Natural Thermal Convection of Nanofluids

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Nanofluids are considered as advanced heat transfer media for thermal management and conversion systems. Research on the convective heat transfer is of paramount importance for their numerous applications. This paper presents development of experimental research on the natural convection heat transfer of nanofluids in different geometries. Experimental results and available experiment-derived correlations for the natural thermal convection of nanofluids are critically analysed. Other features such as nanofluid preparation and thermophysical properties of nanofluids that are important for convection heat transfer are also briefly reviewed and discussed. It is demonstrated that there is considerable inconsistencies of available results on these properties and features of nanofluids.
Although nanofluids exhibit enhanced thermophysical properties like viscosity and thermal conductivity, convective heat transfer coefficients were also observed to deteriorate in some cases when nanofluids were used, especially for higher concentration of nanoparticles (> 0.1 vol%). However, the underlying mechanisms are also not yet well-understood despite its great importance for practical applications.

Keywords: nanofluids ; stability ; thermophysical properties ; natural convection ; thermal management systems

1. Introduction

Nanofluids (NF) which are considered as advanced cooling media, have received immense attention from researchers worldwide. Although the main application of this new class of fluids is in the thermal management and energy conversion systems, most of the research on nanofluids are on their thermal conductivity. Despite of huge importance and potential research works related to their cooling application and thermal energy conversion like applying in solar thermal systems are still very limited. Figure 1 illustrates the global record of publication outputs on NF, its thermal conductivity (TC), natural convection and convective heat transfer (CHT) application of NF as obtained from the Web of Science platform (Clarivate) spanning 2012 to 2019. It is noted that the records of publications (Figure 1) include all types articles from experimental, theoretical, numerical as well as review studies. As can be seen from Figure 1, research on NF continued to grow except last year's slight declination (for the first time), and TC is still dominating as the primary thermophysical property of NF being published. On the other hand, research on the CHT remained considerably behind the publications on the TC of NF with the ups and downs for the period considered. Furthermore, natural convection which doesn't require pumping power cost and is also a key cooling mode which has not received considerable attention from researchers (Figure 1). Also, natural convection studies of NF are significantly smaller compared with those of TC of NF and slightly less than those of CHT (forced convection). Thus, there is a clear need for more comprehensive works on the thermo-convection of NF under various thermal and concentration conditions in different geometries of cavities for their broad applications, particularly in thermal management and conversion.

Before employing NF in any application systems and characterizing their properties, NF must be engineered properly to ensure their long-term stability. Nanoparticles (NP) in NF agglomerate and sediment, which signify a poor degree of stability. This can impact negatively on both the experimental measurements of the thermal properties and convective behaviour of NF in any geometry and flow conditions [1][2][3][4]. Basically, NF are formulated using single- and two-step approaches [5][6][7]. The formal entails a single process of both synthesising the NP and suspending the same in the base fluid, (mainly at a volume concentration) whereas the latter involves a separate process of nanoparticles' synthesis and their suspension into the base fluid. Since the stability of NP prepared by the two-step process is generally not satisfactory, it is important to undertake a proper dispersion process (e.g., sonication, surfactant addition, etc) to ensure their improved stability.

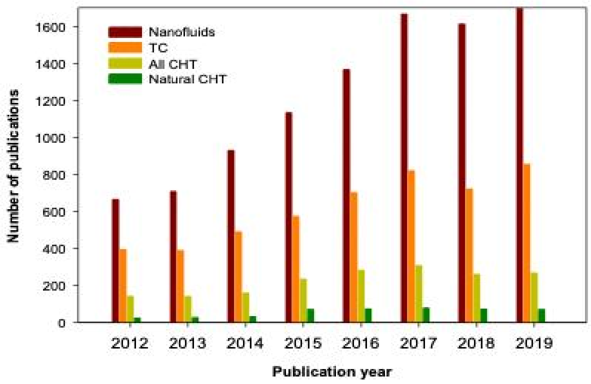

Figure 1 Publication records of NF, its TC and CHT over the past several years (Web of Science).

Apart from the NF preparation and stability condition, the thermophysical properties particularly TC and viscosity of NF are very important for their convective heat transfer performance, and these properties of NF are considerably higher than those of their base fluids [8][9][10][11][12]. Numerous works have also been carried out on the CNT and flow under natural and forced (laminar, transition and turbulence) convection of NF in various geometries (cavities, ducts, macro- to micro-channels, etc.) [13][14][15][16][17]. Literature results showed even larger enhancement (compared with thermophysical properties) of these single-phase heat transfer features of NF[18]. In natural convection, studies are mostly performed using numerical simulations while only a handful conducted experiments and the results are again not consistent and conclusive. Although NF' research focuses have been expanded rapidly from properties characterization to energy harvesting, the main target of using NF in different engineering applications is to improve the cooling performance of conventional cooling media through increased convection heat transfer.

Tuckerman and Pease [19] invented the microchannel heat sink/system (MCHS) as an electronic cooling system, which was later investigated by Lee and Choi [20] for the CNT capability using novel NF. They experimentally demonstrated that the utilization of NF in an MCHS caused thermal cooling in addition to lower thermal resistance and higher power density compared with water [20]. The study of NF's thermal transport behaviour in an enclosure was pioneered by Putra et al. who demonstrated experimentally that heat transfer was not enhanced but deteriorated when NF were used in a horizontal cylinder enclosure. However, no scientific test except visual inspection was conducted to check the stability of the prepared NF.

Another early experimental study on the thermo-convection of NF (TiO_2/water) was conducted by Wen and Ding in a mini-scale (several mm) enclosure. They measured the steady and transient heat transfer coefficients and reported a detraction of the convective heat transfer coefficient with a rise in particle concentration. Possible mechanisms (Brownian motion, slip, thermophoresis, electrophoresis, etc.) for such deterioration of heat transfer were attributed to convection brought about by the difference in concentration and temperature, particle/particle and particle/surface relations, change of the dispersion properties, degree of stability, and viscosity. The findings of these early studies have pioneered research in this area of NF. The stable TiO_2/water NF was prepared by employing the pH control method while the zeta potential (ZP) technique was used to monitor the stability.

The engineering importance of thermal fluids in enclosures for cooling purposes has spurred the study into the heat transfer capability and behaviour of NF in various shapes and sizes of cavities and channels. Numerical studies have inundated the public domain regarding the deployment of NF as transport media in MCHS and cavities with the presence of very few experimental works. However, the experimental study is very vital for a deeper understanding of the physics and mechanisms of thermal cooling afforded using NF in addition to the contribution provided via computational and theoretical methods. The open literature remains uncertain concerning the heat transfer performance of NF in cavities under thermo-convection conditions while that of MCHS appears to be apparent.

