An insight of synthesis, stability and thermophysical properties of hybrid nanofluids

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Abstract. Nanofluids are emerging as more suitable heat transfer fluid compare to conventionally used fluids for transferring heat in various engineering applications. Nanofluid is a fusion of very small quantity of nanoparticles and host fluid with considerable stability. The presence of nanoparticles in host fluid significantly enhance its thermal conductivity, which leads to the improvement in thermal performance. Introduction of submicron particles influence the viscous behaviour of the host fluid. In general viscosity enhancement is not desirable as it imposes a penalty in terms of increased pumping power in many engineering applications. Presence of more than one type of nanoparticles in host fluids provide opportunities to enhance thermal conductivity with control over other properties of resultant nanofluid. The nanofluid having more than one type of nanoparticles termed as hybrid nanofluid are in focus of researchers for investigation. A large variety of hybrid nanofluids are prepared and their properties investigated by various researchers. This review paper is an attempt to compile the research work related to preparation techniques, stability analysis and thermophysical properties of hybrid nanofluids. The potential applications of hybrid nanofluids and challenges associated with it are also discussed.

Key words: Hybrid nanofluid, synthetization, stability, thermophysical properties.

1. Introduction
There are industries like electronics, computer, automobile and many more, whose product’s performance and reliability are very much depend on the cooling ability of the system used for the purpose. Rapid enhancement in performance and technology advancement have led to the exponential increment of the heat flux load. Water ethylene glycol, oil and many more conventionally used fluids to transfer heat need to improve significantly or replace by thermal fluids capable to transfer heat efficiently to manage ever increasing heating load. With the advancement in nanotechnology it become feasible and economic to get nano sized particles of metals or non-metals. In 1995 Choi [1] first time introduced the nanotechnology based thermally superior suspension containing submicron particles. He coined the term Nanofluid for this modified fluid. The characteristics of any nanofluid largely depend on the type and amount of nanoparticles used. But the researches have also shown that combination of different types of nanoparticles and their addition to the base fluid may alter the heat transfer capabilities of the resultant fluid. This class of nanofluids which is having more than one types of submicron particles in host fluid are termed as hybrid nanofluids. Hybrid nanofluids are getting more and more attention of the
research community as these fluids give opportunity to manage rheological and flow properties also along with thermal performance enhancement. The present review is an effort to summaries the recent development and challenges in the field of hybrid nanofluids.

2. Synthesis of Hybrid Nanofluids

The method adopted to prepare mono/hybrid nanofluid plays an important role to get stable nanofluid with improved thermo-physical properties. Thus appropriate method of preparation is a key point in experimentation and research of mono/hybrid nanofluids. It has been observed that one step method and two step method are conventionally used to prepare nanofluid. But the two step method is most preferred as it is convenient and economic.

2.1. Two step method

The two step method comprises of two separate steps, first step is the synthesis of nanoparticles of desired material by suitable chemical or mechanical process, while the second step is the addition of already prepared nanoparticles into the host fluid to get stable nanofluid. This approach is convenient and extensively used but the nanofluids obtained by this method also have a big concern of stability as the suspended nanoparticles agglomerate under the influence of strong Vander wall and cohesive forces. Agglomeration of nanoparticles leads to instability and poor thermo-physical characteristics of nanofluid. To mitigate the agglomeration of nanoparticles different techniques like high-pressure homogenizer, addition of surface acting agents, sonication and magnetic forced stirrer are employed by the researchers. The nanofluids showed improved thermal properties but the increase in viscosity is an undesirable change in characteristics of nanofluid in most of the cases. Thus, a balance between the thermal and rheological characteristics of nanofluids is desirable for successful adoption of nanofluids in actual applications. This justifies the use of hybrid nanofluids as these fluids give us opportunity to maintain the thermal and rheological properties both.

Various research groups prepared hybrid nanofluid on introducing different nanoparticles in to the host fluid. Asadi et. al. [2] mixed Al2O3/MWCNT nanoparticles in oil with help of magnetic stirrer and ultrasonic homogenizer. Persian and Akabari [3] procured Al2O3 (5 nm diameter) and Cu (50 nm diameter) nanoparticles. The appropriate amount of nanoparticle mixture of Al2O3 and Cu is mixed gradually in base fluid Ethylene glycol. In order to make suspension stable and agglomeration free it is subjected to ultrasonication for 7 hours. Wei et. al. [4] also procured the nanoparticles (SiC and TiO2) from outside. The SiC/TiO2 nanoparticles suspended into the base fluid diathermic oil. The volume fraction of SiC/TiO2 is determined by using the following formula

$$\varphi_v = \frac{(m_{SiC}/\rho_{SiC}) + (m_{TiO2}/\rho_{TiO2})}{(m_{SiC}/\rho_{SiC}) + (m_{TiO2}/\rho_{TiO2}) + (m_f/\rho_f)}$$

where $\varphi_v$ is volume fraction of nanofluid (%), $m$ mean mass and $\rho$ is the density and subscript f represent base fluid. Oleic acid in appropriate amount is used as surfactant and ultra-sonication is done for 2 hours in order to make hybrid nanofluid stable.

