel that may include it. During the last decades, many investigators in this field have been attempted to understand the mechanism of such a complex phenomenon deeply in order to save the cost by designing optimal heat exchange system that allows high heat transfer amount.

The flow boiling heat transfer is vastly used in various industrial sectors due to its high cooling efficiency, which can be used to limit the problem of the high heat flux dissipation systems. Examples of these industrial applications include boiler tubes, evaporators, chemical process and cooling of nuclear reactors as well cooling of high technology electronic devices. The fifth section in this review will be presented and addressed the most important applications, which are a notice in the literature for such boiling type. Over the last decades, researches deal with the flow boiling heat transfer which has grown at a very rapid rate, and this is, of course, because of various industrial and technological sectors. Recently, there are numerous published papers and several conferences held around the world, which are devoted to this topic [1–7]. From another side, nanofluids are prepared by Choi [8] in 1995 and are defined as the new generation of heat transfer fluids or a mixture. Nanofluids can be made by adding nanoscale solid metals (such as copper, iron, silver and gold), oxides metals (copper oxide, titania, alumina and silica), carbides or non-metal (diamond and carbon tubes) to conventional fluids such as water, oil and ethylene glycol. This mixing aims to obtain superior thermal properties especially the thermal conductivity that makes them possibly valuable in numerous applications related to heat exchange systems [8–20]. Generally, there are two main methods, which are used for producing nanofluids. The first one is called the one-step method, and the other is named the two-step method. In the first one, direct formation of the nanoparticles in the base fluid occurred, while the preparation of nanoparticles separately mixed into the base fluid happened in the second method.

The flow boiling heat transfer of nanofluids is still in its infant stage and needs more investigations by using both experimental and theoretical methods under various operating conditions. Therefore, the efficient design of the above-mentioned industrial applications involves a whole understanding of several significant parameters such as the heat transfer coefficient (HTC), critical heat flux (CHF), vapor quality, pressure drop and the flow instabilities [21, 22].

With gathering papers from the Scopus database by using analysis tools, there was a significant increase in published articles of the flow boiling of nanofluids especially for the years from 2015 up to date, where there are about fifty-five published papers in this subject as shown in Fig. 1. In addition, it can be seen that the published articles in this field had increased just after 2007. The reason behind this increase is the difficulty and overlapping of this topic with a fluid stream velocity that could influence flow patterns and the heat transfer characteristics. In the next section, great efforts are paid in order to make the readers'

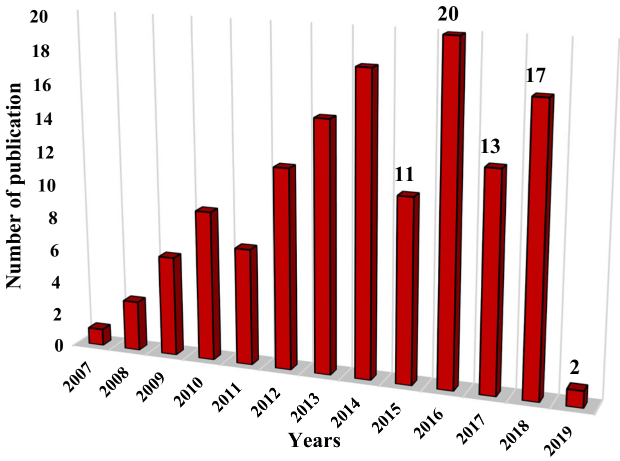


Fig. 1 Publishing works on the Scopus database by words "Flow boiling" AND "Nanofluids" (Date: 8/Dec/2018)

convenience by collecting and discussing the latest review papers regarding the boiling of nanofluids by means of both pool and flow boiling heat transfer processes.

Recent review papers related to the boiling of nanofluids

During the last 2 years, there were some review papers outlined the subject of boiling heat transfer using nanofluids by means of both experimental and theoretical methods. Table 1 summarizes the latest review articles, which are related to the topic of boiling heat transfer using nanofluids. Excellent comprehensive reviews are introduced in 2015 and 2016 by Fang et al. [6, 16] related to the boiling using nanofluids; in their first review work, an emphasis was put on HTC, CHF, bubble dynamics and another influence parameters during the boiling process. They are also discussed and outlined the heat transfer performance represented by HTC and CHF for both pool boiling and the flow boiling using nanofluids by introducing another comprehensive review [16]. They were found from the reviewed works that using nanofluids in the boiling process may be enhanced or degrade the performance of the boiling heat transfer. This is due to the deposition of nanoparticles on the heating surface which

Table 1 Summarized of recent review papers regard boiling heat transfer using nanofluid

References	Type of reviewed boiling/main reported parameters	Concluding and remarks
Fang et al. [6]	Flow boiling/HTC, CHF, pressure drop, flow pattern and stability	They reported from available results that the effect of nanoparticles on the flow boiling HTC is conflicting, while the CHF could enhance about 50%. Other important parameters such as pressure drop and flow pattern influenced by the deposition of nanoparticles during the boiling process
Fang et al. [16]	Pool and flow boiling/HT and CHF	Authors concluded that using nanofluids might intensify or deteriorate the boiling HT and CHF, depending on many parameters related to geometry, additives, nanoparticles concentration and fluid properties
Pinto and Fiorelli [23]	Pool and flow boiling/HTC	They concluded regarding boiling of nanofluids that the interaction between the nanoparticles and the heating surface is the main reason to enhance or decrease the heat transfer performance and it is also could increase the critical heat flux. They also reported that the studies associated with flow boiling of nanofluids are rear and need more efforts to understand this mechanism
Kamel and Lezsovits [24]	Pool and flow boiling/HTC, CHF and other related parameters	Their review summarized the studies from 2012 to 2017, and they concluded from their review that there are two roles in boiling of nanofluids. First, the bulk effect related to thermal properties of nanofluids is caused by suspended nanoparticles in base fluids (e.g., thermal conductivity, viscosity, surface tension and heat capacity). Second, a surface effect is associated with deposit nanoparticles on the heating surface (e.g., surface roughness, enhanced contact angle (wettability) and capillary wicking)
Kamel et al. [25]	Pool and flow boiling/CHF	Their review shows how the nanofluids could play an important role in achieving high heat flux with small temperature differences during the boiling process, which, in turn, modify the critical heat flux
Liang and Mudawar [26]	Pool boiling/HTC, CHF and incipient boiling hysteresis	Their review included works of macroscale, microscale and nanoscale surfaces, as well as multi-scale (hybrid scale) as passive techniques to enhance heat transfer performance. They reported a various degree of enhancement for both HTC and CHF with the aforementioned modification
Xie et al. [27]	Pool and flow boiling/CHF	Authors concluded that the CHF improved for both pool and flow boiling process during various enhanced passive and active methods, which, in turn, enhanced the security of heat exchange systems
Cheng et al. [28]	Pool and flow boiling/heat transfer performance, CHF and relevant physical mechanisms	Their review article reported that the mechanism of boiling heat transfer and two-phase flow using nanofluids is a complicated phenomenon and it is not fully understood due to the contradictories results in the literature. Enhancement in CHF was reported from collected studies, and this improvement could reach over 50%
Moreira et al. [29]	Pool and flow boiling/HTC	They concluded that the behavior of HTC during pool and flow boiling could increase or decrease, and it depends on several parameters related to surface texture on thermophysical properties of working fluid

gets a porous nanolayer, and it is responsible for changing the characteristics of the heating surface such as roughness surface, wettability and capillary wicking forces. Their work was very valuable for researchers who are interesting in this field by introducing the finding of the essential studies regarding the boiling of nanofluids from 2003 until 2016.

Pinto and Fiorelli [23] introduced the boiling heat transfer of nanofluids as a part of their full review paper related to the mechanism that is responsible for intensifying heat transfer using nanofluids. Their work concluded that the main parameters that directly influence the heat transfer performance are listed below:

1. The types of nanoparticles and their concentration in base fluids.
2. The modification of surface characteristics (i.e., wettability, capillary wicking force surface roughness).
3. Change in thermophysical properties such as thermal conductivity, viscosity, heat capacity, density and surface tension.
4. Besides, the operation condition especially the mass and heat fluxes for convective flow boiling.

Kamel and Lezsovits [24] presented the state-of-the-art overview on the subject of boiling heat transfer by using nanofluid and briefly discussed the latest experimental and theoretical studies related to this topic. Their review focused on the works that have done from 2012 until the beginning of 2017. They concluded that using nanoparticles in the boiling process by means of both pool and convective flow boiling processes has two significant roles: Firstly, the nanoparticles could affect the performance of heat transfer due to the bulk effect represented by enhancing thermal properties of nanofluids—secondly, the surface effect is served by surface modification such as surface roughness, wettability and capillary wicking. They also showed that in all reviewed studies the CHF improved and it is not so difficult to achieve 100% enhancement using engineered nanofluids. Kamel et al. [25] outlined the latest studies regarding boiling critical heat flux by using nanofluids for two types of boiling processes, pool boiling and flow boiling heat transfer of nanofluids. Their review was concise and focused on collecting the latest works related to the experimental investigations of the CHF of nanofluids. Authors outlined and discussed the improvement that happened to the CHF during deposition of the nanoparticles on a heating surface through boiling mode which, in turn, intensifies the surface characteristics of heating surface and then enhancing or shifting the critical heat flux of such mechanism. Their review concluded and recommended several points using nanofluids as working fluids in the boiling process.

Liang and Mudawar [26] presented studies that published in the literature for pool boiling improvement due to modifying the working fluids properties via adding surfactants, polymers and nanoparticles during nucleate boiling regime for both the HTC and CHF. They have shown that the nanofluids have undeniable upgrading impact on enhancement of CHF and this due to the improvement of surface characteristics which, in turn, enhancing the wettability of the fluid, on another hand, the concept of HTC is still conflicting and not clearly understood due to the inconsistencies concerning the impact of nanofluids during nucleate boiling regime and there are interlinked parameter that may affect such as operating parameters, surface roughness nature and nanoparticles morphology.

Xie et al. [27] introduced a review on CHF intensifying methods, and one of those methods was adding nanoparticles to working fluids, which is termed nanofluids. They have discussed the approach considering the improvement of thermal properties of the liquid by suspending nanoparticles to conventional fluids for both types of boiling, pool and flow boiling heat transfer. Their reviewed works concluded that for both types of boiling there was an enhancement in CHF for all collected papers. The main influence parameters that might affect the CHF and led to improvements are increasing the wettability, capillary wicking and surface roughness that led to improving the active nucleation sites.

Cheng et al. [28] presented a critical and comprehensive review of the topic of boiling heat transfer by using nanofluids. Their discussion focused on the nucleate pool boiling, flow boiling heat transfer as well as the CHF phenomenon with two phases during the boiling process. They discussed the thermophysical properties of nanofluids and then the boiling heat transfer, CHF and the related subphenomenon. They concluded that there are many parameters, which are effects, the boiling (pool and flow) and CHF such as the thermophysical properties, especially thermal conductivity, viscosity and surface tension. Moreover, they recommended that the boiling heat transfer mechanisms responsible for these inconsistency results should be identified and be able to clarify why nucleate heat transfer may be improved, no change or degraded.

Moreira et al. [29] discussed the behavior of nanofluids under single-phase flow and two-phase flow (i.e., pool boiling and flow boiling) via a comprehensive review. Their review work outlined the results of single phase, and it showed that the HTC is improved by using nanofiller (i.e., nanoparticles, nanosheets and nanotubes), but this is still facing some difficulties related to increasing the viscosity of nanofluids. While the HTC with two-phase boiling showed to be increased or decreased and sometimes no change, such a trend can be attributed to improving the heating surface characteristics during the nanoparticles deposition.