Thus, this work took a specific interest in reviewing experimental studies based on the heat transfer capability of NFin diverse cavity geometries. We delved into the accuracy of measurements on the thermal properties and convective heat transport of NF in these enclosures. Preparation and stability of NF, experimental methods (intrusive and non-intrusive) and conditions were also reviewed and discussed.

2. Formulation and stability of nanofluids

The preparation of involves the suspension of NP of interest into specific base fluids. NF are formulated using the one-step and two-step approach with the synthesis of NPs for the latter carried out under different manufacturing techniques [21][22][23][24]. As NF are formulated by the dispersion of NP into conventional fluids (liquids), the stability of the resultant biphasic nano-based fluids is essential. The one-step approach involves the preparation of NF by the simultaneous synthesis of NP and dispersion in a base fluid. This approach offers the advantage of better stability and homogeneity of NF, and the elimination of laborious processes such as storing and drying compared to the one-step approach by reducing NP agglomeration [21][25]. Conversely, the industrial use of this method is not practicable except for fluids with low vapour pressure, and it is capital intensive [26].

The two-step approach of NF preparation has been mostly reported in the literature, especially for metallic oxides and carbon nanotubes NP; this is due to the possibility of large-scale production of NF for industrial application and cost economy. The demerit of this method has to do with sedimentation and agglomeration of the NP because of the Van der Waal force of attraction among particles [27]. Various manufacturing techniques used by numerous researchers under both the one-step and two-step approach of NF preparation have been well documented, and details can be foundin the literature [28][29][30].

Preparation of NF using both methods requires the need for agitation to achieve homogeneity and better stability of NF. The use of a homogenizer, stirrer (magnetic), ultra-sonicator and higher-shear devices to provide energy for even suspension of the NP into the base fluids is a must for and NF formulation [29]. Furthermore, the agitation time, intensity of agitation, volume/weight concentration or fraction, pH, temperature, surfactants' types and quantity, types, and sizes of NP, and base fluid types are factors that are very important to the stability of the prepared NF [22][23][24].

The stability of NF is strongly linked to the thermal and convective properties of NF which consequently determine their application as heat transfer media [31][32][33]. The use of surfactants is to minimize the interfacial tension between NP and base fluid by increasing the EDL, thus, enhancing stability [34]. The choice of surfactants depends on the base fluid and NP types engaged in the formulation of NF [32][33]. It is worth stressing that the use of surfactants to improve the stability of NF is achievable at an optimum weight fraction above and below which instability is experienced [35][36][37][38][39]. The optimal weight fraction equivalent to the critical micelle concentration is very important to NF stability.

Experimental works on the convection heat transfer of NF involved the determination of both the thermal and convective properties which required good stability of the NF. To enhance the stability of NF, researchers have employed the use of diverse surfactants (e.g. sodium dodecyl sulphate and gum Arabic), pH and surface (functionalization) modification [37][38][39]. The agitation period (stirring and sonication) of few minutes to few hours has been reported in the literature [40]. It is worthy of note that the optimum agitation time, surfactants' quantity, temperature, and pH are key to the stability and thermophysical properties (TC, density, and viscosity) of NF.

Experimental methods have been devised to check the stability of NF. These include sedimentation, centrifugation, spectral absorbency, viscosity, electron microscopy, ZP, poly-disparity index, and light scattering [41][42][43]. In studies involving CHT in enclosures, the sedimentation, centrifugation, spectral absorbency, viscosity, density, ZP, and poly-disparity index are mostly engaged to check the stability of NF [44][45][46][47][48]. To monitor the duration of stability of NF, the spectral absorbency, light scattering, density, and viscosity methods are engaged while the on-the-spot stability of NF is inspected using other techniques. However, the visual method of stability inspection which is not suitable to a large extent as it is not scientific and has been the most reported of the methods for NF stability monitoring.

In order to determine the dispersion/stability state of the colloidal suspensions zeta potential is widely used. Researchers also confirmed that NF having ZP of above 30 mV (absolute value) showed relatively good stability character [49]. However, the ZP of suspensions can be significantly changed by using dispersion techniques like ultrasonication and by changing the pH value. NF has better stability when its pH is distanced from the isoelectric point (IEP). For example, good stability of Al_2O_3/distilled water (DW) NF was found at a pH value of above 8 which was the IEP [38].

3. Thermophysical properties of nanofluids

Thermal properties of NF namely thermal conductivity and viscosity play a prominent role in convective heat transfer performance of NF. Since extensive studies have been conducted on these two properties of NF, a breif overview of these properties as related to NF was briefly presented here.

3.1 Thermal conductivity

Several researchers have contributed to the body of knowledge on the TC augmentation of NF. Early works showed TC improvement of up to 20% above the base fluids for NF when volume/mass fractions of less than 5% were studied [50][51][52][53][54]. Diverse mechanisms (clustering, thermal interfacial resistance, Brownian motion, interfacial Kapitsa resistance, percolation, aggregation, nano-layer, etc.) have been proposed for the uncharacteristic TC augmentation [55][56][57]. Masuda [53] pioneered the investigation of the TC of NF when 13 nm alumina NP were dispersed in water. An enhancement of 30% over the base fluid was recorded for 4.3 vol%. Thereafter, several studies have been carried out using diverse NP (Cu, CuO, etc.) with different nano-sizes and various base fluids (water, ethylene glycol, etc.) to prepare NF and reported various degrees of enhancements under diverse ranges of temperatures and volume/mass fractions or concentrations. The literature revealed the enhancement of TC of NF in comparison with the respective base fluids as the temperature and volume/mass fraction or concentration increased [58][59][60][61][62][63][64][65][66][67]. The influence of magnetic field on the TC of NF has been investigated by a few researchers [68][69][70][71][72][73]. They reported that the TC was enhanced as magnetic field intensity was increased.

The TC of NF was observed to be influenced by volume/mass fraction or concentration, NP type, shape, and size, base fluid, temperature, etc. Despite being the most researched property of NF, TC results from various groups are not consistent but NF exhibit considerably higher TC compared with the base fluids even when the concentration of NP is very low. The enhanced TC further increased with the loading of NP (until some critical concentration). Some representative TC results (ratio of TCs of NF (k_{nf}) and base fluids (k_f)) are shown in Figure 2. However, the underlying mechanisms behind the observed increase in the measured TC are not yet fully understood.