Aparna et. al. [5] preferred to prepare Ag nanoparticles by using chemical reduction method while the Al2O3 nanoparticles are procured from outside. The appropriate ratio of Ag and Al2O3 nanoparticles mixed in distilled water. The Ag particles are also used to decorate the functionalised MWCNTs to get hybrid Ag/MWCNTs nanoparticles. These particles are more suitable to prepare stable suspension as compare to MWCNTs/base-fluid suspension [6]. Thus the two step method provide flexibility to prepare nanoparticles and their composites to enhance the desired effects in nanofluids.

2.2. One step method

As the name indicates in this method of nanofluid formation, the nanoparticles are synthesised as well as dispersed simultaneously into the base fluid. This method gives excellent stability of prepared nanofluid.

Eastman et. al. [8] used one-step procedure to disperse Cu nanoparticles into ethylene glycol. In the technique they adopted, the metallic vapour condensed directly into nanoparticles when the metallic
vapour come in contact with the flowing ethylene glycol having low vapour pressure. Aureen et al. [7] prepared CuO-Polyvinyle alcohol (PVA)/DI water hybrid nanofluid. They initially prepared the PVA-CuO nanocomposite by sol-gel method in single step, then the obtained wet precipitate is dispersed in DI water. Lo et al. [9] prepare and dispersed CuO nanoparticles directly in to DI water by means of submerged arc nanoparticle synthesis scheme. Zhu et al. [10] synthesis Cu nanofluid by single step chemical procedure. CuSO4·5H2O reduced with NaH2PO2·H2O in ethylene glycol (EG) in the presence of microwave irradiation to get Cu nanoparticles in ethylene glycol which produce Cu/ethylene glycol nanofluid. Botha et al. [13] prepared nanofluid having 0.3 wt% Ag on 0.07 wt% SiO2 in base fluid oil. AgNO3 and SiO2 introduced in to the host fluid and the mixture is heated up to 130°C and this temperature is maintained for 2 hours.

Teng et al. [11] used plasma arc technology which is one step procedure to produce Carbon/distilled water nanofluid. Similarly Aberoumand and Jafarimoghaddam [12] and Munkhbayar et al. [14] also followed the single step method to prepare hybrid nanofluids by using Electrical Explosion Wire (E.E.W), and Pulsed-Wire Evaporation (PWE) procedure respectively. The previously prepared MWCNTs nanofluid is placed in PWE instrument. The silver nanoparticles synthesized by PWE method and suspended directly into the base fluid. Similarly Munkhbayar et al. [14] also used one step procedure pulse power evaporation (PPE) to dispersed Ag nanoparticles in the previously prepared MWCNTs/water nanofluid. The review indicate that for preparing nanofluid in single step different techniques were adopted which provide stability and thermophysical characteristics but the high preparation cost and limitation for large scale production make this method less popular.

3. Thermo-physical Properties
Thermo-physical properties of mono/hybrid nanofluid fixed their heat transfer capabilities and overall thermal performance. Thermal conductivity, viscosity, density, and specific heat which are important thermophysical properties may either be measured using instruments or predicted by using available models given by various researchers. Thermo-physical properties rely on several factors like material, concentration, size and shape of nanoparticles, base fluid, and operating temperatures.

3.1. Thermal Conductivity
Thermal conductivity plays an important in thermal performance of any fluid hence its study for mono/hybrid nanofluid is very important. The enhancement in thermal conductivity of mono/hybrid nanofluid gives a base for the improvement in thermal performance and more energy efficient systems. The material, shape, and size of nanoparticle are important factors in deciding thermal conductivity of nanofluids.

Munkhbayar et al. [14] reported that on adding Ag nanoparticles in MWCNTs based aqueous nanofluid ensures considerable improvement in stability and thermal conductivity of resultant ‘Ag/MWCNT’/water hybrid nanofluid. Maximum 14.5% rise in thermal conductivity is recorded for prepared ‘Ag-MWCNT’/water hybrid nanofluid as compare to the MWCNT/water mono nanofluid. It confirms the advantage of hybrid nanofluids against mono nanofluids. The better straightness ratio increment, improved specific surface area and reduction in aggregation are the possible causes for improved thermal conductivity of prepared hybrid nanofluid.

Nine et al. [16] synthesis and investigate the Al2O3-MWCNTs/water hybrid nanofluid for dispersion quality and thermal conductivity. They found Al2O3-MWCNTs/water hybrid nanofluid superior than Al2O3/water mono nanofluid from thermal conductivity point of view. They also conclude that the nanoparticles having cylindrical geometry as compare to spherical one contribute more to improve thermal conductivity of base fluid.

