Recent developments in synthesis, characterization and boiling heat transfer of nanofluids – A Review

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Abstract. The life of a thermal system depends on how effectively the heat (which is released during its operation), being transferred. Selection of the right fluid is imperative in providing the heat transfer solution for a particular thermal system. Nanofluids are the new generation heat transfer fluids which will give better performance with their superior thermos-physical properties. So much research has been done on nanofluids during the recent years on several aspects like synthesizing the stable nanofluids without losing their properties, characterization, application of nanofluids to forced convection, free convection, boiling heat transfer. The present review is concentrated mainly on the experimental investigations on the preparation and characterization of nanofluids and its applications in several areas. Majority of studies reported that critical heat flux improves with the nanofluids. It will be very useful for the researchers who are about to work on the nanofluids.

1. Introduction
Thermal management is the crucial aspect for designers of a product and the life of that product relies on it too. When customers look for the miniature designs of a particular product then thermal management becomes much more complex and in such case natural convective air cooling even with fins may not be sufficient and usage of extended surfaces increase the size and weight of the product. The alternative is liquid cooling. Traditional heat transfer liquids like water, radiator coolants like ethylene, propylene glycols and engine oil are not able to give high performance due to their weak thermal conductivity. Thermal conductivity of the solid materials like silver, copper, aluminum, etc. is hundreds of times to these liquids [1-2]. So it is inevitable to get a composite liquid which is obtained by adding metals in fine powder form to heat transfer liquids. In earlier days, researchers used to disperse the solid particles of micro size in carrier fluids to enhance the properties, but so many problems like particle sedimentation, an increase in pressure drop, moderate enhancement depends on volume fraction but not particle size and erosion of equipment were observed. Choi.et.al [3] first introduced the nanofluids by dispersing the nanoscale sized particles of metallic and metal oxides which are less than 100 nm sized into the carrier fluid and enhancement in thermal enactment of the fluid is perceived. Nanofluids can be used in different heat transfer applications like free convection, forced convection, boiling, solar, refrigeration and so on.
The superior properties of the nanofluids make the research community to get attracted and carry the research in diversified areas with nanofluids. Work done on nanofluids by the researchers so far is shown with the number of publications year wise in Fig.1. According to the Science direct search results
(Searched with the keywords ‘nanofluids’ and the corresponding ‘year’), it is found that the publications on nanofluids are increased exponentially and seen much growth from the last 3 to 4 years. The prime intention of this review is to give the overview of the synthesis of nanofluids, techniques for measuring viscosity and thermal conductivity, to present the experimental results of boiling heat transfers using nanofluids and publications based on various heat transfer applications of nanofluid is shown in Fig.2 and the research is predominantly done on forced convection using nanofluids.

2. Synthesis and characterization

Nanofluids have been prepared either by one step method in which making and scattering of nanoparticles into base fluid done at same time or two stage technique in which preparation of nanoparticles takes place first and dispersion will be done subsequently. Zhu et al. [4] used a single step chemical method to synthesize nanofluids by dispersing Cu nanoparticles in ethylene glycol. Lo et al. [5] proposed a method called VBSA (vacuum based submerged arc) synthesis to prepare the Cu-dielectric nanofluids. Wei et al. [6] synthesized the Cu2O-water nanofluids using chemical solution method which is a single step process and achieved the thermal conductivity increment of 24% compared to water. Faure et al. [7] reviewed the various studies on synthesis, dispersion and surface modification techniques of oxide nanoparticles comprehensively. Two stage technique is the most suitable one for preparing metallic oxide based nanofluids, but the main concern of this method is the stability of the nanofluids. In order to get the stable nanofluids, surfactants or dispersants are to be added in the required quantity to hold the nanoparticles without settling down but it costs some properties of the nanofluid. Techniques for synthesizing nanoparticles and the sequential processes of two step method are shown in Fig.3 (a) and (b) respectively. Various procedures for measuring thermal conductivity is depicted in Fig.4. Murshed et al. [8] prepared the TiO2 nanofluids by scattering rod shaped and spherical nano sized particles in water and determined the thermal conductivity of prepared nanofluids by transient hot wire (THW) method and found that nanofluids shows improved thermal conductivity than base fluids and this augment intensifies with increase in volume fixation of nanoparticles. Syam et al. [9] Synthesized the magnetic Fe3O4/water nanofluids and conducted experiments for finding viscosity and thermal conductivity in the range of volume fraction 0 to 2% and found that viscosity is much increased compared to thermal conductivity for a particular temperature and volume fraction.
Measurement of thermal conductivity of Water-Ag, ethylene glycol (EG)-ZnO nanofluids is done by Han et al. [10] and for aquatic Ag nanofluid at 0.7%, EG-ZnO at 1.3% volume fraction improvement in thermal conductivity is found as as 6.3% and 8.2% respectively. Chandrasekhar et al. [11] prepared Al2O3/water nanofluids in the range of 0.33-5% volume fraction and experimentally investigated the viscosity and thermal conductivity using Brookfield viscometer and KD2 pro analyzer and respectively. It is observed that non-linear increment with volume concentration for viscosity and linear increment in case of thermal conductivity.

