

CHAPTER 2

LITERATURE REVIEW

The present chapter consists of the literature review on preparation, characterization, thermophysical properties of hybrid nanofluids also the application of hybrid nanofluids in the miniature heat exchanger (i.e., mini/microchannel heat sink). The literature review is divided into three sections. The first section contains the preparation and characterization of the mixture as well as composite hybrid nanofluids. In the second part, thermophysical properties such as thermal conductivity, viscosity, density and specific heat are discussed. Experimental and numerical studies on hydrothermal characteristics of mini/microchannel using hybrid nanofluids are discussed in the third part.

2.1 Preparation and characterization of hybrid nanofluids

The preparation method is a crucial step in getting a homogeneous and stable suspension for hybrid nanofluids. One-step and two-step methods have been used for the preparation of hybrid nanofluids. In the one-step method, synthesis and dispersion of different types of nanoparticles in the base fluid are done simultaneously. In this method, agglomeration of nanoparticles is minimized by avoiding drying processes, storing processes, transporting and distribution of nanoparticles and, therefore, also improving the stability of hybrid nanofluids. The two-step method involves the preparation of different nanoparticles followed by dispersion in the base fluid. Nanoparticles are synthesized first in powder form by different physical or chemical methods and then suspended in the base fluid with the help of magnetic force agitation ultrasonic agitation, homogenizing and ball milling. Many studies are available for a

one-step and two-step method to synthesize hybrid nanofluids (Gupta et al., 2018). Various review literature are available on the preparation on hybrid nanofluid depending on different base fluids (Sarkar et al., 2015, Azwadi et al., 2016, Sidik et al., 2016, Sundar et al., 2017, Babu et al., 2017, Kumar and Arasu, 2018, Sajid and Ali, 2018, and Huminic and Huminic, 2018). Table 2.1 represents the preparation of different hybrid nanofluids available in the literature.

Table 2.1 Summary on the preparation of different hybrid nanofluids

Materials	Particle Size	Base fluids	Surfactant	Method, process type	Reference
Ag/Al ₂ O ₃	Ag: 27 nm Al ₂ O ₃ : 89 nm	Water	No	Two-step method	Han and Rhi (2011)
Silver/silica	Ag (spherical)- 5.5±0.4nm	Transformer oil	No	One-step method, chemical	Botha et al. (2011)
Al ₂ O ₃ /Cu	average grain size- 17 nm	DI Water	SLS	Two-step method, chemical	Suresh et al. (2012)
Ag/MWCNT	Ag particle size-10 nm	Water	No	Two-step method, chemical	Chen et al. (2012)
Ag/HEG, CNT/HEG, CuO/HEG	Ag particle size-10 nm CuO crystalline size~8.5 nm	Water, EG	No	Two-step method, chemical	Baby and Ramaprabhu (2011), Baby and Ramprabhu (2011a), Aravind and Ramaprabhu (2012, 2013)
Ag/(MWNT-HEG)	<10nm	EG	No	Two-step method, chemical	Baby and Ramprabhu (2013)
Ag/MWCNT	-	Water	No	One-step method	Munkhbayar et al. (2013)

Silica/ MWCNT	MWCNT dia<10 nm and length- 10 μ m, Silica-10 nm	Water	No	Two-step method, chemical	Baghbanz adeh et al. (2012, 2014)
Al ₂ O ₃ /TiO ₂	75 nm	Lubricating oil	Silane coupling agent (KH- 560)	Two-step method, chemical	Luo et al. (2014)
Mn _{0.5} Zn _{0.5} Fe ₂ O ₄	5.957 \pm 0.05 nm	Hydrocarbon oil	Oleic acid	Two-step method, chemical	Parekh (2014)
SiO ₂ -coated graphene	40 nm	Water	-	Two-step method, chemical	Li et al. (2014)
Silver/TiO ₂	TiO ₂ =15 nm, 300 nm Ag= 100- 120 nm	Water	No	Two-step method, mechanical	Batmunkh et al. (2014)
ND/Ni	ND=4-5 nm	Water	No	Two-step method, chemical	Sundar et al. (2014b)
NiFe ₂ O ₄	8.5 nm	DI water	Tetra methyl ammonium hydroxide	Two-step method, chemical	Karimi et al. (2015)
Cu/Al layered double hydroxide (LDH)	-	Water	No	One-step method, chemical	Chakraborty et al. (2015)
ZnO/TiO ₂		EG		Two-step method, chemical	Toghraie et al. (2016)
ND/Fe ₃ O ₄	-	Water/EG	No	Two-step method, chemical	Sundar et al. (2016a)
MWCNTs/ SiO ₂	MWCNT (OD: 5- 15nm ID: 3-5nm Length: 50 μ m), SiO ₂ :20-30 nm	Engine oil (SAE40)	No	Two-step method, chemical	Afrand et al. (2016)
Ti ₃ SiC ₂ MAXene	-	PG	No	Two-step method, chemical	Mahesh et al. (2016)

Platinum/GNP	-	Water	No	Two-step method, chemical	Yarmand et al. (2016b)
Al ₂ O ₃ /CuO	CuO: 14 nm, Al ₂ O ₃ : 20 nm	Water+EG	No	Two-step method, chemical	Kannaiyan et al. (2017)
Fe ₃ O ₄ /Graphene	Fe ₃ O ₄ : 5 nm	Water	No	One-step method, Chemical	Askari et al. (2017)
TiO ₂ /MWCNTs	TiO ₂ : 10-25 nm, MWCNT: 20-30 nm	Water+EG	CTAB	Two-step method, chemical	Akhgar and Toghraie (2018)
CNT/SiO ₂	SiO ₂ : 7 nm, CNT: 6-10 nm	DI water	No	Two-step method, chemical	Dalkılıç et al. (2018)
TiO ₂ /SiO ₂	TiO ₂ : 50 nm, SiO ₂ : 22nm	Water+EG	No	Two-step method, chemical	Hamid et al. (2018)
Al ₂ O ₃ /TiO ₂	Size < 40 nm	DI water	No	Two-step method, chemical	Maddah et al. (2018)
f-MWCNT/Fe ₂ O ₃	-	DI water	SDBS	Two-step method, chemical	Balaga et al. (2019)
TiO ₂ /Ag	Size: 10-100 nm	water	SDBS and SBS	Two-step method, chemical	Valan et al. (2019)
Ag/GnP	Ag: 40-50 nm, GnP: 2-20 nm width	PG+water	No	Two-step method, chemical	Vallejo et al. (2019)
γ -Al ₂ O ₃ /MWCNT	γ -Al ₂ O ₃ : 20-30 nm, MWCNT: 10-30 μ m length, OD: 10-20 nm	Water	SDS	Two-step method, chemical	Giwa et al., (2020)
TiO ₂ /MWCNTs	TiO ₂ : 20-30 nm, MWCNT: OD: 10-60 nm	EG-water	No	Two-step method, chemical	Moradi et al. (2020)