All reviews as mentioned earlier were good insight in order to give the researchers who are engaging with this topic and what are the future directions on this phenomenon. The purpose of this critical review is to provide the reader with a clear map of the latest experimental studies regarding flow boiling heat transfer using nanofluids. In the present work, recent advancement on this subject from 2015 until up to date is summarized in Table 2 and concisely reviewed. Intensification focused on how nanofluids and deposition of nanoparticles on heating surface influence the boiling heat transfer performance represented by the heat transfer coefficient HTC and critical heat flux CHF and other related sub-phenomenon. In addition, the authors presented an overview of parameters that could affect the flow boiling (e.g., nanocoating of heating surface and bubble dynamics) by using nanofluids. Moreover, this review will help the researchers interesting in this topic to know where the experimental studies going on and what the gaps in this area are?

The boiling phenomenon of nanofluids (general concept)

Boiling heat transfer mode is the process of changing the phase from a liquid state to vapor one during a constant temperature at a given pressure, and such temperature is called saturation temperature. Generally, the boiling process is classified into two types depending on the fluid movement: Pool boiling takes place when the liquid is at a station condition, and the flow boiling type happens, when the fluid stream moves inside or outside the heating surface. However, heat transfer during phase change mechanism (liquid–vapor) is a complex phenomenon which includes different sub-phenomena such as bubble dynamics (i.e., bubbles departure, nucleation site density, waiting time of bubbles growth and detach and frequency of bubbles, etc.) and transient conduction as well as evaporation–condensation. On the other hand, nanofluids are a new class of thermal fluids which are a mixture of nanoparticles and pure liquids, the presence of nanoparticles as another phase (solid phase) during phase change (boiling process) increasing this complexity due to the interaction between the phases. Up to date, this subject is still partially understood and needs more persistent efforts to investigate the physical nature of this phenomenon. In the next section, efforts focused on reviewing the recent improvements of experimental works are related to flow boiling heat transfer of nanofluids.

Recent advances in flow boiling experimental studies

Effect of nanofluids on (HTC) and (CHF)

In spite of the contradictions in results clarified by recent experimental studies, efforts still ongoing regard the flow boiling heat transfer using the nanofluid. This, perhaps, is due to the demand for efficient heat exchange systems. The estimation of the local heat transfer coefficient (HTC) with the presence of nanofluids is necessary for understanding the spatial variations of the temperature along the channel flow [2]. On the other hand, it is imperative to ensure the safety of the heat exchange system by making the burnout phenomenon or CHF not exceeding the necessary limit to overcome the overwhelm problem under consideration. Therefore, intensifying critical heat flux by using a passive method such as solid additives to liquids “nanofluids” to enhance heat transfer plays an essential role to make the boiling process safe under high heat fluxes [16]. Table 2 summarizes the latest experimental studies related to the flow boiling heat transfer of nanofluids from 2015 until the present time.

Sarafraz et al. [30] conducted an experimental study of flow boiling HTC by using deionized water and CuO/water nanofluids at different operating conditions in an annular space. Their results demonstrated that with increasing the applied heat flux, flow boiling HTC increased for DI water and CuO/water nanofluid at forced convective and nucleate boiling regions. Besides, the increased flow rate of fluids led the HTC dramatically to increase in both regions. Moreover, results showed that the inlet temperature of fluids plays a vital role in HTC especially in the nucleate boiling region. Moreira et al. [31] studied experimentally the saturated flow boiling heat transfer coefficient of alumina nanofluid under atmospheric pressure. Their work focused on studying the effects of nanoparticles concentration on flow boiling HTC. Results showed that the HTC was enhanced with dilute volume fraction (i.e., 0.001 vol%) of alumina nanofluids and decreased with increasing concentration.

Setoodeh et al. [32] carried out an experimental study of the subcooled flow boiling by using Al_2O_3–water nanofluid with a constant volume concentration of alumina nanoparticles. Their test rig was a hot spot heating surface (i.e., aluminum circular surface with diameter 12 mm) fixed on the bottom of a rectangular channel as shown in Fig. 2. Results showed that by increasing the surface roughness and stream velocity, the surface heat fluxes increased. Also, the forced convective and the flow boiling HTC of the nanofluid increased concerning water. Wang and Su [19] conducted an experimental study of the flow

Table 2 Summary of experimental details of flow boiling heat transfer using nanofluid in recent years

References	The geometry of the test section	Test section dimension/diameter/mm; length/mm	Heat and mass fluxes/ q''/kW m^{-2}; G/ kg m^{-2} s^{-1}	Pressure system/ kPa	Conventional fluids	Nanoparticles details/type; size/ nm; concentration φ/%	Nanofluids preparation/ method; surfactant	Results of (HTC/CHF) of flow boiling using nanofluids
Sarafraz et al. [30]	Vertical stainless steel annular tube	30(1*); 300	50–132; 0–400	101	Deionized water	CuO; 50; 0.1–0.3 mass%	Two step(2*)	Improved with increasing mass flow rate of fluid/(2*)
Moreira et al. [31]	Horizontal stainless steel tube	1.1; 200	100–400; 200–600	101	Deionized water	Al_2O_3; 20–30; 0.001–0.1 vol%	Two step(2*)	Improved with low concentration and decreased with high concentration/(2*)
Setoodeh et al. [32]	Aluminum circular surface in the bottom of Plexiglas channel	12; 300	0–5500; 490–880	120	Deionized water	Al_2O_3; 20–30; 0.001–0.1 vol%	Two step(2*)	Augmented with surface roughness and mass flow rate/(2*)
Wang and Su [19]	Vertical stainless steel circular tube	6; 1100	50–300; 350–1100	200–800	Deionized water	γ-Al_2O_3; $D = 20$ nm and $L = 50$ nm; 0.1–0.5 vol%	Two step(2*)	Enhanced using nanofluid/(2*)
Rajabnia et al. [33]	Horizontal stainless steel circular tube	10; 1000	26–102; 138–308	101	Distilled water	TiO_2; 20; 0.01 - 0.5 vol%	Two step(2*)	Deteriorated with nanoparticles for two-phase regime (subcooled boiling flow)/(2*)
Soleimani and Keshavaraz [34]	Plexiglas channel with rectangle shape	20 × 30; 1200	0–700; 400–850	120	Deionized water	Al_2O_3; 20–30; 0.1; 0.25 vol%	Two step; sodium dodecyl benzene sulfonate (SDBS)	Enhanced using nanofluid/(2*)
Paul et al. [35]	Vertical Stainless steel circular tube	11.5; 1500	0–2000; 125–453	100	water	Al_2O_3; 26; 0.1; 0.3 vol%	Two step(2*)	(2*)/Enhanced with nanofluid compared for water and this enhancement increase with concentration of particles
Sarafraz and Hormozi [36]	Vertical annuli channel	30(1*); 300	0–175; 400–1200	100	Deionized water	CuO; 50; 0.1–0.3 mass% Al_2O_3; 50; 0.1–0.3 mass% MWCNT(2*); 0.1–0.3 mass%	Two step; polyvinyl-pyrrolidone (PVP)	Enhanced for MWCNT compared to other nanofluids with increasing mass and heat fluxes/(2*)
Salari et al. [37]	Vertical annuli channel	30(1*); 150	0–85; 400–600	100	Deionized water	Al_2O_3; (5, 50 and 80); 0.5–0.1 vol%	Two step; sodium dodecyl sulfate (SDS)	Enhanced for short time study and deteriorated for long time study/(2*)

Table 2 (continued)

References	The geometry of the test section	Test section dimension/diameter/mm; length/mm	Heat and mass fluxes/ q''/kW m^{-2}; G/ kg m^{-2} s^{-1}	Pressure system/ kPa	Conventional fluids	Nanoparticles details/type; size/ nm; concentration φ/%	Nanofluids preparation/ method; surfactant	Results of (HTC/CHF) of flow boiling using nanofluids
Tazarv et al. [38]	(2*)	8.825; 2250	1–28; 192–482	101	R141b	TiO_2; 20; 0.01 - 0.3 vol%	Two step; cetyl trimethyl ammonium bromide (CTAB)	improved for nanorefrigerant compared to pure refrigerant/(2*)
Wang et al. [39]	Vertical stainless circular steel tube	6; 1100	48–289; 350–1100	200–800	Deionized water	AlN; 30; 0.1 vol% γ-Al_2O_3; 20; 0.1 vol%	Two step(2*)	Enhanced about 64%, 61% compared to water for AlN and γ-Al_2O_3, respectively/(2*)
Wang et al. [40]	Vertical stainless steel circular tube	6; 1100	48–289; 350–1100	200–800	Deionized water	γ-Al_2O_3; D = 20 nm and L = 50 nm; 0.1–0.5 vol%	Two step(2*)	Improved about 86% using nanofluid compared to water/(2*)
Zhang et al. [41]	Horizontal copper circular tube	9; 2000	(2*); 300–500	100	R123	MWCNT; D = 30–70 nm and L = 2–19 µm; 0.02–0.2 vol%	Two step; sodium dodecyl benzene sulfonate (SDBS)	Enhanced with increase concentration, mass flux and vapor quality/(2*)
Zangeneh et al. [42]	Vertical annuli channel	20(1*); 150	8–110; 23–50	100	Deionized water	ZnO; less than 50; 0.005–0.02 vol%	Two step(2*)	Improved with ZnO–water nanofluids/(2*)
Wang et al. [43]	Vertical stainless circular steel tube	6; 1100	48–289; 350–1100	200–800	Deionized water	AlN; 30; 0.1 vol% γ-Al_2O_3; 20; 0.1 vol%	Two step(2*)	Enhanced about 64%, 61% compared to water for AlN and γ-Al_2O_3, respectively/(2*)
Karimzadehkhouei et al. [44]	Horizontal stainless steel microtube	0.502; 70 and 120	220–600; 1200–3400	101	Distilled water	γ-Al_2O_3; 20; 0.01–1.5 mass%	Two step; sodium dodecyl sulfate (SDS)	Deteriorated with high concentration/(2*)
Abedini et al. [45]	Vertical stainless steel circular tube	10; 1000	13–76.5; 37–210	101	Deionized water	TiO_2; 10 and 20; 0.1–2.5 vol% Al_2O_3; 10 and 20; 0.1–2.5 vol% CuO; 10 and 20; 0.1–2.5 vol%	Two step(2*)	Improved in single-phase regime and deteriorated with two-phase regime using nanofluids/(2*)
Afrand et al. [46]	Vertical and horizontal stainless steel circular tube	10; 1000	37.5–705; 137–412	150	Distilled water	TiO_2; 20 and 40; 1–3 vol% Al_2O_3; 20 and 40; 1–3 vol%	Two step(2*)	Degraded for both vertical and horizontal tube with presence of nanoparticles/(2*)

Table 2 (continued)

