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Review Article

Hybrid nanofluids development and benefits: A comprehensive review

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ABSTRACT

Hybrid nanofluids (HNFs) have received the prominent attention of researchers due to their improved thermophysical properties than conventional liquids and single-phase nanofluids. Such high potential heat transfer fluids are obtained from the suspension of two or more dissimilar nanoparticles in a regular heat transfer liquid. Owing to the high heat transfer properties of hybrid nanofluid, these are widely used in industrial processes, manufacturing processes, and biomedical engineering. This framework presents a detailed review of hybrid nanofluids preparation, stability, thermophysical properties, and importance in various engineering fields. Furthermore, present analysis addresses the pH control and ultrasound intensity of hybrid nanofluid. This analysis also manifests a hy brid nanofluid preparation method and suitable nanoparticles mixers for various industrial uses. This study reveals some future trends and possibilities related to HNF and a few suggestions regarding the scope in the future research in this area. A big impact with small particles for coming years. The hybrid nanofluid are having higher thermal conductivity which affects significantly to mac hining output response variables. By hybridizing the suitable combination of nanoparticles, the required heat transfer effect can be obtained still at low particle concentrations.

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INTRODUCTION

A nanofluid is developed with the integration of nanoparticle and base fluid. Choi [1] introduced the concept of nanofluid. Nano is a Latin word used to denote 10^{-9}nm part of units. The nanofluid heat conduction depends on several things such as geometrical shape, size and stability of the nanoparticle, type of base fluid thickness and temperature. The base fluids may be water, organic liquids (C_2H_2, refrigerants, etc.), oils, bio-fluids (blood, synovial fluid, etc) and other liquids. The materials used for nanoparticles must be chemically stable (metals: gold,

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copper, metal oxides: Al_2O_3, SiO_2, TiO_2, oxide ceramics: Al_2O_3, CuO, metal nitrides, metal carbides, carbon in various forms: carbon nanotubes, graphite, and diamond) and functionalized nanoparticles [2, 3]. The applications of nanofluids are found in various fields like electronics [4,5], solar energy [6-8], nuclear reactors [9–11], pool boiling [12, 13], automotive industry [14–16], medical [17–19], food industry [20, 21], machining processes [22–25], and in heating and cooling of buildings [26, 27]. In comparison to single nanoparticle fluids and traditional fluids, the nanofluids demonstrated improved thermal characteristics [28-36]. So, this field looks emerging for future studies.

In parallel to the continuation of these fluids, scientists also used a novel class of nanofluids called a "hybrid" nanofluid acquired by suspending nanocomposite or nanoparticles of different metals into the base fluid as shown in fig.1. These HNFs are more stable and suitable than the mono nanofluids.

There is no doubt that the thermal conductivity of base fluids enhanced with the addition of nanoparticles, but it also raised some problems in the form of pumping power, erosion, convection heat transfer, stability, and pressure drop due to the enhancement in viscosity resulting from the creation of clusters that increases the hydrodynamic diameter and reduces the specific surface area. The hybrid nanofluids exhibited higher viscosity as compared to the conventional fluids and most of the unitary nanofluids. However, it depends on the selected nanoparticles and their combinations. Hybrid nanofluids have better rheological properties and less clogging in pipes.

The main intention of this review is to get general idea of production, nature and use of hybrid nanofluids. Here many experimental and numerical works finished by several investigators have been reviewed. At last, feasible applications and challenges are discussed.

PREPARATION OF HYBRID NANOFLUID

Nanofluid preparation is just mixing a nano powder in a liquid. But, in reality it is more critical to determine the stability of the nanofluid. For real time applications stability, durability and chemical unresponsiveness of the nano particles in the underlying fluid which is extremely significant. The technique that performs effectively to prepare HNF is suspending nanoparticles of particular elements or the composite nanoparticles are suspended in a host fluid at definite ratio. To get a homogeneous and stable distribution sonication technique is customized. By mixing a suitable surfactant the glomeration can be decreased further.

