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HYBRID NANOFLUIDS FOR EFFICIENT HEAT AND MASS TRANSFER: CHALLENGES, ADVANCES, AND EMERGING OPPORTUNITIES

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Abstract: Hybrid nanofluids, which are created by blending multiple nanoparticles into a base fluid, show great promise as next generation working fluids for improved heat and mass transfer. Synergistic interactions among nanoparticles greatly enhance thermal conductivity, heat transfer, stability, and thermodynamic efficiency in comparison to mono nanofluids. This review discusses some of the recent developments in hybrid nanofluid synthesis and thermophysical characterization as well as applications of hybrid nanofluids in heat exchangers, solar thermal systems, microchannels, refrigeration and industrial cooling applications. Although hybrid nanofluids exhibit a lot of potential, the field of hybrid nanofluids still faces some important challenges that remain to be resolved, such as particle agglomeration, maintenance of stability, viscosity, increased pumping power, and standardized correlations. The review considers several emerging opportunities for hybrid nanofluids, including artificial intelligence to optimize performance, particle that are environmentally friendly, bio-based toners, and smart adaptive nanofluids that have tunable thermal properties. Overall, hybrid nanofluids have the potential to revolutionize the use of nanofluids in thermal systems as long as on-going challenges are addressed through experimental, computational and material-level innovations integrating the aforementioned opportunities and challenges.

Keywords: Hybrid nanofluids, heat transfer, mass transfer, thermal conductivity, stability, rheology, CFD, energy systems

1. Introduction

Heat and mass transfer processes are crucial to the effective operation of many engineering systems, including power producing units, industrial heat exchangers, refrigeration cycles, chemical reactors, automotive powerplants, and modern electronic cooling systems [1]. As advanced technologies have developed, systems have begun to require fluids not only capable of rapidly transporting heat, but also able to maintain stability under extreme conditions and experience operating efficiencies. While fluids like water, ethylene glycol, and various oils have been used for years as heating and cooling media, they have low thermal conductivity, limited heat carrying capacity, etc. low thermal conductivity and heat carrying capacity [2], essentially limiting their application in high-performance applications with high heat and energy requirements, and researchers have been seeking advanced fluids to accommodate the new temperature management challenges [3].

Nanofluids [4], a dispersion (suspension) of a nanoparticle in a base fluid, presented a novel solution to improve thermal transport. Related research has demonstrated that even a small amount of nanoparticles can improve the thermal conductivity, heat transfer coefficient, etc. of the base fluid. Research has also investigated the use of mono nanofluids, with mixed results. These limitations included nanoparticle agglomeration, sedimentation, increase in viscosity, instability in use after long periods or cycling, etc. In some cases, they had lower performance because of these limitations, require more energy to pump than a generic fluid, and limited use in commercial situations. It is also the case, and has been demonstrated in research studies, that the thermal transfer properties of a single nanoparticle are not always predictable, as shown in Fig 1 [5].

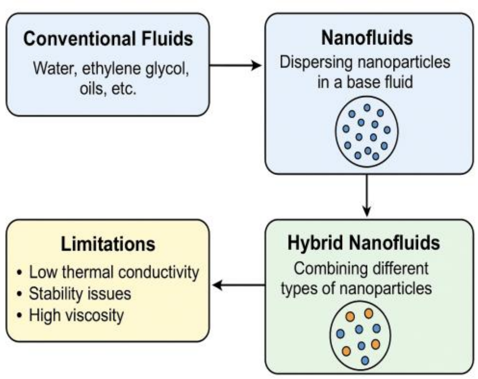

Fig. 1 - Evolution from Conventional Fluids to Hybrid Nanofluids.

The use of two or more types of nanoparticles in a single base fluid is a concept that is referred to as hybrid nanofluids. This approach capitalizes on the advantages of each type of nanoparticle and further improves the thermophysical characteristics relative to using simple nanofluids [6]. For instance, metal nanoparticles can provide high thermal conductivity, and for this reason, metal oxides can enhance stability. Carbon-based materials including graphene or carbon nanotubes have exceptional thermal and mechanical properties. The combined use of these nanoparticles often provides a synergistic improvement to the thermal conductivity, specific heat capacity, viscosity control, and long term stability of the fluid. The ability to vary particle size, shape, concentration, and combination ratio allows a significant ability to tailor hybrid nanofluids to a wide variety of applications [7].