Batmunkh et al. [17] added modified “Ag” nanoparticles to the TiO2 based nanofluid to prepared three samples of Ag·TiO2 based aqueous hybrid nanofluid. Experimentally they demonstrated that the adding small quantity of modified silver nanoparticles improve thermal conductivity of TiO2 based mono nanofluid. The combination of Ag/TiO2 facilitate phonon conduction and hence improve thermal
conductivity. Chen et al. [18] prepare hybrid nanofluid by suspending Ag-NPs decorated functionalized MWNT in water. The Ag-MWNT based hybrid nanofluid exhibited more thermal conductivity compare to the functionalized MWNT suspended mono nanofluid.

Ramaprabhu and Jha [20] dispersed Pd, Au, and Ag crystalline nanoparticles separately on multi walled carbon nanotubes to get metal-MWNTs composite nanoparticles. These composite nanoparticles are added to DI water and ethylene glycol separately to synthesizing hybrid nanofluids. The results confirmed that rise in temperature and concentration of metal-MWNTs in base fluid causes improvement its thermal conductivity. The thermal conductivity of hybrid nanofluid containing metal-MWCNT follow the same order which is that of constituent metal particles. The order of thermal conductivity of water based hybrid nanofluid is Ag-MWCNT/water > Au-MWCNT/water > Pd MWCNT/water and the same order is followed by EG based hybrid nanofluid also. Authors suggest that as the rise in temperature increases Brownian movement as well as thermal energy of the suspended nanoparticles which ultimately improves the thermal conductivity of the hybrid nanofluid. In their previous work [19] Cu particle-loaded MWCNTs, synthesised by chemical reduction method, suspended in two different base fluids DI water and EG in the absence of any surface active agent. Maximum thermal conductivity recorded at extremely less concentration Cu/MWCNTs which may be due to the homogeneous suspension of Cu/MWCNTs in the host fluid. Among the DI water and EG based hybrid nanofluids the DI water based experienced more improvement in thermal conductivity.

Moldoveanu et al. [21] prepare and perform experiments on water based hybrid nanofluid containing alumina and silica nanoparticles. They investigate the effect of concentration of nanoparticles (ranging from 1.0% to 3.0%) and temperature (within 20°C to 50°C) on thermal conductivity of hybrid nanofluid. A linear increase in thermal conductivity is observed along the rise in temperature. The hybrid nanofluid exhibits improvement in thermal conductivity with the growth in volume fraction of both Al2O3 as well as SiO2 particles, but the influence of increase of SiO2 is more as compare to Al2O3. A remarkable enhancement in thermal conductivity recorded with the increase in temperature at all the concentration of nanoparticle.

The nanofluids containing metallic nanoparticles have more thermal conductivity as compare to non-metallic nanoparticles. Cylindrical shaped nanoparticles contribute more as compare to spherical shaped nanoparticles in improving thermal conductivity of base fluid. On changing proportion of constituent nanoparticles only, while keeping the total concentration of nanoparticles intact, a significant variation in thermal conductivity of the hybrid nanofluid is observed.

3.2. Viscosity
Flow characteristics of working fluid is an important aspect while considering it for heat transfer applications. Penalty in terms of increase in pumping power is an undesired impact on using mono/hybrid nanofluids in thermal management devices as working fluid. Increase in viscosity is responsible for intensification of friction factor as well as pressure drop both, which ultimately rises the needed pumping power. The several research groups studied mono/hybrid nanofluid focussing on viscosity and the factors affecting it.

Bahrami et al. [23] considered the Fe-CuO/EG-water hybrid nanofluid to investigate their rheological behaviour under the influence of variation in volume fraction of nanoparticles. About 2200% growth in viscosity is recorded on changing volume fraction from 0.05% to 1.5%. Similar type of study done by Asadi and Asadi [24] considered engine oil based hybrid nanofluid containing MWCNT-ZnO nanoparticles for investigation. But they reported only 45% viscosity enhancement on increasing the solid fraction. Dalkılıç et al. [37] prepared hybrid nanofluid by suspending SiO2 along with Graphite nanoparticles in water. The viscosity of hybrid nanofluids is determined, keeping volume concentration in between 0.1% to 2%. A maximum 36.12% increase in viscosity observed for hybrid nanofluid of 2vol% at 15°C. An increase in viscosity from 0.65 to 36.32% is recorded along the growth of volumetric concentration of hybrid nanofluids. Sharma et al. [31] dispersed TiO2-CuO/C nanocomposite in base fluid ethylene glycol to prepare hybrid nanofluid. The experiments were performed to determine the viscosity and its dependency on temperature and volume fraction. About 80% enhancement in viscosity
is recorded at 2% volume fraction and 313.4 K temperature as compare to ethylene glycol. Esfe et al. [36] estimate the viscosity of SAE50 based hybrid nanofluid having suspended MWCNT-CuO(30%-70%) nanoparticles at different volume fractions (0 to 1%) and temperature (25 to 50°C). The authors reported a reduction in viscosity of the fluid on adding nanoparticles from 0.0625% to 0.25% volume fraction. A maximum reduction of 15% was recorded in viscosity and then it improves as the volume fraction becomes 0.5% or more. A maximum 14% increase in viscosity observed at the volume fraction of 1%. Thus the use of hybrid nanoparticles can provide thermal fluid with enhanced heat transfer characteristics along with reduced or very low increase in pumping power as penalty.