References	The geometry of the test section	Test section dimension/diameter/mm; length/mm	Heat and mass fluxes/ q''/kW m^{-2}; G/ kg m^{-2} s^{-1}	Pressure system/ kPa	Conventional fluids	Nanoparticles details/type; size/ nm; concentration φ/%	Nanofluids preparation/ method; surfactant	Results of (HTC/CHF) of flow boiling using nanofluids
Hashemi et al. [47]	Horizontal stainless steel circular tube	10; 2000	60–200; 320–920	101	Water	MWCNT; D = 10–20 nm and L = 30 µm; 0.001 and 0.01 mass%	Two step; Gum Arabic (GA)	Improved for both water and nanofluids with increasing heat flux and mass flux/Enhanced for flow boiling of nanofluid
Patra et al. [48]	Vertical annuli channel	33(1*); 880	30–250; 4–10	101	Deionized water	Al_2O_3; 20–25; 0.001–0.01 vol% TiO_2; 30–38; 0.001–0.01 vol%	Two step(2*)	Increased with dilute concentration/(2*)
Moreira et al. [49]	Horizontal stainless steel circular tube	1.1; 200	100–350; 200–600	101	Deionized water	Al_2O_3; 20–30 and 40–80; 0.001–0.1 vol% SiO_2; 15 and 80; 0.001–0.1 vol% Cu; 25; 0.001–0.1 vol%	Two step(2*)	Degraded for all nanofluids compared to DI water/(2*)
Choi et al. [50]	Vertical stainless circular steel tube	10.92; 250	(2*); 1000–5000	100	Deionized water	Fe_3O_4; 25; 0.01 vol%	Two step(2*)	(2*)/enhanced up to 40% for nanofluid compared to water
Zhang et al. [51]	Horizontal copper microchannels	2.5 Width 0.5 Height	0–100; 0.04–0.07	101	water	GO; 500–1000; 0–0.05 mass%	Two step(2*)	Decreased/enhanced
Sarafraz et al. [52]	stainless steel chamber together with a copper disk with horizontal surface	10 (diameter of copper disk inside SS chamber)	(2*)/30–700	101	Therminol 66	MgO; 50; 0.1 and 0.3 mass%	Tow step; nonyl phenol ethoxilate	Improvement about 23.7% for 0.1 mass%./(2*)
Wang et al. [53]	Vertical stainless circular steel tube	6; 500, 600 and 800	98.9–348.4; 350–1100	400–890	Deionized water	AlN; 30; 0.1–0.5 vol% γ-Al_2O_3; D = 20 and L = 50; 0.1 vol%	Two step(2*)	(2*)/CHF intensifying about 18% compared to conventional fluid
Balasubramanian et al. [54]	31 parallel U-shaped copper microchannels	0.308(1*); 30	1100–4450; 100–800	101	Deionized water	Al_2O_3; 40–50; 0.01–0.1 vol%	Two step(2*)	Improved during the transient state/enhanced up to 15% for moderate volume concentration
Mohammed et al. [55]	Rectangular channel	0.0211(1*); 150	2–14(2*)	100	Acetone + zinc bromide	Graphene; 6–8 nm thickness and 5 µm width; 0–0.5 vol%	Two step(2*)	Enhanced/improved

Table 2 (continued)

References	The geometry of the test section	Test section dimension/diameter/mm; length/mm	Heat and mass fluxes/ q''/kW m^{-2}; G/ kg m^{-2} s^{-1}	Pressure system/ kPa	Conventional fluids	Nanoparticles details/type; size/nm; concentration φ/%	Nanofluids preparation/ method; surfactant	Results of (HTC/CHF) of flow boiling using nanofluids
Patra et al. [86]	Vertical annuli channel	35$^{(1*)}$; 700	30–250; 3.8–13.33	101	water	Al_2O_3/water; SiO_2/ water	Two step$^{(2*)}$	Enhanced with low concentration/$^{(2*)}$

$^{(1*)}$Hydraulic diameter, $^{(2*)}$data not recorded

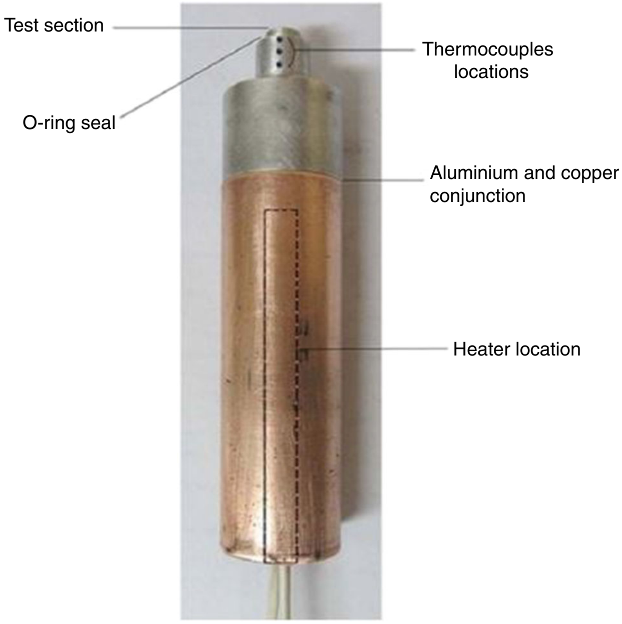


Fig. 2 Heating element used by [32] as a hot spot heating surface of flow boiling study, with permission from Elsevier

boiling heat transfer in a vertical tube under different pressure conditions by using γ Al_2O_3-based water nanofluid. Their nanofluid was tested under different operating conditions such as pressure system, heat flux and mass flux to show the effects of these parameters on boiling heat transfer behavior. Results found that the most enhancement is about 86% for nanofluid saturated flow boiling compared with base fluid. Their results indicated that the heat transfer performance was increased with increasing the heat flux, nanoparticles concentration and the pressure system, respectively. In addition, observation by transmission electron microscope (TEM) for nanoparticles after boiling has shown that there was no any change in shape or size of nanoparticles as shown in Fig. 3.

Rajabnia et al. [33] investigated the subcooled flow boiling of TiO_2–water nanofluid in a horizontal stainless steel circular tube experimentally. They used three nanoparticles volume concentration (i.e., 0.01%, 0.1% and 5%) with 20 nm diameter size. Their results showed that the heat transfer coefficient of nanofluids in the single-phase region was enhanced when the volume concentration of nanoparticles was increased, while in the subcooled flow boiling region, a significant decrease with increasing the volume concentration was observed. With the aim of enhancing heat transfer performance, Soleimani and Keshavarz [34] conducted an experimental study of an internal subcooled flow boiling over a hot spot. Their rig was consisted of Plexiglas channel with a rectangular cross section by using water and Al_2O_3/water as working fluids. Their experiment was performed with four different

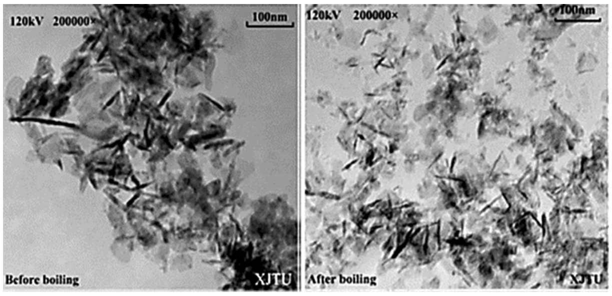


Fig. 3 Transmission electron microscope (TEM) for nanoparticles used by [19] before and after the boiling process, with permission from Elsevier

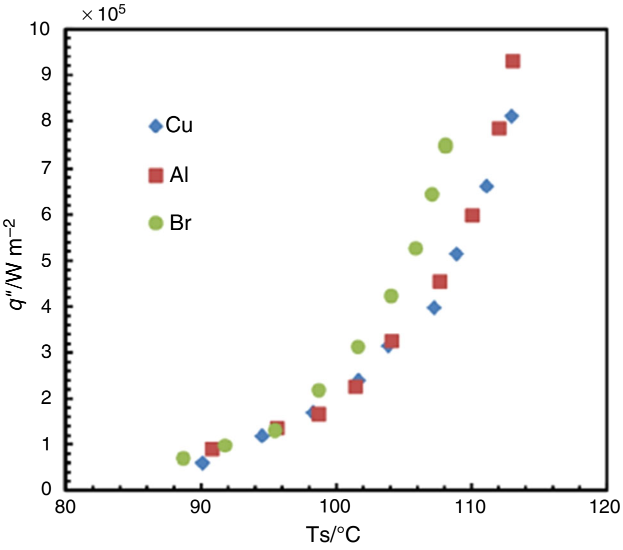


Fig. 4 Experimental result for nanofluid 0.25 vol%, at $Ra = 4.4\ \mu m$ and, $U = 0.9$ m/s presented by [34], with permission from Elsevier

heaters constructed from the brass (with and without mini-channels), aluminum and copper. Their results showed that the brass heater with mini-grooves had a better performance of the flow boiling by using the nanofluid compared with corresponding copper and aluminum heaters as shown in Fig. 4. They go back to this behavior due to the high heat removal by the brass surface. Moreover, they referred that surface heat flux increased with an increase in the surface roughness and stream velocity for both single- and two-phase regions.

Paul et al. [35] estimated the visible rewetting temperature and the structure of the boiling curve from the temperature–time responses that recorded during the rewetting phenomenon in a vertical bottom flooded tube by an alumina–water nanofluid. Their results indicated that the CHF was enhanced with nanofluid compared to water and this enhancement increased with the concentration of nanoparticles. They also detected that the deposition of particles caused the early rewetting, which led to improving the CHF. One of their results included the influence of the initial temperature of the tube on the variation of heat flux at a mass flow rate $m° = 0.02667$ kg/s and a distance from the bottom of the tube equaled to 580 mm, and they observed that both the boiling curves of water and nanofluid were increased for CHF with high initial temperature as shown in Fig. 5.

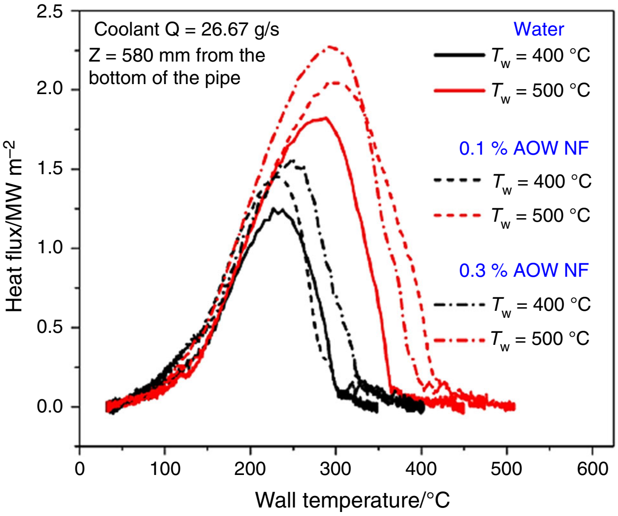


Fig. 5 Effect of initial temperature of the tube on the boiling curves of water and nanofluid by [35], with permission from Elsevier

Sarafraz and Hormozi [36] experimentally studied the heat transfer characteristics of the flow boiling of CuO, Al_2O_3 and multi-walled carbon nanotubes (MWCNT) dispersed with deionized water inside vertical annuli. Their experiment focused on the heat transfer performance and thermal fouling resistance parameter with different operating conditions such as the concentration of nanoparticles, heat flux and mass flux. They are also used different methods like pH, ultrasonication process and stabilizer (surfactant) to obtain stable nanofluid in their investigation. Their results showed that the MWCNT-based deionized water had better boiling thermal performance and lower thermal fouling resistance value in comparison with other nanoparticles. They presented a comparison of the thermal resistance for different tested nanofluids and concluded that the thermal performance of MWCNT was the highest followed by alumina and CuO nanofluids, respectively, in both heat transfer regions as shown in Fig. 6. Besides, it was found that the heat transfer coefficient of MWCNT increased with increasing concentration, mass and heat fluxes of nanofluid.