In the literature preparation of oxide and metal nanoparticles suspended hybrid nanofluid are available in abundance. **Bhosale and Borse (2013)** prepared the Al_2O_3 -CuO water-based hybrid nanofluid by mixing 2.5 mg of CuO and 2.5 mg of Al_2O_3 each in 2 liters of distilled water. Later on, the concentration was varied to 0.25%, 0.5% and 1.0% by volume. **Toghraie et al. (2016)** prepared ZnO-TiO₂/EG hybrid nanofluid by dispersing an equal volume of ZnO and titanium dioxide (TiO₂) nanoparticles in a specified amount of pure EG as a base fluid. The suspensions with volume fraction ranging from 0.0 % to 3.5 % were stirred for 2.5 h followed by ultrasonication (6-7 h) at a frequency of 24 kHz. It was found that the prepared nanofluids were stable and there was no sedimentation for a long time. **Paul et al. (2011)** synthesized Al-Zn nanoparticles by mechanical mixing. Aluminium (95%) and zinc (5%) were mixed in powder form by mechanical alloying using a high energy planetary ball mill at room temperature. They prepared the hybrid nanofluids by two-step process by adding Al-Zn nanoparticles in ethylene glycol (base fluid) and subjecting the suspension for ultrasonication followed by magnetic stirring. **Suresh et al. (2011)** prepared hybrid alumina-copper powder using a thermo-chemical method involving the following phases: spray-drying, precursor powder oxidation, reduction of hydrogen and homogenization. They prepared hybrid nanofluid with different particle volume concentrations (0.1%, 0.33%, 0.75%, 1.0% and 2.0%). **Nine et al. (2013)** reported a cost-effective and highly productive synthesis method of nanoparticles of cuprous oxide (Cu₂O) and copper / cuprous oxide (Cu / Cu₂O) with an average size of less than 30 nm. The wet ball milling process was used to synthesize Cu/ Cu₂O -water hybrid nanofluid. The process of synthesizing Cu to Cu₂O involves oxidizing Cu into Cu₂O, forming Cu₂O layer on Cu particles and breaking Cu₂O layer into a smaller (around 20 μm) particle. **Madhesh et al. (2014)** and **Madhesh and Kalaiselvam (2015)** synthesized Cu-TiO₂ hybrid

nanofluid through uniform dispersion of an aqueous solution of titania (5 gm) with copper acetate (0.5 gm), using ascorbic acid and sodium borohydride as a reducing agent, in ultrasonic vibrator for 2 h at 45°C and ambient pressure. Very few studies are available on phase change material (PCM) suspended hybrid nanofluid. **Ho et al. (2011)** used interfacial polycondensation and emulsion technique in the preparation of PCM suspension. The Al₂O₃-water nanofluid was prepared using a magnetic stirrer to disperse Al₂O₃ nanoparticles of different mass fractions in water. The hybrid water-based suspensions were then developed by combining the nanofluid in an ultrasonic bath with the PCM suspension for at least two hours. **Luo et al. (2014) and Maddah et al. (2018)** synthesized Al₂O₃-TiO₂ mixture suspended hybrid nanofluid with lubricating oil and water as a base fluid, respectively. Other similar studies on the preparation of hybrid nanofluids are existing in the open literature, eg. **Han and Rhi (2011), Suresh et al. (2011), Balla et al. (2013), Batmunkh et al. (2014), Vallan et al. (2016) and Kannaiyan et al. (2017)**. NiFe₂O₄ nanoparticles were suspended into the base fluid (water) to synthesize hybrid nanofluid using tetramethyl ammonium hydroxide surfactant to prevent aggregation of magnetite nanoparticles (**Karimi et al., 2015**).

In this part, we focused on the allotropes of carbon suspended hybrid nanofluids. **Baby and Ramaprabhu (2011a)** synthesized CuO decorated graphene (CuO/HEG) by hydrogen-induced exfoliation of graphite oxide (GO) followed by chemical reduction. The synthesized HEG was functionalized with an acid treatment and then used for coating CuO nanoparticles. CuO/HEG was dispersed in the base fluid (Water-EG) by ultrasonication for a duration from 45 min to 1 h. **Baby and Ramaprabhu (2013)** also synthesized ethylene glycol-based hybrid nanofluid with the suspension of Ag/(MWNT-HEG) nanoparticles. **Chen et al. (2012)** prepared Ag/MWCNT nanocomposites using a silver mirror reaction. Functionalized MWCNTs were used to

prepare Ag/MWCNT nanocomposites using the aqueous solution of sodium dodecyl sulfate (SDS) as a surfactant and formaldehyde as a reduction agent. **Balaga et al. (2019) and Giwa et al. (2020)** worked on MWCNT-oxide hybrid nanofluid with a surfactant to increase stability. Other similar studies on CNT with oxides and metals suspended hybrid nanofluids are available, eg. **Abassi et al. (2013), Baghbanzadeh et al. (2012 and 2014), Afrand et al. (2016), Akhgar and Toghraie (2018), Moradi et al. (2020)**. The other studies related to graphene suspended hybrid nanofluid are also existing in literature, eg. **Baby and Ramaprabhu, (2011), Yarmand et al., (2016), Vallejo et al., (2019)**. The study was performed by **Aravind and Ramaprabhu (2012 and 2013)** on CNT-HEG hybrid nanocomposite suspended nanofluids. First, they synthesized graphene oxide by the Hummers method and then the chemical vapor deposition technique was used to synthesize graphene wrapped CNT. **Baby and Ramaprabhu (2013)** further synthesized composite nanoparticles of metal, CNT and graphene. The acid-treated MWNT-HEG composite and this composite were decorated by silver nanoparticles by chemical reduction technique. Then these composite nanoparticles were suspended in EG with the help of ultrasonicator to prepare hybrid nanofluid without surfactant. **Sundar et al. (2014b) and Sundar et al. (2016)** prepared nanodiamond (ND) suspended hybrid nanofluids.

Parekh et al. (2014) and Mahesh et al. (2016) synthesized ternary system nanoparticles suspended hybrid nanofluids. $Mn_{0.5}Zn_{0.5}Fe_2O_4$ ternary compound was first synthesized by thermal decomposition technique and then suspended in hydrocarbon oil (**Parekh et al., 2014**). Ti_3SiC_2 MAXene nanoparticles were dispersed in propylene glycol to prepare hybrid nanofluid via ultrasonication (**Mahesh et al., 2016**).

Very few literature are available for a one-step method to synthesize composite based nanofluids. Some of them are discussed here. **Botha et al. (2011)** used a typical

one-step method to synthesis hybrid nanofluid containing composite made of silver + silica. A fixed quantity of Precursors as AgNO_3 (1.29 mmol) and 0.0294 g SiO_2 (0.49 mmol) was added to the oil and stirred for 30 minutes to synthesise composite based nanofluids containing 0.3 wt % silver + 0.07 wt % silica. After that, the temperature was increased up to 130 °C and the continuous stirring for 2 hours was done. The TEM images at the initial stage and after 4 months confirmed that silver nanoparticles were dispersed on the support and all the silver nanoparticles remained attached to the silica surface. **Munkhbayar et al. (2013)** synthesized Ag/MWCNT composite nanofluid using the following process. A 500 ml exploding bottle contained previously prepared 0.05 wt% MWCNTs nanofluids was installed in the main part of the PWE instrument. PWE method used to synthesis Silver nanoparticles and these nanoparticles made direct interaction with the base fluid inside the chamber wall. Ag-MWCNT/DI-water nanofluid was finally obtained without contamination problems. **Chakraborty et al. (2015)** prepared Cu-Al LDH nanofluid. Two solutions were first prepared, Solution 1 contained an aqueous solution of three nitrate precursors $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and NaNO_3 in the molar ratio of 2:1:2, respectively. To reached pH level up to 10.7, 2 M NaOH solution (Solution 2) as the precipitate agent was supplied as dropwise in solution 1. The present solution was continuously stirred for 16 hours at ambient conditions. The precipitate was collected after filtration. Excess NaOH from precipitate was removed after washing with water several times to reach pH level of precipitate 7. Cu-Al LDH based solution was prepared by dispersing precipitate into the water and stirring the mixture for 12 hours and consecutive sonicated (40 kHz ultrasonic bath) for ½ hours. Different concentration based nanofluids were prepared by adding and mixing various quantities of the solution to DI water. **Askari et al. (2017)** also synthesized water-based Fe_2O_3 /graphene hybrid nanofluid by a single-step method.