Murshed et al. [12] investigated the rheological behavior of Silicone oil based titania, silica nanofluids and found that 22% and 17% increment in viscosities of TiO2, SiO2 nanofluids at 0.05% concentration and at the same concentration decrement in the viscosity was observed by 37% and 42% when the hike in temperature is from 20 °C to 59 °C. Nasiri et al. [13] prepared CNT/water nanofluids using various methods and performed experiments to measure thermal conductivity and stability studies and understood that the functionalization technique is better among other ones in terms of thermal conductivity enhancement and better stability. Ruan and Jacobi [14] conducted the experiments to find the influence of ultrasonication duration on viscosity and thermal conductivity of EG - CNT nanofluids at 0.5 wt% and found that sonication time is related non-linearly with thermal conductivity and observed the maximum enhancement of 23% with sonication time of 1355 minutes. It is also observed that, viscosity is also increased up to 40 minutes of sonication time and then decreased as shown in fig.5. Influence of free convection on thermal conductivity measurement of EG based ZnO nanofluids was
experimentally investigated using THW method by Sung et al. [15] and concluded that the temperature readings should be taken after the conductive delay time and up to crossover point where free convection becomes significant. Yang and Liu [16] synthesized the Silica nanofluids by functionalized silica nanoparticles and obtained good stability and no deposition layer was observed on the heater when it is used in pool boiling process. Mahbubul et al. [17] prepared Alumina/water nanofluid at 0.5% volume fraction and did the experimentation to know the influence of span of ultrasonication (at quarter, half power amplitudes) on stability and improved stability was achieved at 5, 3 hours for quarter, half power amplitudes respectively. Ravikanth and Debendra [18] conducted experiments for finding the thermal conductivity of Al₂O₃, CuO, ZnO nano suspensions up to 10% volume concentration and proposed a new correlation.

Abdolbaqi et al. [19] investigated experimentally for determining the thermal conductivity and viscosity of bio glycol/water (20:80 and 30:70) based silica nanofluids of 0.5% and 2% volume fraction and observed 7.2% enhancement in thermal conductivity at 2% concentration, 38% enhancement in viscosity and proposed correlations. Adnan et al. [20] determined the thermal properties of prepared water based Al₂O₃, TiO₂, SiO₂ nanofluids at 1-2.5% volume fraction and found that alumina nanofluid has highest thermal conductivity and silica nanofluid has highest viscosity among others. Li et al. [21] reported the experimental results of thermal conductivity and viscosity of diathermic oil – silicon carbide (SiC) nanofluid and observed that 7.36% enhancement was obtained at 0.8% volume fraction and viscosities decreased with increment in temperature. Hosseini et al. [22] proposed a method for measuring thermal conductivity of nanofluids which is based on the consumed heat power for conduction and convection. Zawrah et al. [23] prepared the Al₂O₃/water nanofluids by adding the SDBS dispersant at an optimized quantity for volume fixations of 0.1 to 0.75% and measured electrical conductivity and viscosity. It is showed that stability achieved for nanofluid contains 1% SDBS and highest viscosity is observed at 0.75 vol % Al₂O₃. Electrical conductivity was increased up to 0.2 vol% of Al₂O₃ and after that it is decreased. Ravi et al. [24] synthesized water, ethylene glycol, engine oil based CuO nanofluids and measured the thermal conductivity and found that at 2 vol % concentration, water based CuO nanofluids gave 40% improvement in thermal conductivity, ethylene glycol and engine oil based nanofluids show 27%, 19% enhancement respectively. Syam et al. [25] synthesized water based nanodiamond nanofluids and conducted experiments for determining the thermal conductivity and viscosity and results indicated that at 1.0 vol % enrichment in the thermal conductivity was 12.7% and 22.8% at 20°C, 60°C respectively.
viscosity was enhanced by 1.57 times and 1.8 times respectively and a new correlations were reported. Li and Zou [26] reported the results of experiments conducted for measuring viscosity and thermal conductivity of water, EG based SiC nanofluids and perceived the highest increment in thermal conductivity at 1 vol% was 33.84% compared to base fluid and viscosities decreased with the increasing temperature. Raja et al. [27] reviewed various works done on heat transfer characteristics of nanofluids and also presented the potential applications. Dhinesh et al. [28] reviewed the recent studies and presented in the order of Al₂O₃, AlN, ZnO, TiO₂, Fe₂O₃, Cu, CNT, gold and silver nanofluids. Das et al. [29] reviewed and presented the results of thermal conductivity measurement with respect to volume fraction, temperature and viscosity of various nanofluids. Xiang and Arun [30] reviewed the works done on convective heat transfer using nanofluids and summarized thermal conductivity measurement of several studies, forced convective heat transfer, natural convective heat transfer results. Wei and Huqing [31] studied preparation techniques and stability mechanisms of various nanofluids and possible potential applications of nanofluids are presented. Rodrigo and Flávio et al. [32] reviewed the mechanisms responsible for heat transfer augmentation of nanofluids and presented how the nanoparticles affect the properties, thermal transport mechanisms, heat transfer coefficient (HTC), and boiling heat transfer. Babita et al. [33] reviewed and summarized the preparation techniques used for the synthesis of nanofluids with improved stability and also presented the challenges for the commercialization of nanofluids. Suhaib et al. [34] comprehensively gone through the progress in preparation techniques of nanofluids, stability mechanisms and summarized the investigations on the influence of surfactants on stability of nano suspensions. Various measuring techniques of thermal conductivity are reviewed by Paul et al. [35] and presented a detailed thermal comparator principle on which the device works out.