Dardan et al. [27] compare the viscosity of pure SAE40 engine oil and hybrid nanofluid obtained on adding Al2O3-MWCNTs nanoparticles. The investigations were done at temperature ranging from 25°C to 50°C. A reduction in viscosity recorded on rising temperature. Baghbanzadeh et al. [28] prepared four types of nanoparticles SiO2, MWCNTs, SiO2 (80 wt%) + MWCNTs (20 wt%) termed as H1, and SiO2 (50 wt%) + MWCNTs (50 wt%) termed as H2. Four different types of mono/hybrid nanofluids synthesised on adding above mentioned nanoparticles separately in to the host fluid distilled water. The trend of rise in viscosity with the increase in nanoparticle concentration and fall in viscosity with the increase in temperature are same as reported by other researchers. At high concentration the nanofluid with H2 hybrid particles registered least increase in viscosity as compare to others. The addition of nanoparticles of MWCNTs affect most negatively the viscosity of base fluid. Shahsavaran and Hormozi [34] concluded that the dynamic viscosity of hybrid nanofluids is more than the mono nanofluid after performing experiments on Al2O3/water, SiO2/water nanofluids and Al2O3-SiO2/water hybrid nanofluids. Rise in viscosity with the growth in nanoparticle concentration, and fall in viscosity with rise in temperature are the trend followed by mono/hybrid nanofluids. Afshari et al. [38] also confirmed the same trend of variation in viscosity in their investigation of MWCNTs+Al2O3/(water80%+ethylene glycol80%) hybrid nanofluid. Kumaresan et al. [26] reveal that the dependency of viscosity over temperature is a function of concentration of nanoparticles in the base fluid. Thus the intensity of change in viscosity with temperature may be controlled by regulating the concentration nanoparticles of mono/hybrid nanofluid.

Shahsavaran and Bahiraei [33] dispersed C6H12NO coated Fe3O4 nanoparticles and GA coated CNTs nanoparticles in to base fluid water to get hybrid nanofluid which is investigated for variation in viscosity and thermal conductivity. The hybrid nanofluid showed shear-thinning behaviour, which intensified at low values of shear rate. Akilu et al. [31] performed the rheological analysis of ethylene glycol based hybrid nanofluid containing suspended TiO2-CuO/C nanoparticles. They observed Newtonian behaviour of all samples at various shear rate and temperature. On the other hand Esfe et al. [36] reported non-Newtonian behaviour of SAE50 based hybrid nanofluid having MWCNT(30%)+CuO(70%) nanoparticles.

Sundar et al. [25] investigate the impact of concentration of MWCNTs-Fe3O4 nanoparticles in base fluid water over viscosity, friction factor and pumping power. For friction factor experiments the particle concentration were 0.1% and 0.3%. The hybrid nanofluid observed 1.5 times enhancement in viscosity at 0.3% concentration and 60°C temperature and friction factor enhanced by 1.11 times as compare to the base fluid. 1.18 times increase in pumping power as penalty is also recorded at 0.3% particle loading and 22000 Reynolds number. Suressh et al. [29] focused on the friction behaviour of Al2O3-Cu/water hybrid nanofluid. They found that the presence of 0.1% volume fraction of Al2O3-Cu in base fluid causes 16.97% average increase in friction factor and rise in pumping power also. They suggested that the agglomeration and surface adsorption are the root cause for the rise in viscosity which eventually affect the friction factor and pumping power as penalty. Allahyar et al. [30] also suggested that the particle agglomeration and clusters formation may be responsible for affecting the viscosity of hybrid nanofluid which leads to rise of pressure drop.