Salari et al. [37] experimentally studied the thermal performance of alumina–water nanofluids during the flow boiling conditions for both convective and nucleate boiling regions. Their work was focused on the nanoparticles

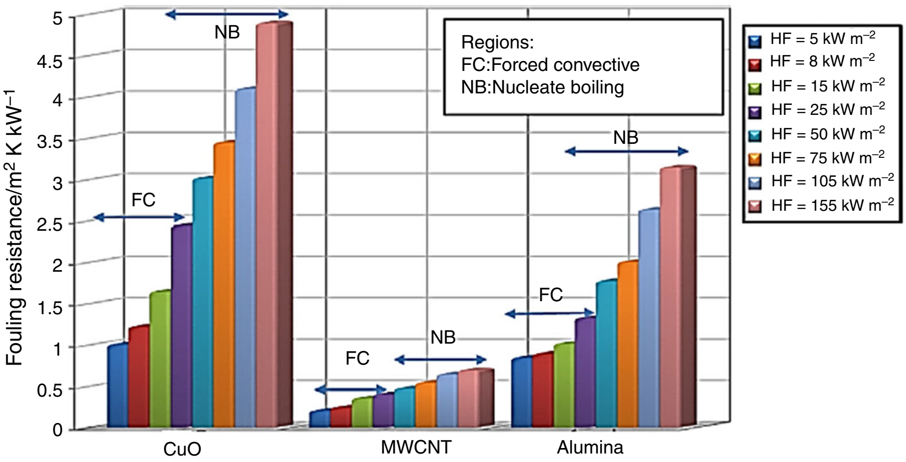


Fig. 6 Comparison between fouling resistance of different tested nanofluids; mass% = 0.1, $T = 353$ K, $G = 1400$ kg m^{-2} s^{-1} [36], with permission from Elsevier

deposition role on the boiling heat transfer coefficient. The experiments were divided into two studies, namely short time and extended time studies. For a short time study (0–60 min), they have neglected the deposition of nanoparticles and concluded that the HTC was improved for all nanofluid with smaller nanoparticles diameter, while for extended time study (60–1000 min), they showed that the heat transfer coefficient was deteriorated considerably, for all nanofluids. Tazarv et al. [38] utilized a dilute mixture of TiO_2-R141b as a nanorefrigerant to investigate experimentally the saturated flow boiling heat transfer performance. They are reported that the convective heat transfer coefficient enhancement for the particle concentration in the range of 0.01–0.03 vol% compared to base fluid R141b was more robust for a higher concentration. Furthermore, they concluded that the heat transfer coefficient decreased with mass flux, while an increase in the saturation temperature led to an enhancement in the heat transfer coefficient of the flow boiling.

Two types of nanofluids (i.e., AlN/water and Al_2O_3/water) were prepared by Wang et al. [39, 40] via an ultrasonic vibration to investigate experimentally the flow boiling heat transfer inside the vertical tube. Their results showed that the heat transfer performance for AlN/water and Al_2O_3/water nanofluids was enhanced by about 64% and 61%, respectively, compared to the deionized water. Moreover, this improvement was increased with increasing the heat flux on the heating surface and pressure, while no influence for the mass flux on the heat transfer performance was found. Zhang et al. [41] experimentally investigated the characteristics of the flow boiling heat transfer and the pressure drop of MWCNT-R123 nanorefrigerant flowing inside a horizontal copper circular tube. They have tested the effects of various operating conditions such as volume fraction of solid particles, mass flux and vapor quality on the performance of the flow boiling heat transfer coefficient of nanorefrigerant. They found that the (HTC) was significantly increased with concentration, mass flux and vapor quality.

Zangeneh et al. [42] performed an experimental study of the forced convection and subcooled flow boiling heat transfer in a vertical annulus by using various novel functionalized ZnO nanoparticles. Four types of these nanoparticles were synthesized by using the solgel hydrothermal method. Their results showed that the synthesized ZnO nanoparticles had a high heat transfer performance compared with deionized water for both tested regions. Wang et al. [43] introduced an experimental study on flow boiling heat transfer of nanofluids by dispersing two types of nanoparticles into deionized water. They tested the influence of various parameters related to operation condition and the nanoparticles concentration on the performance of flow boiling heat transfer. They proposed a new correlation by taking all the aforementioned factors on their account, and this will introduced in the next section. Karimzadehkhouei et al. [44] experimentally examined the subcooled flow boiling heat transfer performance of nanofluids inside the horizontal stainless steel microtubes together with the effect of surface characteristics and nanoparticles deposition. Various mass fraction (0.05–1.5 mass%) and mass fluxes (1200 and 3400 kg m^{-2} s^{-1}) were used with horizontal stainless steel microtube to investigate the heat transfer performance of nanofluids. Their results showed that the subcooled flow boiling heat transfer coefficients for nanofluids with low concentration were nearly the same as those of the distilled water as shown in Fig. 7. Dynamic light scattering (DLS) measurements were used to detect the nanoparticles accumulation for all concentrations before and after the experiment. It was found that this parameter was necessary for the degradation of the heat transfer coefficient during the study. Abedini et al. [45] carried out an experimental study at atmospheric pressure to investigate the transition flow from single-phase to two-phase flow boiling heat

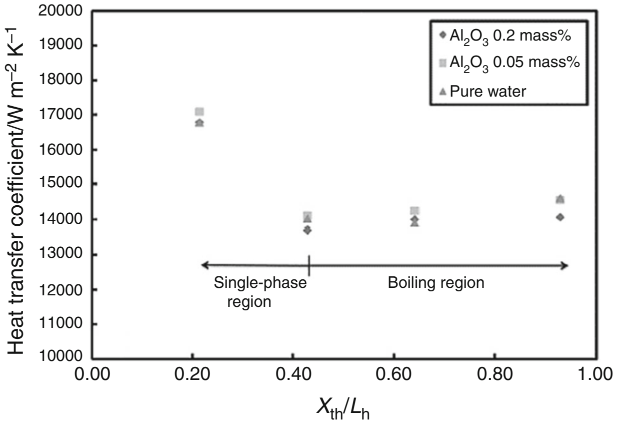


Fig. 7 Results of subcooled heat transfer coefficients: $G = 3400$ kg m^{-2} s^{-1} and $q'' = 628$ kW m^{-2}, which show no considerable alteration for low mass fractions (0.05 mass% and 0.2 mass%). By [44], with permission from Elsevier

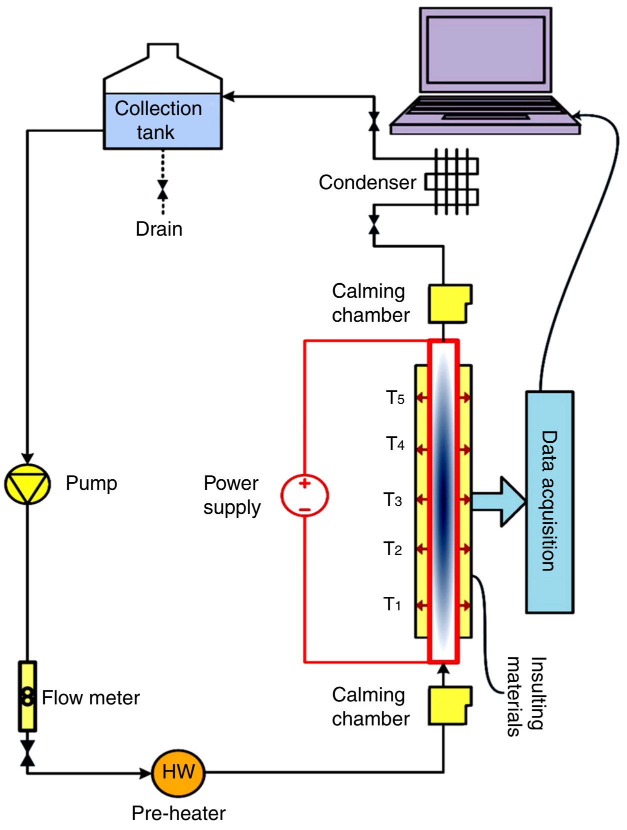


Fig. 8 Experimental schema of flow boiling loop that is used by [45], with permission from Elsevier

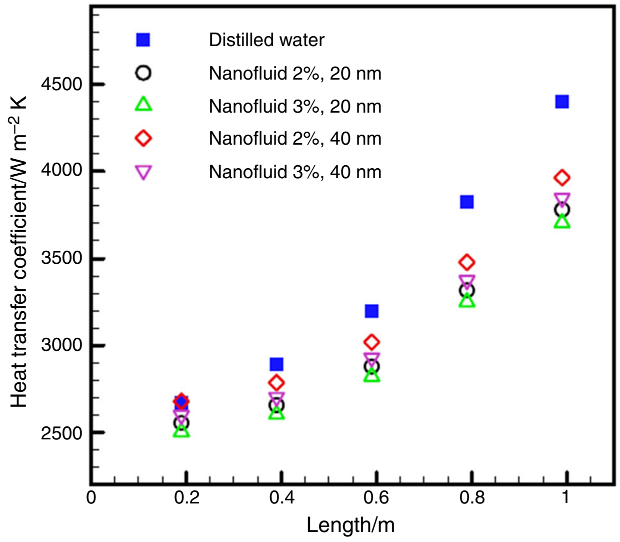


Fig. 9 Effect of increasing size and concentration of nanoparticles on heat transfer coefficient (vertical tube). $T_{in} = 62$ °C, $G = 303$ kg m^{-2} s^{-1}), $q'' = 102$ kW m^{-2} by [46], with permission from Elsevier

transfer behavior of nanofluids inside a circular vertical channel subjected to constant heat flux. Three types of oxide nanoparticles, namely TiO$_2$, Al$_2$O$_3$, and CuO, were utilized in their investigation, while the deionized water (DI water) was used as a base fluid in their loop as shown in Fig. 8. Results showed that the heat transfer coefficient was improved in single-phase regime and deteriorated for two-phase flow one by using nanofluids.

With the aim of investigation on the heat transfer performance, Afrand et al. [46] studied both experimentally and numerically the flow boiling heat transfer of nanofluid in different channel orientations. Two kinds of oxide nanoparticles, namely TiO$_2$ and Al$_2$O$_3$, were used in their work. They found that the heat flux did not have a significant effect on the heat transfer performance of nanoparticles. Figure 9 shows the results of heat transfer coefficient with the presence of nanoparticles, which is concluded from their study. Moreover, they found that increasing the mass flux had a negative influence on the subcooled flow boiling heat transfer of nanoparticles with the distilled water. Hashemi and Noie [47] presented an experimental study to investigate the flow boiling heat transfer performance by utilizing MWCNT–water nanofluid inside 10-mm horizontal stainless steel tube at atmospheric pressure. In their work, a stable nanofluid was obtained by using gum Arabic GA as a stabilizer with 1:1 concentration and the stability was found by measuring the zeta potential technique. They showed that the critical heat flux could be improved using nanofluid compared to pure water. Besides, results found that the nanofluid heat transfer coefficient is more significant than that of water base fluid and this enhancement increased with increasing mass and heat fluxes for both conventional fluids and nanofluids. Patra et al. [48] investigated experimentally the flow boiling of two types of nanofluids, namely Al$_2$O$_3$–water and TiO$_2$–water, with various concentrations inside a vertical annulus equipped with a concentric cartridge heater. Their results showed that the heat transfer coefficient for nanofluids increased with using a dilute concentration of nanoparticles. Moreira et al. [49] conducted an experimental study to evaluate the flow boiling heat transfer coefficient through a small horizontal tube (i.e., an inner diameter equal to 1.1 mm) by using aqueous nanofluids. They tested several types of spherical nanoparticles (i.e., SiO_2, Al_2O_3 and Cu) with various sizes to study the influence of their thermal conductivities and size on the heat transfer coefficient. Different operating conditions and nanoparticles characteristics such as heat and mass fluxes, vapor quality, volume fraction and nanoparticles diameter were investigated in their work. Results revealed that the HTC for all tested nanofluids decreased compared to deionized water and this returns to the fact that the deposition of nanoparticles depends on their size and concentration.