There are many factors such as stability, particle shape and size, homogeneity and thermophysical properties (thermal conductivity, density, specific heat and density) affecting the performance of hybrid nanofluids in the heat transfer system (**Hamzah et al., 2017**). The characterization of nanofluid consists mainly (i) measure the shape and size of suspended nanoparticles and agglomeration size (ii) Homogeneity and stability of synthesized hybrid nanofluids. The stability of the synthesized hybrid nanofluids is one of the prominent issues. Stable hybrid nanofluid preparation is essential to avoid clogging, agglomeration, and sedimentation, which causes the suspension characteristics to decline (**Xian et al., 2020**). UV-Vis spectrophotometer, zeta potential, sediment photography method, TEM (Transmission Electron Microscopy) and SEM (Scanning Electron Microscopy), light scattering, three omega and sedimentation balance system (**Ghadimi et al., 2011, Yarmand et al., 2016**) are used to inspect the stability of hybrid nanofluids. Methods for preparing stable nanofluids include adding a surfactant, surface modification of the suspended particles or applying forces on the clustered nanoparticles. **Baby and Sundara (2011b)** employed a cost-effective synthesis method for silver decorated functionalized hydrogen-induced exfoliated graphene (Ag/HEG) and prepared nanofluids by dispersing the material. Ag/HEG dispersed in DI water/EG mixture using ultrasonic agitation without any surfactant. The stability of the hybrid nanofluid was observed for more than three months. **Aravind and Ramaprabhu (2012)** prepared graphene wrapped MWCNT nanocomposite and synthesized by a chemical vapor deposition technique. The prepared hybrid nanofluids are stable for more than 6 months. **Megatif et al. (2015)** prepared CNT- TiO₂ hybrid nanocomposite and dispersed them in the water for producing hybrid nanofluids. For proper dispersion, they added SDBS surfactant in the suspension. They sonicated the

solution for 15 minutes and checked the stability. The solution was found stable for 2 days.

2.2 Thermo-physical properties of hybrid nanofluids

While studying the hydrothermal behavior of nanofluid/hybrid nanofluids, thermophysical properties (especially thermal conductivity, viscosity, specific heat and density) play a significant role. In literature, empirical relations and experimental measurements for these thermophysical properties of nanofluid/hybrid nanofluids are available (**Chamka et al., 2017 and 2019, Mehryan et al., 2019, Ghalambaz et al., 2019**). In this section, the effect of nanoparticles addition in different base fluids on effective thermal conductivity, dynamic viscosity, density and specific heat is presented (**Sarkar et al., 2015, Askari et al., 2016, Sidik et al., 2016, Nabil et al., 2017, Sundar et al., 2017 and Babu et al., 2017, Babar and Ali, 2019, Salman et al., 2020**); Some of the authors correlated the experimental data and presented the empirical correlations for different properties.

2.2.1 Thermal conductivity of the hybrid nanofluids

Thermal conductivity is one of the important properties of fluid for improving the heat transfer performance of working fluid because of the heat transfer rate and heat transfer coefficient increases with thermal conductivity. Transient hot wire method, transient plane source technique, 3ω technique, thermal constants analyzer and steady-state parallel plate are the different techniques used for the thermal conductivity measurement of hybrid nanofluids.

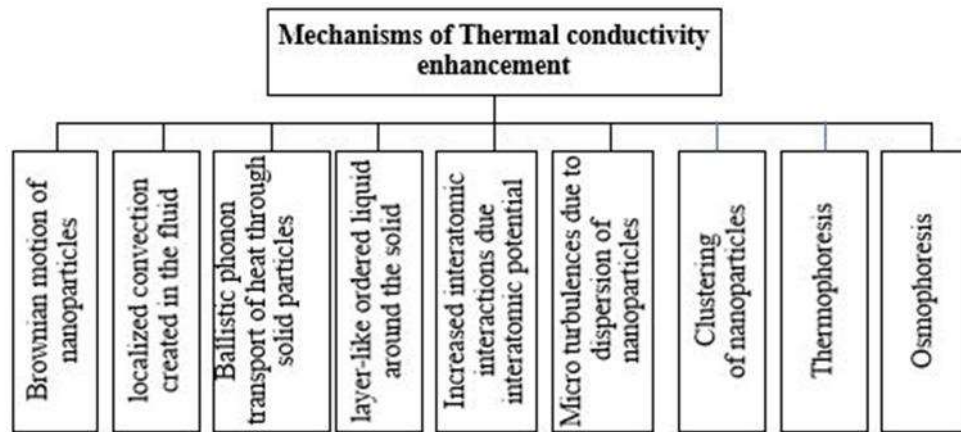


Fig. 2.1 Different mechanism responsible for enhancement in thermal conductivity

Various researchers proposed many possible mechanisms to explain the reasons for the peculiar increase in the thermal conductivity of hybrid nanofluids. However, precise mechanisms are not available to describe enhancement in thermal conductivity yet. Possible mechanisms available in the literature are Brownian motion and micro-convection of nanoparticles (Madhesh et al., 2014; Sundar et al., 2014; Botha et al., 2011; Sundar et al., 2018), clustering of nanoparticles and liquid layer around the solid surface, increased kinetic energy due to higher rate of collision between molecules at elevated temperature, increase surface area (Trinh et al., 2017), the presence of nanoparticles in various regions of suspension and contact between different layers of fluid (Madhesh et al., 2014; Hussein, 2017), chain formation of nanoparticles at high concentrations, presence of hybrid nanoparticles causing increased diffusive heat conduction, increased electrostatic repulsive force (Farbod and Ahangarpour, 2016), the percolation effect due to high concentration further reducing the distance between particles and increasing lattice vibrational frequency (Trinh et al., 2018; Yarmand et al., 2015), etc. Different Possible mechanisms for thermal conductivity enhancement are presented in Fig. 2.1.

Literature available on thermal conductivity of oxide and metal suspended hybrid nanofluids are deliberated here. **Batmunkh et al. (2014)** exhibited an increase in thermal conductivity for silver-titania hybrid nanofluids of 0.8%. **Esfe et al. (2015a)** considered silver-magnesia hybrid nanofluids and observed that the thermal conductivity increases by 8.6% at a concentration of 0.02 vol%. **Charab et al. (2017)** established a model for the thermal conductivity of Al₂O₃- TiO₂ hybrid nanofluids. They found non-linear behavior between particle volume concentration and thermal conductivity due to nanofluid's stability problem. **Botha et al. (2011)** investigated the oil-based silver-silica hybrid nanofluids (nano lubricant). They observed that thermal conductivity increases by 15% for 0.6 wt.% Ag and 0.07 wt.% silica combination. Although this enhancement was very less when using only silica nanofluids. **Suresh et al. (2011)** observed that Al₂O₃-Cu hybrid nanofluids give a better result than alumina nanofluids. The hybrid combination shows the maximum enhancement of 12.11% in thermal conductivity. **Okonkwo et al. (2019)** found that the mean increase in thermal conductivity of Al₂O₃-Fe hybrid nanofluids was observed at 0.2 vol% as compared to water. **Nagarajan et al. (2020)** found the thermal conductivity of Al₂O₃/SiO₂ in water/EG solution and showed the enhancement of 78.32% for 0.2 vol% at 60°C. Similar types of studies are available for thermal conductivity of hybrid nanofluids at different temperature and volume fraction (**Esfe et al., 2015a and 2016c, Toghraie et al., 2016, etc.**).