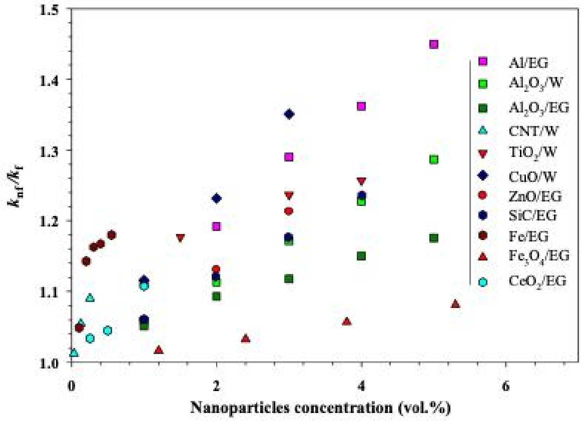

Figure 2 Enhanced thermal conductivity of various nanofluids as related to nanoparticles loading [abreviation note, CNT: carbon nanotubes, EG: ethylene glycol, W: water] (adapted from authors' earlier study [74]).

3.2 Viscosity

The open literature showed that more studies had been conducted on the TC of NF than the viscosity. The dispersion of NP and HNP into the base fluid leads to an enhancement of viscosity of the base fluid. Several factors have been reported to be responsible for the viscosity enhancement of NF compared with those of base fluids. These include volume/weight fraction, temperature, nano-size, interfacial nanolayer etc., with a recent study revealing that nano-confinement, nanoparticle-fluid interaction and viscous dissipation as other factors have an effect on the viscosity of NF [75][76]. This viscosity enhancement affects the heat and flow characteristics of NF as the pumping power is increased. This appears to be one of the downsides of the applications of NF. The primary purpose of engaging NF as cooling media is because of the improved TC leading to the circulation of fewer coolant liquids with less pumping power. However, enhancing the viscosity of NF above a certain limit would rub off the benefit afforded by the augmentation of TC. Conclusively, the viscosity of NF has a substantial impact on the overall CHT performance.

Pak and Choi [77] pioneered the measurement of the viscosity of NF. They engaged DW-based Al_2O_3 and TiO_2 NF (Φ = 1 – 10 vol%) and measured the viscosity at temperatures of 20 to 65 °C. At 10 vol%, the viscosity of Al_2O_3/DW NF was enhanced by 200-fold while that of TiO_2/DW NF was 3-fold, when compared with DW. Several studies have been conducted on the experimental determination of the viscosity of NF in relation to temperature and volume/mass concentration or fraction [78][79][80][81][82][83]. These works involved different types of NP dispersed in various base fluids and measured at different ranges of temperatures and concentrations or fractions. The result revealed that the viscosity of NF was more than the corresponding base fluids and that as volume/mass fraction or concentration increased viscosity was enhanced. Also, an increase in temperature caused the augmentation of NF viscosity. Additionally, the viscosity of NF was found to be dependent on nanosize, shear rate, and sonication time.

The viscosity of NF is also crucial for their practical applications as cooling or heating media in flow systems. Some selective results of relative viscosity (ratio of the viscosity of NF (subscript, *nf*), and base fluids (subscript, *f*)) are shown in Figure 3 in which the data is used from the author´s previous study. In most cases, the viscosity of NF was found to decline with increasing temperature.

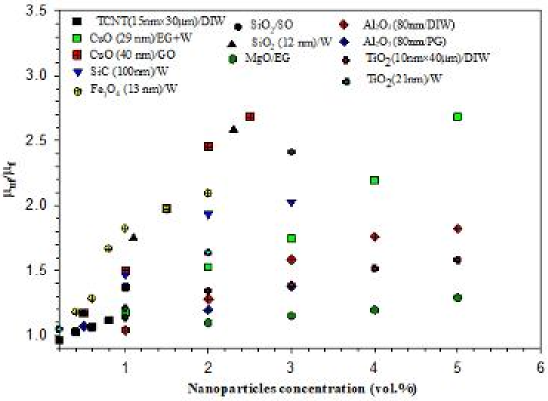

Figure 3 Enhanced viscosity of various nanofluids as related to nanoparticles loading [abreviation note, TCNT: treated carbon nanotubes, GO: gear oil, SO: silicone oil, PG: propylene glycol] (data adapted from author´s previous study).

4. Convective heat transfer performance of nanofluids

In this section, findings from available experimental studies on the convective heat transfer of NF in diverse geometries and under different flow regimes and thermal conditions have been critically analyzed. It was observed that most of the experimental studies employed square cavities. Thus, based on the geometry of the system available findings and their discussion are grouped into four subsections; square, rectangular, cylindrical and other geometries. In addition, a detailed summary of natural convection heat transfer of nanofluids in various cavity geometries is presented in Table 1.

Table 1. Summary of natural thermo-convection of nanofluids in various cavity geometries.

Researchers	**NF (Φ)**	**Cavity Dimension**	**Rayleigh Number(*Ra*)**	**Measured Thermal Properties**	**Preparation Method (Stability Test)**	**Remark**
Kouloulias et al. [48]	γ-Al_2O_3/DIW (0.01–0.12 vol.%)	Cubic with 1 × $10^{-3}$$m^3$.	2.5×10^9–5.2×10^9	-	2-step (-)	*Nu* and *h* deteriorate with Φ increase at different ΔT conditions.
Ilyas et al. [84]	MWCNT/Thermal oil (0–1 mass%)	Vertical rectangular (12 × 4 × 3 cm) with AR = 4.	2.5×10^5–2.7×10^6	*μ*, C_p, β and *κ*	2-step (-)	Deterioration of h_{av} (21.3%) and Nu_{av}(35.74%) as Φ increases despite high TC.
Rao and Srivastava [85]	Al_2O_3/DIW (0.01–0.04 vol.%)	Rectangular (l = 60 mm, b = 25 mm, h = 20 mm)	5.0×10^4–3.5×10^5	-	2-step (visual)	Enhancements of h_{av} (28.43–38.03) and Nu_{av} (1.92–14.97) of NF in comparison to BF with increasing Φ at different ΔT regimes.