In another experimental study, Choi et al. [50] investigated the enhancement of the CHF of subcooled flow boiling by using magnetite nanoparticles, i.e., Fe_3O_4-based deionized water inside vertical annuli. Their experiment conducted with a range of mass flux up to 5000 kg/m^2 s and various inlet subcooled temperatures as 40–80 °C. Their results showed that the critical heat flux increased up to 40% in subcooled regime using the nanofluids and this enhancement increased with increasing mass flux as well. Figure 10 illustrates the ratio of critical heat flux enhancement with mass flux for different subcooled inlet temperatures in their work and the main reason for this enhancement was increasing the surface wettability, which related to decreasing contact angle of the liquid with the surface. They have measured the contact angle after nanoparticles deposition and found reduction in contact angle from 82° to about 30°.

Zhang et al. [51] performed an experimental study of flow boiling heat transfer by using graphene–water nanofluid inside the microchannel. Various nanoparticles concentration was used to prepare their nanofluid. Results showed that with higher concentration the HTC decreased and this is due to the deposition of graphene nanosheets on the heating surface, which are covered by the nucleation sites on the heating surface. Furthermore, they concluded that the CHF increased compared to pure water due to the wettability enhancement. Sarafraz et al. [52] conducted an experimental study of the flow boiling with a new type of nanofluid. The MgO nanoparticles with size 50 nm were dispersed in Therminol 66 as a base fluid via two-step method, and they used mass concentration 0.1 to 0.3 mass%. Their experimental study represented via schema diagram as shown in Fig. 11. The loop was consisted of three primary systems: the circulation loop, the testing chamber of boiling and the instruments for measurements. Their results revealed that the heat transfer coefficient decreased with testing time and this is due to the formation of nanolayer on the heating surface through deposition of the nanoparticle. In addition, the HTC of flow boiling increase compared to therminol 66 and the best value of increase were in a mass concentration of 0.1 mass%. Finally, they concluded that the MgO nanoparticles might offer good performance with dilute concentration for boiling application.

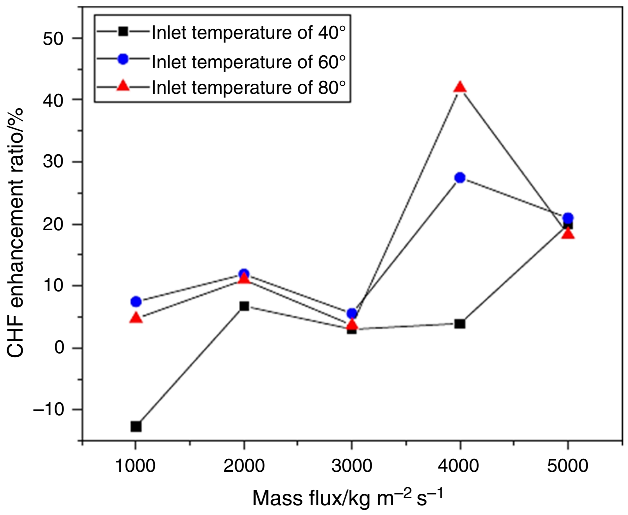


Fig. 10 Ratio of CHF enhancement against mass flux for various inlet temperature, by [50] with permission from Elsevier

Wang et al. [53] experimentally investigated the CHF inside a vertical channel by using Al_2O_3 and AlN nanoparticle-based deionized water. Their experimental loop is shown in Fig. 12. In addition, it consisted of the following main sections: The test section (vertical stainless steel tube with an inner diameter equal to 6 mm), the tank that is used for collecting the working fluids provided with sonication unit, and the preheater to preheat the desired subcooled temperature before entering the tube. Their work focused on testing some parameters affecting the CHF of flow boiling such as the mass and heat fluxes, pressure system, subcooling temperature, particles concentration and type. The mechanism of depositing the nanoparticles on the heating surface and creating the porous layer is shown in Fig. 13. Their results found that the CHF of flow boiling is improved up to 18% compared to conventional fluid and this improvement increases with increasing some parameters such as mass flux, the diameter of channel and pressure system. Moreover, other parameters such as types of nanoparticles, dilute concentration between 0.1 and 0.5 vol% and subcooling temperature found that they have no noticeable effects on the CHF.

Balasubramanian and his co-authors [54] conducted an experimental study for transient flow boiling performance by using Al_2O_3–water nanofluids in copper U-shaped microchannel. The hydraulic diameter of the microchannel is about $D_h = 308$ µm, it is a U shaped with width

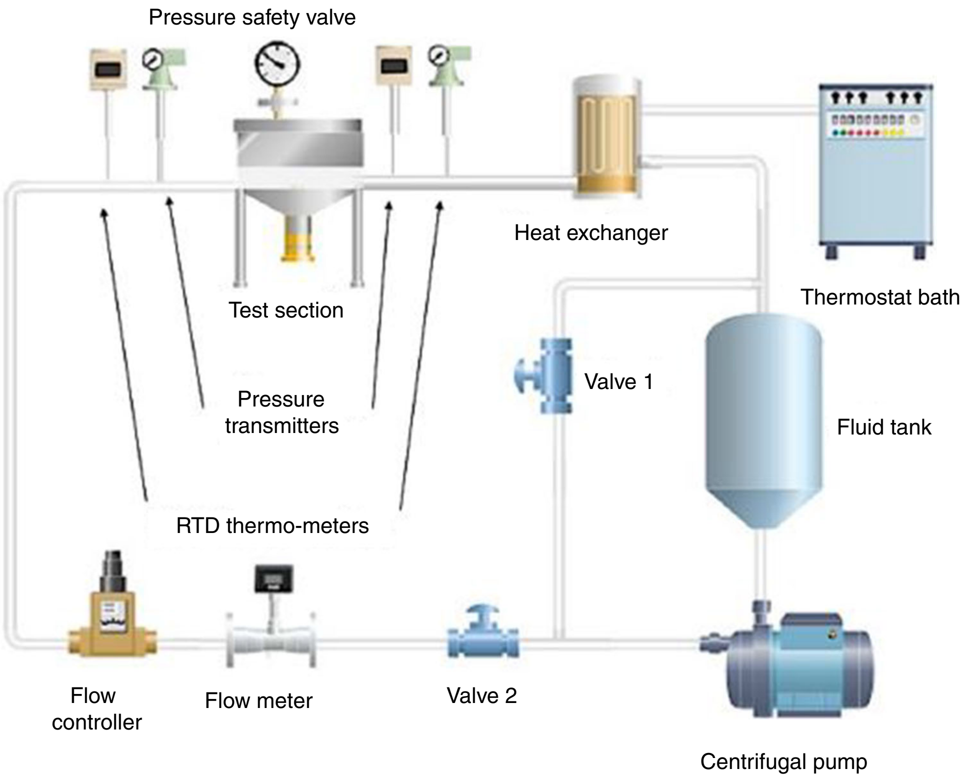


Fig. 11 Schema of flow boiling loop utilized by [52], with permission from Elsevier

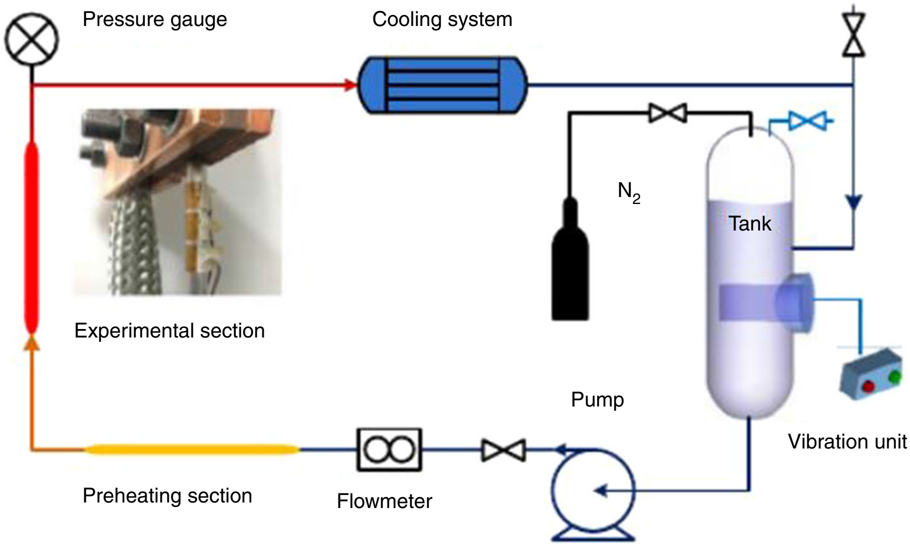


Fig. 12 Test system of flow boiling critical heat flux used by [53], with permission from Elsevier

$w = 305$ µm, depth 290 µm and length 30 mm, and it was made via CNC machine. They used nanofluid by suspended Al_2O_3 nanoparticles to deionized water with a volume concentration range (0.01–0.1 vol%), and there was no surfactant to added in this suspension. The results showed that the CHF of nanofluid was intensified about 15% compared to water. Mohammed et al. [55] investigated experimentally the effects of graphene nanosheets concentration, boiler temperature and flow rate of flow boiling by using zinc bromide and acetone salt solution as a base fluid in a rectangular channel. Their results demonstrated that for all tested boiler temperatures the salt nanofluid solution demonstrates characteristics of nucleate flow boiling behavior and could offer a significant enhancement over the properties of the salt fluid in terms of boiling effectiveness, indicating that it was provided an improvement of operation in absorption refrigeration systems situation.

From all above-reviewed studies, we can conclude that there were various affected parameters and sub-

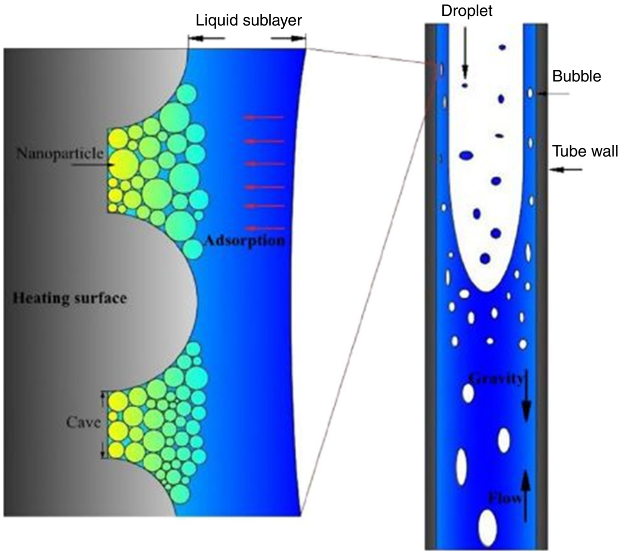


Fig. 13 Illustration of the mechanism of flow boiling CHF using nanofluid introduced by [53], with permission from Elsevier

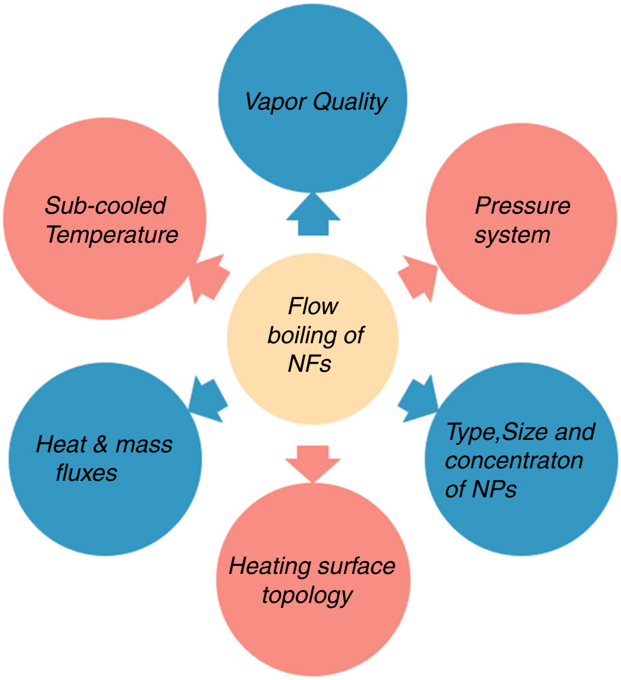


Fig. 14 Factors effects flow boiling heat transfer using nanofluids

phenomenon may influence generally the flow boiling heat transfer by using nanofluids and some of those associated with operating conditions and nanoparticles morphology as shown in Fig. 14, which, in turn, makes the flow boiling of nanofluids a complex mechanism. Besides, the most important factors, which effect HTC and CHF during flow boiling using nanofluids, are presented in Fig. 15.

