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RESEARCH ARTICLE

Intelligent thermal management through nanofluids in porous media: a review of AI-driven design and optimization for high-performance systems

Kaustav Dey[1], Suman Debnath[2,*], Raj Kumar[3]

[1]Department of Mechanical Engineering, UIE, Chandigarh University, Mohali, Punjab, 140413, India
[2]Department of Mechanical Engineering, UIE, Chandigarh University, Mohali, Punjab, 140413, India
[3]Department of Mechanical Engineering, UIE, Chandigarh University, Mohali, Punjab, 140413, India

Abstract

Nanofluids, engineered colloidal suspensions of nanoparticles in base fluids, demonstrate superior heat-transfer capabilities in industrial and energy systems, outperforming conventional fluids because of enhanced thermal conductivity and convective heat-transfer performance. Their performance is even better in porous media, mainly because of the larger surface area and the complicated fluid–solid interactions that naturally improve heat transfer. That said, there are still some practical issues that prevent wide use. The main ones are colloidal instability, sedimentation of nanoparticles, and the relatively high computational cost of simulating these coupled multi-physics systems. This review tries to bring together what has been done recently, especially the combination of hybrid nanofluids, porous structures, and artificial intelligence methods. A particular point of interest here is the growing use of machine learning models like artificial neural networks and support vector machines for prediction and optimization, and how these are being coupled with CFD models to deal with computational limitations. When the experimental, theoretical, and numerical results are considered together, a more consistent picture starts to appear. Most studies report a thermal improvement of around 20–30% compared to base fluids, although the exact value changes depending on conditions. At the same time, there are still clear limitations that need to be addressed before real-scale applications become practical. Overall, it seems that the best performance does not come from improving nanofluids or porous media separately, but from using them together. Looking ahead, efficient thermal systems will likely depend on both stable hybrid nanofluids and AI-based design tools. For aerospace applications like unmanned aerial vehicles, the key issues will probably be flowing stability and developing lightweight porous structures that can be manufactured reliably.

Keywords: Nanofluids, porous media, heat transfer enhancement, machine learning, computational fluid dynamics, thermal management, unmanned aerial vehicles

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1. Introduction

Nanofluids are base fluids in which nanoparticles (1–100 nm) are dispersed; they have improved heat-transfer properties in industrial and energy applications. Many of the studies indicate that performance of nanofluid is superior to the traditional fluids because of the higher thermal conductivity, an increased convective heat transfer and the energy efficiency [1-2].The thermal transport at the microscale is different because of the profound nanoparticle-fluid interactions[3].Enhancement in thermal conductivity is observed experimentally, computationally, and theoretically in the study of nanofluid optimization, and Al2O3, TiO2, and CuO nanoparticles are found to be optimal in performance. One-step and two-step synthesis processes have been reported as to ensure colloidal stability, which is important for industrial applications. Stability is enhanced by sonication and surfactant modification using SDS, SDBS, and CTAB to prevent aggregation of the nanoparticles. Besides, porous media structures maximize the contact areas between matrix materials and fluids, thus one characteristic of these materials is that they enhance heat transfers bending over theoretical considerations [4]. The models include

*Corresponding Author
E-mail Adress: suman.e11804@cumail.in

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Darcy's law, the Brinkman-Forchheimer equation, and LTE/LTNE modelling. Studies by Delgado have shown that integrating porous structures with nanofluids improves heat-transfer performance in thermal devices by enhancing conduction and convection. However, challenges include nanoparticle sedimentation, increased viscosity at high concentrations, and difficulties in scaling up. Nanofluids can be applied to solar collectors, electronic cooling systems, and combustors, but applications in UAV component cooling systems are on the rise because of their multifunctional heat-transfer properties in aerospace technology.