Hybrid nanofluids [8] have begun to capture added interest, due to their potential to revolutionize thermal systems for various applications. Hybrid nanofluids have been found to increase the solar thermal efficiency and optical absorption of solar thermal collectors, resulting in improved sustainability of energy harvesting. Also, in automotive and aerospace applications, hybrid nanofluids can improve engine cooling, prevention of overheating, and high load functioning. Hybrid nanofluids also enhance convective heat transfer characteristics in microchannel heat sinks widely used in modern electronics, allowing for reliable operation of compact devices with high heat flux. In industrial processes, such as chemical.

Notwithstanding the advantages, there are many barriers that need to be resolved before hybrid nanofluids can be adopted on a practical scale [9]. Perhaps, the most urgent barrier is maintaining long-term stability because nanoparticles can still cluster and settle out over time. Moreover, researchers implement surfactants or modify the surface of the nanoparticles, but these additives may change the system by way of foaming or introducing chemical reactivity. Furthermore, one concern that needs to be dealt with, is the increase in viscosity, as increases in viscosity lead to consequential higher frictional losses and higher pumping power requirements. Lastly, due to an inconsistent approach towards practices for preparation and for measuring properties, studies cannot be united under standardized procedures, making it necessarily impossible to arrive at any propor system or expected models or methodology to predict behavior [10].

Emerging research avenues involve using greener nanoparticle materials, developing bio-based base fluids, or engineering a "smart" hybrid nanofluid to respond to temperature or stimulation. Developing new machine learning and artificial intelligence focused avenues, to combine nanoparticles or predict thermophysical properties are also feasible [10].

In summary, hybrid nanofluids have emerged as a promising development in the area of heat and mass transfer. Their unique prospects for incorporating the favorable properties of multiple nanoparticles, applications with superior thermal management efficiencies are possible in more heat transfer applications. However, more research is necessary to address the challenges of stability, viscosity, safety, and scalability of hybrid nanofluids if their full potential is to be realized. This review paper examined these areas in depth and summarized the most recent developments, limitations that remain in hybrid nanofluids, and points towards future directions for hybrid nanofluid development.

2. Hybrid nanofluids Fundamentals

Hybrid nanofluids making them an effective option for use in thermal applications. The synthesis process of hybrid nanofluids can also use a two-step method [11]. In this approach nanoparticles are synthesized and homogeneously dispersed into a base fluid before proceeding to use it. This additional stage of nanoparticles formation enables the synthesis of nanoparticles with improved traits and can be customized for hybrid use. Generally, the two-step method tends to create more stable and reliable nanoparticles and subsequently a more stable hybrid nanofluid than the one-step method [11].

The mixing and/or cooling of hybrid nanoparticles [12] may also be conducive to their successful application in both nano and micro spaced heat transfer devices. Hybrid nanofluids tools for thermal applications should be developed alongside strategies to mitigate stability issue coming from the unique separation conditions, surface development conditions, particle shape, or electrically charged surfaces for hybrid nanoparticles, as in Fig 2. As hybrid nanofluids enhance cooling capacity and have shown promise in micro-channel applications, there is a good likelihood thermal application for hybrid nanofluids will continue research in the thermal studies community.

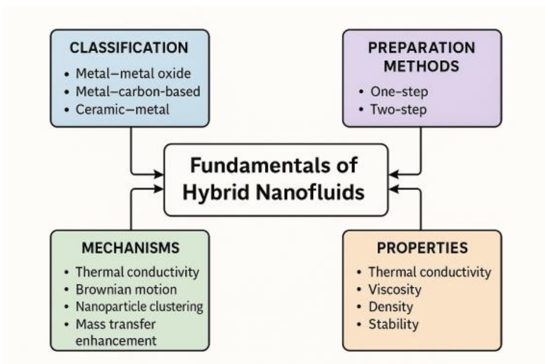

Fig. 2 - Fundamentals of Hybrid Nanofluids

The mechanisms responsible for the enhanced heat and mass transfer performance of hybrid nanofluids are complex and involve multiple physical interactions. The primary mechanism is the added thermal conductivity provided from high-conductivity nanoparticles that promote better energy transport throughout the fluid. In addition, the motion of the nanoparticles promoted by Brownian motion would aid micro-convection at the fluid level, thus promoting heat transfer. Depending on how one manages the clustering of particles, these may then create conductive links, which would subsequently enhance thermal conduction. Furthermore, carbon-based nanoparticles further enhance phonon transport with its respective surface area and layered structure [12]. Regarding mass transfer, the impact of nanoparticles includes changes in fluid viscosity, changes in boundary layer thickness, and enhancement of molecular diffusion through increased collision frequency. These effects provide hybrid nanofluids with a significant advantage over traditional working fluids and generally compared to mono nanofluids.