Combination of a suitable surfactant can decrease the glomeration. Generally, Hybrid nanofluids can be made in 2 distinct ways. There are two types of methods: one-step and two-step. Other innovative ways for synthesizing quality and stability in hybrid nanofluids for heat transmission and experimentation are also being developed.

(a) Single-step method:

In this method, production of nanoparticles and preparation of nanofluid are finished at the same time. Here, nanoparticles are synthesized and suspended in the base fluid in a single step. [37,38]. There are so many one-step techniques by which nanofluids are prepared, for example Laser ablation process [39], Electro discharge process [40], micro electrical discharge machining (micro-EDM) process [41]. However, One-step physical method is unable to produce nanofluids in large scale because of too much cost, hence the chemical method with one step was developed. In chemical techniques When reduction processes or ion exchange occur, the base fluids contain additional ions and reaction products that are difficult to remove from the fluids. Besides, nanoparticles generated by chemical processes have a propensity to agglomerate, which restricts the potential of the high surface areas of the nanoparticles. Thus, particle scattering must be carried out.

To avoid oxidation in high heat conductive metals this scheme is most suitable. In this process, uniform scattering of particles and high stability can be achieved. In addition, drying, storage, dispel of the nanoparticles can be prevented. The negative aspect of this method is not cost effective at mass production used for small scale production.

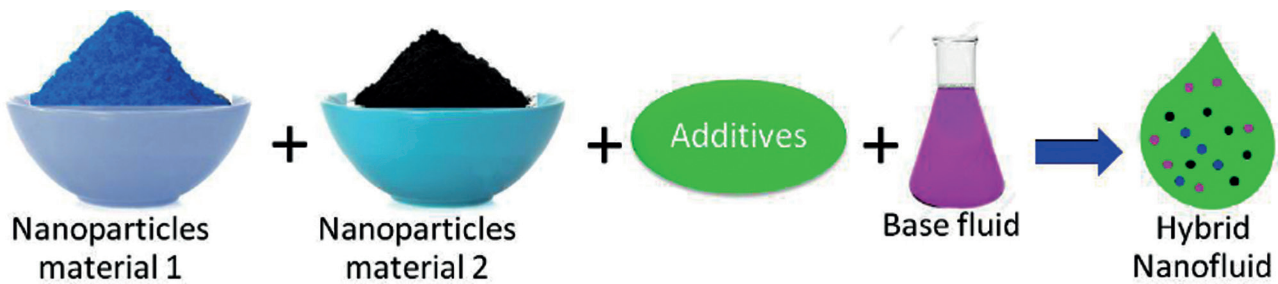

Figure 1. Graphical representation of Hybrid nanofluid.

Table 1. Variety types of nanoparticles and base fluids used in developing nanofluids

Origin	Nanoparticles	Base fluids
Metals	Cu*	Water, EG, oil, acetone and water & EG mixture.
	Ag*	Water and toluene.
	Au*	Water and toluene.
	Al*	Water, EG, oil & kerosene
Oxides	Al_2O_3*	Water, EG, oil, water & glycerine mixture.
	CuO*	Water, oil, and R-134a*.
	ZnO*	Water, EG, & oil.
	TiO_2*	Water, EG, oil, water & EG mixture and bioglycol & water mixture.
	SiO_2*	Water, EG, glycerol, oil and glycerol & EG mixture.
Carbon-based	MWCNTs*	Water, EG, water & EG mixture and fullerenes oil.
	DWCNTs*	Water & EG.
	SWCNTs*	Water, Water & EG mixture.
	Nanodiamond	Water, EG, propylene glycol, midel oil, silicone oil, mineral oil, transformer oil and engine oil
	Graphene	Water, Water & EG mixture.
	Graphite	Water, texatherm oil.

(*) Note: Cu, Ag, Au, Al, Al_2O_3, CuO, ZnO, TiO_2, SiO_2, MWCNTs, DWCNTs, SWCNTs, and R-134a are mentioned to copper, silver, gold, aluminium, aluminium oxide (also known as alumina), copper oxide (also known as cupric oxide), zinc oxide, titanium oxide, silicon dioxide (Silica), multi-walled CNTs, double-walled CNTs, single-walled CNTs and 1,1,1,2-Tetra fluoro ethane respectively.