It has been observed that the theoretical equations may not provide the viscosity of hybrid nanofluids at all volume fraction and temperature range. Kumaresan et al. [26] experimentally investigate the discrepancies in between the results of viscosity obtained from experiments and
predicted by using the well-known correlations for nanofluid viscosity. The investigations reveal that the equations are fail to predict the experimental results within desired accuracy. Even Einstein’s law of viscosity fails to provide the viscosity of nanofluids having very less concentration of nanoparticles. Esfe et al. [36] collect the viscosity of SAE50 based hybrid nanofluid containing MWCNTs and CuO at various temperatures and volume fraction of nanoparticles. A mathematical correlation (equation 3) is suggested to predict the viscosity of hybrid nanofluid.

\[
\frac{\mu_{nf}}{\mu_{bf}} = 0.99 + 0.49\phi - 0.0077T + 6.81 \times 10^{-6}\dot{\gamma} - 0.00249\phi T - 2.19 \times 10^{-7}T\dot{\gamma} - 0.19\phi^2 + 0.00011T^2
\]  

Shahsavar et al. [22] study the viscosity of hybrid nanofluid prepared by adding aqueous ferrofluid and water based CNT nanofluid under the influence of magnetic field. The results indicated that the rise of magnetic field strength causes the fluid more viscosity. Sahoo and Kumar [35] reported that the hybrid nanofluid having platelet shaped nanoparticles experienced maximum viscosity and the viscosity while the spherical shaped nanoparticle causes maximum rise in viscosity.

The rise in viscosity with the growth in nanoparticle concentration is the general observation in most of the research work. The appropriate ratio of constituent material of hybrid nanoparticles can help to control the viscosity change as per requirement. The temperature also plays a critical role to regulate the viscosity as with rise in temperature the nanofluid become less viscous. The effect of shape of nanoparticles, and applied magnetic field are less investigated parameter for mono/hybrid nanofluid from viscosity point of view.

### 3.3. Density and specific heat capacity

Thermophysical properties of mono/hybrid nanofluids are responsible for their feasibility and usefulness for any thermal device. The mono/hybrid nanofluids are focused less to investigate their density and specific heat capacity.

Density is a significant characteristic of hybrid nanofluid to investigate as it directly influences stability, friction factor, pumping power, Reynolds number along with thermal performance. The mass of a substance per unit volume can be defined as density. As the density of solid is more as compare to the liquid, hence the presence of solid nanoparticles into host liquid tend to increase the density of resultant nanofluid. The density will vary with the concentration of nanoparticles in the mono/hybrid nanofluid. The conventional mixture relations can be used to predict the density of nanofluids. For determining the density of nanofluid researchers used the equation (2), which is a modified form of the basic model.

\[
\rho_{nf} = \frac{m_{np} + m_{bf}}{V_{np} + V_{bf}} = \frac{\rho_{np}V_{np} + \rho_{bf}V_{bf}}{V_{np} + V_{bf}}
\]  

Pak and Cho [39] preferred the model given by equation (3) to predict the density of nanofluid.

\[
\rho_{nf} = \phi \rho_{np} + (1 - \phi)\rho_{bf}
\]  

Several research groups[40-42] confirm that the equation (3) is capable to predict the density of nanofluid very accurately and hence it is widely used to validate the experimentally obtained density of nanofluids.

Takabi and Salehi [43] specified the viscosity of hybrid nanofluid by equation (4) which is extension of equation (3) to hybrid nanofluids.

\[
\rho_{nf} = \phi \rho_{np1} + \phi \rho_{np2} + (1 - \phi)\rho_{bf}
\]  

where \(\phi = \phi_{np1} + \phi_{np2}\).

Sahu and Sarkar [44] also used the equation (4) to calculate the density of hybrid nanofluids. Microencapsulated phase change material(MEPCM)-Al2O3/water hybrid nanofluid is prepared and investigated for density by Ho et al. [32]. The mixture theory formula i.e. equation (4) is used to get the predicted values of effective density for hybrid nanofluid. They validated the correctness of the equation (4) also, and the results were in accepted range.
Yarmand et al. [45] dispersed Ag decorated graphene nanoplatelets (GNP) in distilled water. The density of obtained hybrid nanofluids are investigated for different weight concentration and temperature ranging from 20 to 40°C. A minute rise in density is recorded as the nanoparticle fraction increases. About 0.09% increase in density of hybrid nanofluid is observed against the base fluid at 40°C and 0.1% fraction of nanoparticles.

The accurate and reliable knowledge of specific heat of mono/hybrid nanofluids is crucial because the analysis of energy and exergy of nanofluid depends on it. But it is comparatively less focused property of mono/hybrid nanofluids. The specific heat of nanofluid is less than the base fluid, which means for the same rise in temperature, less heat is required for nanofluid as compare to the base fluid [47]. Specific heat of nanofluid can be considered as a mixture of heat capacities of solid and liquid phases under the condition of thermal equilibrium with each other [46]. The model (equation 5) which is analogous to mixture theory is simple and widely adopted for predicting the specific heat of nanofluid [48-50].

\[ c_{p,nf} = (1 - \varphi) c_{p, bf} + c_{p, np} \]  
where nf, bf, and np are abbreviations for nanofluid, base fluid, and nanoparticle respectively.