Studies available on the allotropes of carbon suspended hybrid nanofluids are discussed here. **Baghbanzadeh et al. (2012)** observed the maximum (23.3%) and minimum (8.8%) enhancement in the thermal conductivity for MWCNT nanofluids and silica nanofluids, respectively. The performance of hybrid nanofluids was in between them. **Nine et al. (2012)** reported the effect of the nanoparticle shape on the thermal

conductivity of the fluid using alumina-MWCNT hybrid nanofluids. They observed an enhancement in the thermal conductivity using hybrid nanofluids. However, spherically shaped particles showed a better result than the cylindrical particles. **Sundar et al. (2014) and Shahsavar et al. (2015)** found an enhancement in the thermal conductivity using CNT- Fe_3O_4 hybrid nanofluids. **Farbod and Ahangarpour (2016) and Munkhbayar et al. (2013)** studied the thermal characteristics of Ag-MWCNT water-based hybrid nanofluids. They observed that the thermal conductivity obtained was higher than the base fluid by 20% and 14.5%, respectively. **Soltani and Akbari (2016)** analyzed the ethylene glycol-based hybrid nanofluid containing MgO and MWCNT nanoparticles. Thermal conductivity was increased by 14.5% at 40°C for 0.05 wt% MWCNT and 3wt% Ag combination. **Harandi et al. (2016)** studied experimentally the thermal conductivity of EG based hybrid nanofluids comprising functionalized MWCNT and Fe_3O_4 nanoparticles. They found a maximum boost of 30% in thermal conductivity for 50°C temperature and 2.3% volume concentration. **Sundar et al. (2016)** observed that the thermal conductivity of water increases by 17.8% by adding 0.2 vol% of ND- Fe_3O_4 nanoparticles. **Yarmand et al. (2016a)** studied the thermal conductivity of the suspension containing activated carbon graphene (0.06 wt.%) in ethylene glycol. An enhancement of 4.17% and 6.47% at 20°C and 40°C, respectively, found for the same concentration. Similar types of investigation on CNT were carried out by many authors (**Ese et al., 2015b and 2015d; Afrand, 2017; Vafaei et al., 2017; Akhgar and Toghraie, 2018; Taherialekouhi et al., 2019; Moradi et al., 2020**).

Different authors proposed many correlations for hybrid nanofluids with various base fluids (DI water, Engine oil, vegetable oil, glycols, the mixture of glycol and water). The correlations for water-based hybrid nanofluids were developed by many authors for different temperature range and solid concentration (e.g., **Takabi and**

Salehi, 2014; Zadkhast et al., 2017; Esfahani et al., 2018; Taherialekouhi et al., 2019). Effect of temperature range and different volume concentration on ethylene glycol (EG) based hybrid nanofluid is presented in the literature (Akilu et al., 2017; Esfe et al., 2017b-f). Some authors developed the correlation for water+EG based hybrid nanofluids (e.g., Nabil et al., 2017; Rostamian et al., 2017; Kakavandi and Akbari, 2018). Table A1 (shown in Appendix A) shows the summary of the correlations proposed by different authors for the thermal conductivity of hybrid nanofluids. Elias et al. (2014) proposed a correlation for the thermal conductivity of the hybrid nanofluids based on the shape function. They considered different shapes like a cylinder, blade, brick and platelets. They observed that cylindrical-shaped particles give better performance in comparison to other shapes.

$$\frac{k_{nf}}{k_{bf}} = \left(\frac{k_{p1} + (n_1 - 1)k_{bf} - (n_1 - 1)(k_{bf} - k_{p1})\phi_{p1}}{k_{p1} + (n_1 - 1)k_{bf} + (k_{bf} - k_{p1})\phi_{p1}} \right) \left(\frac{k_{p2} + (n_2 - 1)k_{nf} - (n_2 - 1)(k_{nf} - k_{p2})\phi_{p2}}{k_{p2} + (n_2 - 1)k_{nf} + (k_{nf} - k_{p2})\phi_{p2}} \right) \quad (2.1)$$

Where, n_1 and n_2 are shape functions whose values are different for different shapes.

k_{nf} and k_{bf} are thermal conductivities of hybrid nanofluids and base fluid, respectively.

k_{p1} and k_{p2} are thermal conductivities of particles 1 and 2, respectively.

ϕ_{p1} and ϕ_{p2} are volume fractions of particles 1 and 2, respectively.

2.2.2 Viscosity of hybrid nanofluids

Viscosity is one of the main thermo-physical properties while studying the behavior of hybrid nanofluid because the pressure drop and pumping work required depends on it. In general, nanofluid rheological behavior and viscosity depend on concentration, temperature, particle size, and shape of the particles. Brookfield cone and plate viscometer (LV DV-I PRIME C/P), Rotational viscometer (Brookfield DV-II + Pro), ETC Bohlin, Rheometer (Physica, MCR, Anton Paar), CAP 2000 are the instruments used to measure the viscosity of hybrid nanofluids. The viscosity of hybrid

nanofluids found to increase with solid fraction and decrease with the increase of temperature because of the weakening of inter-particle and inter-molecular adhesion forces. The specific surface area is an important factor for viscosity. The dispersed nanoparticles having a larger specific surface area receive more friction, which leads to higher viscosity (**Yarmand et al., 2016**). Particles larger in size have comparatively more viscosity than particles small in size (**Nguyen et al., 2008**). The authors further analyzed the effect of shear rate on nanofluid viscosity. Newtonian behavior is shown by nanofluid with low volumetric concentrations (**Yu et al., 2009**).