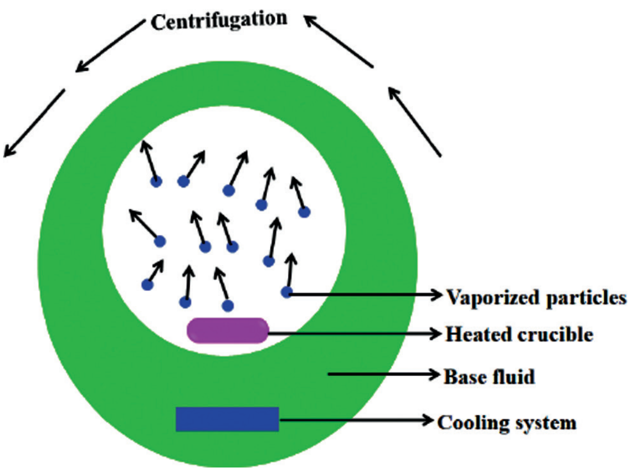

Figure 2. One-step method for nanofluids fabrication.

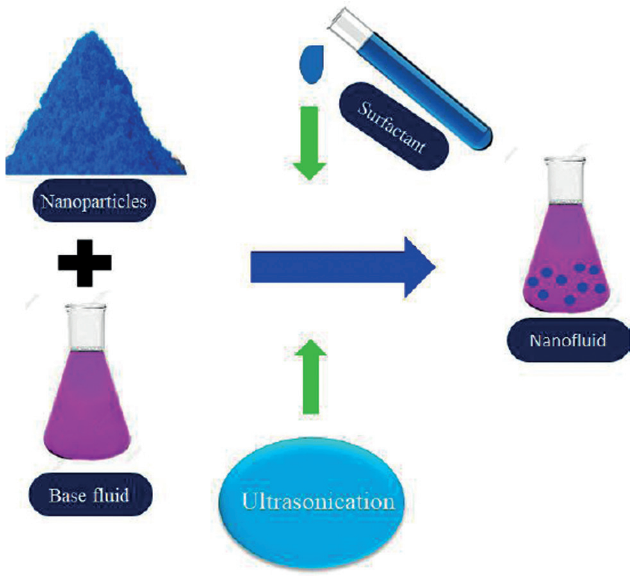

Figure 3. The two-step nanofluid fabrication procedure with an ultrasonicator device.

(b) Two-step method:

Firstly, physical and chemical procedures such as grinding, milling, or the vapour stage approach are used to create hybrid nano powder. Secondly, hybrid nano powder which is prepared in the first step is distributed in the base liquid with the assistance of ultrasonic vibrator or shear mixing apparatus which is shown in Fig.3. This is not expensive to produce hybrid nanofluid in mass [42,43]. The main intricacy is agglomeration which cannot avoid because Vander Waal and Cohesive forces exist with non-dependent nanoparticles. This agglomeration can deprive by means of suitable surfactant or by dissolving devices such as magnetic stirrer, homogenizer with high-pressure, ultrasonic bath and disrupter.

Table 2. The various types of hybrid nanoparticle were stated by eminent researchers:

Al_2O_3/Cu	TiO_2/SiO_2	Ag/GNPs	CNTs/Fe_2O_3	MWCNTs/Si	GNPs/SiO_2
Al_2O_3/CuO	TiO_2-CuO/C	Ag/WO3	DWCNTs/ZnO	MWCNTs/ZnO	Cu/Zn
Al_2O_3/CNTs	TiO_2/Ag	Ag/Si	AQl_2O_3/Graphene	MWCNTs/Ag	Ni/ND
Al/Zn	TiO_2/SiC	Ag/MgO	MWCNTs/ Al_2O_3	MWCNTs/SiO_2	TiO_2/CNTs
AIN	TiO_2/Cu	Ag/ZnO	MWCNTs/GO	MWCNTs/Fe_3O_4	TiO_2/MWCNTs
Co_3O_4/ND	TiO_2/ZnO	GNPs/Pt	$Co3O_4$/GO	MWCNTs/MgO	GNPs/Pt

Hybrid nanofluids with various nanoparticles and host liquids are prepared by any of the above two methods. The different types of base fluids and hybrid nanoparticles are given below and in table 2.