The thermophysical properties of hybrid nanofluid such as thermal conductivity, viscosity, density and specific heat capacity are key determinants of its die performance in real food applications. Generally speaking, thermal conductivity should often increase significantly as a result of the synergistic effect from mixed nanoparticles, while viscosity will increase based on concentration and particle size. The greater viscosity could provide better heat transfer under laminar conditions, but also has the downside of increased pumping power needed. Similarly, density and specific heat capacity will vary depending on the type and amount of nanoparticles used, affecting thermal inertia and flow behavior for the fluid. Stability is also a key property, as improper stability of the nanoparticles or sedimentation of nanoparticles will lower heat transfer efficiency and change the properties of the fluid over time. Therefore, careful attention to establish the best thermophysical properties of hybrid nanofluids will entail optimization in areas such as particle morphology, concentration, quality of dispersion, and choice of surfactant [13].

Overall, the concepts of hybrid nanofluids illustrate their considerable potential as next generation thermal working fluids. Improved performance is mainly the result of the interactions from mixed nanoparticles, improved thermophysical behaviour and up to date preparation methods. Once the engineer and key components of hybrid nanofluids are understood, researchers will be able to improve the design of hybrid nanofluids for employed in those demanding applications that expect high heat and mass transfer performance and reliability across a broad range of industries across multiple technological fields.

3. Research Designs and Methodology

This review article systematically and methodically provides a comprehensive approach for searching, extracting, and reviewing the most pertinent and contemporary studies on hybrid nanofluids and their application as heat and mass transfer enhancers. The aim of the approach is to ensure the inclusion of quality articles and exclusion of irrelevant and/or outdated articles, while reviewing all existing progress, impediments, and opportunities within the context of hybrid nanofluids. The methodology involves intentional selection of databases, pre-determined inclusion/exclusion criteria, a well-defined keyword strategy, and a well-structured multi-step screening process to enhance rigour and reliability.

The literature searches were conducted with a number of well-established and reputable databases known for publishing credible work surrounding thermal sciences, nanotechnology, advanced materials, and fluid engineering. Databases such as Elsevier’s ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, IEEE Xplore, and Google Scholar were chosen due to the strong representation of experimental, numerical, and theoretical papers on nanofluids and heat transfer enhancement. These sources would have ample peer-reviewed studies and therefore incorporated findings and recent advancements. In addition to journal articles, conference proceedings from international conferences related to thermal engineering, and nanotechnology were scrutinized.

In order to preserve scientific validity, rigorous selection criteria were enforced throughout the study selection process. The review was focused on papers published from 2020 onwards as hybrid nanofluids (HNFs) began to receive more attention during that time. However, some earlier papers are included because they are foundational. Only studies specifically related to HNFs—through synthesis, stability analysis, thermophyscial characterization and/or their thermal performance in an engineering application, were included. Studies strictly related to conventional or mono nanofluids were excluded unless they provided novel or essential theoretical foundations, and studies that lacked sufficient methodological rigor, incomplete experimental data, or too general a discussion related to heat and/or mass transfer were also excluded to ensure scientific robustness.

An effective keyword strategy was also a necessity for screening for our review. Relevant terms investigating HNFs included: "hybrid nanofluids", "nanofluids heat transfer enhancement," "hybridization of nanoparticles," "hybrids thermal conductivity," "convective performance," "mass transfer enhancement," "nanoparticle dispersion stability," and "CFD studies hybrid application," although Boolean operations were also used to join keywords and build specific combinations of studies related to hybrid nanofluids performance hybridization; ensuring the literature harvest was specific but complete.

The harvest of studies resulted in over 180 initial articles. These articles underwent a multi-step review process that began with a review of the title and abstract, dismissing articles that were obviously not related to HFNs, or the heat and mass transfer applications. The remaining articles then underwent a full-text screening to examine the methodological rigor, experimental or analysis rigor, and identifiable relevant applications in hybrid nanofluid applications. After discarding lower-quality or non-relevant studies, 25 articles representative of high-quality studies were chosen for further analysis, providing useful detail on hybrid nanofluid preparation, stability, thermophysical behavior, facilitation of enhanced heat and mass transfer applications, and other relevant findings related to specific applications. Lastly 10 main articles selected as shown in Fig 3.

Fig. 3 - Funnel Diagram for Literature Review

With this comprehensive methodology, the review successfully portrays the major themes of research, existing difficulties, and potential future opportunities in hybrid nanofluid research. Additionally, the rigor in methodology provides confirmation that the synthesized summary is meaningful and valid representation of the current state of knowledge in hybrid nanofluids research.