Ho et al. (2010) observed three times enhancement in the viscosity for 10 wt.% hybrid suspension, when compared to water. The rheological properties of water-based hybrid nanofluids composed of silica and MWCNT were analyzed by **Baghbanzadeh et al. (2012)** at different weight ratios of 80:20 and 50:50. They found an increase in the nanofluid viscosity with a rise in concentration and a decrease in temperature. The 50:50 weight ratio shows the least enhancement in viscosity. The viscosity of the MWCNT-TiO₂-water suspension was measured by **Abbasi et al. (2013)**. They found an enhancement in the fluid viscosity, and the enhancement was high, with an increase in MWCNT nanoparticle fraction in the hybrid nanofluid. **Sundar et al. (2014)** experimentally measured the viscosity of MWCNT-Fe₃O₄ nanocomposite hybrid nanofluids and found an improvement in viscosity up to 1.5 times at a concentration of 0.3 vol% at a temperature of 60 °C compared to water. **Esfe et al. (2016) and Dardan et al. (2016)** conducted investigations into MWCNT nanoparticles containing oil-based hybrid nanofluids. They noticed a major enhancement in viscosity. **Soltani and Akbari (2016)** performed an investigation on the ethylene glycol-based hybrid nanofluid containing MgO and MWCNT nanoparticles. They have found a maximum enhancement of 168% in viscosity when the volume fraction of particle increases from

0% to 1.0%. **Asadi and Asadi (2016)** proposed a viscosity correlation for an engine oil-based hybrid nanofluid consisting of nanoparticles MWCNT and ZnO (15:85). The concentration of nanoparticles ranges from 0.125% to 1.0% and temperature ranges from 5°C-55°C. The maximum enhancement in viscosity was around 45% for 55°C and 1.0% concentration. **Suresh et al. (2011)** experimented with the alumina-copper hybrid nanofluid, showing that viscosity increases by 115% at 2.0 vol% concentration. However, the effect was negligible at lower concentrations. The study on silver hybrid nanofluids was conducted by **Botha et al. (2011) and Esfe et al. (2015a)**. **Botha et al. (2011)** found that suspension having both silica and silver particles shows less viscosity in comparison to the suspension with only silica particles. While, **Esfe et al. (2015a)** observed 24% enhancement in viscosity at 0.02 vol% concentration. **Yarmand et al. (2015)** found an increase of 30.0% and 0.09% in the viscosity and density, respectively, for GNP-silver nanocomposite hybrid nanofluid at 40°C. **Sundar et al. (2016)** prepared and measured the thermal conductivity and viscosity of the nanodiamond-Fe₃O₄ nanofluid in the temperature range of 20-60°C and up to 0.2 vol% particle concentration.

Sundar et al. (2016) proposed the correlation at different temperatures for the viscosity ratio, which was exponential in nature and depends only on the concentration of the volume. The correlations for the viscosity ratio for water-based hybrid nanofluids were presented by many authors, eg. **Esfe et al., 2015 and Giwa et al., 2020**. Viscosity correlation for ethylene glycol-based hybrid nanofluids was developed by **Soltani and Akbari, 2016; Akilu et al., 2017; Hamid et al., 2018** for a wide range of temperature. Some authors suggested correlations for the viscosity of oil-based hybrid nanofluids with different temperature range (**Asadi and Asadi, 2016, Afrand et al., 2016, Asadi et al., 2016, Dardan et al., 2016, Esfe et al., 2016, and Esfe et al., 2017a**).

Correlations for the viscosity and viscosity ratio for different hybrid nanofluids are summarized in **Table A2 (shown in Appendix A)**. Most of the proposed correlations are nanofluid-specific. Some authors (like **Sheikholeslami and Shamlooei, 2017**) proposed a correlation for the viscosity of the hybrid nanofluids based on the shape function.

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + \Psi_1\phi + \Psi_2\phi^2 \quad (2.2)$$

Where, ϕ is total volume fraction of particles.

μ_{nf} and μ_{bf} are viscosities of the hybrid nanofluids and base fluid, respectively.

Ψ_1 and Ψ_2 are coefficients whose values are given by (**Sheikholeslami and Shamlooei, 2017**).

2.2.3 Density and specific heat of hybrid nanofluids

Density and specific heat are essential thermo-physical properties of hybrid nanofluid while studying the heat transfer performance. **Ho et al. (2010)** performed an investigation on the water-based hybrid nanofluids of Al_2O_3 nanoparticles and microencapsulated phase change material particles. They measured different thermo-physical properties of the hybrid nanofluid. At $30^\circ C$, they observed a decreasing trend in the specific heat with the volume fraction of the particles. **Baghbanzadeh et al. (2012)** studied the thermo-physical properties of water-based hybrid nanofluids containing silica and MWCNT in different weight ratios. They observed that the density and viscosity of the hybrid nanofluids augment with the concentration, while decreases with increasing temperature. **Labib et al. (2013)** found that density increases more as compared to the viscosity, with volume fraction, for hybrid suspensions containing carbon nanotubes and oxides. Some researches on hybrid nanofluids concluded that the specific heat increases with the particle volume concentration and temperature while

density increases with a volume concentration and decreases with temperature. An increase in the specific heat is due to nanostructure formation at the solid-liquid interface and the aggregation of particles has a detrimental effect on specific heat enhancement. Most of the available open literature revealed that specific heat capacity decreases with the addition of nanoparticle, but some unexpected results were also observed (**Yarmand et al., 2016**). Due to the paucity of experimental data on their temperature dependence, the density and specific heat of the nanofluids are supposed to be a linear function of volume fraction. The relation for the density of hybrid nanofluid is derived from the mass balance and for specific heat is obtained from the energy balance. The generalized form of the density and specific heat capacity equations for hybrid nanofluids are as follows:

$$\rho_{nf} = (1 - \phi) \rho_{bf} + \sum_p \phi_p \rho_p \quad (2.3)$$

$$\rho_{nf} c_{p,nf} = (1 - \phi) \rho_{bf} c_{p,bf} + \sum_p \phi_p \rho_p c_{p,p} \quad (2.4)$$

Where, ρ is density, ϕ is volume fraction, and c_p is specific heat. Suffix p is used for particle.

2.2.4 Effect of particle mixing ratio on thermophysical properties

The mixture ratio of nanoparticles influences the thermophysical properties of hybrid nanofluids, though studies on this important issue are very few. **Charab et al. (2017)** proposed the model of thermal conductivity for 1.0 vol% Al₂O₃-TiO₂ hybrid nanofluid with different particle ratios and reported maximum heat transfer enhancement up to 35.3% for 2:3 ratio. **Moldoveanu et al. (2018)** experimentally investigated the thermal conductivity of Al₂O₃-SiO₂/Water hybrid nanofluids and noticed that the hybrid nanofluid has higher thermal conductivity compared to alumina

nanofluid. **Hamid et al. (2018)** performed an experimental investigation on thermal conductivity and viscosity of hybrid nanofluids with different particle ratio. They observed maximum thermal conductivity enhancement up to 16% for 1:4 ratio of TiO₂-SiO₂ and the highest dynamic viscosity for the ratio of 5:5. **Dalkılıç et al. (2018)** experimentally investigated the viscosity of Graphite-SiO₂ hybrid nanofluid at different volume concentrations and different weight ratios and showed a viscosity increase of 0.65-36.32% with an increase in volumetric concentration. **Siddiqui et al. (2019)** studied the stability and thermophysical properties of Cu-Al₂O₃ hybrid nanofluid for different mixing ratios and showed that 5:5 was the optimum mixing ratio because of its better thermal conductivity and good stability to achieve overall hydrothermal properties. **Zawawi et al. (2019)** investigated the thermophysical properties of Al₂O₃-SiO₂/PAG nanolubricants for various particle mixture ratios and found that 60:40 was the optimum mixture ratio with the lowest property enhancement ratio. **Esfe et al. (2019)** experimentally investigated the optimized ratio of MWCNT (30 vol%)-Al₂O₃ (70 vol%) in 5W50 oil with total volume concentrations of 0.05%, to 1%. They found that the maximum enhancement of 24% was observed in viscosity at 1% volume fraction. **Table 2.2** summarized the literature review on particle mass or volume mixing ratio.