The different types of base fluids:

1. Water
2. Ethylene glycol
3. Water + ethylene glycol mixture
4. Vegetable oil
5. PAO oil
6. Transformer oil
7. Naphthenic mineral oil
8. Paraffin oil
9. SAE oil
10. Dia-thermic oil

FACTORS AFFECTING THE HYBRID NANOFLUID:

1. Stability:

The significant property that affect the running of a thermal system at desired capacity. The Vander Waal and cohesive forces exist among the nano particles is the main cause for agglomeration. By heat transferring HNFs decreases the potential because of proneness to coagulation. The flow behaviour also decreases by amplifying frictional resistance which in turn increase the pressure drop. Not having of good stability of HNF can change the thermo physical properties which in turn effect the heat transfer rate. Stability analysis can be made by different methods such as Spectral Analysis method, Sedimentation method, Light Scattering method, Zeta Potential analysis, and Centrifugation method. Some common methods are developed in literature for minimizing the agglomeration. They are:

(i) Addition of surfactant (ii) Controlling pH with electrostatic stabilization and (iii) Ultrasonic vibration. By adding appropriate surfactants many researchers prepared stable nanofluid.

Stability period of different nanofluid in various articles are given in table 3.

Table 3. Stability period of different nanofluids

References	Nanofluid	Stability period
[44]	Al_2O_3-MWCNTs/thermal oil	7 days
[46]	Sic-TiO_2/diathermic oil	10 days
[48]	MWCNTs-Fe_2O_3/H_2O	60 days
[47]	Cu-Zn/vegetable oil	03 days
[49]	SiO_2-graphene/naphthenic mineral oil	14 days
[50]	Cu-TiO_2/ H_2O and EG	07 days
[45]	Al_2O_3-Cu/ethylene glycol	03 days
[54]	MWCNTs-ZnO/ H_2O and EG	10 days
[51]	GNPs-Pt/ H_2O	22 days
[52]	TiO_2-SiO_2/ H_2O	14 days
[53]	Carbon black/water	7 days

2. pH control:

Nanofluid stability depends on electro-kinetic properties. Because of the strong repulsive forces, the stability can increase the pH control. A good stability of water with CNTs can be attained with acid treatment [55]. Fovet et al. [56] examined Al_2O_3nano-fluid with assorted pH values and noticed the variations in agglomeration by fluctuating the pH value. For different samplings different pH value exist. For example, the pH value which is apt for copper, alumina distributed and graphite in water are almost 8, 2, and 9.5, respectively.

3. Ultrasound intensity:

Ultrasound intensity acts a key role in changing the shapes or structures of nanoparticles and its characteristics. By rising the ultrasound intensity, the exceptional cavitations also escalates and the collapsed cavity generates a shockwave inside the solution. Thus, reduces the size of the particle and improving the nanofluid stability [57].

4. Thermal conductivity:

In literature so many studies describe an increase in heat conductivity of the hybrid nanofluids. In recent times, Sundar et al [58] equated graphene and GO/Co_3O_4 hybrid nanofluid. The result illustrations improvement of