Effect of surface nanocoating on flow boiling heat transfer

It is widely reported that the boiling heat transfer performance could be improved by changing heating surface topology, and recent investigations on the nanoscale coating surface of flow boiling by deposition nanoparticles via some techniques have prompted astounding improvement in heat transfer performance during the boiling process [56].

Bin Seo and Bang [57, 58] conducted an experimental study of R-123 flow boiling critical heat flux by deposition Al_2O_3 nanoparticles on the inner surface of stainless steel tube. They prepared bare and Al_2O_3 nanoparticle-coated surfaces inside the stainless steel tube with an inner diameter of 5.45 mm and heating length of 280 mm by quenching process. They used R-123 as working fluids with a range of mass flux (1600–2800 kg m^{-2} s^{-1}) to examine the CHF of flow boiling heat transfer in their loop. Results showed that the nanoparticle-coated surface gives a little difference in HTC, while CHF improved up to 17% compared to the bare surface and the trend behind this enhancement was attributed to the increasing the wettability of porous nanolayer. Gupta and Misra [59] studied experimentally the flow boiling heat transfer with different mass fluxes of DI water by using bare and (Cu + TiO_2) hybrid nanoparticle-coated copper surfaces. They covered a thin layer of (Cu + TiO_2) nanocomposite by using an electrodeposition method, and the created layer has various surface properties such as wettability, porosity and crystallinity. Their results showed that the hybrid nanoparticle-coated surfaces found to enhance the single-phase HTC somewhat, while the improvement in the two-phase region is up to 94% depending on the mass flux and surface temperature. Besides, the CHF increased for the nanocomposite-coated surfaces up to 92% and the enhancement in CHF and HTC of hybrid-coated surfaces is due to the enhanced characteristics such as surface roughness, wettability improvement, and increasing the density of active nucleate site on the heating surface.

Kumar et al. [60, 61] conducted an experimental study of the flow boiling HTC and CHF by using spray pyrolysis technique of Fe-doped (Al_2O_3–TiO_2 and ZnO–Al_2O_3) hybrid coatings over the copper heater blocks. They tested the flow boiling heat transfer characteristics of the coated as well as the bare blocks at different mass flux conditions. Their results demonstrated that the boiling HTC enhanced for coating surface due to its higher nucleation sites density is caused by high porosity. In addition, the CHF of the coating surface was increased with Fe doping increasing for both hybrid coatings with and without surfactant. A maximum enhancement in CHF was 44.6% and 29.7% in

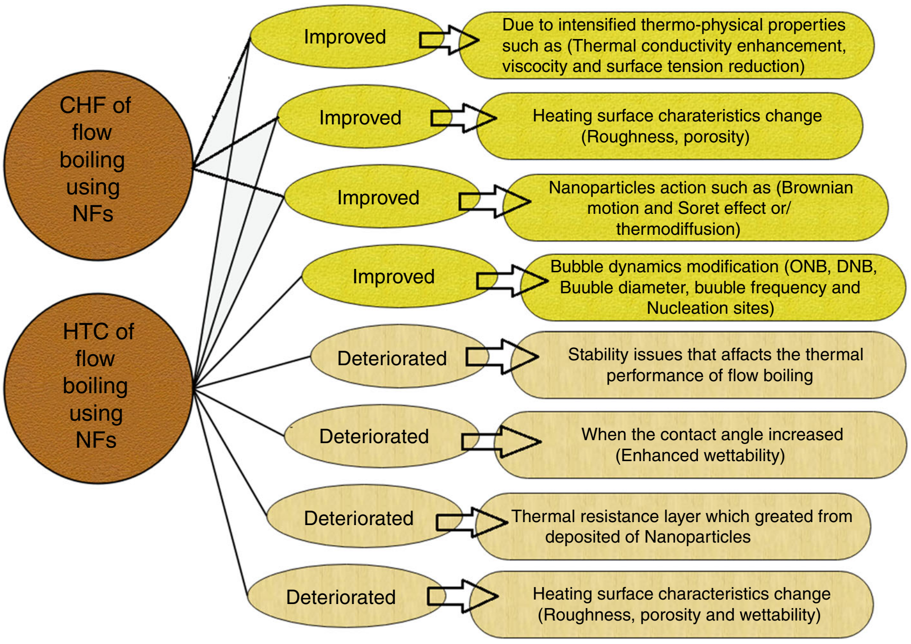


Fig. 15 Parameters and sub-phenomenon influence the HTC and CHF during flow boiling heat transfer using nanofluids

HTC for surfactant concentration (4 mass%) which is added for ZnO–Al_2O_3 hybrid coating, for the mass flux of 88 kg m^{-2} s^{-1}.

Alam et al. [62] performed a force analysis study of bubbles dynamic and nucleation on flow boiling heat transfer of silicon nanowire and plain-wall microchannel. They focused on investigating the relative effects of different forces on flow boiling regimes, instabilities and CHF of flow boiling in silicon nanowire microchannel. Results showed the wettability and CHF of nanowire surface enhanced and this is due to higher surface tension force at the liquid–vapor interface and dominant capillary wicking force resulting from silicon nanowires. Kim et al. [63] suggested two smart-coated surfaces (titanium dioxide and zinc oxide nanocoatings) to study the flow boiling HTC and CHF. They observed that the HTC for both smart surfaces was enhanced compared to the reference surface. Furthermore, the results of CHF were found to be improved and this is due to the surfaces hydrophilicity after the coating process.

From all the above aforementioned studies, it can be concluded that the nanoscale coating surfaces could offer an enhancement for flow boiling heat transfer performance represented by CHF and HTC and this improvement is limited with some parameters related to mass flux, pressure system of flow boiling as well as the stability of nanocoating surfaces (i.e., nanofin array coating).

Effect of nanoparticles suspension on other related flow boiling sub-phenomenon

Although there were many studies shown broad interest in flow boiling HTC and CHF by using nanofluids [30–54], studies of other sub-phenomenon related to flow boiling subject (i.e., the onset of nucleate boiling (ONB), departure from nucleate boiling (DNB), bubble dynamics, pressure drop and flow patterns) are rare during the last 2 years. It is imperative to investigate this sub-phenomenon to understand the flow boiling of nanofluids well. Table 3 summarizes the latest experimental studies related to flow boiling sub-phenomenon by using nanofluids.

Zhang et al. [41] studied the characteristics of the flow boiling heat transfer and the pressure drop of MWCNT-R123 nanorefrigerant inside a horizontal copper circular tube. They have tested the effects of different operating conditions such as the concentration of solid particles, mass flux and vapor quality on the pressure drop across the nanorefrigerant test section. Their results showed that the frictional pressure drop increased with nanoparticle concentration, mass flux and vapor quality. Patra et al. [48] studied the behavior of bubble dynamics during flow boiling of nanofluid. They used a high-speed camera to visualize the effect of heat flux and concentration of two types of nanoparticles (Al_2O_3 and TiO_2). Their results showed that the DNB of nanofluids delayed compared to water. Also, in the case of using nanoparticles with dilute concentration, bubble size was smaller, but bubble density is found to be more with the same heat flux applied to water. Yu et al. [64] conducted an experimental study of forced convective flow boiling and two-phase flow of

Table 3 Summary of the latest experimental investigations related to flow boiling sub-phenomenon by using nanofluids

References	Nanofluids type	Flow boiling sub-phenomenon	Results and remarks
Zhang et al. [41]	MWCNT–R123 nanorefrigerant	Pressure drop	Results showed that the frictional pressure drop increased with nanoparticle concentration, mass flux and vapor quality
Patra et al. [48]	Al_2O_3/water and TiO_2/water	bubble dynamics and (DNB)	Results showed that the DNB of nanofluids delayed compared to water. Besides, in case of using nanoparticles with dilute concentration, bubble size was smaller, but bubble density was found to be more with the same heat flux applied to water
Yu et al. [64]	Al_2O_3/water	The onset of nucleate boiling and the onset of flow instabilities (ONB and OFI)	Results found that the presence of nanoparticles delays (ONB) and suppresses the (OFI) and the extent of delay/suppression is proportional to the nanoparticle volume fraction
Edel and Mukherjee [65]	Al_2O_3/water	Bubble dynamics (ONB) and (OBE)	Results showed that the addition of nanoparticles affects the flow regime transition represented by the onset of nucleate boiling (ONB) and the onset of bubble elongation (OBE). Also, they revealed that the nanoparticles suspension stabilizes the growth and nucleation of bubbles and enhanced heat transfer of flow boiling

Al_2O_3–water nanofluids through a mini-channel. They studied 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). They found that the presence of nanoparticles delays ONB and suppresses the OFI and the extent of delay/suppression is proportional to the nanoparticle volume fraction. These effects were attributed to the changes in available nucleation sites and surface wettability as well as thinning of thermal boundary layers in the nanofluid flow. Edel and Mukherjee [65] investigated the flow boiling dynamics of water and nanofluid in a rectangular microchannel at different heat fluxes. Their results showed that the addition of nanoparticles affects the flow regime transition represented by the onset of nucleate boiling (ONB) and the onset of bubble elongation (OBE). They revealed that the nanoparticles suspension stabilized the growth and nucleation of bubbles and enhanced the heat transfer of flow boiling.