Table. 2.2 Literature review for particles mixing ratio in hybrid nanofluids

Nanofluids, Particles %	Mixing ratio	Findings	References
Al ₂ O ₃ -TiO ₂ /water, total volume fraction = 1%	0:100, 25:75, 50:50, 75:25, 100:0	maximum thermal conductivity enhancement up to 35.3% for 1:3 ratio.	Charab et al. (2017)
SiO ₂ -graphite/water, total volume fraction=0.1-2 vol%	1:4, 2:3, 3:2, 4:1 (weight ratio)	Highest increment of viscosity was observed to be 36.12% in the nanofluid of 2 vol% at 15 °C	Dalkılıç et al. (2018)

TiO ₂ - SiO ₂ /water, total volume fraction=2%	1:4, 2:3, 2.5:2.5, 3:2, 4:1	The highest thermal conductivity enhancement of 16% was obtained at ratio of 1:4. highest dynamic viscosity for the ratio of 2.5:2.5.	Hamid et al. (2018)
Al ₂ O ₃ - SiO ₂ /water, total volume fraction=1-3 vol%	1:1, 1:2, 1:3, 1.5	Higher volume fractions of SiO ₂ nanoparticles placed in studied hybrid nanofluids leads to higher thermal conductivities.	Moldoveanu et al. (2018)
f-MWCNT- Fe ₂ O ₃ /water total weight concentrations 0.01%-0.03%	4:1, 3:2, 1:1, 2:3 and 1:4	thermal conductivity enhanced up to 2:3 beyond get decreased for all total concentrations, due to MWCNT aggregations of negative effect.	Balaga et al. (2019)
Cu-Al ₂ O ₃ /water	3:7, 5:5, 7:3 (volume ratio)	5:5 was the optimum mixing ratio because of its better thermal conductivity and good stability	Siddiqui et al. (2019)
Ag-GnP/ PG+W total wt%=0.05%-1%	0:1, 1:4, 1:1, 4:1 and 1:0 (mass ratio)	The increasing amount of fAg contributes more to the viscosity increase than the rising presence of pGnP.	Vallejo et al. (2019)
γ-Al ₂ O ₃ +MWCNT / water, total wt%=0.1	80:20, 60:40, 40:60 and 20:80 (wt ratio)	Viscosity augments with rise in MWCNT fraction	Giwa et al. (2020)

2.3 Hydrothermal characteristics of mini/microchannel

Many experimental studies are available on the hydrothermal performance of mono nanofluids in MCHS. However, investigations on hybrid nanofluids flow in mini/microchannel heat sink (MCHS) are very limited in the open literature. Heat transfer can be improved by increasing the heat transfer coefficient, which is enhanced by the use of hybrid nanofluids due to an increase in thermal conductivity and several slip mechanisms (inertia, Brownian diffusion, thermophoresis, diffusiophoresis,

Magnus effect, gravity). It has been found that both heat transfer and pressure drop increase with the use of hybrid nanofluids and the overall impact of employing hybrid nanofluid may be marginal. Some of the related studies with their findings are listed in Table 2.3 and 2.4.

2.3.1 Experimental studies using mono/hybrid nanofluids

This section is divided into two parts (i) Nanofluids in MCHS and (ii) hybrid nanofluids in MCHS. Many experimental studies are available on the hydrothermal performance of mono particles suspended fluids in MCHS (**Ho et al., 2010; Kalteh et al., 2012; Rimbault et al., 2014; Hussien et al., 2016; Soheli et al., 2015; Taha et al., 2016; Thansekhar and Anbumeenakshi, 2017; Alfaryjat et al., 2019; Yildiz et al., 2020; Peyghambarzadeh et al., 2014; Manay and Sahin, 2016; Wang et al., 2016; Sivasubramanian et al., 2018**).

Investigations on the circular channel with nanofluids are available in the open literature. An experimental study was done by **Liu and Yu (2011)** in circular minichannel with a 1.09 mm inner diameter using Al_2O_3 /water nanofluid. They revealed that heat transfer and pressure drop both increases by nanoparticle fraction in the base fluid. Titania-water nanofluid was used by **Ding et al. (2019)** in a circular microchannel of 0.9 inner diameter for thermal energy storage. Nusselt number was enhanced by in the range of 4-18% at 0.5wt% solid concentration when PCM melted. Other studies were reported in circular MCHS using nanofluids (e.g., **Hussien et al., 2016; Ghasemi et al., 2017; Shahsavari et al., 2019**).

Studies on the rectangular channel with spherical and non-spherical nanoparticles dispersed nanofluids are presented here. The effect of heating power on heat transfer and pressure drop behavior in straight minichannel using TiO_2 nanofluid was

experimentally investigated by **Arshad and Ali (2017)**. They show pressure drop decreases with an increase in heat flux from 100 to 150 W. **Narendran et al. (2018)** performed an experimental analysis on exergy in rectangular minichannel using TiO₂/water nanofluid. The highest outlet exergy of 147.52 W was found at a flow rate of 360 ml/min. Other similar studies were performed experimentally in rectangular MCHS with spherical nanoparticles (**Ho et al., 2010; Kalteh et al., 2012; Khaleduzzaman et al., 2014; Ahammed et al., 2016a; Zhang et al., 2016; Peyghambarzadeh et al., 2014; Manay and Sahin, 2016; Wang et al., 2016; Thansekhar and Anbumeenakshi, 2017; Alfaryjat et al., 2019**). **Yildiz et al. (2020)** performed an experimental study in microchannel with graphite/water nanofluid and observed heat transfer enhancement with the increase in volume concentration, mass flow rate and heat flux.

The combined effect of fins and nanofluid was investigated by many authors. Some of them are stated here. **Naphon and Nakharintr (2013)** did an experimental study to show the effect of ribs in minichannel using TiO₂/water nanofluid. Hydrothermal performance of minichannel was investigated by **Zhang et al. (2017)** using nanofluid and fin. They showed the maximum performance evaluation criteria (PEC) value of 2.0 at Re=5150. Effect of fins was experimentally investigated by **Tullius and Bayazitoglu (2013)** using Al₂O₃/water nanofluid and revealed that presence of MWNTs fins enhanced heat removal. **Xu et al. (2020)** studied the behavior of graphene oxide/water nanofluid in microchannel with pin fins and observed heat transfer enhancement with a rise in nanoparticle mass fraction.

However, studies on hybrid nanofluids are scarce in the literature. **Hussien et al. (2019)** experimentally investigated the performance of MWCNTs+GNPs hybrid nanofluids in microtubes in the range of Re=200-500. They found that the average heat

transfer coefficient enhances 58% for MWCNTs/GNPs hybrid nanofluid. **Selvakumar and Suresh (2012)** investigated hydrothermal characteristics of $\text{Al}_2\text{O}_3+\text{Cu}$ hybrid nanofluids in minichannel and observed 24.35% enhancement in the convective heat transfer coefficient and 12.61% increase in pumping power. An experimental study was done by **Nimmagadda and Venkatasubbaiah (2017)** for $\text{Al}_2\text{O}_3+\text{Ag}$ hybrid nanofluid in microchannel showed that Nusselt number enhances with volume concentration. An experimental study was carried out by **Ho et al. (2014, 2014a and 2018)** using $\text{Al}_2\text{O}_3+\text{MEPCM}/\text{water}$ hybrid nanofluid in minichannel. They concluded that Al_2O_3 based nanofluid is a better option compared to the $\text{Al}_2\text{O}_3+\text{MEPCM}$ hybrid based nanofluid at higher Reynolds number. They also revealed that the cooling effectiveness of the working fluids depends significantly on their flow rates through the MCHS and found an optimum value below which hybrid suspension provided better performance compared to single particles-based fluid due to synergistic influence of the Al_2O_3 and PCM suspension both. **Ahmed et al. (2016)** did an experimental study on $\text{Al}_2\text{O}_3+\text{graphene}/\text{water}$ hybrid nanofluid in multiport minichannel. They show 63.13% and 20.35% enhancement in convective heat transfer coefficient and pressure drop compared to water, respectively. The effect of supplied heat load presented that the cooling capacity and coefficient of performance improved with an increase in heat load. Experimental studies on ribbed mini/microchannel with hybrid nanofluid are not available in the open literature. Table 2.3 lists experimental studies on mini/microchannel using hybrid nanofluid.

