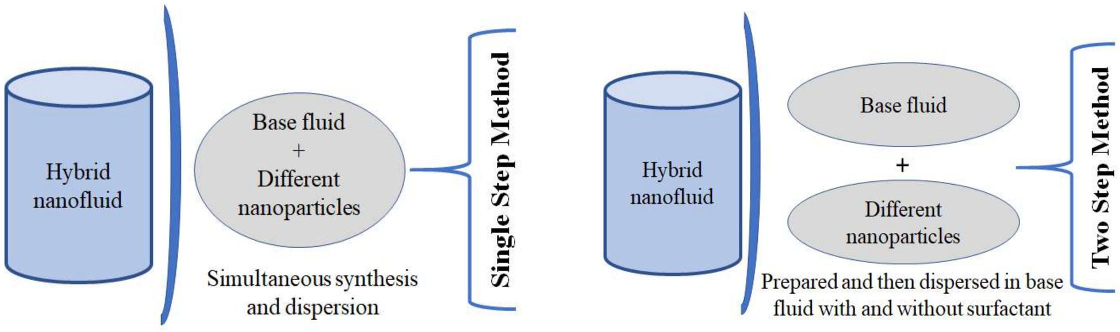
CHAPTER 3

PREPARATION AND CHARACTERIZATION

3.1 Preparation of hybrid nanofluids

Hybrid nanofluids can be prepared using either a *single-step* method or a *two-step* method. Instead of having stability and agglomeration problems, the two-step method is mostly used to prepare the nanofluids over a single-step method **(Sidik et al., 2017; Sundar et al., 2017; Afzali-Tabar et al., 2017; Yarmand et al., 2016b; Baby and Sundara, 2013).** Flowchart for producing hybrid nanofluids using *single-step* and *two-step* methods are shown in Fig. 3.1. In the *single-step* method, nanoparticles are prepared and dispersed directly into base fluids simultaneously. Whereas first nanoparticles are prepared in the two-step process, using the chemical method or mechanical methods followed by their dispersion into base fluids. The two-step method is commonly used to prepare hybrid nanofluids where the agglomerates are not completely isolated so that nanoparticles are only partly dispersed. The thermal conductivity of the hybrid nanofluids may be decreased because of this poor dispersion efficiency. Thus, different techniques are used to get a proper suspension of nanoparticles in the base fluid without agglomeration in order to achieve a significant improvement in the properties of hybrid nanofluids. Water-based different hybrid nanofluids have been synthesized by a two-step method using such a technique in the present study. Distilled water (DI water) is taken as a base fluid throughout the research work.



(a) **(b)**

Fig. 3.1 Hybrid nanofluid synthesis methods (a) single-step method (b) two-step method

Different types of nanoparticles such as oxides (Al_2O_3, MgO, CuO, TiO_2), carbide (SiC), nitrite (AlN), allotropes of carbon (MWCNT and Graphene), metal (Cu) and phase change material (capric acid) have been used in the present investigation. Different nanoparticles and aqueous alumina solution have been commercially purchased from Alfa Aesar, Otto Chemika and SRL companies. Acid treated MWCNT has been taken in this study to make it hydrophilic to DI water to synthesize a better colloidal solution. 0.01 and 0.1% volume total concentration of solid nanoparticles have been used to prepare nanofluids in this study by taking Al_2O_3 nanoparticle and all other nanoparticles in 50/50, vol/vol ratio. Capric acid has been used as a phase change material in the present study. The reason for considering capric acid as PCM because of its melting point, which is slightly above the room temperature (~32°C) to take advantage of its latent heat. The present study has been done on low concentration due to the following two reasons (i) higher stability at lower concentration and (ii) channel clogging problem at higher concentration.

In the present investigation, hybrid nanofluids have been prepared by using a *two-step* method. The flow chart for the two-step method in the present investigation with different processes is shown in **Fig. 3.2.** First, an electronic weighing machine (model: ATX224, SHIMADZU, Japan) with ±0.0001 accuracy has been used to measure the calculated amounts of nanoparticles. Hybrid nanofluid is represented as a nanoparticle (a:b) where a represents the volume of Al_2O_3 nanoparticle and b represents the volume of another nanoparticle. For fixed volume concentration and composition, the mass of different types of nanoparticles has been calculated.