4. Related Works

Ragulkumar, E., & Anwar, T. (2025) [14] investigated heat and mass transfer in a graphene-based hybrid nanofluid flowing over a heated vertical cone, utilizing nondimensional governing equations solved using the Crank–Nicolson method, obtaining reputable outcomes for the applications in heat exchangers and thermal management systems. **Ndede, C. O., et al. (2025) [15]** numerically investigated the unsteady MHD Cu–TiO_2/water hybrid nanofluid flow occurring in a solar collector utilizing bvp4c and investigated how the Reynolds number, Schmidt number, and magnetic effects influence the temperature, skin friction, Nusselt number, and Sherwood number; helping analyze efficient solar-thermal designs. **Galal, A. M., et al. (2025)** [16] analyzed the flow of the magnetized trihybrid nanofluid with radiation and chemical reactions in Stenotic arteries and demonstrated how the Yamada–Ota model produces superior results concerning heat and mass transfer in comparison with the Xue model and the implications for the use in biomedical drug delivery and cardiovascular analysis. **Nihaal, K. M., & Mahabaleshwar, U. S. (2024)** [17] investigated thermophoresis and Brownian motion effects on hybrid nanofluid flow around a rotating cylinder in porous media, solved using the RKF-45 method, and noted greater drag behaviour with the varying impacts of thermophoresis and Brownian motion influencing heat transfer and mass transfer results in opposite directions. **Mahariq, I., et al. (2024)** [18] utilized fractal fractional derivatives and the Crank-Nicholson approach to analyze tetra-hybrid nanofluids for solar applications, discovering that all nanofluids showed superior heat transfer performance compared to solely using water as a heat transfer medium and that the four-nanoparticle combination was the best of the four solutions examined for comparing thermal performance for renewable energy systems that undergo heat transfer. **Khan, Z., et al. (2024)** [19] examined a hybrid nanofluid of MHD Maxwell fluid, their results displaying around a 20% improvement in heat transfer based on Nu number generated heat transfer using Al_2O_3–Fe_3O_4 nanoparticles when thermally enhanced. **Nagaraja, K. V. et al. (2023)** [20] studied modified ternary hybrid nanofluids within the vicinity of exponentially stretching surfaces with opposing flow, and assisting flow to demonstrate thermal enhancement is enhanced through hybrid-nanofluids as a formulation governed by mean temperature, along with mass-transfer as it was coupling flow based for solar-thermal applications. **Afzal, S., et al. (2023)** [21] looked at the flow of an entropic hybrid nanofluid between two rotating disks using the homotopy analysis method and affected velocity, temperature, heat transfer, and entropic generation with drastic effects from the nanolayer type. **Arif, U., et al. (2022)** [22] used the FEM to numerically quantify the flow and thermal characteristics of Cu and Cu–Al_2O_3 nanoparticles dumping through a circular pipe and determined superiority in thermal conductivity for Cu–Al_2O_3, and they suggested double the suitability of particles for enhanced heat transfer. **Berrehal, H., et al. (2022) [23],** using a mass-based Tiwari–Das model stream in wedge-type geometries to numerically study a hybrid nanofluid with magnetite and graphene oxide, considered entropic analysis and indicated strong performance output for cooling technology enhancement.

Table 1 – Literature Review Findings.

Author Name (Year)	**Main Concept / Study Focus**	**Key Findings**	**Limitations / Gaps**
Ragulkumar, E., & Anwar, T. (2025)	Heat and mass transfer of graphene-based hybrid nanofluid over a heated vertical cone using numerical simulation.	Reliable model validated by literature; improved skin friction, Nusselt and Sherwood numbers; suitable for thermal management systems and heat exchangers.	Limited to 2D monolayer nanofluids; industrial-scale experimental validation not performed.
Ndede, C. O., et al. (2025)	Unsteady MHD Cu–TiO_2/water hybrid nanofluid flow in a solar collector using bvp4c.	Increased Reynolds number improved temperature; magnetic field and Schmidt number enhanced Nusselt and Sherwood numbers; useful for solar collector optimization.	Assumes linear variation of thermo-physical properties; lacks real-world prototype testing.
Galal, A. M., et al. (2025)	Magnetized trihybrid nanofluid with radiation and chemical reaction through a stenotic artery	Yamada–Ota model showed superior heat and mass transfer; results beneficial for drug delivery and cardiova	Biological complexity simplified; real arterial wall elasticity and pulsatile flow not included.