Several thorough reviews have provided the basis for understanding these components separately. Seminal works on nanofluids have extensively investigated thermophysical properties, synthesis, and convective heat transfer. In the same way, the principles of heat and fluid flow in a porous medium, both at the Darcy scale and LTNE scales, have been well-characterized [4]. More recently, there has been a movement towards reviews that attempt to address the overlap between two fields: heat transfer of nanofluids and porous-media systems. Nevertheless, such works are mostly based on traditional numerical and experimental analyses. A critical review of this synergy, viewed through the transformative prism of AI and ML for designing and optimizing models and overcoming basic modelling bottlenecks, remains conspicuously absent. Although solar and electronics applications are usually mentioned, the urgent thermal management challenges posed by new high-power-density systems, i.e., aerospace and electric propulsion, have not been comprehensively reviewed in a unified way.

This review synthesizes traditional research and cutting-edge artificial intelligence, going beyond standalone research on nanofluid properties or transport models. It uniquely examines the strong synergy between hybrid nanofluids, advanced immutable porous materials, and machine learning (ML) for predictive optimization and builds on earlier intelligent systems, such as fuzzy-logic expert systems applied to solar thermal collectors. One of its key novelties is its critical focus on combining ML methods, such as ANNs and SVMs, with CFD. This integration addresses the high cost and complexity of modelling dynamic flows in porous media. Finally, the review provides a systematic indication of performance improvements of up to 30% in industrial practice, coherently translating advances from theory to practice. The primary objective is to consolidate and comprehensively assess recent developments in nanofluid heat transfer in porous media. This is achieved by synthesizing experimental results, simulation outcomes, and theoretical models to construct a holistic view of the underlying mechanisms. The review also attempts to systematically analyse and critically examine important adoption issues, such as colloidal instability and settlement, and potential solutions, including the use of surfactants. Furthermore, it aims to elucidate the role of the hybrid nanofluid and its synergism with optimized porous structures. This work targets ML to predict systems behaviour and to pave the way for efficient multi-objective design optimisation with the aid of a CFD-ML hybrid for next-generation thermal systems. From this analysis, some important findings can be drawn. As such, the intelligent synergy between nanofluids and porous media is responsible for the greatest improvement in heat transfer, which cannot be achieved by optimizing either component individually. Machine learning promises to be a gamechanger, providing non-intuitive conditions for optimality, that is, enabling a departure from the standard to which one is accustomed. Furthermore, the review may identify a key research gap, namely the need for standardized experimental validation under real-world conditions. Thus, the future of high-efficiency thermal management lies in the simultaneous development of stable hybrid nanofluids and the implementation of AI-based design models, while new applications in aerospace and UAV propulsion and cooling require focused studies on lightweight porous composites and flow stability. Although this review evaluates these challenges and opportunities within the high-energy, emerging thermal-management application of UAVs, the synthesized findings on AI-driven nanofluid-porous-media design can nevertheless be generalized to solar thermal engineering, electronic cooling, industrial heat-exchanger engineering, and other high-flux thermal-engineering scenarios. This gap is addressed in this review. The main novelty of it is tripartite. It goes beyond examining nanofluids or porous media at isolated heights to critically assess their synergistic heat-transfer enhancement. It specifically focuses on the role of ML- and AI-based schemes—especially ANNs and SVM combined with CFD—as transformative agents for eliminating modelling bottlenecks and enabling optimal design. It places this discussion in the context of an up-and-coming, high-stakes application—thermal management in UAVs— which poses the main challenges for dynamic stability, lighting design, and extreme heat fluxes.

The main aims of the review are to summarize and evaluate recent advances in nanofluid heat transfer in porous media; to assess it both experimentally and through simulations and theory; to conduct a coherent analysis of the main barriers to adoption, such as colloidal instability; to elucidate the presence of hybrid nanofluids and optimized porous structures; and to show how AI/ML can predict system behaviour and allow it to perform multi-objective design optimization of next-generation thermal systems. This conceptual framework is represented in the flowchart in Figure 1. Thus, the flowchart is illustrated in Figure 1 as follows.