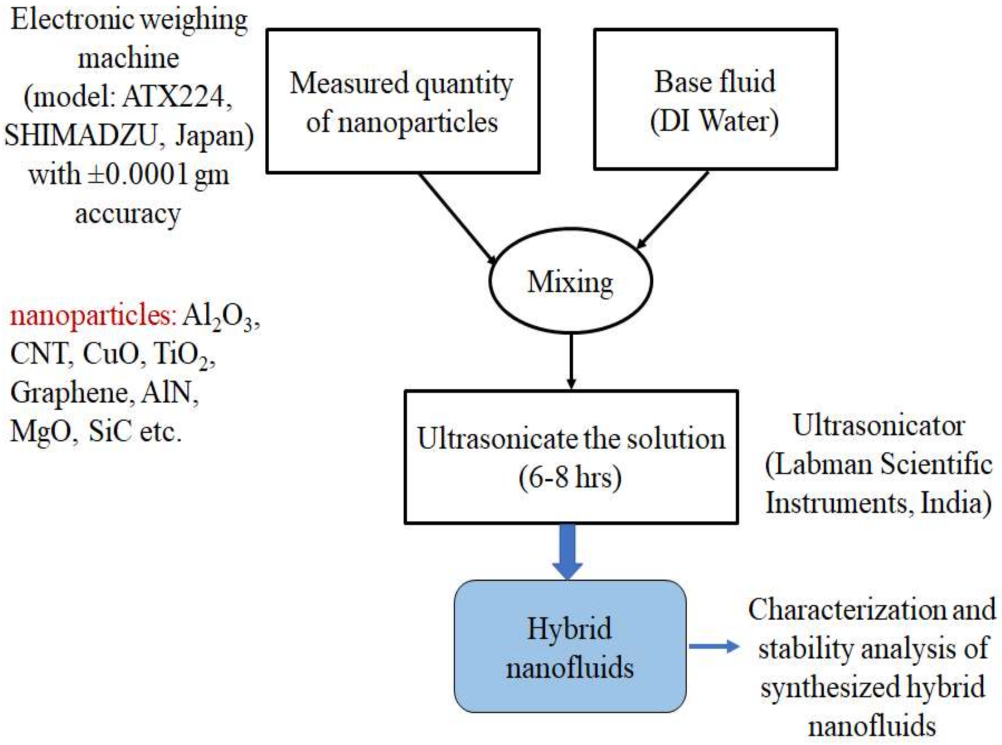
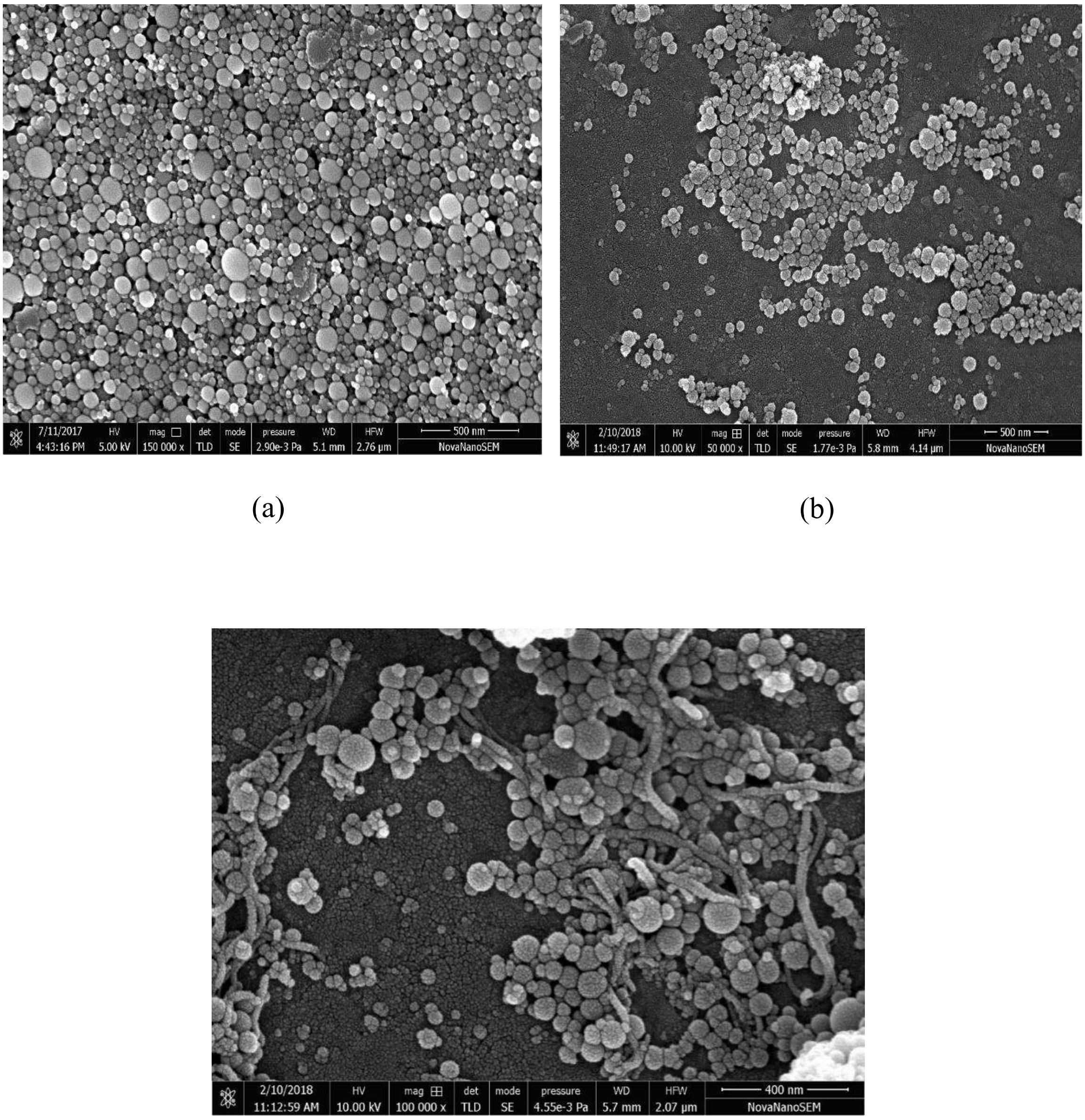


Fig. 3.2 Flow chart for the two-step method in the present investigation

Then, the nanoparticles, along with surfactants (if required), have been mixed with base fluid and then ultrasonicated for some time at a particular temperature. Al_2O_3 nanofluid with 0.01 % and 0.1 % volume concentration have been prepared using a mechanical stirrer and ultrasonicator (Labman Scientific Instruments, India 40 kHz) and then the second particle has been added to it. The solution has been stirred for 1 hour through stirrer followed by ultrasonication at 40°C for 6-8 hrs. Through the same procedure, various hybrid nanofluids have been prepared, for different ultrasonication time, containing the different combinations of nanoparticles in different ratios with 0.01 % and 0.1% volume concentration. Cetyltrimethyl ammonium bromide (CTAB) has been used to synthesized Al_2O_3+Cu/DI water hybrid nanofluid to increase stability. All other hybrid nanofluids have been prepared without using surfactants. In the case of PCM based nanofluid, PCM added in the solid condition and during the sonication, the temperature was above its melting point temperature to ensure that the PCM nanofluid is homogenously synthesized in the liquid state. Similar to the preparation of mixture-dispersed hybrid nanofluid, the reduced graphene oxide-Zinc oxide (rGO-ZnO) nanocomposite particles dispersed hybrid nanofluid has also been synthesized using the two-step method.