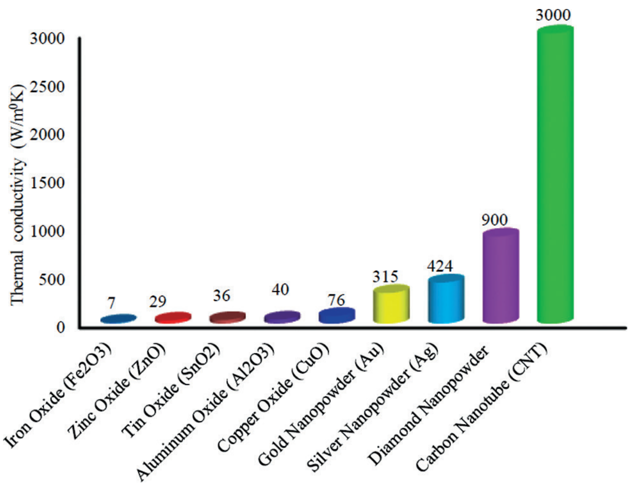

Figure 4. Thermal conductivity of selected nanomaterials.

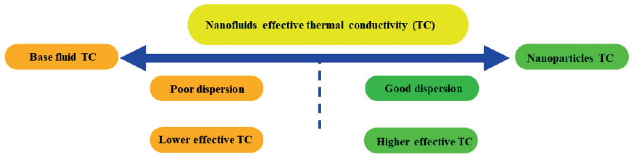

Figure 5. The relationship between the stability of nanofluids and their effective thermal conductivity (TC).

the thermal conductivity of hybrid nanofluids is greater than that of graphene but viscosity remains same. This is because of the synergistic thermal property. A comparison is shown with some mono nanofluids in figure 2 and observed that an enhancement is noticed in the hybrid nanofluid thermal conductivity when compared to Carbon Nanotube/Ethylene Glycol nanofluid, clustering is prevented in the fluid by adding of MgO in the working fluid. The thermal conductivity of different nanomaterials is displayed in Fig.4. Here we noticed that the thermal conductivity for carbon nano tubes is more when compared with other selected nanomaterials. The relation between stability of nanofluid and its effective thermal conductivities are shown in Fig.5.

5. Viscosity:

The hybrid nanofluid viscosity depends upon the selected nanoparticles, concentration, and temperature. Dardan et al. [59] exhibited viscosity and its relationship with the temperature variations and solid volume fractions of Al_2O_3 – MWCNT/SAE40 oil hybrid nanofluid. According to his outcomes, viscosity responsiveness to temperature was small and it affects a lot to the solid volume fraction. This is because when temperature rises, the intermolecular connections between molecules weaken, lowering viscosity. However, its impact is more significant at a lower temperature and high particle volume fraction. Due to the van der Waals forces between nano-additives, larger nano-clusters form, which can prevent oil layers from moving on top of each other. It could result in a larger increase in viscosity.

Some important facts about the augmentation of viscosity of hybrid nanofluids are:

- High volume fraction of nanoparticles triggered the development of nano-clusters of greater size due to Vander Waals forces existing among the particles that could cause the viscosity augmentation by reducing the movement of fluid layers [60].
- Enhance in volume fraction of nanoparticles caused internal shear stress to enhance which will, in turn, increases the hybrid nanofluid viscosity [61,62]
- An enhance in hydrodynamic diameter of nanoparticles results adsorption and clustering will tend to enhance the viscosity [63].
- High resistance between two fluid layers due to the existence of nanoparticles caused enhancement in viscosity of hybrid nanofluid [58, 64]. At lesser concentration of nano particles, this resistance is little, whereas high for higher concentration.

Kinds of hybrid nanofluids flows:

a. Turbulent flow: Hybrid nanofluids has a synergistic effect by which they offer all the properties of its components. Nano lubricants and turbulent hybrid nanofluid has many applications in heat exchangers was specified by Minea [65], Teng et al. [66] and Nabil et al. [67].
b. Laminar flow: TiO_2-CNT was used by Kalidasan et al. [68] in heat exchanger under laminar flow condition which is a hybrid nanofluid. Owing to its high stability it was suggested for heat transfer applications [69]. The laminar flow of hybrid nanofluid performed better.