Ho et al. [86]	Al_2O_3/W (1–4 vol.%)	Vertical rectangular (l = 60 mm, b = 25 mm, h = 25 mm)	5.78×10^5–3.11×10^6	-	(visual)	Enhancement of Nu_{av} with . Sedimentation has more impact than Brownian motion and Ludwig-Soret effect.
Amiri et al. [47]	MWCNT-hexylamine/TO ((0.001 and 0.005 wt%)	Cubic (203 × 100 × 221 mm^3)	ND	μ, ρ, PP, σ, C_p, voltage breakdown, FP, and κ	2-step (UV-vis, ZP and poly-disparity index)	Both *Nu* and *h* are enhanced with .
Choudhary and Subudhi [87]	Al_2O_3/DW (0.01 and 0.1 vol.%)	Rectangular (120 × 120 × 365 (h) mm^3) with AR (0.3–2.5)	10^7–10^{12}	-	2-step (visual)	At low Φ, heat transfer is enhanced but deteriorated at high . Heat transfer is related to AR, *Ra*, and .
Qi et al. [88]	TiO_2-W (0.1, 0.3 and 0.5 wt%)	Three rectangles with AR = 0.25, 0.5 and 1, and inclined at −45°, 0°, 45° and 90°)	ND	-	2-step (UV-Vis, visual)	*Nu* is augmented with increasing Φ and Q. Highest heat transfer is achieved using the cavity with AR = 1 and at 0°.
Hu et al. [89]	TiO_2/DIW (3.85, 7.41 and 10.71 wt%)	Vertical square (180 × 80 × 80 mm^3)	4.04×10^7–21.07×10^7	μ and κ	2-step (-)	Heat transfer of NF is deteriorated when compared with the base fluid.
Joshi and Pattamatta [90]	Al_2O_3/DW, MWCNT/DW and Graphene/DW (0.1, 0.3 and 0.5 vol.%)	Square (40 × 40 × 200)	7×10^5–1×10^7	μ and κ	1-step (G), 2-step (Al_2O_3 and MWCNT) (visual)	At *Ra* = 10^6, DW-based MWCNT and Graphene NF enhance heat transfer for 0.1 and 0.3 vol.%, whereas at *Ra* = 10^7, only MWCNT/DW and Al_2O_3/DW NF reveal the same at similar concentrations.

Dixit and Pattamatta [91]	SiO_2/DW, MWCNT/DW, Graphene/DW, and Cu/DW (0.057, 1, and 2 vol.%)	Cubic (25 × 50 × 50 mm^3) + magnetic field (0.13 T and 0.3 T)	1×10^6–1×10^7	*μ* and *κ*	2-step (ZP)	Heat transfer is augmented for all the graphene samples and MWCNT at 0.1 vol.%, without magnetic field. Generally, heat transfer in all the NF samples is deteriorated with magnetic field.
Li et al. [92]	ZnO/EG-DW (75:25, 85:15 and 95:5 vol) (5.25 wt%)	Square (180 × 80 × 80 mm^3)	5.25×10^7–1.08×10^8	*μ* and *κ*	2-step (PVP)	Under the experimental condition, heat transfer is deteriorated with an increase in EG content.
Nnanna [93]	Al_2O_3/DIW (0.2–7.9 vol.%)	Cuboid (35 mm × 40.32 mm × 215 mm)	0.3×10^7–3.2×10^7	*μ* and *κ*	1-step (visual)	Heat transfer is augmented at low concentration of NF (0.2–2 vol.%) but detracts at higher concentration.
Ho et al. [94]	Al_2O_3/DIW (0.1–4 vol.%)	Cuboid (25 × 25 × 60, 40 × 40 × 90, and 80 × 80 × 180)	6.21×10^5–2.56×10^8	*μ*, ρ, and *κ*	2-step (-)	Enhancement of heat transfer at lower concentrations (0.1 and 0.3 vol.%) is observed, which increases with cavity size.
Yamaguchi et al. [95]	Mg-Zn ferrite/kerosene (ND)	Cubic (7.5 mm each side) with a heat-generating object (brass and square)	Gr = 0–160; $Gr_m = 1.22 \times 10^3$–4.4×10^4	*μ*, ρ, C_p, β, M, and *κ*	2-step (-)	Exposure to the magnetic field enhanced heat transfer and irrespective of the size of the heat-generating objects.

Sharifpur et al. [17]	TiO_2/DIW (0.05–0.8 vol.%)	Rectangular (96 × 103 × 120 mm^3)	4.9×10^8–1.47×10^9	-	1-step (-)	Heat transfer is enhanced for 0.05–0.2 vol.% and thereafter decreased, with maximum of 8.2% attained with 0.05 vol.% at ΔT of 50 °C.
Solomon et al. [44]	Al_2O_3/DIW (0.1–0.6 vol.%)	Rectangular with AR = 1,2 and 4.	6.9×10^6–4.0×10^8	-	1-step (UV-Vis and viscosity)	Enhancement of heat transfer is observed to be related to AR, *Ra* and . Highest heat transfer occurs at 0.1, 0.2 and 0.3 vol.% for AR = 1,2, and 4, respectively.
Ghodsinezhad et al. [15]	Al_2O_3/DIW (0.05–0.6 vol.%)	Rectangular (96 × 120 × 102 mm^3)	3.49×10^8–1.05×10^9	μ	1-step (ZP, UV-vis and visual)	Enhancement of *h* up till 0.1 vol.% is observed. At 0.1 vol.%, *h* is 15% augmented compared to base fluid
Garbadeen et al. [16]	MWCNT/DIW (0–1 vol.%)	Cuboid (96 × 96 × 105 mm^3)	1×10^8	μ and κ	2-step (viscosity and visual)	Optimum heat transfer occurred at 0.1 vol.% with 45% enhancement of *h*relative to the base fluid.
Ilyas et al. [96]	f-MWCNT/THO (0.5–3 wt%)	Cuboid (12 × 4 × 3 cm^3)	4.43×10^5–2.59×10^6	μ, ρ, C_p, and κ	2-step (-)	The *h* is enhanced as volume concentration increased whereas *Nu* is attenuated.
Solomon et al. [97]	Mango bark/DIW NF (0.01–0.5 vol.%)	Cuboid (120 × 96 × 103 mm^3)	0.2 $\times 10^8$–6×10^8	μ and κ	2-step (UV-vis and viscosity)	Deterioration of NF is observed with increase in volume concentration.

Roszko and Fornalik-Wajs [98]	Ag/DW (0.1 vol.%)	Cubical with 0.032 m under magnetic field (10 T)	2.5×10^6–2.2×10^7	-	2-step (-)	*Nu* is dependent on the magnetic field and structure of the flow. The energy transfer is altered because of the magnetic field.
Solomon et al. [99]	Al_2O_3/EG (60%)-DIW (40%) (0.05–0.4 vok%)	Cuboid (120 × 96 × 103 mm^3)	3×10^3–$1.3 \times 10^4$and 1.2×10^8–4×10^8	*μ* and *κ*	1-step (UV-vis, viscosity and visual)	Heat transfer is enhanced by 10% for the porous cavity at 0.1 vol.% and ΔT = 50 °C, compared to the base fluid.
Joubert et al. [33]	Fe_2O_3/DIW (0.05–0.3 vol.%)	Rectangle (99 × 96 × 120 mm^3) under magnetic field intensity of 300 G and 700 G.	1.77×10^8–4.26×10^8	*μ*	2-step (visual and viscosity)	Without magnetic field, *Nu* is maximally enhanced by 5.63% for 0.1 vol.% NF while with magnetic field, an additional maximum augmentation of 2.81% is recorded.
Putra et al. [6]	Al_2O_3/DW and CuO/DW (1 and 4 vol.%)	Horizontal cylinder (inner diameter = 40 mm) at AR = 0.5 and 1.	1.6×10^7–9.2×10^7	*ρ, μ, κ*, and *γ*	2-step (visual)	For both NF, heat transfer deteriorates as AR and concentration increased but decreased with *Nu.*
Ali et al. [5]	Al_2O_3/W (0.21, 0.51 and 0.75 vol.%)	Two vertical cylinders (D = 0.2 m) with AR = 0.0635 and 0.127. Heated on the top wall.	3.0×10^5–1.3×10^8	*ρ, μ,* and *κ*	1-step (-)	The *Nu* and *h* of the NF are more deteriorated than the base fluid, which is related to volume concentration and AR.