3.2 Characterization of nanoparticles

The microstructure, morphology of nanoparticles and particle distribution have been captured using SEM (Scanning Electron Microscopy), model EVO-Scanning Electron Microscope MA15/18 provided by Carl Zeiss Microscopy Ltd. Fig. 3.3 displays the SEM images of the Al_2O_3 nanoparticles, Al_2O_3-TiO_2 nanoparticles mixture and Al_2O_3-MWCNT nanoparticles mixture. To prepare the sample for SEM characterization, a drop of prepared nanofluid/hybrid nanofluid is taken on a glass slide. This glass slide is left in atmosphere to vaporize the water from it. Here it is assumed that the particles do not displaced from its position and particles stick to the surface when all the water evaporates. The prepared sample on glass slide is taken for the SEM characterization. Then mixing is done for 2 hoursFig. 3.3 (a) shows that the size range of Al_2O_3 particles is within 50 nm as predicted by ImageJ software. In Fig. 3.3 (b) the larger one represents Al_2O_3 nanoparticles (avg. size 40 nm) and smaller represents TiO_2 nanoparticles (avg. size 20 nm). In Fig. 3.3 (c), the cylindrical shape particles represent MWCNT nanoparticles, while smaller (spherical shape) represents alumina nanoparticles. The length of MWCNT is in the micrometer range.



(a) (b)

(c)

Fig. 3.3 SEM image of (a) Al_2O_3 nanoparticles (b) Al_2O_3-TiO_2 nanoparticles mixture and (c) Al_2O_3-MWCNT nanoparticles mixture

Reduced graphene oxide with zinc oxide (rGO-ZnO) composite nanoparticles has been synthesized by the sol-gel method. First graphene oxide (GO) was synthesized by employing Hummers method. In the second step, $ZnSO_4 \cdot 7H_2O$ (Sigma-Aldrich) solution of 0.01 M was prepared in deionized water. The solution was stirred on a magnetic stirrer to get a clear solution. This solution was further heated in an oven at a constant temperature of 280°C for thermal decomposition to yield zinc sulfate and water. Then drop by drop dilute ammonium solution added to it with the addition of 0.01 mg/ml concentration of a sonicated solution of GO at room temperature. After this, the solution is stirred at a temperature of 70°C and centrifuged at 2500 rpm for 30 min. From centrifuging, the precipitate was removed and washed with DI water. It was put to dry overnight in the vacuum oven. For further characterizations, the dried precipitates are grinded to a fine powder. Further information can be obtained by **Yadav et al. (2019)**. This nanocomposite may be a better candidate for heat transfer due to the lotus-like structure of ZnO on the rGO sheet because of the leaf of the flower.

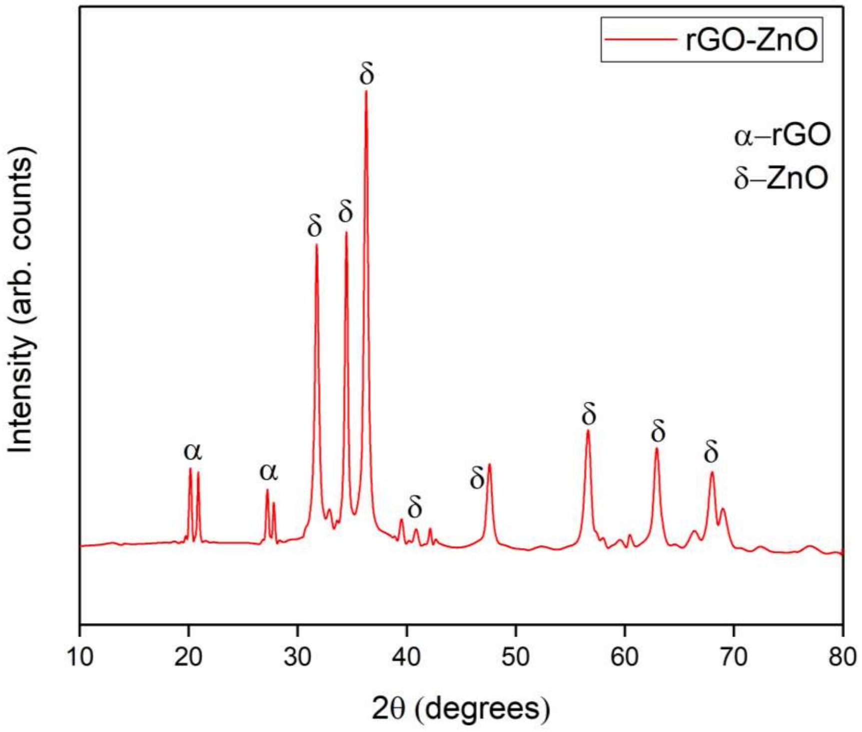
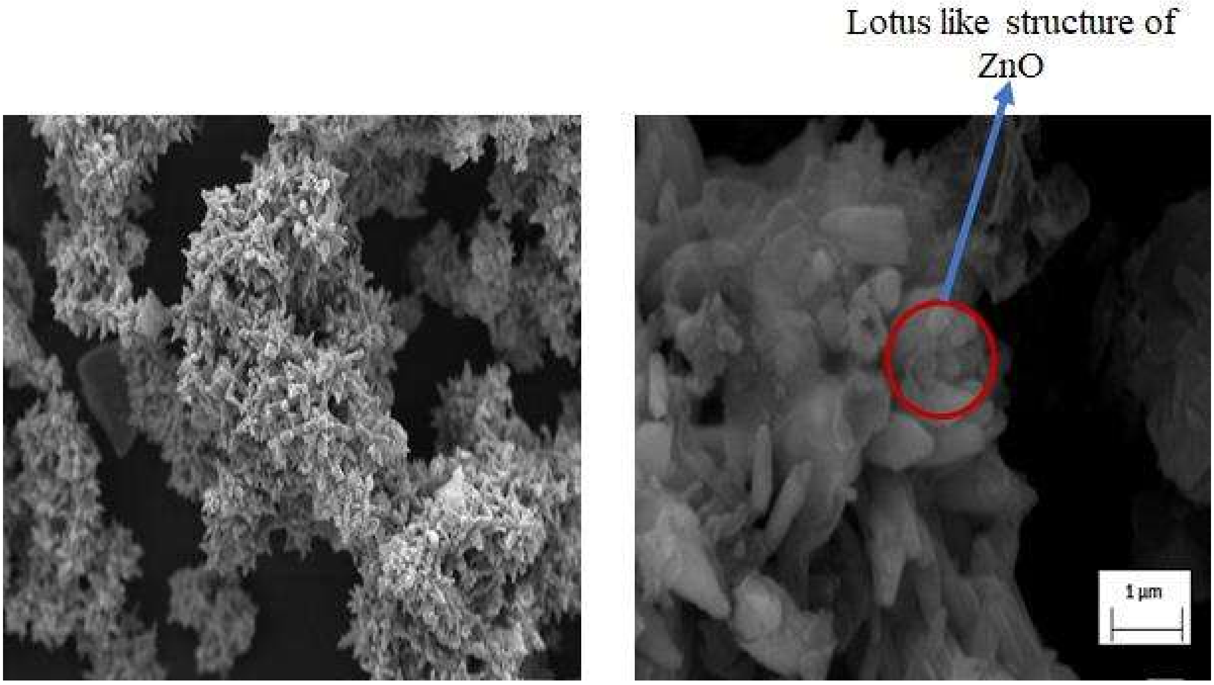