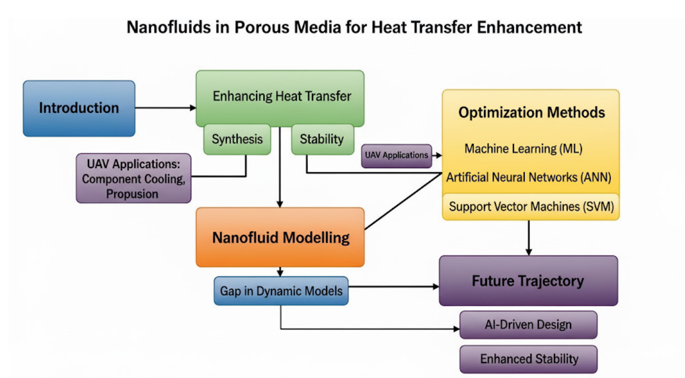

Figure 1. Conceptual framework of nanofluid-enhanced heat transfer in porous media systems with AI-driven optimization for UAV thermal management

Several authoritative reviews in the past five years have comprehensively mapped the landscape of nanofluids and their interaction with porous media. Mahian et al. [66] provided a foundational overview of modelling and simulation techniques for nanofluid flows, while Xu et al. [143] specifically reviewed heat conduction, convection, and phase change of nanofluids within porous structures, consolidating theoretical and experimental progress. More recently analysed hybrid nanofluids in thermal systems, and Riyadi et al. [26] surveyed the intersection of nanofluids and machine learning for heat exchangers. These studies have established a robust understanding of component properties and conventional analytical methods. However, a critical synthesis that places AI and ML as the central, enabling paradigm for the design and optimization of the synergistic nanofluid-porous media system remains absent. Furthermore, prior reviews often generalize applications; this work distinguishes itself by contextualizing the discussion within the rigorous demands of an emerging, high-stakes domain such as thermal management for high-performance aerospace systems, specifically UAVs. Thus, this review aims to bridge the gap between established nanofluid-porous media science and next-generation intelligent design frameworks, offering a forward-looking perspective on a critical technological frontier.

2. Enhancing heat transfer in porous media using nanofluids

Nanofluid technologies are having a major influence on shaping industrial energy systems with versatile applications, now making inroads into advanced aerospace areas like unmanned aerial vehicle (UAVpropulsion [[5]. Nanofluids are a development in the field of fluid dynamics, in which 1-100 nm nanoparticles are dispersed in standard fluids such as water, oil, and coolants. Nanoparticles impart distinctive thermal and fluidic properties to base fluids. Advances in nanotechnology have enabled the creation of nanofluids designed to optimize heat transfer across a wide range of technological applications, such as the thermal control of high-performance drone motors and propellers. Numerous research demonstrates an improvement in solar system performance, heat and mass transfer by nanofluids, as well as improving the thermal properties of materials [2-9]. Nanofluid research practice combines dynamic experimental design, post-processing and characterization, computational modelling, and optimization of critical parameters and their impacts [10-14]. Metal or metal-oxide nanoparticles, such as CuO, titanium dioxide, or aluminium oxide, are dispersed in a base fluid to create a nanofluid. The addition of nanoparticles improves the thermal conductivity of the base fluids drastically [15-17]. The addition of nanoparticles drastically changes the thermophysical properties of the base fluid, with thermal conductivity (k) increasing most significantly. This improvement depends on nanoparticle content (metallic > oxide), size (smaller tends to be better), form (e.g., high-aspect-ratio nanotubes), and volume fraction. This advantage, however, is accompanied by a significant rise in dynamic viscosity (μ), thereby increasing pumping power. In addition, the base fluid has a relatively high specific heat capacity (Cp), which is not necessarily preserved in the nanofluid because the Cp of solids is usually lower and may reduce thermal storage capacity. Density (ρ) increases according to the simple rule of mixtures. The maximization of a nanofluid formulation can be obtained then with the maximization of the k enhancement whilst controlling the penalties in μ and Cp to the net system level gain [15-17, and 20]. Research shows that addition of nanoparticles dramatically boosts the thermal conductivity of water and propylene glycol [18-21]. The production of nanofluids is one step method and two-step method as main methods [22-25]. Illustrated in Figure 2. The one-step method involves synthesis and distribution of nanoparticles and the two-step method involved preparing nanoparticles prior to the ingredients being mixed with the base fluid [26].