Zhou and Ni [51] studied Al2O3/water nanofluid and experimentally determine the specific heat. They observe a fall in specific heat of nanofluid on increasing Al2O3 concentration. The experimental values of specific heat are close to the values predicted from thermal equilibrium model i.e. equation (6), while the simple mixing model i.e. equation (5) fails to provide accurate values. Hence the equation based on thermal equilibrium model is more preferred to predict the specific heat of nanofluids [15, 62]

\[ \rho_{nf} c_{p, nf} = (1 - \varphi)(\rho c)_p \]  
where (bf, np) represent base fluid, nanoparticles, hybrid nanofluids, nanoparticle type 1 and nanoparticle type 2, respectively. Madhesh et al. [53] and Mund et al. [54] used equation (7) for predicting the specific heat of Cu-TiO2/water and Al2O3-TiO2/water hybrid nanofluids, respectively.

\[ c_{h, nf} = \frac{(1 - \varphi)(\rho c)_{bf} + (\varphi \rho c)_{p1} + (\varphi \rho c)_{p2}}{\rho_{nf}} \]  

The model obtained by extending conventional mixture relation is capable to predict the density up to considerable correctness. The influence of mono and composite nanoparticles on the specific heat of nanofluid are not consistent. The impact of temperature and volume fraction of hybrid nanoparticles over the density and specific heat of hybrid nanofluids need to explore further.

4. Stability

Stability is a crucial parameter for mon/hybrid nanofluids. The nanoparticles have strong tendency to agglomerate because of Vander Waal and cohesive forces, which lead to sedimentation of the particles. The hybrid nanofluid with agglomerated nanoparticles are not improved form of heat transfer fluid. The presence of large sized agglomerated particles enhance the viscosity, friction factor as well as pressure drop. Thus agglomeration and particles sedimentation make the hybrid nanofluid unsuitable for use in heat transfer application. From the literature, it is found that the techniques such as ultrasonication addition of surface active agents, and electrostatic stabilization are commonly adopted for minimizing the agglomeration.

Surfactant is a surface active agent, which function as a bridge among suspended nanoparticles and the host fluid. Surfactant creates continuity within the nanofluid. The stability of a nanofluid will depend on the nature of nanoparticles as well as host fluid both. The nanoparticles used may be of the nature of hydrophobic or hydrophilic, while the host fluid may have polar or non-polar nature. The dispersion of hydrophilic nanoparticles in to the polar host fluid and the hydrophobic nanoparticles in to the non-polar host fluid is convenient and do not required any third component in general for achieving the stability. But if the dispersion is having opposite combination of nanoparticles and host
fluid as mentioned above, then surfactant need to introduce for achieving stability of suspension [55]. The surfactant can be classified on the basis of charge on their head group. The surfactant may have negative charge, positive charge, neutral, or both positive and negative charge. Table 1 summarises the commonly used surfactant along with nanoparticles and host fluids.

| Reference               | Surfactant                                | Nanoparticle | Host fluid               |
|-------------------------|-------------------------------------------|---------------|--------------------------|
| Zhu et al. [56]         | Sodium odecylbenzene sulphonate (SDBS)    | Al2O3         | water                    |
| Hwang et al. [57]       | Sodium dodecyl sulphate (SDS)             | MWCNTs        | DI water                 |
| Kim et al. [58]         | Sodium dodecyl sulphate (SDS)             | Al2O3, ZnO, TiO2 | Water and ethylene glycol (EG) |
| Yu et al. [59]          | Sodium dodecyl sulphate (SDS)             | MWCNTs        | Distilled water          |
| Madni et al. [60]       | Sodium Octonate (SOCT)                    | MWNTs         | Dimethyl formamide (DMF) |
| Kim et al. [61]         | Cetyl trimethyl ammonium bromide (CTAB)   | MWCNTs        | water                    |
| Avsec et al. [62]       | Dodecyle Trimethyl Ammonium Bromide (DTAB)| MWNTs         | Dimethyl formamide (DMF) |
| Shanbedi et al. [63], Shahsavar and Bahiraei [33] | Gum arabic (GA) | MWCNTs | water                    |
| Li et al. [64]          | Polyoxyethylene (10) nonyl phenyl ether   | Cu            | water                    |
| Tang et al. [65]        | Poly vinyl pyrrolidone (PVP)              | CNTs          | Dimethylacetamide        |
| Ghadimi and Metselaar [66] | Poly vinyl pyrrolidone (PVP)              | TiO2          | distilled water          |
| Choi et al. [67]        | Oleic acid                                | Al2O3 and AlN | transformer oil          |
| Drzazga et al. [68]     | Rokanol K7                                | CuO           | water                    |
| Utomo et al. [69]       | Octyl silane                              | Al2O3, TiO2   | water                    |
| Suresh et al. [70]      | Sodium lauryl sulphate (SLS)              | Al2O3–Cu      | deionized water          |

The addition of suitable surfactant help to stabilized the nanofluid by improving the repulsive force among the nanoparticles on strengthening the electric double layer. Surfactant may also improve the charge over the surface of nanoparticles and hence may rise the zeta potential of nanofluid [57, 71]. Adoption of appropriate surfactant according to the material of nanoparticle and base fluid is an important activity as it not only decides the stability/durability of prepared mono/hybrid nanofluid but the thermophysical properties are also may affect.