Fig. 3.4 XRD of rGO-ZnO composite



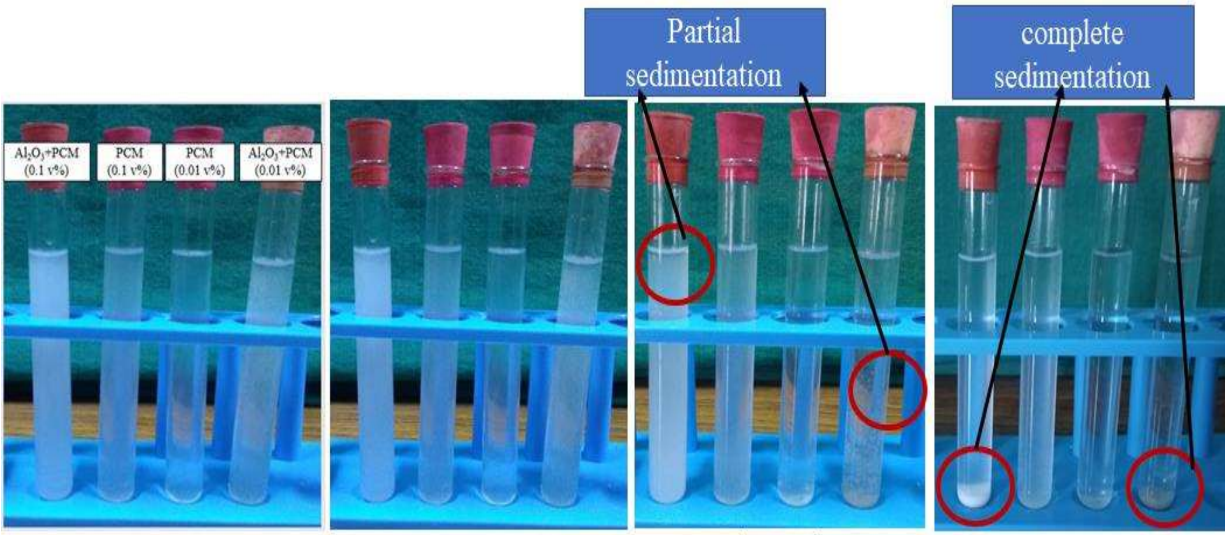
(a) (b)