Figure 2 illustrates the two major methods of nanofluid synthesis. The one-step technique generates and disperses nanoparticles in the base fluid simultaneously, usually through chemical precipitation or direct evaporation/condensation. This will reduce the likelihood of hard aggregation during storage, which normally impairs initial dispersion and stability. Nevertheless, it is less scalable, may leave residual chemicals, and provides limited control over final nanoparticle size. The more widely used two-step procedure is preferred for its scalability; in this technique, dry nano powders are prepared separately on a large scale and are then dispersed into the base fluid by mechanical agitation in the presence of a chemical surfactant. The main challenge in this case is that dry nanoparticles are prone to forming strong, irreversible agglomerates; therefore, dispersion of the nanoparticles is difficult to achieve, and the nanoparticles may eventually begin to sediment. It is the methodology that will introduce a structural trade-off between stability (one-step) and scalability/manufacturing cost (two-step) [22-26].

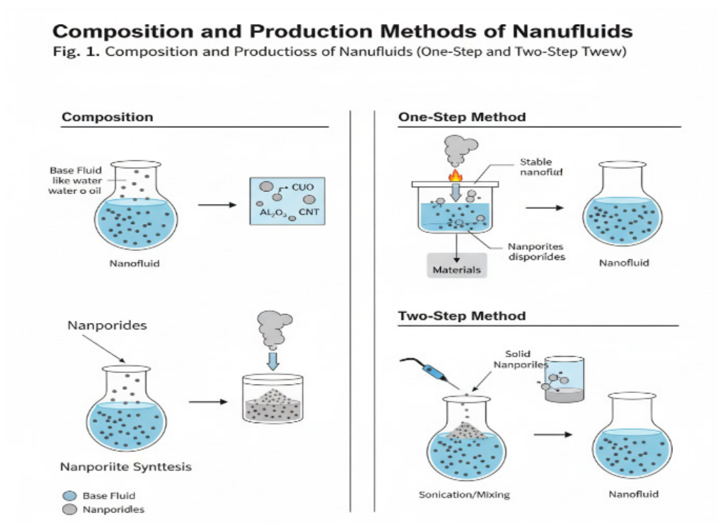

Figure 2. Composition and production methods of nanofluids (one-step and two-step)

Currently, two-step methods are the predominant processes for nanofluid preparation, but they are not stable enough for industrial use and perform poorly when systems are subjected to high-vibration environments such as drone propellers [27-28]**.** The stabilization of polypeptide-coated nanoparticles is attributed to the surface modification of nanoparticles, changing the properties of the surface through the presence of surfactants [29-30]. Surfactants shift nanoparticle surfaces, basically changing the hydrophobic character of the nanoparticle surface to a hydrophilic one; this change repels it more from motion, as depicted in Figure 3, and makes it more stable through surfactants [31-33]. Common surfactants for stabilizing the nanoparticles are Sodium dodecyl sulphate (SDS) [34-35], Sodium dodecyl benzenesulfonate (SDBS) [35-36], Oleic acid [24-25], Cetyltrimethylammonium bromide (CTAB)[2], Polyvinylpyrrolidone (PVP)[37]. The stabilization strategy and the surfactant of choice are also dependent on the properties of the nanoparticle. Metal nanoparticles (e.g., Cu, Ag) are highly electrophilic and can be easily oxidized, so selecting appropriate their capping materials or certain surfactants that adhere firmly to their metal surface is necessary to keep particles apart. Metal oxide nanoparticles (e.g., Al_2O_3, TiO_2) also frequently have surface hydroxyl groups, which may help in electrostatic stabilization of polar base fluids, such as water. Nanoparticles made of carbon (e.g. CNTs) are intrinsically hydrophobic and prone to stacking; they need to be dispersed with a surfactant containing aromatic rings (such as SDBS) or to have covalent functional groups attached to them to be stabilized. This behaviour that is dependent on materials requires customized methods of colloidal stability [29-33]. Research on heat transfer in porous media is of significant practical importance for industries that use heat exchangers, storage systems, geothermal systems, and drying systems. Passive thermal performance improvement in mechanical systems is generally achieved with the incorporation of porosities [38]. The theory informs the design of next-generation drone propellers, in which a lightweight porous metal foam can be incorporated into blade design. While colloidal stability in laboratory settings is well understood for SDS- and SDBS-type surfactants, the actual performance has scarcely been studied under the strain conditions encountered on a rotating drone propeller subjected to extreme centrifugal forces and vibrations. This merely represents a knowledge gap between laboratory synthesis and field application. These studies show that enhancement of the thermal conductivity of the system can be obtained by addition of porous materials, which change the fluid flow patterns [39-42]. Conductive nanoparticles are known to improve heating efficiency when combined with base fluids. The addition of conducting nanoparticles to a base fluid resulted in the formation of a nanofluid. These nanoparticles can be metallic (e.g., aluminium and copper), metal oxides, or carbon-based. The highest percentage use of nanoparticles incorporation to fluids is for fluid thermal conductivity improvement[43].For UAVs, such nano-thermodynamic loading of a porous propeller-blade spar by a circulating nanofluid has the potential to provide a revolutionary active cooling **m**echanism that can directly counter the aerodynamic and electromagnetic heating mechanisms that reduce performance and lifespan.