3. Boiling heat transfer applications of nanofluids

There are several boiling heat transfer applications especially one can observe in process industries like preparation of alcohol etc. It is very much important to understand the importance of improving boiling heat transfer performance with the addition of nanofluids. Peng et al. [36] investigated the effect of R113 refrigerant based CuO nanofluids (0 to 0.5 wt%) on flow boiling in a horizontal smooth tube at an evaporation pressure of 78.25 kpa, inlet vapor quality from 0.2 to 0.7, heat flux between 3.08 to 6.16 kW/m² and results show that the performance of refrigerant is improved with addition of nanoparticles and the maximum enhancement in the boiling HTC of 29.7% is achieved and proposed a correlation for HTC. He et al. [37], experimentally found the CHF and HTC for EG and water based nanofluids and depicted in Fig. 6 (a) and (b) respectively.

![Fig. 6. (a) Variation of heat flux with superheat (b) HTC with heat flux of ZnO nanofluids [37].](image-url)
Sarafraz and Peyghambarzadeh [38] experimentally calculated the nucleate pool boiling HTCs of water based alumina, titania nanofluids (0.1, 0.5, 1 vol %) on horizontal smooth tubes with different materials with same surface roughness at atmospheric conditions and observed that the nucleate pool boiling HTC increases with the addition of nanoparticles to the base fluid in case of stainless steel, brass tubes and for copper tube no significant change is observed. With alumina nanofluids HTC is enhanced by 47% in case of stainless tubes, 33% for brass tubes and for titania nanofluids. HTC is enhanced by 44% for stainless tubes, 29% for brass tubes. Xing et al. [39] studied the effects of surface functionalization (covalent, non-covalent) on pool boiling HTC of MWCNT/water nanofluids (0.1 to 1 vol%) and maximum enhancements of pool boiling HTC are observed as 34.2% and 53.4% respectively for MWCNT-COOH and MWCNT-OH nanofluids and comparision for various MWCNT functionalization is shown in Fig.7.

Xu and Zhao [40] conducted experiments to find the effect of alumina nanoparticles and SDS, Triton X-100 on pool boiling HTC of gradient porous metals and surfactants in water and observed the enhancement level of three layers gradient foam is less compared to two layers and temperature of liquid-gas surface is better than nickel fiber with aluminum nanoparticles. Sarafraz and Hormozi [41] experimentally investigated the pool boiling HTC of water-MWCNT nanofluids (0.1, 0.3 wt%) on micro finned surfaces with various properties and observed that pool boiling HTC was decreased for plain surface and it was enhanced as 56% and 77% for 0.1 wt%, 0.3 wt% respectively for micro finned surfaces and CHF was enhanced up to 95% in case of 0.3 wt% and it is shown in Fig.8. Sulaiman et al. [42] experimentally determined the pool boiling HTC of water based TiO₂, Al₂O₃, SiO₂ nanofluids (0.04, 0.4, 1 kg/m³ mass concentration) and observed that wall superheat likely to enhance considerably when heated surface is covered with nanoparticle layer and critical heat flux was increased 2.5 to 3 times higher than water alone with similar conditions and it is depicted in Fig.9.
Fig. 8 Variation of enhancement ratio of HTC with mass concentration for different microstructures. [41]

Fig. 9 Variation of CHF with nanoparticle concentration for various materials and dispersion time [42]