Application of flow boiling heat transfer

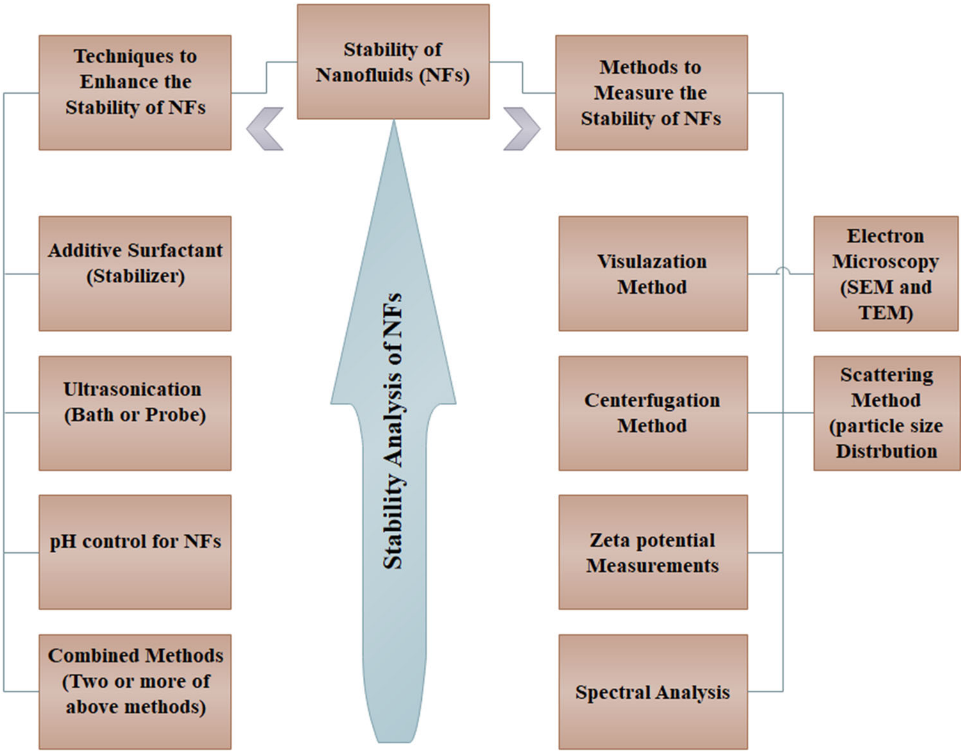
Boiling heat transfer has received considerable attention during the last decade, due to the effective removal heat that happens in this heat transfer mode. As flow boiling heat transfer is one of the essential boiling types, it was widely used in various industrial applications due to its ability to offer high cooling efficiency, which can be used to limit the problem of high heat flux dissipation systems. It has been recorded that there are many essential applications for flow boiling heat transfer in the literature and some of them can be listed as below:

1. Compact heat exchangers such as the plate heat exchangers [66].
2. Pulsating or oscillating heat pipes [67].
3. Wick and wickless heat pipes [68].
4. Magneto-hydrodynamics and electro-hydrodynamics fields [69].
5. Microchannels and microtubes [70–73].
6. Steam boilers [74].
7. Jet impingement applications [75].
8. Helically coiled tubes [76].
9. Water jacket of heavy-duty diesel engine [77].
10. Nanorefrigerants and their applications [78].
11. Tube bundles [79].
12. Applications of microgravity [80].
13. Absorber tubes of linear Fresnel reflector solar collectors [81].
14. Metal forming [82].
15. Other industrial applications such as cooling of the nuclear reactor system, purification of water, petroleum oil refineries, impulse drying of the paper web in paper industry and processing of sugarcane juice for jaggery making [81].

Stability of nanofluids during the boiling process

Nanofluids are a colloidal dispersion which consists of nanoscale solid particles in a base fluid such as water, ethylene glycol and mineral oil. Unstable solid phase in nanofluid could affect the performance of heat transfer due to the inter-particle adhesion forces causing the accumulation and sedimentation of nanoparticles. Nanoparticles tend to agglomerate, and their settlement can be detected

Fig. 16 Stability analysis methods and enhancement techniques of nanofluids



due to the gravity forces, which results in clogging of channels, and then, it might cause failure of heat exchange systems [6, 83]. Stability of nanofluids is considered as a critical issue when working with such new thermal fluids, many researchers studied this issue, and they reported the most important factors that could influence the stability of nanofluids such as nanoparticles types, size, concentration and preparation methods. Nanoparticles should be dispersed good enough in order to avoid the agglomeration within the suspensions by applying different techniques such as ultrasonication, additive stabilizer and pH control [84, 85].

Figure 16 illustrates the methods and techniques used in the literature to measure and enhance the stability of nanofluids. According to our best knowledge, the stability of nanofluid is a very challenging technical problem in the nanofluid community up to date, not just for marketing and applications issues, but also to understand the underlying mechanism for both single-phase and two-phase phenomenon [86]. For nanofluids, it was considered that the zeta potential index is a key role to measure the stability of nanofluid. Zeta potential is the electric potential difference between the dispersion phase (particles) and the stationary layer of base fluid which is in contact with the dispersed particle [87, 88].

Boiling of nanofluids is considered as a complicated process and involving strong interaction between the phases. Stable nanofluid is indispensable in such process and could enhance the performance of heat transfer by avoiding the extra nanoparticles deposition on the heating surface with higher surface temperature which, in turn, reduces the deposition of porous layer during boiling and keeps the bulk effect (associated with thermophysical properties) to dominate for those fluids. Based on the literature review, it can be concluded that the importance of nanofluids stability in flow boiling topic considered as not a big problem due to the forced circulation using pumping power and the gravity acceleration in the vertical channels [39, 40, 43]. Aforementioned reasons could offer good enough mixing to make nanofluids stable as long as possible during this type of boiling heat transfer process; otherwise, the stability in pool boiling heat transfer is considered as an important issue due to the bubble formation and related sub-phenomenon such as microevaporation layer and deposition of nanoparticles on heating surface resulting change in nucleation site density and topology of heating surface.

Sarafraz and Hormozi [36] used a functionalized MWCNT and metal oxide-based DI water nanofluids for their flow boiling test. They employed different techniques such as pH setting, sonication as well as adding a surfactant in order to make their suspension stable enough for boiling investigation. They revealed that the stability of metal oxide (i.e., Al_2O_3 nanoparticles) could stay more than 45 days by applying all the above-mentioned techniques.

Tazarv et al. [38] examined their nanofluids stability after left it about 1 week without movement. Their

Table 4 Summary of stability investigations for experiments of flow boiling using nanofluids

References	Nanofluids types	Stability enhancement methods	Stability measurement techniques	Stability duration
[36]	(MWCNT, Al_2O_3 and CuO) + DI water	pH control, sonication and PVP surfactant as well as functionalization of MWCNT	TEM	About 45 days
[38]	TiO_2 + R141b	Sonication and CTAB surfactant	Visual method by eye naked	For 1 week
[41]	MWCNT + R123	Sonication and SDBS surfactant	Visual and spectrophotometer	For 12 h
[42]	ZnO + DI water	Sonication and functionalization of nanoparticles	Visual method	More than 1 day
[43]	(Al_2O_3 and AlN) + DI water	Stirrer mixing and sonication	Visual method and density measurements each day to checking the deposition	Stable for 10 h
[44]	γ-Al_2O_3 + DI water	Sonication and SDS surfactant	SEM	Not recorded
[45]	(TiO_2, AL_2O_3 and CuO) + DI water	Sonication	SEM and TEM	Less than 24 h
[46]	(TiO_2 and Al_2O_3) + distilled water	Sonication	Not recorded	About 24 h
[47]	MWCNT + water	Sonication and AG surfactant	Zeta potential measurements	Not recorded
[48]	(TiO_2, AL_2O_3) + water	pH control, sonication and surfactant	Visual methods	About 7 days
[49]	(AL_2O_3, SiO_2) + DI water	Sonication	Visual methods and zeta potential measurements	For 24 h
[51]	GO + DI water	Sonication + pH adjusting	Visual methods and DLS	About 15 days
[52]	MgO + Therminol 66			

preparation method was done by implementing the ultrasonication probe and CTAB surfactant in order to get mixture suspension. Prepared nanofluids with different concentrations were found to be stable for 1 week, and this means the proposed method was suitable in order to get stable nanofluid for the whole period of the experiment. Zhang et al. [41] investigated the stability of their prepared nanofluid by using a visual method as well as measuring the transmittance with a visible spectrophotometer. They found that the nanofluids cannot be stable enough with just applied mechanical agitation; rather, the presence of the surfactant will enhance the stability together with the sonication method. The stability of their nanofluids was found to be stable more than 12 h, and this indicated that they are in the safety side according to their experiment time. Zangeneh et al. [42] used four types of synthesized ZnO nanoparticles with deionized water for flow boiling heat transfer. Their nanofluids stability for different concentrations were checked after using about 6-h sonication, and it was found to be stable for more than 1 day and this was quite enough to do their flow boiling test.

In another flow boiling experiments, Wang et al. [43] prepared their nanofluids in flow boiling heat transfer experiment by dispersing their nanoparticles with deionized water. They used the ultrasonic vibration unit with the main tank over 24 h/day in parallel with the pump to make the nanofluid suspension stable as long as possible. They revealed that there is no sedimentation after 10 h and this was checked via TEM and density measurement for nanofluids every day.

Abedini et al. [45] also prepared three types of nanofluids for their flow boiling investigation. They used ultrasonication homogenizer with a power of 100 W to disperse different concentrations of nanofluids, and the duration was about 1 h. No surfactant or additives was used in their preparation method, and the suspension was checked to be stable for 1 day approximately without any strong agglomeration. Patra et al. [48] used two types of nanoparticles (Al_2O_3 and TiO_2) with water to prepare their nanofluids. They applied ultrasonication to disperse the nanoparticles into the water for 4 h in order to enhance and check the stability of the suspension three effective methods adopted to prepare nanofluids which are pH setting, adding surfactant and sonication. The measured stability for different concentrations was checked and found to be good stability for their suspensions. Zhang et al. [51] prepared the graphene oxide nanofluid via two-step method by dispersing the graphene nanosheets into deionized water. Their procedure was firstly sonicated the suspension for 1 h and then tried to set the pH in order to get stable nanofluid. The stability of prepared nanofluid was checked by not observing any sedimentation for 15 days; also, for all the period of the test, the nanofluids were kept stable without any cluster or sedimentation, this suspension was quite good for the purpose of the experimental study. Table 4 summarised the recent investigations on the stability of flow boiling using nanofluids.

Based upon the data reported in this section, it can be said that the stability of nanofluids during flow boiling process is an important issue and it cannot be neglected, but it can be said that if flow boiling and with the presence of circulation of working fluid using pumping power or in some studies the researchers put the vibration into the mean tank [19, 39, 43], the stability becomes better than the pool boiling situation. In addition, all experimental studies in the literature showed that the dilute concentration with range (0.0001–0.1 vol%) considered being good for boiling of nanofluids.

Correlations to predict flow boiling heat transfer of nanofluids

Nanofluid flow boiling is becoming an interesting topic in recent years, but still, the correlations regarding flow boiling heat transfer using nanofluids are rare. In this review, we reported the most important correlation for predicting heat transfer of flow boiling using nanofluids. Table 5 summarizes the recent correlation related to flow boiling heat transfer using nanofluids. Zhang et al. [41] proposed correlation for predicting this coefficient of nanorefrigerant by using a surfactant which was modified as shown below. Besides, it can predict 95% of data points with a deviation of minus/plus 20%.

$$F_{\mathrm{ht}} = \exp\left(\varphi\left[894.3\left(\frac{k_{\mathrm{nf}}}{k_{\mathrm{f}}}\right)^{0.6}\left(\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{f}}}\right)^{-0.4}\left(\frac{(\rho C_{\mathrm{p}})_{\mathrm{nf}}}{(\rho C_{\mathrm{p}})_{\mathrm{f}}}\right)^{0.4} + 1171x(1-x) - 0.011Re - 908.3\right]\right) \tag{1}$$

where

$$F_{\mathrm{ht}} = \frac{h_{\mathrm{nf,sur}-(\mathrm{h_{f,sur}}-\mathrm{h_f})}}{h_{\mathrm{f}}} \tag{2}$$

Wang et al. [43] proposed a new correlation for saturated flow boiling heat transfer using two types of nanofluids, AlN–water and Al_2O_3–water. They used some dimensionless parameters of flow boiling to introducing their correlation depending on different influence parameters such as heat flux, mass flux and pressure system on flow boiling using nanofluids. Their new correlation was with mean absolute deviation about 4.3%, and it can predict 99% of the entire database within ±15% for AlN–water nanofluid and 94.5% of the whole database within ±15% for Al_2O_3–water nanofluid. The range of examined parameters in this proposed correlation was within 0.1–0.5 vol% for volume concentration, 200–800 Kpa for pressure system, 48–289 kW m^{-2} for heat flux and 350–1100 kg m^{-2} s^{-1} for mass flux.