Fig. 3.5 SEM image of rGO-ZnO nanocomposite in increasing magnification

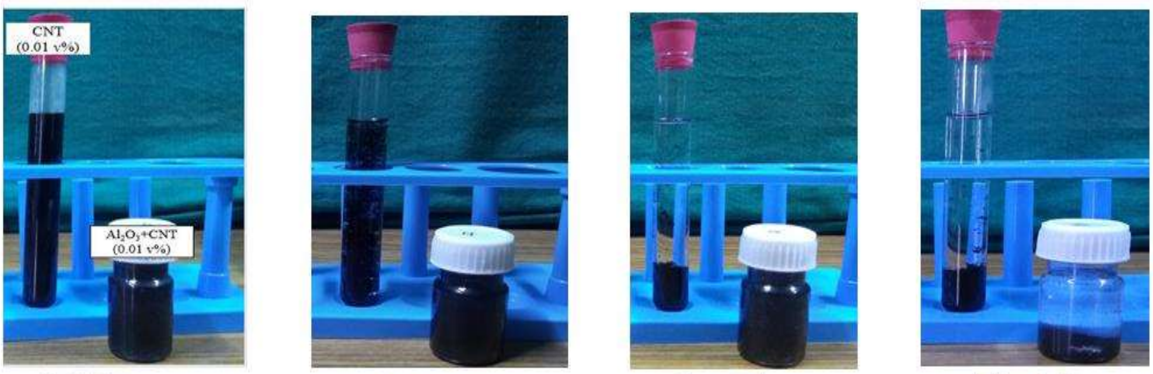
XRD and SEM images of the synthesized rGO-ZnO composite are presented in Fig. 3.4 and Fig. 3.5, respectively. XRD was done by X-ray diffractometer (Model Bruker D8, U.K.) having Cu-Kα radiation with the angle range of 10-80° with 5°/min scanning speed. rGO is represented by peak marked ‘α’ and ZnO marked as ‘δ’. These can be classified according to the standardized JCPDS No.36–1451 of ZnO to a crystalline hexagonal wartzite structure. No characteristic peaks were, however, found in the corresponding area for either GO or graphite. That may be due to GO's transformation into rGO. The crystalline size was measured corresponding to the major peak having (hkl) value (101) using the Deby-Scherrer formula. The crystalline size was observed as 20 nm. **(Yadav et al., 2019).** In this work, rGO sheets are well dispersed in the solution and provide numerous negative charged sites to attract the positively charged Zn^{+2} ions result in the formation of ZnO crystal having a large number of nanorods as lotus-like structures as shown in Fig. 3.5.

3.3 Characterization of hybrid nanofluids

Characterization of hybrid nanofluids is very important with respect to utilizing it in heat transfer applications. Some of the characterizations, such as thermal and rheological characterizations and pH are performed for all the hybrid nanofluids considered in the present study. In this section, stability and homogeneity analyses are discussed. Thermophysical properties (thermal and rheological characterization) are discussed in section 3.4.



Initial stage After 48 hrs After 5 days After 7 days



Initial stage After 60 hrs After 72 hrs After 5 days

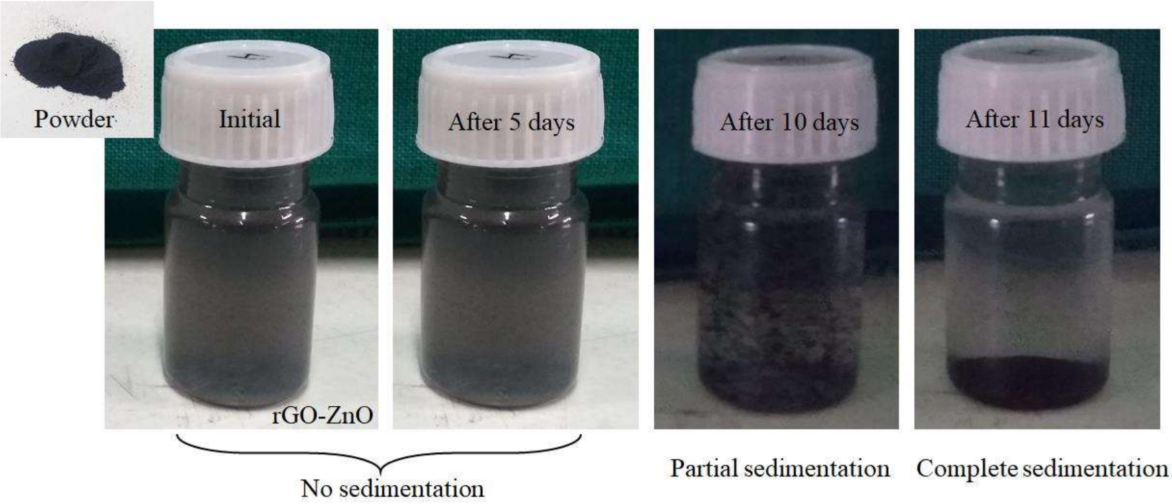


Fig 3.6 Photographs of different mono/hybrid nanofluids of 0.01 vol% at different times

The stability of synthesized hybrid nanofluid has been analyzed with the concept of isoelectric point (IEP) and conventional photography method. Sedimentation photography is the simplest and qualitative method to check the stability of nanofluids visually. From which the sedimentation of dispersed nanoparticles can be observed from naked eyes. This method also has limitations as it can not be used for partial sedimentation and higher concentration nanofluids. But in the present investigation, a lower concentration (0.01 and 0.1 vol%) is considered, so this method is reliable to check the stability. Photographs of different mono/hybrid nanofluids of 0.01 vol% at different times are shown in Fig. 3.6. Settling of nanoparticles has not been observed for at least 2 days, which is sufficient time for conducting present experimental investigations. A similar case has been observed with other samples, which were found stable for a minimum of around 4 days. The investigation of isoelectric point of the Al_2O_3, MgO, TiO_2, CuO, SiC, AlN, MWCNT, graphene and Cu nanoparticles is available in the literature and shown in Table 3.1 **(Singh et al., 2005; Singh et al., 2007; Singh et al., 2012; Smolen et al., 2013; Sousa and Teixeira et al., 2013; Hetlani et al., 2017; Wang et al., 2017; Bahreini et al., 2018)**. Stability is ensured when the pH is far away from the IEP because of the large repulsion force between the nanoparticles. **Suresh et al. (2011)** explained that the pH of hybrid nanofluids approaches the IEP (i.e., nanoparticle carries no net charges) at a higher concentration of nanoparticles in the base fluid. So, it is ensured by the pH that at a higher concentration, the stability of nanofluid is poor. The pH of hybrid nanofluids was investigated by digital pH meter and has been provided in Table 3.2 and 3.3 at different volume concentrations. From Table 3.1 and 3.2, it is ensured that each hybrid nanofluid has pH value far away from the isoelectric point of respective nanoparticles. Thus, the pH value and photography method confirmed the stability of hybrid nanofluids. From Table 3.3, it can be concluded that the pH of hybrid nanofluids are approaching towards IEP. Furthermore, for assuring the homogeneity of the prepared hybrid nanofluids, the pH, density and viscosity of synthesized hybrid nanofluids were determined for the different samples from random positions in the beaker. No appreciable change was measured in the pH, density and viscosity for all the samples at room temperature. This test can ensure the homogeneity of the prepared samples of hybrid nanofluids.