Shogli et al. [43] investigated experimentally on the boiling HTC of water based ZnO, α-Al2O3 (0.01 and 0.05 wt%) and MWCNT nanofluids (0.01, 0.02 wt% with 0.01 wt% SDS) for heat fluxes up to 30,000 W/m². It is observed that ZnO and Al2O3 nanofluids deteriorate the boiling heat transfer performance and MWCNT nanofluids increase the performance of boiling heat transfer. Yaghem et al. [44] studied experimentally on pool boiling HTC and CHF for water based Al2O3, CuO and hybrid nanofluids and observed that hybrid nanofluids show good performance in all cases. Yao et al. [45] reviewed the performance of boiling heat transfer due to the effect of nanofluids and presented. Rashidi et al. [46] also presented phenomenon of boiling and reviewed various applications of boiling heat transfer. Wang et al. [47] performed experiments to determine the performance of boiling heat transfer using SiC/water nanofluids and obtained an improvement from -24.7% to 30.6%. Summary of the experimental studies on boiling heat transfer performance using nanofluids is presented in Table 1.

### Table 1. Summary of experimental studies on boiling heat transfer using nanofluids.

| Authors          | Experimental setup | Nano particle used | Base fluid / Parameters | Remarks                           |
|------------------|--------------------|--------------------|-------------------------|-----------------------------------|
| Peng et al. [36] |                    | CuO R113 refrigerant | 0 – 0.5 wt%            | Maximum enhancement in heat transfer occurs is 29.7%. |
| He et al. [37]   |                    | ZnO EG, Water      | Φ = 0 to 8.25 wt%       | The HTC and CHF are enhanced till 7.25 wt%. |
| Study                                | Nanoparticles | Medium | Volume Fraction | Results                                                                 |
|-------------------------------------|---------------|--------|-----------------|-------------------------------------------------------------------------|
| Sarfaraj et al. [38]                | Al₂O₃, TiO₂    | Water  | ϕ = 0.1, 0.5, 1% | Nanoparticle’s presence is not effecting the pool boiling heat transfer.|
| Xing et al. [39]                    | MWNT          | Water  | Wt: 0.1 – 1%    | Maximum heat transfer enhancements are up to 34.2% and 53.4%.            |
| Xu and Zhao [40]                    | Al₂O₃         | Water  | ϕ = 0.5%        | Nickel fiber’s temperature in presence of Al < the bubble liquid–gas interface, heat transfers to nickel fiber from bubble. |
| Sarafraz and Harmozi [41]           | MWCNT         | Water  | Wt: 0.1, 0.3%   | For plain surface HTC was deteriorated, but it was improved up to 56% and 77% for 0.1 and 0.3 wt% respectively in case of micro-finned surfaces. |
| Sulaiman et al. [42]                | TiO₂, Al₂O₃, SiO₂ | Water  | Wt: 0.04, 0.4, 1 kg/m³ | Compared to water, CHF in nanofluid was 2.5–3 times higher in all cases. |
| Shogal et al. [43]                  | Al₂O₃, ZnO, CNT | Water  | 0.01 wt%       | CNT nanofluids show better improvement in HTC and ZnO and Al₂O₃ nanofluids show deterioration. |
| Yagnem et al. [44]                  | Al₂O₃, CuO, hybrid | Water  | 0.1 vol%       | In all cases, hybrid nanofluids exhibit good performance.               |
| Wang et al. [47]                    | SiC           | Water  | 0.1 vol%       | Compared to water, SiC/water nanofluid shows promising improvement in HTC from -24.7% to 30.6%. |
4. Conclusions

Though there are some reviews on studies of nanofluids, this comprehensive review is concentrated mainly on the experimental investigations of synthesis, characterization, measurement of thermal conductivity, viscosity and boiling heat transfer applications of nanofluids to enhance the thermal performance of the systems. Based on this review it is evident that Synthesis of stable nanofluids without losing the thermal properties is the key factor for the application of nanofluids in a wide range. Two stage technique is most successful method for preparing the metallic oxide nanofluids where as single step method is so successful for metallic particles.

1. With the addition of nanoparticles, enhancement in the thermal conductivity and viscosity is observed.
2. For boiling heat transfer using nanofluids, there is a significant increase in CHF of nanofluids particularly at lower volume fractions.
3. Hybrid nanofluids with the usage of two or more nanoparticles to mix with carrier fluid and can be tested for different convection and boiling applications.
4. Commercialization of the nanofluids is very much possible by overcoming the challenges like preparation of stable and homogenous nanofluids, cost associated with preparation, inconsistent thermal conductivity, high viscosity, increased pressure drop etc. There is still a possibility and scope for lot of research work to be done on nanofluids in several applications.

Nomenclature

| CHF | Critical heat flux | kW/m² |
| HTC | Heat transfer coefficient | W/m² K |

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