Table. 2.3 Experimental studies on mini/microchannel using hybrid nanofluids

Nanofluids, Particles %	Channels dimensions	Operating Condition	Findings	References
Al ₂ O ₃ +Cu/DI water, 17 nm, 0.1 vol%	Rectangular, w _{ch} =0.3mm	Re=2576.56-9261.62, volume flow rate= 0.79-2.45 lpm, Heat Input= 101.8 W,	h enhances by 24.35% and 12.61% increase in pumping power for hybrid nanofluid.	Selvakumar and Suresh (2012)
Al ₂ O ₃ +PCM/water, 2-10 wt%	w _{ch} =1 mm, h _{ch} =1.5 mm, L _{ch} =50 mm h _d =1.2 mm	Re=133 to 1515, uniform heat flux	Better effectiveness is noticed for Al ₂ O ₃ -water nanofluid over hybrid suspensions at higher Reynolds number.	Ho at al. (2014, 2014a and 2018)
Al ₂ O ₃ +Graphene/water, 0.1 vol%	h _d =1.184 mm	Re=200 to 1000, Heat flux= 6250 W/m ² to 25,000 W/m ²	Enhancement of 88.62% in the convective heat transfer coefficient. Total entropy generation decreased with Re	Ahammed et al. (2016)
Al ₂ O ₃ +Ag/water, 3 vol%	L=58.5 mm w _{ch} =1000 μm h _{ch} =200 μm	Re = 10-50, Heat flux=51282 W/m ²	As Ag fraction increases, Nu enhances	Nimmagadda and Venkatasubbaiah (2017)
MWCNTs+GNPs/water, 0.075-0.125 wt. %.	Microtube ID=300 μm L=0.27 m	Re = 200-500	Maximum h enhances by 58% occurred at maximum concentration and Re=200	Hussien et al. (2019)

2.3.2 Numerical studies using mono/hybrid nanofluids

Many numerical studies are available on microchannel using mono/hybrid nanofluids. Numerical studies are divided into two parts (i) MCHS with nanofluids and

(ii) MCHS with hybrid nanofluids. Investigations on the circular channel with spherical and non-spherical nanoparticles dispersed nanofluids were available in the open literature. Some of them are stated here. The effect of nanoparticles size was investigated by **Kamali and Binesh (2013)** on heat transfer characteristics in minichannel. The results show that the convective heat transfer coefficient increased by decreasing nanoparticle sizes. **Sohel et al. (2014)** performed an analytical study on circular minichannel heat sink using different oxide and metal dispersed nanofluids and shows that Ag-water nanofluid showed the highest performance compared to the other nanofluids. The effect of nanoparticle shape was investigated by **Al-Rashed et al. (2019)** and **Alsarraf et al. (2019)** in double pipe minichannel. They found that that platelet shape and spherical shape nanoparticles have the highest and lowest total entropy generation and overall heat transfer coefficient, respectively. **Toghraie et al. (2018)** performed a study in circular shared serpentine minichannel with CuO/EG+water nanofluid.

Investigations on rectangular-shaped mini/microchannel with spherical and non-spherical nanoparticles dispersed nanofluids were reported in the open literature. **Ijam et al. (2012)** and **Ijam and Saidur (2012)** investigated the performance of minichannel using water-based Al₂O₃, TiO₂ and SiC nanofluids. A similar study was performed by **Utomo et al. (2012)** using alumina/water nanofluid at 3 vol%. A numerical study was carried out by **Krishna and Kumar (2019)** in microchannel using water-based alumina and titania nanofluid. The effect of channel height was performed by **Martínez et al. (2019)** using TiO₂ nanofluid. Similar numerical studies were carried out by many authors, eg. **Mohammed et al., (2010)**, **Manay et al., (2012)**, **Nebbati and Kadja, (2015)**, **Mittal, (2013)**, **Yue et al., (2015)**, **Bahiraei and Heshmatian, (2017)**, **Datta et al., (2019)**, **Sharaf et al., (2019)**, **Sarafraz et al., (2019)**, **Yang et al., (2020)**, **Jovic et**

al. (2019). Nimmagadda and Venkatasubbaiah (2015) performed a numerical study on microchannel using gold and CNT nanofluids. They observed that 1.5 vol.% and 0.5 vol.% SWCNT nanofluids exhibit similar heat transfer characteristics as compared to 2 vol.% gold nanofluid. **Sarlak et al. (2019)** performed a numerical study on a double-layered microchannel heat sink with MWCNT/water nanofluid. They showed an enhancement of 14% in thermal performance using MWCNT/water nanofluid. **Ghasemi et al. (2017a)** did a study on minichannel heat sink having a triangular-shaped channel using Al_2O_3 /water nanofluid and revealed that thermal performance improved with nanofluid as compared to water.

The combined effect of fins and nanofluids are reported in the literature. **Kristiawan et al. (2019)** did a numerical investigation in square minichannel using TiO_2 /water nanofluid with microfin. The maximum $\text{PEC}=1.2$ was achieved at $\text{Re}=380$ and 0.01 vol.%. **Naphon and Nakharintr, 2015** also showed the effect of ribs in minichannel using TiO_2 /water nanofluid. **Gholami et al. (2018)** investigated the effect of different ribs shape on the hydrothermal behavior of rectangular microchannel using MWCNT/oil nanofluid. They showed the maximum flow rate for rectangular ribbed microchannel and the performance of microchannel was affected by Reynolds number. Many other authors performed a numerical investigation on minichannel using nanofluids.

In this part, numerical studies on MCHS using hybrid nanofluids are discussed. Here studies on the circular-shaped channel are explained. **Hussein et al. (2019)** examined Al_2O_3 +graphene hybrid nanofluid flow inside mini tubes, numerically. Maximum enhancement in heat transfer coefficient with Al_2O_3 +graphene hybrid nanofluid was found about 13.7% over Al_2O_3 /water nanofluid. Hydrothermal performance of Fe_3O_4 +CNT/water hybrid nanofluid in double pipe minichannel was

evaluated by **Shahsavari et al. (2019)** numerically by considering non-Newtonian and Newtonian fluid both. They found that the heat transfer rate, overall heat transfer coefficient, and effectiveness of the non-Newtonian hybrid nanofluid are greater than those of the Newtonian hybrid nanofluid. **Bahiraee et al. (2017 and 2018)** investigated the CNT+Fe₃O₄ hybrid nanofluid in the double pipe minichannel heat exchanger. They showed better performance of hybrid nanofluid over base fluid (water) and found an optimum point for the total entropy generation at low Fe₃O₄ concentration. **Khosravi et al. (2019)** did an investigation on entropy generation due to graphene-platinum hybrid nanofluid in cylindrical microchannel liquid block using an artificial neural network (ANN). They noted that the heat transfer coefficient and entropy generation rate increase and decrease with Reynolds number, respectively.