APPLICATIONS OF HYBRID NANOFLUIDS:

Hybrid nano fluids have many applications:

1. **Electro-mechanical application**:
   In electrical equipment and electrical power transformers where oil is cooled the thermal conductivity and dielectric properties of the operational liquid can be enhanced by adding nano diamond to the mineral oil as an additive, with no changes in the electrical insulation of the liquid, the lifespan and power of the transformer can be enhanced with minimum maintenance and decrease the break downs because of overheating. In 1995, Choi discovered a heat transfer fluid called nanofluid and tested it in transformers and the out puts of his study [70] was for cooling transformers alumina nanoparticles are used in thermal oils.

2. **HVAC [heating, ventilation, and air conditioning application**:
Jiang et al. [71] firstly worked on the effect of CNTs on refrigerants and explained that CNT nano-refrigerants thermal conductivity is plentiful further than CNT–water nanofluids and as the diameter of CNTs decreased, increase in thermal conductivity is noticed. Also, adding nanoparticles raise the coefficient of the heat transfer to the system [72].
3. **Renewable energy application**:
Usage of Energy is inexorable. Renewable energy is gorgeous further admired and eco-friendlier. Sun be the very important source for it. Solar energy predominantly used in production of electricity and also in water heating and drying of agricultural products. By using hybrid nanofluids as the working fluid. [73-76] the ability of the solar collector for water heater can be increased.
4. **Application in Manufacturing process**:
In Grinding process high amount of energy is converted to heat and a reason for damage to the work piece, for example, cracks, burning of work piece, phase transformations so forth. Hybrid nanofluids' tribological feature enables for better cooling and lubricating in the grinding process, as well as cost-effective production [25, 77].
5. **Cooling in Automotive:**
In automobiles the braking system mainly depends on the motion of the fluid which diffuse energy. While braking heat is produced which in turn absorbed by the breaking fluids results reduction in the kinetic energy of the automobile. The nanoparticles in the base fluid shows better properties like, more viscous, high conductive nature, high boiling point and also cut down the incidents like vapor-lock and also improve safety during driving [78-82]. Similar studies can be seen in the mentioned references [67, 83].
6. **Application in heat exchanger**:
At low concentration, the metallic nanoparticles are hybridized with the intention that the rate of heat transfer is improved with low cost. Due to this reason, CNT-TiO_2 hybrid nanofluid is suggested for heat transfer applications. The uses, production, and thermophysical properties of hybrid nanofluids were briefly reviewed in these studies. (see [84, 85]).
7. **Application in miniaturized cooling systems:**
One important advantage of hybrid nanofluids are in the miniaturized cooling systems that supply magnetic field agitation of the nanofluids to enhance the heat transfer rate of the system. The influence of magnetic field on different hybrid nano fluids with different geometries was discussed by many authors [86–88].

Because of their large absorption potential due to their high surface area, hybrid nanoparticles have various uses in sectors such as medicine (genomics, pharmacogenomics, drug delivery, optics, surgery, general medicine), agriculture (tissue engineering, prosthesis), industry (fabric sciences, energy), and the environment (physical sciences, health sciences). Applications of hybrid nano fluids are portrayed in Fig.6.

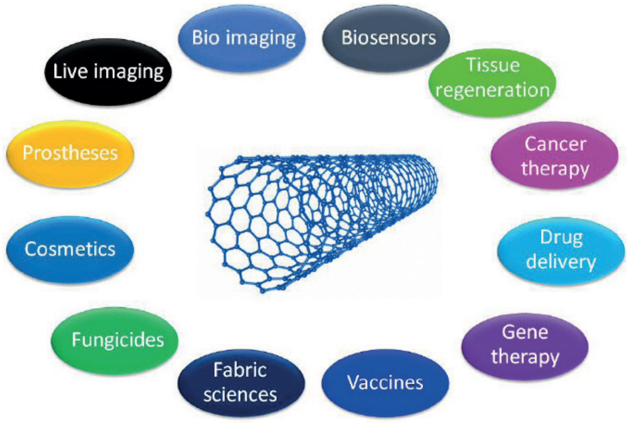

Figure 6. Applications of hybrid nanofluids.