	compared using Yamada–Ota and Xue models.	scular modeling.	
Nihal, K. M., & Mahabaleshwar, U. S. (2024)	Thermophoresis and Brownian motion effects on hybrid nanofluid flow over a rotating cylinder in porous medium.	Drag coefficient increases with porous medium; thermophoresis reduces heat transfer; Brownian motion increases mass transfer.	Model excludes turbulent regimes; experimental validation not provided.
Mahariq, I., et al. (2024)	Tetra-hybrid nanofluid behavior in solar heat transfer using fractal fractional derivatives and Crank–Nichols	Significant enhancement in heat transfer performance; beneficial for solar collectors and energy storage applications.	Fractal fractional modeling may not reflect physical behavior fully; no comparison with experimental data.
	on method.		
Khan, Z., et al. (2024)	2D MHD hybrid Maxwell nanofluid flow over stretching sheet embedded in porous medium.	Nusselt number increases by 12–20% using Al_2O_3–Fe_3O_4 hybrid nanoparticles; skin friction decreases with higher Grashof number.	Constant nanofluid properties assumed; no instability or transient analysis.
Nagaraja, K. V., et al. (2023)	Modified ternary hybrid nanofluids (THNFs) over exponentially stretched surfaces under aiding and opposing flows with radiation.	Higher heat transfer in aiding flow; radiation significantly enhances heat transport; reaction rate increases mass transfer.	Radiation modeled linearly; lacks experimental comparison with real solar devices.

Afzal, S., et al. (2023)	Entropy optimization of blood-based hybrid nanofluid between rotating disks with different nanoparticle shapes.	Platelet shapes show highest heat transfer; spherical shapes minimize entropy; validated semi-analytical results.	Limited to laminar flow; medical application assumptions simplified.
Arif, U., et al. (2022)	Heat and mass transfer of Cu and Cu–Al_2O_3 nanofluids in sodium alginate over circular pipe using FEM.	Cu–Al_2O_3 hybrid nanofluid improves thermal conductivity most; Cu-only nanofluid shows higher velocity; recommended dual dispersion for maximum heat transfer.	Magnetic and thermal properties assumed constant; lacks experimental validation.
Berrehal, H., et al. (2022)	Hybrid nanofluid (magnetite + graphene oxide) over wedge/plate/vertical surfaces using mass-based Tiwari–Das model with entropy analysis.	Demonstrated reliable entropy modelling; hybrid nanoparticles enhance thermal distribution; applicable to cooling technologies.	Only steady, laminar flow studied; nanoparticle agglomeration not considered.

From the studies presented, it is noted that there is a distinct research gap with respect to experimental validation and application of hybrid and multi-hybrid nanofluid models, since most studies are based solely on theoretical or numerical studies. Though the studies show considerable enhancements in heat and mass transfer, as well as, entropy performance and thermal energy performance, these studies are often still limited by idealized assumptions that include laminar, constant thermophysical properties, simplified geometry and neglect of turbulence effects as well as nanoparticle agglomeration. Additionally, modeling of biomedical and solar-thermal applications does not fully account for the complexities of the biological physiology or ambient environments. There is also a lack of comparative benchmarking between hybrid nanofluid formulations, as well as, limited age-stability and cost–feasibility evaluations which will create an even wider research gap, thus showing a need for comprehensive experimental investigation, prototype development, and multi-scale modelling for validation, and optimization of hybrid nanofluids in practice of applications within industry, biomedical, or energy systems.

5. Conclusion

Hybrid nanofluids have shown great promise as next-generation working fluids to increase heat and mass transfer in many thermal systems. These nanofluids consisting of two or more nanoparticles provide the ability to synergistically improve the thermal conductivity, stability, and convection performance more than conventional fluids or mono nanofluids. The studies reviewed here provide promising results for applications in a heat exchanger, solar collector, microchannel device, refrigeration systems, and industrial cooling. However, there are continuing challenges for the widespread adoption of hybrid nanofluids such as stability over time, nanoparticle agglomeration, operating with higher viscosity, increased pumping power, and no standard preparation and testing methods. Overcoming these challenges must take place before hybrid nanofluids can be practical in the field. Opportunities for green nanoparticle construction, bio-based base fluids, and artificial intelligence provide food for thought on how to be innovative with hybrid nanofluids. In summary, hybrid nanofluids appear to be a solution to enhancing energy efficiency and thermal performance of any system if these challenges are removed with interdisciplinary work.

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