The investigations on rectangular-shaped mini/microchannel using spherical and non-spherical dispersed hybrid nanofluids are stated here. **Nimmagadda and Venkatasubbaiah (2015)** numerically investigated alumina-silver hybrid nanofluid through microchannel using a homogeneous model. They revealed a 126-148% enhancement in the heat transfer coefficient. **Nimmagadda and Venkatasubbaiah (2017)** also used a two-phase mixture model for the numerical investigation of microchannel under laminar flow using Cu+Al hybrid nanofluid. They explained that hybrid nanofluid is better as compared to base fluid and mono nanofluids based heat transfer characteristics. A numerical investigation was done by **Uysal et al. (2019)** in rectangular minichannel using Diamond+Fe₃O₄/Water hybrid nanofluid and showed that hybrid nanofluid has higher convective heat transfer coefficient and Nusselt number over the mono particles nanofluids. The performance of different microchannel heat sinks using graphene+Ag hybrid nanofluid was numerically investigated in the laminar regime (**Bahiraee et al., 2018 and Goodarzi et al., 2019**) and revealed that nanofluid is

a better cooling option in comparison to water. **Ho et al. (2020)** studied the performance of minichannel heat sink using Al_2O_3 +PCM/water hybrid nanofluid. They depicted that the heat transfer coefficient ratio (i.e., h_{nt}/h_{bf}) is more than one for all Reynolds number and heat flux.

Many authors showed the effect of ribs and fins in mini/microchannel. **Bahiraei et al. (2020)** investigated the effect of ribs in microchannel heat sink. They explained that the thermal entropy generation increases and friction entropy generation decreases with a rise in Reynolds number and volume concentration. A numerical investigation was carried out by **Ambreen et al. (2019)** in a micro pin fin heat sink using Al_2O_3 +Cu hybrid nanofluid. They found 25.14% enhancement in Nusselt number for diamond fins with nanofluids. Hydrothermal features of chaotic twisted minichannel were studied by **Bahiraei and Mazaheri (2018)** using graphene nanoplatelets decorated with platinum hybrid nanofluid. They found a figure of merit always more than 1.5. Numerical studies on mini/microchannel using mono/hybrid nanofluids are presented in **Table 2.4**.

Table. 2.4 Numerical literature survey on mini/microchannel using hybrid nanofluids

Nanofluids, Particles %	Channels dimensions	Operating Condition	Findings	References
Al_2O_3 +Ag/ Water, Total-3 vol%	Rectangular, $w_{ch}= 14$ mm $h_{ch}= 295$ μ m.	Re=200-600, Heat flux=150000 W/m ²	Hybrid nanofluid shows higher h than that of water and mono nanofluids due to the dominating nature of momentum diffusivity over thermal diffusivity.	Nimmagadda and Venkatasubbaiah (2015)
Cu+Al, Water +Methanol, Total-3 vol%	$L_{ch}=58.5$ mm $w_{ch}=1000$ μ m $h_{ch}=200$ μ m	Re=200- 1000, Heat flux=150000 W/m ²	Hybrid nanofluid is better as compared to mono nanofluids.	Nimmagadda and Venkatasubbaiah (2017)

Coated Fe ₃ O ₄ +CNT/ Water, 0-1.35 vol%	double-pipe minichannel, L=1 m, ID=1 mm, OD=2 mm	Re=500-2000	At low Fe ₃ O ₄ concentration, an optimum point found for the total entropy generation. At low Re, better heat transfer achieved.	Bahiraee et al. (2017 and 2018)
Diamond+ Fe ₃ O ₄ /water, 0.05-0.20 vol%	h _{ch} = 1.5 mm, w _{ch} = 1 mm L _{ch} = 50 mm	Re=100 to 1000, heat flux=10000 W/m ²	Heat transfer coefficient enhancement of 29.96%, at Re=1000	Uysal et al., (2018)
Fe ₃ O ₄ +CNT/ Water, 0-1.35 vol%	Double-pipe minichannel, L=1 m, ID=1 mm, OD=2 mm	Re=9000-15000	Maximum Nusselt number=125 found at maximum Re.	Shahsavari et al. (2019)
Graphene+Ag/ water, 0-0.1 vol%	w _{ch} = 0.2 mm h _{ch} = 0.4 mm	Re = 200-1000, heat flux=100 W/cm ²	Hybrid nanofluid is better cooling option in comparison to water.	Bahiraee and Heshmatian (2018), Goodarzi et al. (2019)
Graphene+ Platinum/water, 0-0.1 vol%	d _h = 564 μm	Re=300-600, heat flux=70 Kw/m ²	Increase of the Re from 300 to 600 improves the heat transfer coefficient by 16%.	Khosravi et al. (2019)

2.4 Highlights

From the literature available, it has been observed that different types of hybrid nanofluids were prepared from nanocomposites, mixing various nanoparticles consisting of different oxides, metals and phase-changing materials of different shapes, such as spherical, cylindrical and plates in a base fluid using one and two-step methods. Prepared nanofluids were characterized and different thermo-physical properties were calculated on the basis of which some correlations were also proposed to predict hybrid nanofluid properties. Some literature is also available on experimental and theoretical investigations with hybrid nanofluids in miniature heat exchanger devices (mini/microchannel heat sink) to enhance their performance. There are few literature available in minichannel heat sink using hybrid nanofluids.

2.5 Research gaps and scope

Though there is a lot of work to be done, there are still some loopholes. From the above survey, following research gaps have been observed:

1. Open literature is not available to show the effect of different nanoparticles mixture (oxide-oxide, oxide-PCM, oxide carbide, oxide-nitride, oxide-metal, oxide-allotropes of carbon) dispersed hybrid nanofluids on the hydrothermal characteristics of the minichannel heat sink.
2. So far, the effect of fluid inlet temperature is not found in open literature while considering different nanoparticles mixture dispersed hybrid nanofluids in minichannel heat sink for moderate Reynolds number.
3. Studies on minichannel heat sink using similar (same shape and approximately same size) and dissimilar nanoparticles combination (completely different in terms of shape, size and properties) by varying the ratio are not available, which can equally affect both the hydrodynamic and thermal behavior.
4. Few literature on the effect of heat flux and no literature on the effect of channel aspect ratio on hydrothermal behavior using hybrid nanofluids are available.
5. Few experimental investigations are available in the open literature on the hydrothermal performance of minichannel heat sink using nanocomposite dispersed hybrid nanofluids.
6. Studies on minichannel heat sink with enhanced heat transfer surface using hybrid nanofluids are not available in the open literature.

Hence, an attempt has been made in this thesis to fulfill the above-stated research gaps. This thesis is primarily focused on the effect of various nanoparticles suspended hybrid nonfluids on the efficacy of minichannel heat sink. There is a need of in-depth analysis So, it has been decided to synthesize hybrid nanofluids at

different concentrations, different nanoparticle combinations and at different mixing ratios followed by both numerical and experimental studies (various combinations of nanoparticles with different shapes like spherical, cylindrical and platelets are considered). This thesis also aims to include the effect of various ribs with hybrid nanofluids on the performance of minichannel heat sink.

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