$$\left\{Nu = 1.1817\left(\frac{q''D_{\mathrm{in}}}{\mu_{\mathrm{nf}}h_{\mathrm{fg}}}\right)^{0.1814}\left(\frac{\mu_{\mathrm{nf}}C_{\mathrm{p,nf}}}{k_{\mathrm{nf}}}\right)^{4.1506}\left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{v}}}\right)^{0.8871}\right\} \tag{3}$$

where

$$Nu = \frac{h_{\mathrm{nf}}D_{\mathrm{in}}}{k_{\mathrm{nf}}} \tag{4}$$

Wang et al. [53] experimentally studied the CHF inside a vertical channel by using Al_2O_3 and AlN nanoparticle-based deionized water. Their experimental loop is shown in Fig. 12. In addition, it consisted of the following main sections: The test section (vertical stainless steel tube with an inner diameter equal to 6 mm), the tank that is used for collecting the working fluids provided with sonication unit, the preheater to preheat the desired subcooled temperature before entering the tube. Their work focused on testing some parameters affecting the CHF of flow boiling such as the mass and heat fluxes, pressure system, subcooling temperature, particles concentration and type. The mechanism of depositing the nanoparticles on the heating surface and creating the porous layer is shown in Fig. 13. Their results found that the CHF of flow boiling improved up to 18% compared to conventional fluid and this improvement increases with increasing some parameters such as mass flux, the diameter of channel and pressure system. Moreover, other parameters such as types of nanoparticles, dilute concentration between 0.1 and 0.5 vol% and subcooling temperature found that they have not noticeable effects on the CHF. They introduced a correlation for CHF as shown below.

$$q_{\mathrm{chf}} = \Delta T_{\mathrm{sub}}C_{\mathrm{p}}G\frac{D_{\mathrm{in}}}{4L} + 0.7073Gh_{\mathrm{fg}}\left(\frac{D_{\mathrm{in}}}{L}\right)^{0.9708} \times \left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\right)^{0.2013}\left(\frac{(\rho_{\mathrm{l}}-\rho_{\mathrm{g}})^{0.5}u^{2}}{g^{0.5}\sigma^{0.5}}\right)^{-0.1135} \tag{5}$$

The proposed correlation works with good accuracy for a range of parameters D_{in} (6–8 mm), heating length l (500–800 mm), inlet subcooled temperature ΔT_{sub} (13.5–35.9 °C), pressure system P = 400–890 (KPa) and mass flux G = 98.9–348.4 (kg m^{-2} s^{-1}).

Sarafraz et al. [52] developed a new correlation to assess the thermal performance of a thermosiphon heat pipe using

Table 5 A summary of published correlations for heat transfer performance of flow boiling using nanofluids

References	Proposed correlation	Notes and limitations
Zhang et al. [41]	$F_{\mathrm{ht}} = \exp\left(\varphi_{\mathrm{V}}\left[894.3\left(\frac{k_{\mathrm{nf}}}{k_{\mathrm{f}}}\right)^{0.6}\left(\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{f}}}\right)^{-0.4}\left(\frac{(\rho C_{\mathrm{p}})_{\mathrm{nf}}}{(\rho C_{\mathrm{p}})_{\mathrm{f}}}\right)^{0.4} + 1171x(1-x) - 0.011Re - 908.3\right]\right)$	The Sodium dodecyl benzene sulfonate SDBS Surfactant significantly affected on heat transfer enhancement by nanoparticles
Wang et al. [43]	$Nu = 1.1817\left(\frac{q'' D_{\mathrm{in}}}{\mu_{\mathrm{nf}} h_{\mathrm{fg}}}\right)^{0.1814}\left(\frac{\mu_{\mathrm{nf}} C_{\mathrm{p,nf}}}{k_{\mathrm{nf}}}\right)^{4.1506}\left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{v}}}\right)^{0.8871}$	The mean absolute deviation for this correlation is 4.3% and it predicts about 99% of the entire database within ± 15% for AlN/water nanofluid and 94.5% of the whole database within ± 15% for Al_2O_3/water nanofluid. The range of examined parameters was: (200–800) (kPa) for pressure system (48–289) (kW m^{-2}) for heat flux 350–1100 (kg m^{-2} s$^{-1)}$ for mass flux
Wang et al. [53]	$q_{\mathrm{chf}} = \Delta T_{\mathrm{sub}} C_{\mathrm{p}} G \frac{D_{\mathrm{in}}}{4L} + 0.7073 G h_{\mathrm{fg}}\left(\frac{D_{\mathrm{in}}}{L}\right)^{0.9708}\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\right)^{0.2013}\left(\frac{(\rho_{\mathrm{l}}-\rho_{\mathrm{g}})^{0.5} u^2}{g^{0.5}\sigma^{0.5}}\right)^{-0.1135}$	It works with good accuracy for a range of parameters: Internal diameter; 6–8 (mm) Heating length; 500–800 (mm) Inlet subcooling; 13.5–35.9 (°C) Pressure system; 400–890 (kPa) and Mass flux; 98.9–348.4 (kg m^{-2} s^{-1})
Sarafraz et al. [52]	$Ku = 6.68 \times Gr^{0.018} \cdot Bo^{-1.61} \cdot Mo^{0.019} \cdot Pr^{-3.36} \cdot Ja^{-0.1447}$	The developed correlation showed a good agreement with those of experimentally investigated within ±14% against the experimental data. In addition, this correlation enables one to accurately predict a wide range of heat pipe by using Kutateladze number

zirconia/acetone nanofluids. In their work, they employed dimensional analysis together with the regression analysis in order to introduce their new correlation, which enables one precisely to predict a range of operating conditions of the heat pipe using Kutateladze number (Ku). The following correlation was introduced for the Ku number:

$$Ku = 6.68 \times Gr^{0.018} \cdot Bo^{-1.61} \cdot Mo^{0.019} \cdot Pr^{-3.36} \cdot Ja^{-0.1447} \tag{6}$$

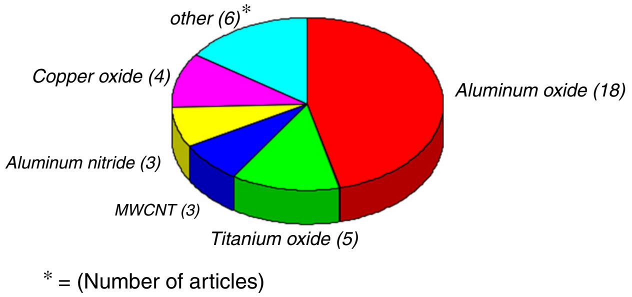


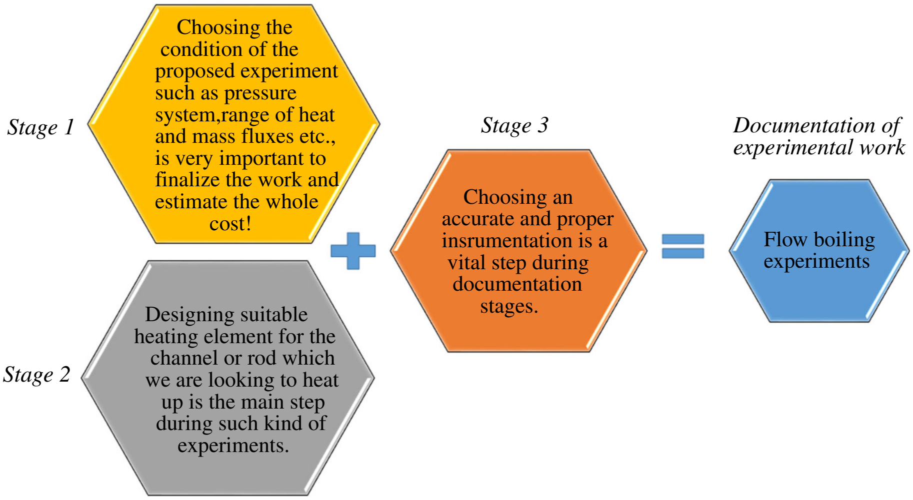
Fig. 17 Types of nanoparticles used in the present collected works

where Gr, Bo, Mo, Pr and Ja are non-dimensional numbers identified in their study with regression analysis to develop their correlation. Their proposed correlation showed a good agreement with those of experimentally obtained within $\pm 14\%$ against the experimental data.

Concluding remarks

The current review presents a critical review of the latest experimental studies associated with the flow boiling heat transfer by using nanofluids. The survey divided into seven parts. The first part introduced the importance of flow boiling topic using nanofluids. The second section discussed the recent review papers that have been done during the last 3 years on the topic of boiling heat transfer using nanofluids. General concept of boiling phenomenon using nanofluids was addressed in part three, and the fourth part discussed and summarized the results on the heat transfer performance of flow boiling with an emphasis on the HTC

Fig. 18 Representation to the stages that should be following during documentation of flow boiling heat transfer experiments



and the CHF with the presence of nanoparticles in the conventional nanofluids and as a coating of the heating surface. In addition, the effect of nanoparticles on the other related flow boiling sub-phenomenon is discussed. Fifth part deals with some applications related to flow boiling, and sixth part was discussed the stability of nanofluid during the boiling process and how this critical issue could play a significant role in boiling performance. Last part is related to current heat transfer correlations associated with flow boiling of nanofluids. Recent advancement in the experimental works of the flow boiling using nanofluids was uneven, especially within the last 3 years. Nevertheless, a number of significant points must be achieved for studying this vital subject to reach the commercial potential. Some important conclusions and recommendations for future studies are listed below:

- First, it was observed that there is not an experimental database for the flow boiling using nanofluids inside conventional tubes with an internal diameter greater than or equals (i.e., 19 mm) or in another word, a typical tube diameter of the steam generator. For this purpose, the flow boiling studies by using nanofluids with large diameter channels must be replicated to improve the understanding regards this mechanism.
- Second, the heat transfer performance of the flow boiling using nanofluids is relatively unquantified and have still somewhat disputable. Therefore, further experimental investigations are required with an emphasis on the HTC to find the significant factors affected by the performance of the flow boiling heat transfer using nanofluids.
- Third, in all reviewed articles it is clear that the CHF under the flow boiling of nanofluids was enhanced and the mechanism behind this is the deposited nanoparticles on the heating surface which modified the topology of heating surface.
- Fourth, the long-term stability of prepared nanofluids is a crucial issue and must be demonstrated under realistic field operation conditions that involve high-pressure and temperature system. In addition, developing new technologies make nanofluid stable as long as possible especially for application in which boiling takes place is recommended.
- Fifth, the most common nanoparticles used by many researchers were Al_2O_3 as shown in Fig. 17 since it is relatively abundant material, low-cost nanoparticles synthesis and it has acceptable thermal properties compared to other oxide metals nanoparticles. However, it is recommended to use another type of nanomaterials with different sizes and concentrations especially for those which have a high thermal conductivity.
- Sixth, more efforts must be directed toward inventing non-toxic and low-cost nanoparticles to reduce the cost of nanofluids preparation and to meet quickly with the market needs.
- Seventh, the effects of pressure system on the flow boiling heat transfer performance by using nanofluids are not studied well. Therefore, future researches must be directed toward the study of this critical research point.
- Eighth, efforts should be focusing on investigating the flow boiling of the nanocoating surface by depositing the nanoparticles via different deposition techniques. In addition, some flow boiling-related parameters such as mass flux, pressure system and type of working fluids have to study in conjunction with this topic in future works.
- Ninth, it is crucial to correlate some bubble dynamics mechanism to superheat temperature by using nanofluid; only a few closure correlations regarding this topic are available. A systematic experimental study

should be conducted to measure some bubbles parameters (i.e., bubble diameter, frequency and nucleation site density) by using nanofluid.

- Tenth, in order to start with an experimental study related to flow boiling heat transfer, authors are highly recommended to make a documentation for the experimental investigation, and Fig. 18 illustrates the stages of successful documentation for such experiments.
- Last, to release the potential of real-life application of nanofluids in flow boiling heat transfer, effective large-scale, low-cost manufacturing methods for nanofluids must be developing.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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