Cadena-de la Peña et al. [100]	AIN and TiO_2/mineral oil (0.01, 0.1 and 0.5 wt%)	Annular and vertical (opened) with *AR* of 3.98 and 4.78.	1.4×10^9–3.2×10^{13}	*μ,* and *κ* (at 24 and 40 °C)	2-step (visual)	Nu_{av} and h_{av} are improved relative to the base fluid at certain conditions (low AR and φ, and high *Ra*). TiO_2/mineral oil NF (h_{av} = 2.63 -5.35% and Nu_{av} = 3.45% maximum) performing better than the AIN/mineral oil NF (h_{av} = 3.91% maximum)
Ali et al. [101]	Al_2O_3/W (0.21, 0.51 and 0.75 vol.%)	Two vertical cylinders (D = 0.2 m) with AR = 0.0635 and 0.127. Heated at the bottom.	3.0×10^5–1.3×10^8	*ρ, μ,* and *κ*	1-step (visual)	Compared to the base fluid, *h* is augmented for 0.21 vol.% and attenuated with concentration increase. HTC is AR dependent with higher *h* for lower AR.
Wen and Ding [7]	TiO_2/DW (0.8, 1.5, and 2.5 wt%)	Horizontal cylinder (240 mm diameter)	2.3×10^4–1.4×10^5	*μ* and *κ*	2-step (ZP and visual)	HTC attenuates with increase in NF concentration with maximum reduction of 30% recorded.
Mahian, et al. [3]	SiO_2/W (0.5, 1.0, and 2.0 vol.%)	Square, inclined square (45°) and triangular	1.0×10^5–1.0×10^6	*ρ, μ,* and *κ*.	2-step (visual)	For all the cavities, the maximum HTC ratio is observed at Ra = 10^6 and 0.5% concentration. High prediction accuracy of the HTC is noticed when the thermophysical properties of the NF are measured.

Mahrood et al. [46]	Al_2O_3 and TiO_2/CMC (0.1 ≤ φ ≤ 1.5 vol.%)	Vertical cylinder with AR = 0.5, 1.0 and 1.5.	4.0×10^6–3.0×10^7	n.d.	2-step (-)	Heat transfer is enhanced below 0.5 and 1 vol.% with optimum values at 0.1 and 0.2 vol.%, for CMC-based TiO_2 and Al_2O_3 NF, respectively. TiO_2 NF is a better heat transfer medium than Al_2O_3NF. Increasing *AR* is found to enhance heat transfer for both NF.
Moradi et al. [102]	Al_2O_3/DIW and TiO_2/DIW (0.1 ≤ φ ≤ 1.5 vol.%)	Inclined (30°, 60° and 90°) vertical cylindrical (diameter = 80 mm and length = 250 mm) with AR (0.5, 1.0 and 1.5)	1.2×10^8–3.7×10^8	*P*	2-step (visual)	Maximum enhancements of *Nu* (6.76% and 2.33% relative to DIW) occur at 0.2 vol.% and 0.1 vol.% for Al_2O_3/DIW and TiO_2/DIW NF, respectively. *Nu* is noticed to augment with increase in AR.
Yamaguchi et al. [103]	Mg-Zn ferrite/alkyl-naphthalene	Cubic with a magnetic field.	Ra (3.0×10^3–8.0×10^3), Ra_m (1.0×10^8–1.25×10^8)	-	2-step (-)	Heat transfer is enhanced on exposure to magnetic field. An increase in the magnetic strength enhanced heat transfer further.
Ni et al. [104]	Al_2O_3/W (0.0108 vol.%)	Cylindrical (ID = 19.3 cm, h = 2.00 cm)	2.6×10^8–7.7×10^8	-	1-step (-)	Deterioration of *Nu*.
Babu and Rao [105]	Al_2O_3/DIW (0.05–0.6 vol.%)	Vertical cylinder (D = 12.7mm, l = 250mm)	2.7×10^9–6.4×10^9	-	2-step (UV-vis)	Improvement of heat transfer by 13.8% for 0.1 vol.%.

Torki and Etesami [106]	SiO_2/DIW (0.01–1.0 vol.%)	Inclined rectangle (60 × 60 × 135 mm^3)	1.0×10^7–8.0×10^7	-	2-step (-)	Maximum *h* and *Nu* at Φ = 0.01 vol.% and *θ* = 0°. Attenuation are observed at >0.01 vol.% and >0°.
Haddad et al. [108]	ZnO/W (0.01–0.1 vol.%)	Inclined hemisphere with a cubical object.	5.21×10^7–7.29×10^{10}	*μ*, *κ*, Cp, β, Φ, and B.	2-step (-)	Heat transfer is slightly enhanced with an increase in Φ while increasing *θ* does not affect it.
Dixit and Pattamatta [109]	Fe_3O_4/DI (0.05 and 0.2 vol.%) and Fe/DI (0.2 vol.%)	Cubic (25 mm each) with a magnetic field of 0.3 T.	4.23×10^5–1.0×10^7	*μ*, *κ*, and B.	2-step (ZP)	For both types of NF, deterioration is observed on exposing the vertical walls (heated and non-heated) to the magnetic field. Heat transfer is enhanced by 11.0% (0.05 vol) and 28% (0.2 vol) for Fe_3O_4/DI NF on exposing the heated bottom wall to the magnetic field.