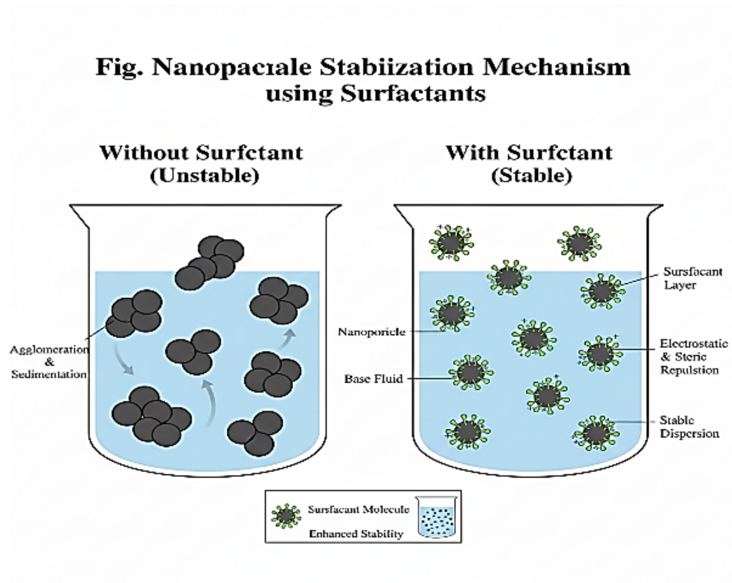

Figure 3. Nanoparticle stabilization mechanism using surfactants

Although nanoparticles can enhance the performance of fluids, their incorporation may introduce problems. High concentrations of nanoparticles increase the fluid's viscosity, which reduces heat transfer efficiency. Nanofluids are prepared by dispersing 10–100-nm nanoparticles into base fluids at controlled volumes that provide a balance between thermal enhancement and manageable fluid properties. In general, nanoparticles have lengths of 10 to 100 nm, depending on the application for which they are intended. Diverse views on the mini processes have prompted different approaches to modelling and formulation. In some models, the motion of the two types of nanoparticles and the base fluid particles is disregarded. The pseudo two-phase approach differs from the homogeneous analysis by considering the transport of the nanoparticles, whose concentration is uneven throughout the flow domain due to transport, compared with the initial distribution. In this way, this approach is a non-homogeneous, pseudo-two-phase model that accounts for heat transfer behaviour affected by gravity, Brownian motion, and thermophoretic forces. For a rotating drone propeller, these forces are intensified by strong centrifugal acceleration, which can particularly promote particle migration and sedimentation. Therefore, two-phase modelling should be used to accurately map the drone's long-term performance and to prevent clogging. The Brownian and thermophoresis forces have been established as the basic forces which determine the behaviour [43]. The two-phase model represents nanofluids as solid particles, base fluid, and their combination, and solves the conservation equations independently for each constituent. A nanofluid is made up of hybrid systems of multiple types of nanoparticles [40]. Mixing different nanoparticles in a base fluid increases thermal conductivity. For instance, when aluminium oxide is introduced into water, heat transfer increases. Another small quantity of Cu added to this mixture can improve it still further [41, 44]. This synergy is being investigated for UAVs, because a hybrid CNT-CuO nanofluid can provide enhanced cooling performance while meeting lower density requirements to minimize influence on flight dynamics.