3.4 Thermo-physical properties of hybrid nanofluids

The precise information on thermophysical properties is required to evaluate the performance of any thermal device operated with hybrid nanofluids. Such properties depend strongly on the quantity of nanoparticles that are added to the base fluid. In order to analytically or experimentally obtain the thermophysical properties of hybrid nanofluid, the nanoparticles were believed to be distributed uniformly (i.e., homogeneity) within the base fluid. In the present study, these thermophysical properties have been measured experimentally using different instruments.

3.4.1 Measurement procedure

Different properties have been tested in the present investigation using various equipment such as the TPS 500 hot disk thermal constant analyzer for thermal conductivity and specific heat, Brookfield viscometer for viscosity and automated weighing machine for the density of different working fluids. Measurement of the density (ρ) of various fluids is performed using the relation $\rho = m/v$. Here m is mass in kg and v is the volume in m^3. For this, a marked beaker has been taken and weighted it using electronics weighing balance (model: ATX224, SHIMADZU, Japan), as shown in Fig. 3.7 (a). Then a specified amount of fluid sample was taken and weighted in that beaker. The mass of the beaker was subtracted from the measured mass, and hence the mass of the fluid was obtained. This mass was then divided with the volume to get the sample density. DV1 Brookfield Digital Viscometer (cone and plate) was used to measure the viscosity of the different fluids, as shown in Fig. 3.7 (b) with a temperature bath setting the temperature of the test fluid to different values. DV1's operating principle is to drive through a calibrated spring a spindle attached to a plate that is submerged in the test fluid. The viscous drag of the fluid against the plate and spindle is determined by the spring deflection. This system provides continuous measurement sensing and displays over the whole study. Low viscosity fluids generally require spindles with larger surface areas and at high rotational speeds. The spindle used was CP-42, which is used in the viscosity samples starting at 0.3cP. The minimum amount of fluid needed for analysis of the viscosity is 1.0 ml. Hybrid nanofluids are low volume concentrations (0.01% and 0.1%) prepared for the present investigation. Thus, due to the linear variation between shear stress and shear strain rate, hybrid nanofluids can be treated as Newtonian fluids at such low volume concentration **(Eshgarf and Afrand, 2016; Bahrami et al., 2016; Zareie and Akbari, 2017)**.

Thermal conductivity and specific heat of the fluid have been measured by Hot Disk Thermal Constants Analyzer (as shown in Fig. 3.7 (c) with their components), which works on the transient plane source technique. The used sensor is a nickel foil that is embedded between two thick layers of Kapton polyimide film. The nickel foil wound in a double spiral pattern has a radius of 3.189 mm. Spherical waves are generated through the probe end, which travels through the sample while passing the heating power. For a constant heating rate, the hot disk tests the thermal conductivity and thermal resistivity from the temperature increase rate of the probe. The thermal conductivity of fluids within the range of 0.2–2 W/m. K can be measured with an accuracy of ±2%. Volumetric heat capacity (ρc_p) value has been taken directly from the TPS-500 analyzer and the specific heat c_p was obtained by dividing ρc_p with density (ρ).

(a) (b) (c)

Fig 3.7 Photograph of (a) Digital weighing balance (b) Brookfield DV1 digital viscometer and (c) Hot disk thermal constants analyzer apparatus

3.4.2 Results and discussion

Various properties of different nanoparticles with their particle size and isoelectric point (IEP) and phase change material are listed in Table 3.1. Al_2O_3, TiO_2, MgO, CuO, SiC, AlN, MWCNT, Cu, graphene nanoparticles and capric acid as phase change material were used in the present investigation. DI water is considered as base fluid throughout the study. Graphene nanoplates have the highest thermal conductivity among the nanoparticles, and titanium has the lowest thermal conductivity. In the case of density, graphene has the lowest and Cu has the highest density. Phase change material has the lowest thermal conductivity and density in between all the particles (i.e., nanoparticles and PCM). The melting point and latent heat of PCM are 31.6°C and 157.8 KJ/kg, respectively. Different nanoparticles and PCM with their size, properties and isoelectric point (IEP) are listed in Table 3.1.

Thermo-physical properties of different alumina hybrid nanofluid (0.01 vol%) in equal nanoparticle proportion (50/50, vol/vol) at ambient temperature are given in Table 3.2. Whereas, thermo-physical properties of Al_2O_3-MWCNT hybrid nanofluid (0.01 vol%) and Al_2O_3-TiO_2 hybrid nanofluid (0.1 vol%) for different nanoparticle proportion (5:0, 4:1, 3:2, 2:3, 1:4 and 0:5) at ambient temperature are given in Tables 3.3 and 3.4, respectively.