4.1. Convection in square cavities

The convective heat transfer behaviour of ZnO/DIW-EG (Φ = 5.25 wt%) NF enclosed in a square-shaped enclosure was experimented by Li et al. [93]. The result showed that the heat transfer capability of the NF was deteriorated in relation to the base fluid as the EG content was increased. In a vertical square cavity, Hu et al. [90] utilized DIW-based TiO_2(3.85 – 10.71 wt%) NF to investigate the free convection heat transfer performance. They noticed the detraction of heat transfer for the NF when compared with DIW. Kouloulias et al. experimented the thermo-convection behaviour in a square enclosure saturated with Al_2O_3/water (0.01 – 0.12 vol%) NF. Their result also revealed the attenuation of heat transfer for the studied NF in relation to water. Nevertheless, the work of Garbadden et al. reported enhancement of heat transfer when DIW-based MWCNT (0 – 1 vol%) NF was engaged in a square cavity to investigate the thermo-convection performance. Maximum heat transfer enhancement of 45% at Φ = 0.1 vol% was reported. In addition, the convective heat transfer of Al_2O_3/DW (0.1 – 4 vol%) NF in a square geometry with three different square cavities was experimented by Ho et al. [95]. They demonstrated that heat transfer was enhanced at lower Φ (maximum at 0.1 vol%) for all the cavities and increased with cavity size. In comparison with DW, maximum heat transfer coefficient enhancement of 18% was achieved with the largest cavity. On investigating the natural convection heat transfer behaviour of graphene, MWCNT, and Al_2O_3, /DW (0.1 – 0.5 vol%) NF in a square cavity, Joshi and Pattamatta [91]also reported heat transfer augmentation of the NF relative to DW, which agreed with the works of Garbadden et al. and Ho et al. [95].

The current trend of investigations on NF has established that the thermal and convective properties of NF can be improved through the utilization external magnetic field [99]. The influence of a uniform magnetic field on the thermo-convection characteristics in a square enclosure filled with a magnetic NF was examined by Yamaguchi et al. [104]. The imposition of the magnetic field was observed to increase thermal transport in the cavity, which was further enhanced with increased magnetic field intensity. Using an identical experimental set up as Yamaguchi et al. [104] and mounting heat-producing objects within the cavity, Yamaguchi et al. [96] examined the natural convection thermal transport performance. An increase in the size of the heat-producing objects was observed to slightly decrease heat transfer. By engaging a non-magnetic NF (Ag/water) in a cubic enclosure and stimulated by a variable magnetic field, the influence of ΔT and magnetic field on the thermo-convection performance was experimentally investigated [99]. The result demonstrated that the enhancement of *Nu* depended on ΔT and magnetic field strength. This finding was found to be contrary to that reported by Dixit and Pattamatta [92] as they revealed the attenuation of heat transfer on the exposure of non-magnetic NF (graphene/, SiO_2/, MWCNT/, and Cu/DW; 0.057 – 2 vol%) contained in a squareenclosure to magnetic fields. However, without a magnetic field, they reported augmentation of heat transfer for DW-based graphene and MWCNT NF at 0.1 vol%.

Recently, Dixit and Pattamatta [109] experimented the impact of magnetic field orientation on the convective heat transfer performance in a square cavity containing DI-based Fe_3O_4 (0.05 vol% and 0.2 vol%) and Fe (0.2 vol%) NF. They reported heat transfer attenuation on exposing the heated and non-heated vertical walls to the magnetic field for both types of NF. However, heat transfer was enhanced by 11% and 28% on exposing the heated bottom surface to the magnetic field for 0.05 vol% and 0.2 vol%, respectively. The orientation of the magnetic field and heated surface were observed to be accountable for the attenuation and enhancement of heat transfer for both types of NF.

4.2. Convection in rectangular cavities

Ilyas et al. [85] studied the thermo-convection inside a vertical rectangular cavity (AR = 4) filled with thermal oil-based MWCNT (0 – 1.0 wt%) NF. They reported that h_{av} and Nu_{av} were attenuated with an increase in . Deterioration of 21.3% and 35.7% was observed for h_{av} and Nu_{av} respectively, relative to thermal oil at Φ = 1.0 wt.%. It was stressed that the observed deterioration was due to high enhancement of viscosity by 62% for Φ = 1.0 wt.% despite the high TCafforded by MWCNT. Contrary to the results highlighted above, Ilyas et al. [97] and some studies showed that heat transfer of NF in rectangular cavities was enhanced with an increase in volume concentration. Using thermal oil-based Al_2O_3 (0 – 3 wt%) NF in a rectangular geometry with AR = 4, Ilyas et al. [97] revealed that heat transfer was enhanced as *h* increased from 1594 to 3175 W/m^2 in comparison with thermal oil. Ho et al. [87] and Amiri et al. [47] reported that heat transfer was enhanced as the volume concentration increased when the thermo-convection behaviour of Al_2O_3/water (1 – 4 vol%) NF and MWCNT-hexylamine/transformer oil (0.001 – 0.005 wt%) NF filled into rectangular cavities were investigated. Nnanna et al. [94] experimented the thermo-convection behaviour of DIW-based Al_2O_3 (0.2 – 8 vol%) NF in a rectangular enclosure and observed enhancement of heat transfer for 0.2 – 2 vol% after which it detracted (>2%). The highest augmentation of heat transfer was achieved with 0.2 vol%.

Ghodsinezhad et al. reported the highest increase (15%) in convective heat transfer coefficient (HTC) for DIW-based Al_2O_3 (0.05 – 0.6 vol%) NF inside a rectangular enclosure with 0.1 vol% in relation to DIW. In addition, Rao and Srivastava employed a non-intrusive method (interferometer) of measurement to study the thermo-convection of Al_2O_3/DIW (1 – 4 vol.%) NF in a rectangular geometry. They revealed that the convective HTC of the NF was enhanced by 38% in comparison to DIW. Also, increasing the volume concentration was observed to enhance heat transfer. The considerable enhancement in heat transfer achieved with a small temperature difference of 2.3 °C can be connected to the use of a non-intrusive temperature measurement technique in the cavity. It should be noted that this result is hard to come by using the intrusive method of temperature measurement via thermocouples. Also, the use of interferometric measurement by these authors led to the provision of conceivable explanations for the heat transfer augmentations accomplished by engaged Al_2O_3/DIW NF. Furthermore, they showed that three plausible mechanisms existed within the cavity and were accountable for the overall enhancement of the heat transfer rates recorded in the study. These were; dominant convection structures, thermal boundary layer disruption phenomenon, and TCenhancement.

Sharifpur et al. experimented the thermo-convection behaviour of DIW-based TiO_2 (0.05 – 0.8 vol%) NF in a rectangular cavity and noticed that heat transfer was enhanced for 0.05 – 0.2 vol% and after that, it decreased. A maximum enhancement of 8.2% was recorded for 0.05 vol%. With the use of Rao and Babu [106] examined the effects of heat inputs (30 – 50 W) and Φ (0.05 – 0.6 vol%) on the thermo-convection thermal transport behaviour in a cylindrical cavity (AR = 0.0508) containing Al_2O_3/W NF. In comparison with water, their results exhibited enhancement of heat transfer for ≤ 0.1 vol% and attenuation for > 0.1 vol%. The maximum *Nu* augmentation of 13.8% was recorded as *h* harmoniously increased from 382 W/m^2 – 435 W/m^2 for 0.1 vol% and heat input of 50 W.