Electro kinetic characteristics of suspended nanoparticles plays a crucial role to stabilize mono/hybrid nanofluids. Electric charge which may be at the outer most shell of the atom is the reason behind the electro kinetic characteristics of nanoparticles in the host fluids. Ions present on particles
and in the base fluid form an electric static double layer, it helps to stabilize the suspension. At a particular pH, at which the net charge on the particle becomes zero is termed as isoelectric point (IEP). At pH_{IEP} the repulsive forces between the particles become zero, which causes the agglomeration. As the pH of suspension deviates from pH_{IEP} the force of repulsion among the nanoparticles increases and the stability of suspension improves. For example the pH_{IEP} for water based nanofluid having suspended Al2O3 and Cu nanoparticles separately are 10 and 9.6 respectively [100, 101]. Suresh et al. [70] measured the pH of water based hybrid nanofluid having Al2O3 and Cu both and reported it about 6 which is much less than the nanofluids containing Al2O3 and Cu separately. This ensures that the prepared hybrid nanofluid is stable. A model to predict the pH of hybrid nanofluid will be very helpful to estimate the stability also.

The most widely used method to stabilize the mono and hybrid nanofluid is ultrasonic vibration as it is economical and easy to use. The basic principle of this technique is to uniform disperse nanoparticles in the host fluid by using high frequency vibrations. There is no alteration in the surface characteristics of suspended nanoparticles is an important advantage of this technique. The suitable time duration needed for sonication in order to get stable nanofluid based on material, size and concentration of nanoparticles. Ultrasonic bath/vibrator along with homogenizer are commonly used devices for sonication process. But the ultrasonic horn or prob devices as compare to ultrasonic bath are more effective to reduce the size of nanoparticle [72].

Stokes law indicate that the minimum velocity needed for a spherical particle to be suspended stably in host fluid is given by equation (8) [102]. This equation indicates that smaller the size of particle more will be its velocity and hence the particle will be more stable in the suspension.

\[ V = \frac{2\pi^2}{9\mu} (\rho_{np} - \rho_{bf}) \]

where V, R, \( \rho_{np} \) refers to velocity, radius and density of nanoparticle, respectively while \( \mu, \rho_{bf} \) stands for viscosity and density of host fluid, respectively. Asadi et al. [72] reviewed the literatures focusing on stability of nanofluids and the factors affecting it such as sonication time and power. They observed that higher the sonication duration and power more will be the reduction in cluster size, which improves the stability of nanofluid, it is also supported by the equation 8. Thus it is significant to investigate further about the influence of sonication time duration and power to stabilize the mono/hybrid nanofluids.

5. Applications of hybrid nanofluids

The research work on mono/hybrid nanofluid revealed strong possibilities of significant improvement in thermal performance of traditional heat transfer fluids. After introducing nanofluid by Choi [1] in 1995 large number of research work has been conducted regarding application of mono and hybrid nanofluids. Heat exchanger [73-75], electronic cooling [76-79], heat pipes [80-82], engine cooling [83-85], transformer oil [67, 86], nuclear plant [87-89], solar heating [90,91], chillers and domestic refrigerators [92, 93]] are some of the application areas where mono or hybrid nanofluid may be used.

The use of mono/hybrid nanofluid not only improve the thermal performance but it may extend the life span of the device. and minimize the chance of overheating. Choi et al. [67] confirmed that the transformer oil having suspended Al2O3-AIN nanoparticles performed better as compare to pure oil. Sundar et al. [95] prepared Nanodimond-Fe3O4 nanofluid and proposed it as a new heat transfer fluid for heat exchanger application. They conduct experiments for electrical conductivity along with thermal conductivity and viscosity. Zyla et al. [96] investigate the ethylene glycol based nanofluid containing graphite and nanodiamonds. On varying ash content they reported a big impact on electrical conductivity with negligible effect on thermal conductivity. Aberoumand and Jafarimoghaddam [12] investigated dielectric strength along with thermal conductivity of transformer oil having suspended Ag-WO3 nanoparticles. A reduction in dielectric strength is recorded as compare to the pure oil. Contreras et al. [94] reviewed the research work on nanofluid application in electrical transformer. They conclude that heat transfer and dielectric properties enhancement of conventionally used transformer coolant on
adding nanoparticles is reported by researchers. The thermal conductivity improvement may be associated with rise in electrical conductivity. The results related to the dielectric strength of mono/hybrid nanofluids having transformer oil as base fluid are not consistent and need to investigate further.