Table 3.1 Different nanoparticles and PCM with their size, properties and IEP

Types of nano-particles	**Average particle size, nm**	**Thermal cond-uctivity, (W/m.K)**	**Specific heat, (J/kg.K)**	**Density, (kg/m^3)**	**Melting point (°C)**	**Latent heat (kJ/kg)**	**Iso-electric point (IEP)**
Al_2O_3	<50	36	880	3960	-	-	9.1 (Singh et al., 2005)
PCM	-	0.151 (l)	2100 (s), 2090 (l)	1004 (s), 870 (l)	31.6	157.8	-

TiO_2	<30	8.9	697	4260	-	-	5.98 (Hetlani et al., 2017)
MgO	90	48.4	877	3580	-	-	10.5 (Wang et al. 2017)
CuO	<50	33	530	6400	-	-	~10 (Sousa and Teixeira, 2013)
SiC	50	350	1340	3210	-	-	4.9 (Singh et al., 2007)
AlN	<40	300	780	3260	-	-	9-10 (Smolen et al., 2013)
Cu	40	401	385	8933	-	-	~10 (Sousa and Teixeira, 2013)
MWCNT	OD: 20-30, Length: 2μm	3000	740	2600	-	-	4.5 (Singh et al., 2012)
Graphene	Thickness: 0.6-1.2 nm, Length: 0.8-2μm	5000	790	2200	-	-	3-4 (Bahreini et al., 2018)

Table 3.2 Thermo-physical properties of different hybrid nanofluids (50/50 vol/vol) at total concentration of 0.01 vol% at ambient temperature

Working fluids	**Thermal conductivity (W/m.K)**	**Specific heat (J/kg.K)**	**Density (kg/m^3)**	**Viscosity (Pa.s)**	**pH value**
DI water	0.617	4182.40	997.30	0.000910	6.93

Al_2O_3/DI water	0.619	4181.00	998.80	0.000930	7.62
Al_2O_3+PCM/ DI water	0.614	4178.42	998.60	0.001042	7.21
Al_2O_3+TiO_2/ DI water	0.619	4176.54	999.86	0.001042	7.05
Al_2O_3+CuO/ DI water	0.620	4176.52	999.93	0.001035	8.07
Al_2O_3+MgO/ DI water	0.620	4176.85	999.32	0.001025	8.23
Al_2O_3+SiC/ DI water	0.621	4177.47	999.33	0.001026	6.82
Al_2O_3+AlN/ DI water	0.622	4178.40	999.20	0.001023	7.56
Al_2O_3+Cu/ DI water	0.624	4176.49	1000.34	0.001043	8.12
Al_2O_3+MWCNT/ DI water	0.627	4178.37	998.90	0.001049	7.73
Al_2O_3+Graphene/ DI water	0.630	4176.52	998.85	0.001051	6.45

Table 3.3 Thermo-physical properties of different hybrid nanofluids (50/50 vol/vol) at total concentration of 0.1 vol% at ambient temperature

Working fluids	**Thermal conductivity (W/m.K)**	**Specific heat (J/kg.K)**	**Density (kg/m^3)**	**Viscosity (Pa.s)**	**pH value**
DI water	0.617	4182.40	997.30	0.000910	6.93
Al_2O_3/DI water	0.622	4180.71	999.10	0.000934	8.32
Al_2O_3+PCM/ DI water	0.618	4178.02	999.70	0.001053	7.93
Al_2O_3+TiO_2/ DI water	0.621	4176.12	1000.15	0.001054	5.69
Al_2O_3+CuO/ DI water	0.623	4176.00	1000.82	0.001047	8.37
Al_2O_3+MgO/ DI water	0.625	4176.23	1000.56	0.001040	8.53

Al_2O_3+SiC/ DI water	0.628	4176.99	1000.48	0.001033	6.63
Al_2O_3+AlN/ DI water	0.631	4177.98	1000.20	0.001034	7.42
Al_2O_3+Cu/ DI water	0.638	4176.03	1001.92	0.001050	8.40
Al_2O_3+MWCNT/ DI water	0.643	4177.91	999.17	0.001057	7.56
Al_2O_3+Graphene/ DI water	0.647	4175.93	999.10	0.001063	6.10

From Table 3.2, it is observed that hybrid nanofluids with high conductivity particles show high thermal conductivity and so on. Hence, allotropes of carbon suspended hybrid combination possess the highest thermal conductivity followed by AlN, SiC, MgO, CuO, TiO_2, PCM hybrid nanofluids. In addition, viscosity is found the maximum for Al_2O_3-TiO_2 and minimum for Al_2O_3-PCM hybrid nanofluids. With the addition of nanoparticles in the base fluid, thermal conductivity, density and viscosity increase while specific heat decreases. Al_2O_3+graphene hybrid nanofluid has 2.1% and 1.78% enhancement in thermal conductivity compared to base fluid (DI water) and Al_2O_3/DI water nanofluid, respectively. Al_2O_3+Cu hybrid nanofluid possesses the maximum density enhancement as compared to Al_2O_3 nanofluid due to the higher density of copper nanoparticles. Specific heat has been found to minimum for Al_2O_3+graphene hybrid nanofluid. Table 3.3 listed the thermo-physical properties of different hybrid nanofluids (50/50 vol/vol) at a total concentration of 0.1 vol% at ambient temperature. It is observed that at higher concentration (i.e., 0.1 vol%), thermal conductivity, density and viscosity increase and specific heat decreases as compared to lower concentration (0.01 vol%). Maximum enhancement of 2.7% is observed for Al_2O_3+Graphene/ DI water hybrid nanofluid when volume concentration increases from 0.01 vol% to 0.1 vol%.