Some authors also studied the influence of AR and inclination angle (θ) as active techniques for the enhancement of thermo-convection performance of NF in rectangular cavities. Choudhary and Subudhi [88] studied the thermo-convection of Al_2O_3/DW (0.01 and 0.1 vol%) NF in a rectangular cavity with varying AR (0.3 to 2.5). They revealed that *Nu* enhancement was dependent on Φ, thermal boundary layer, AR, and *Ra*. For both samples of NF, *Nu* was observed to be enhanced in comparison with DW. The highest enhancements of 29.5% (at AR = 0.5 and $Ra = 7.89 \times 10^8$) and 14.2% (at AR = 0.3 and $Ra = 1.86 \times 10^8$) were recorded for Φ = 0.01 vol% and 0.1 vol%, respectively.

Solomon et al. [44] experimented the convective heat transfer behaviour of DIW-based Al_2O_3 (0.1 – 0.6 vol.%) NF in an enclosure with varying AR (1, 2, and 4). They observed that heat transfer was related to AR, *Ra*, and . The cavity with AR = 1 (for 0.1 vol.%) has the highest augmentation of heat transfer. Qi et al. [89] also experimented the effects of AR (0.25, 0.5, and 1) and θ (-45° – 90°) on the thermo-convection of TiO_2-water NF in a rectangular enclosure. They observed that the *Nu* was enhanced with power input and . Peak heat transfer was observed with the enclosure having AR = 1 and θ = 0°. In recent work, Torki and Etesami [107] examined the impact of Φ (0.01 – 1.0 vol.%), ΔT (2.3 – 30.9 °C), and θ (0° – 120°) on the thermo-convection performance in a rectangular enclosure saturated with water-based SiO_2 NF. Result showed maximum enhancement of *h* and *Nu* for Φ = 0.01 vol% at θ = 0°. Increasing θ (> 0°) and Φ (> 0.01 vol%) was observed to attenuate *h* and *Nu* while an increase in *Ra* and ΔT enhanced *h* and *Nu*. For the influence of Φ on the natural convection performance of the NF in the cavity, increasing θ was observed to lead to deterioration.

Furthermore, the influence of porous media on the thermo-convection in a rectangular cavity containing Al_2O_3/EG (60%)-DIW (40%) (0.05 – 0.4 vol%) NF was experimented by Solomon et al. [100]. The result showed that the enhancement of heat transfer was a function of φ and porous media. By engaging the porous media and NF in the enclosure, heat transfer was enhanced by 10% with Φ = 0.1 vol% at ΔT = 50 °C, in comparison to DIW. Bio-based NF was investigated for the thermo-convection performance in a cavity. The pioneering work of Solomon et al. [98] in which a bio-based NF was engaged showed attenuation of heat transfer for all tested samples on investigating the hydrothermal behaviour in a rectangular enclosure filled with mango bark/DIW NF (0.01 – 0.5 vol%).

The influence of Φ and magnetic field using three configurations of permanent magnets on the thermo-convection behaviour in a rectangular cavity saturated with Fe_2O_3/DIW NF (0.05 – 0.3 vol%) was investigated. The result demonstrated that heat transfer enhancement pertaining to the NF depended on magnets' configuration, φ, and magnetic field intensity. Maximum enhancement of heat transfer was achieved with Φ = 0.1 vol% when 700 G magnets were placed on the hot side (above and below) of the enclosure. On exposing the cavity to the magnetic field, *Nu* was improved by 2.81% (Φ = 0.1 vol%) in comparison with the case in which no magnetic field was applied.

4.3. Convection in circular cavities

Ni et al. [105] experimented the turbulent thermo-convection of Al_2O_3/water NF in the classical Rayleigh–Bénard system with a cylindrical convection cell. They found a transition at Ra_c (2.5×10^9). When $Ra > Ra_c$, almost no changes in *Nu* of NF (compared with water) was observed while at $Ra < Ra_c$, *Nu* of NF was found to be lower than water and the reduction in trend was larger with decreasing *Ra*. They suggested that the significant decrease in the *Nu*of NF relative to water was due to the mass diffusion of NP. Ali et al. experimented the thermo-convection performance of aqueous Al_2O_3 NF with different volume concentrations (0.21 – 0.75 vol.%) inside vertical circular enclosures having AR = 0.0635 and 0.127 and heated below the cavities. They demonstrated that heat transfer was enhanced up to Φ ≤ 0.51 vol%, and the coefficient of heat transfer was also enhanced by AR. The heat transfer coefficients were noticed to be enhanced by 40% (when Φ = 0.21 vol% and AR = 0.0635) and 8% (with AR = 0.127 and Φ = 0.51 vol%), respectively.

On heating the same cavity engaged in the work of Ali et al. on the top, Ali et al. [102] experimented thermo-convection in a cylinder (having AR of 0.0635 and 0.127) saturated with DW-based Al_2O_3 (0.21 – 0.75 vol%) NF. They demonstrated the attenuation of heat transfer of NF in the enclosure, which was related to AR and Φ in relation to DW.

Putra et al. examined the thermo-convection in a horizontal cylinder (with AR of 0.5 – 1.5) containing DW-based Al_2O_3 and CuO (Φ = 1 – 4 vol%) NF. The result showed that heat transfer was detracted for the NF samples. The attenuation observed was found to depend on AR, Φ, nanoparticle density. Mahrood et al. [46] engaged carboxymethyl cellulose-based Al_2O_3 and TiO_2 NF in a cylinder (having AR = 0.5 – 1.5) to study the convective heat transfer behaviour. They reported the highest heat transfer for Φ = 0.1 vol% (TiO_2 NF) and 0.2 vol% (Al_2O_3 NF), with TiO_2 NF appearing to be a better thermal fluid. By increasing AR, heat transfer was found to be enhanced for both types of NF.

A combination of two active techniques (θ and AR) for the improvement of heat transfer of NF in cavities was also examined. To study the impact of heat fluxes (500 – 1500 W/m^2), AR (0.5 – 1.5), and θ (30° – 90°) on the thermo-convection performance in a cylindrical cavity heated below, Moradi et al. [103] engaged DIW-based Al_2O_3 and TiO_2(Φ = 0.1 – 1.5 vol%) NF. An attenuation of the heat transfer for TiO_2/DIW NF was observed whereas heat transfer was augmented for Al_2O_3/DIW NF. Maximum heat transfer improvement was attained when Φ = 0.2 vol%, AR = 1, and θ = 30°.