CONCLUSIONS, CHALLENGES AND FUTURE WORKS:

The nanofluid technology has vastly expanded to meet industrial ethics, and increased investments to scale down designs that may be made healthier and gain additional profits with the use of unique hybrid nanoparticles are immobile incomplete to explore. The current review perusal introduces preparation, performance, factors affecting, and applications of hybrid nanofluid. The thermal characteristics of such a fluid are superior to the conventional fluid and mono nano particle fluid. It was also determined that as temperature and volume fraction raise, so do the features of hybrid nanofluid.

The heat transfer concert of hybrid nano fluids is very much appealing, but some encounters exist in their development. They are:

- There is lack of uniformity among the outcomes of various researchers
- There is deficiency of theoretical model which forecast the activities of the hybrid nanofluids; while preparing a nanofluid, dissimilar methods tends to different results and volume fraction.
- In hybrid nanofluid synthesis, the nano particles used are mostly hydrophobic. Some times their characteristics are affected while making them into hydrophilic. As a result, thorough investigations are required to calculate thermophysical and hydrodynamic performance for clear engineering applications.

- One of the foremost factors that impinge on the functioning of hybrid nanofluid is stability. Some researchers observed that stability of the nanofluid decline as time passes for long period. The surface tension in the fluid is reduced by adding surfactants and assists the scattering of the nano particles in the fluid. Surplus amount of adding surfactant to hybrid nanofluid have an effect on viscosity, thermal conductivity and stability.
- While examine the functioning of the working liquids viscosity take an important part, liquids with high viscosity has low thermal performance. When two dissimilar particles are united to do a single task, compatibility is very significant. More number of experiments are needed to spot out the nanoparticles which are compatible.
- Appropriate selection of nanoparticles in a hybrid nanofluid is most significant to get a required synergistic effect. Methodical technical insight, high manufacture cost, etc. are the other issue which has to be focused. The production of hybrid nanofluids at commercial scale must be increased so that they can be used in many industries.
- Choosing the right individual components of a hybrid nanofluid is crucial for achieving the desired synergistic result. Other issues related to high production costs for synthesis and investigations, for example, must be effectively addressed through technological awareness.
- The more complicated the innovation process for hybrid nanofluids, the higher the cost of generating nano fluids, which is one of the constraints that could limit the usage of hybrid nanofluids in industry.

CONCLUSIONS:

Investigators are treading to the examination of the rheological and heat transfer behaviours of hybrid nanofluids. Moreover, the examinations are necessary to be carried out to talk the origin source behindhand the peculiar variations of thermal conductivity, heat transfer features and viscosity of hybrid nanofluids.

Some examinations are given below:

a. Heat transfer qualities can be enhanced by raising nanoparticles to mono nanofluids due to their polished thermophysical properties, and this enrichment is more for hybrid nanofluids.
b. The flow properties of hybrid nanofluids are also optimized with the inclusion of hybrid nanoparticles. The relative viscosity of the hybrid nanofluid increased as a result of the formation of nano clusters in the working fluids, which caused the hydraulic diameter of hybrid nanoparticles to rise, hence increasing the relative viscosity.
c. Hybrid nanofluids have markedly higher thermal conductivity than traditional fluids and mono nanofluids of individual ingredients.

There are various inconsistencies between the researchers on the mentioned causes behindhand peculiar behaviour of these new type of heat transfer fluids many key issues must be addressed in a methodical manner.

The following are some main concerns:

a. There are huge gaps between experimental results and theoretical expectations, as well as between experimental results from different researchers for the same type of nanofluids.
b. A lack of standard and appropriate nanoparticle suspension characterization.
c. Insufficient understanding of intricate phenomenon and Thermodynamic network and rheological alterations in hybrid nanofluids are complicated mechanisms.
d. Preparing stable and homogeneous nanoparticle suspensions for long-term stability is a significant issue for real-time applications.

So, more attention has to be given in finding the higher boundaries of volume fraction and the proportion of the nanoparticles in the liquid. Nevertheless, to be aware of the complex mechanism with hybrid nanofluids following heat transfer optimization and real-world applications with hybrid nanofluids.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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