Table 3.4 Thermo-physical properties of Alumina-MWCNT hybrid nanofluid (0.01 vol%) for different proportion at ambient temperature

Different Fluids	**Thermal conductivity (W/m.K)**	**Specific heat (J/kg.K)**	**Density (kg/m^3)**	**Viscosity (Pa.s)**
DI water	0.6170	4182.4	997.3	0.00091
Al_2O_3+CNT (5:0)/ DI water	0.6185	4181.0	998.8	0.00093
Al_2O_3+CNT (4:1)/ DI water	0.6202	4180.8	998.7	0.00094
Al_2O_3+CNT (3:2)/ DI water	0.6259	4180.4	998.2	0.00095
Al_2O_3+CNT (2:3)/ DI water	0.6273	4180.3	998.0	0.00095
Al_2O_3+CNT (1:4)/ DI water	0.6294	4180.1	997.9	0.00097
Al_2O_3+CNT (0:5)/ DI water	0.6307	7179.9	997.7	0.00099

Table 3.5 Thermo-physical properties of Alumina-Titania hybrid nanofluid (0.1 vol%) for different proportion at ambient temperature

Different Fluids	**Thermal conductivity (W/m.K)**	**Specific heat (J/kg.K)**	**Density (kg/m^3)**	**Viscosity (Pa.s)**
DI water	0.6170	4182.4	997.3	0.00091
Al_2O_3+TiO_2 (5:0)/ DI water	0.6219	4180.7	999.1	0.00093
Al_2O_3+TiO_2 (4:1)/ DI water	0.6210	4180.6	999.1	0.00093
Al_2O_3+TiO_2 (3:2)/ DI water	0.6202	4180.5	999.1	0.00093
Al_2O_3+TiO_2 (2:3)/ DI water	0.6196	4180.2	999.2	0.00093
Al_2O_3+TiO_2 (1:4)/ DI water	0.6190	4180.0	999.2	0.00094
Al_2O_3+TiO_2 (0:5)/ DI water	0.6181	7179.7	999.3	0.00094

The thermal conductivity has been found the minimum for Al_2O_3 nanofluid (5:0) and maximum for CNT nanofluid (0:5) in the case of Al_2O_3-MWCNT hybrid nanofluids

(Table 3.4). The maximum enhancement of 2.22% and 1.97% is observed in the thermal conductivity for the CNT nanofluid (0:5) as compared to DI water and Al_2O_3 nanofluid (5:0). Density and viscosity are found the maximum for (5:0) and minimum for (0:5) alumina-MWCNT hybrid nanofluids. As the fraction of MWCNT particles in hybrid nanofluid increases, thermal conductivity and viscosity increase, whereas density and specific heat of hybrid nanofluid decrease. The findings are dissimilar, as in the case of Al_2O_3-TiO_2 hybrid nanofluids. It is observed from Table 3.5 that the thermal conductivity of hybrid nanofluids is higher than the base fluid. It is a minimum for 100% titania (TiO_2) nanofluid and maximum for 100% alumina (Al_2O_3) nanofluid. This is because the titania particle has less thermal conductivity and alumina has more thermal conductivity. Thermal conductivity goes down when the fraction of titania nanoparticles increases in the hybrid nanofluid. The maximum enhancement of 0.61% is observed in the thermal conductivity for the Al_2O_3 nanofluids (0.1 vol%) compared to pure titania nanofluid. The density and viscosity of the hybrid nanofluids are higher than that of the base fluid. Both are found the maximum for TiO_2 nanofluid and minimum for Al_2O_3 nanofluids. Titania possesses more and alumina to possess less density. By adding the nanoparticles to the base fluid, its specific heat decreases. The specific heat is found the maximum for Al_2O_3 nanofluid and it decreases with an increase in the portion of titania nanoparticles. As shown in Table 3.3 and 3.4, the thermal conductivity increases with a rise in volume concentration from 0.01% to 0.1% for Al_2O_3 nanofluid. The enhancement of 0.24% for 0.01 vol% and 0.8% for 0.1 vol% is observed. It shows that the thermal conductivity is not linearly varying with volume concentration.

The thermal conductivity, specific heat, density and viscosity of prepared composite based hybrid nanofluid at a solid concentration of 0.01 vol% is 0.626 W/m^2.K, 4177.89 J/kg.K, 999.46 kg/m^3 and 0.001045 Pa.s, respectively.

3.5 Highlights

In the present investigation, the two-step method has been employed for preparation of hybrid nanofluids. Then synthesized hybrid nanofluids have been characterized and different thermo-physical properties have been measured and tabulated. Morphology (shape and size) of particles has been confirmed by the SEM image. The stability of the hybrid nanofluids has been justified by the conventional photography method and isoelectric point (IEP). For proper dispersion of nanoparticles in the base fluid, a homogeneity test has been performed. From results and discussion, the following observations are made:

1. All the particles are of spherical shape (dimension lies within 10-100 nm) except MWCNT and graphene. MWCNT is in a cylindrical shape (diameter is in nm and length is in μm range) and graphene is in platelet shape (thickness in nm and length is in μm range).
2. The pH value and photography method confirmed the stability of hybrid nanofluids. The prepared hybrid solution was stable for a minimum 2 days (by nanofluid photographs), which is a sufficient time interval for conducting the present experimental investigations. Minimum and maximum stability are observed for CNT nanofluid and composite hybrid nanofluid, respectively. The stability of hybrid nanofluids is poor with a rise in volume concentration (based on IEP).

3. The prepared suspensions are homogeneous concerning the measured thermo-physical properties at different locations of the prepared sample.
4. Allotropes of carbon (non-spherical shape) dispersed hybrid nanofluids have high thermal conductivity, low density and high viscosity. While spherical shaped nanoparticles dispersed, hybrid nanofluids have low thermal conductivity and high density.
5. Thermal conductivity, viscosity and density increase and specific heat decrease when volume concentration rises from 0.01 vol% to 0.1 vol%.
6. As the MWCNT fraction rises in Al_2O_3+CNT/DI water hybrid nanofluids, thermal conductivity and viscosity increase while specific heat and density decrease. But in the case of Al_2O_3+TiO_2/DI water hybrid nanofluids, thermal conductivity and specific heat decrease while density and viscosity increase with a rise in TiO_2 fraction.