4.4. Convection in other cavities

Most of the experimental studies on the thermo-convection transport of NF were performed with square, cylindrical, and rectangular geometries and only a couple of studies with other geometries can be found in the literature. The significance of two empirical models and an experiment-based model on the *Nu* and *h* ratio of SiO_2/water (0.5 – 2.0 vol%) NF in a triangular cavity was studied by Mahian et al. . They showed that *Nu* deteriorated as Φ increased, which was independent of *Ra*. At any *Ra*, *h* of NF was observed to be higher than water. Also, the highest heat transfer for the NF occurred at Φ = 0.5 vol%. Moreover, the authors stressed the use of measured thermophysical properties in thermo-convection studies against those of empirical models. Umar et al. performed experiments on the thermo-convection of water-based ZrO_2 NF in triangular and rectangular sub-channels and reported augmentation of HTC of 5 – 10 % for Φ = 0.05 vol% in comparison to water.

Cadena-de la Peña et al. [101] experimented the thermo-convection of MO-based AIN and TiO_2 (0.01 – 0.50 wt%) NF contained in a vertical annular cylinder. The result revealed that for both NF, *Nu* was enhanced when Φ = 0.10 wt% and it deteriorated at higher Φ. The h_{av} and Nu_{av} of TiO_2/MO NF were noticed to be higher than those of OA treated AIN/MO NF and AIN/MO NF. Both h_{av} and Nu_{av} were found to augment with an increase in *Ra* and a reduction in AR. The highest enhancement of h_{av} and Nu_{av} for TiO_2/MO NF was noticed with Φ = 0.10 vol%, while that of AIN/MO NF occurred at Φ = 0.10 vol%, all at AR = 3.98.

The applicability of hemispherical enclosures for the management of convective heat transfer in electronic assembly and device was investigated by Haddad et al. [108]. Haddad et al. [108] experimented the impact of θ (0° – 180°) and Φ(0.01 – 0.1 vol.%) on the thermo-convection thermal transport performance of water-based ZnO NF filled into a hemispherical-shaped enclosure (with AR = 1.79) containing a cube-shaped object. The hemispherical dome was heated while the base was thermally insulated, and the object mounted inside the cavity was maintained at a cold temperature. They showed that the *Nu* was slightly augmented as Φ increased. It was also observed that as θ increased no noticeable enhancement on *Nu* was found. Figure 4 provides the heat transfer enhancements of different NF in diverse cavities using different parameters.

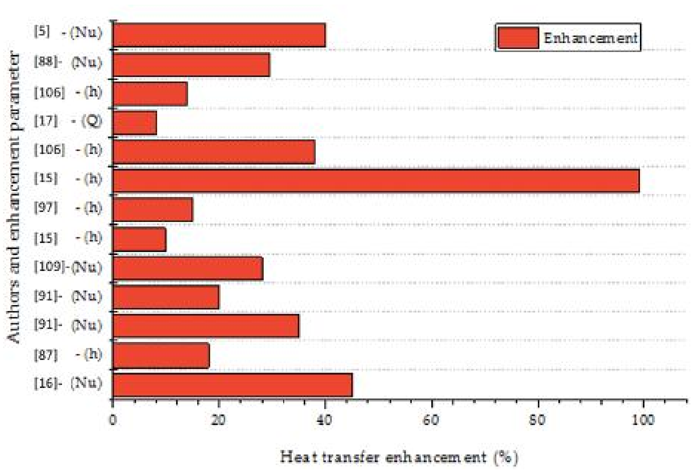

Figure 4 Heat transfer enhancement of different NF in diverse cavities.

Subject to the afore-discussed studies, three characteristics of heat transfer have been reported in the open literature for thermo-convection of NF in cavities; deterioration and augmentation of heat transfer with volume/mass concentration, and the occurrence of optimum heat transfer at certain concentration NP (after which a decline was noticed). Nevertheless, no specific mechanisms behind such results were identified and discussed except that reported by Rao and Srivastava .

5. Conclusions

In the context of this study, the following conclusions and remarks are herein highlighted:

The diversity in the preparation of NF in terms of the base fluid type, the size and type of NP, and agitation time and method can seriously affect the stability, thermal properties and convective heat transfer of NF in cavities. There is outright non-uniformity in the manner NF preparation was reported in the literature and hence, such cannot be reproduced. Detailed and reproducible procedure for the preparation of NF is highly recommended in future studies. To reproduce NF, the sonication time, frequency, and amplitude, stirring duration and weight fraction of surfactant (if used) are to be provided. Measurement of stability is suggested to be conducted before, during and after the thermo-convective experiment.

Literature results showed three different characteristics of natural thermo-convection of NF: deterioration of heat transfer, especially for Φ > 0.1 vol%, (in most cases) and the occurrence of optimum heat transfer at certain Φ value after which a decline was noticed. The sensitivity of convective heat transfer of NF in various cavity geometries to viscosity and other variables such as natural convection of base fluid, poor stability, high Φ values, AR values of AR (in some cases), increase in θ, and orientation magnetic field has been attributed to the deterioration reported outside the slip mechanisms, Brownian motion, thermophoresis, etc. However, there is a clear scarcity in identifying the underlying mechanisms behind such results. On the other hand, each NF may enhance heat transfer in an exact volume fraction for an exact case (like natural convection) depending on the stability, base fluid, thermal condition, cavity geometry, etc. Therefore, the experimental results of a few volume fractions cannot conclude in general that an NF is good or bad, and more investigations are needed to conclude about an NF heat transfer capability in a known cavity geometry.

It is again suggested that the thermophysical properties used for data reduction should be experimentally determinedfor the NF being studied and not from empirical or theoretical or empirical correlation. It is observed that for the same type of NF, the NP size, preparation, and stability are different, which may cause a change in the thermophysicalproperties and subsequently affect the thermo-convection performance. Future studies are to focus on the effects of other NP (apart from Al_2O_3 and MWCNT), hybrid nanofluids, porous media, bio (green)-nanoparticles as well as θ, magnetic and electric fields intensity and orientation, AR, micro-organisms, and base fluids (ionic, green and others) on the thermo-convective heat transfer performance in various cavity geometries. A combination of some of these enhancement techniques (passive and active) on the convective heat transfer in cavities would herald a new dawn in this field of study, particularly for thermal management and conversion systems.

Furthermore, it was noticed that the intrusive nature of temperature measurement via thermocouples mounted in the cavity can affect the convective flow and thermal transport and must be investigated further. Finally, depending on the cavity geometry and thermal condition imposed, the deployment of AR, θ, Φ, porous media, and magnetic field have been experimented to yield augmentation or attenuation of heat transfer. The use of baffle and diverse types, partition and other CNT enhancing techniques is missing in the public domain in relation to this study.

From the state of the art of nanofluids, there is a clear need for more systematic research on the thermal convection of NF under various conditions and cavities for their applications in thermal management and energy conversion systems.

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