The performance of HVAC systems may be improved by using mono/hybrid nanofluids as primary or secondary refrigerant. Wang et al. [98] appending nanoparticle n-TiO2(r) into mineral lubricant and get new nanolubricant which is used with HFC134a based refrigeration system. The presence of nanoparticle n-Ti2(r) in general mineral oil can intensify the polarity of the oil and it helps to enhance the compatibility between the new lubricant and HFC refrigerants. This supports the returning of more lubricating oil back to compressor which is an essential condition for safe working of a refrigeration system. Ahmed and Elsaid [97] studied chilled water air conditioning system under the influence of Al2O3-TiO2/water hybrid nanofluid, as secondary working medium. The investigation reveals that the supply fluid temperature decreases more rapidly as the ratio of Al2O3 in hybrid nanofluid increases as compare to TiO2. It also has been noticed that at the same mass fraction of mono nanofluid (Al2O3/H2O) and hybrid nanofluid (0.3%Al2O3+0.1%TiO2)/H2O the evaporator and condenser pressure difference is lower in case of mono nanofluid. In HVAC system the use of nanofluid may help to ensure the presence of lubricating oil in the compressor along with thermal performance improvement.

6. Challenges associated

The researchers expresses their concern about the challenges associated with mono and hybrid nanofluid while reporting about their capabilities of improving thermal performance. The major limitation of mono or hybrid nanofluid is stability, which restricts the implementation of these nanofluids. Siddiqui et al. [99] identified that the Cu nanoparticles have poor dispersion stability with high thermal conductivity and the Al2O3 nanoparticles have good dispersion stability with poor thermal conductivity. They prepared three samples of hybrid nanofluids with different Cu and Al2O3 ratio. The most suitable ratio of Cu and Al2O3 is 0.5:0.5, at which the hybrid nanofluid have significant enhancement in thermal conductivity along with relatively better stability. The stability of mono nanofluids is achieved by various proved methods, but for hybrid nanofluids the stability becomes more complicated as the different types of nanoparticles may possess different surface charges. To get stable hybrid nanofluids the factors such as pH value, surfactants used and the combination of nanoparticle material need to be considered.

The addition of more than one type of nanoparticles for preparing hybrid nanofluid gives us an opportunity to minimize the factors causing penalties such as viscosity, friction factor, pumping power etc. with an affordable compromise of percentage enhancement in thermal performance. The combination of any two type of nanoparticles give rise of entirely different type of characteristics to the composite nanoparticles and hence to the resultant hybrid nanofluid. The various combinations of nanoparticles such as Al2O3+MWCNTs, Cu+TiO2, Cu+CNTs, Cu+MWCNTs and much more like these have been synthesized and used to prepared nanofluids. But the choice of suitable grouping of nanoparticles along with base fluid depends upon the application for which the resultant hybrid nanofluid is targeted.

The selection of proper material of constituent nanoparticles for preparing hybrid nanofluid is not properly defined. The limited studies are available on the collective effect of the factors such as sonication time, use of surfactant, along with nanoparticle combination. The high cost of nanoparticles make the mono and hybrid nanofluid less favourable for the end users. To make nanoparticles and their hybrids affordable is a challenge yet to answer.

7. Conclusion

This paper, is an attempt to get inside on the research on hybrid nanofluid related to their synthesis, important characteristics like thermal conductivity, viscosity, specific heat capacity, and density. The contradictory results are related to thermophysical properties of mono/hybrid nanofluids.
Getting stable mono/hybrid nanofluid is still a major challenge that need to address for their successful implementation in industries. Through this review following points could be concluded.

- To synthesis hybrid nanofluid the two step method is more convenient as here two or more type of nanoparticles can be combined to prepare their composite and then they can be dispersed by any of the established techniques. On the other hand one step method have benefits of stability but their high production cost and small scale production are major drawbacks.
- The metallic nanoparticles contribute more as compare to the non-metallic nanoparticles in improving thermal conductivity of host fluids. Cylindrical shaped nanoparticles are more capable as compare to spherical shaped nanoparticles to rise the thermal conductivity of host fluid. The study of thermal performance under the influence of combination of various nanoparticle materials with different shape and size could be an area to investigate.
- The hybrid nanofluid become more viscous as the concentration of nanoparticles increases on the other hand it becomes less viscous on rise the temperature. On varying the proportion of constituent nanoparticles of hybrid nanoparticle the viscosity of nanofluid may be changed, although the overall concentration of hybrid nanoparticles in the host fluid kept constant.
- The research on density and specific heat of hybrid nanofluids are less. Inconsistency is observed in the results reported regarding change in specific heat of host fluids on adding nanoparticles.
- Selection of appropriate constituent nanoparticle material of hybrid nanoparticles according to base fluid is first and important step. The introduction of surface active agents generally hinders the positive impacts of nanoparticle addition in the host fluid, hence its selection as well as concentration must be optimized to get stable suspension.
- More studies are suggested on collective influence of sonication, use of surfactant, along with nanoparticle shape, size and proper combination, on thermal behaviour of hybrid nanofluids.

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