3. Nanofluid modelling in porous media

The average Nusselt number (Nu_{ave}) for Cu/water nanofluid in square cavity with varying concentration (0.1-0.7 wt%) increase the Ra but decrease the porosity as reported by Sheremet et al. [45], using the Tiwari and Das model. Such fundamental relationships between porosity and heat transfer are critically important for the design and performance of porous composite cores in drone propeller blades, which require an optimized pore structure to maximize cooling potential without compromising structural integrity. Using a model of thermal hydraulic flows of stress engineer Buongiorno applied to Al2O3/water nanofluid system (1.0-4.7 vol%) and horizontal plate showed that Nusselt number decreases with increase of buoyancy ratio, according to Zargartalebi et al. [46]. Hossain et al. [47] melt rate of nano-PCM (Cyclohexane + CuO, 10% vol.) is in the decreasing trend with increase in porosity values. Grosan et al. [48] investigated that Cu /water nanofluid heat transfer was studied in square cavities using extended Buongiorno model at different particle concentration. Ghalambaz et al. [49] stated that Cu/water nanofluids in a parallelogram cavity showed enhancement in heat transfer with nanoparticles. Sheremet et al. and Pop et al. investigated the influence of porosity enhancement on Nu_{ave} for Cu/water (2.5% vol.) flow around a horizontal cylinder. Table 1 summarizes key studies, revealing a critical contradiction while Sheremet et al. and Pop et al. [50] studied Cu/water (2.5 vol%) around a horizontal cylinder and showing that Nu_{ave} increases with porosity. Study found that in a triangular cavity, Nu_{ave} rises with Ra and number but decrease both because of Brownian motion, buoyancy ratio and thermophoresis [51]. These complex multi-force interactions are particularly relevant to the rotating, heated environment of a drone propeller, in which centrifugal forces are the dominant factor in the formation of a resultant force field that determines nanoparticle distribution and thermal performance.

Rosmila et al. [52] found thermal stratification increases the heat transfer in Cu, Al_2O_3, and Ag nanofluids by an enhancement provided by magnetic fields. Ferdows et al. [53] proved that viscous ratio has an important effect on thickening of boundary layer on exponentially stretching sheet. Chamkha et al. reported an improvement of heat transfer in a square domain while conducting a study Cu/water, Al_2O_3/water, and TiO_2/water jointly with the wall thickness and Ra [54]. Umavathi et al. [55] showed that the increased heat and mass transfer with Ra and with nanoparticle volume fraction on a horizontal plate. Ismael et al. [56] demonstrated in square channel that porous Cu/water nanofluid transfers heat via the layer permeability. The research puts that increase in transfer of heat for the thicker walls using CuO/water for triangular solid at low Ra values [57]. The results of heat transfer through permeable layers and the effect of wall thickness directly determine the design of a propeller's internal spar and skin; these components must be thick enough to accommodate a porous cooling channel, yet thin enough to remain aerodynamically efficient. Thus, the works described in Table 1 provide meaningful information on the behaviour of nanofluids in porous media. Commonly, heat transfer, as indicated by the Nusselt number, is highly sensitive to the Rayleigh number, porosity, and nanoparticle concentration. However, a critical contradiction arises concerning the role of porosity. Some authors have reported a reduction in Nusselt number as the porosity of the vascular region increases, whereas others have noted an increased Nusselt number [45, 50]. This difference makes it clear that the relation is not a general one. It is strongly influenced by certain system geometry, flow regime, and dominant heat-transfer mechanism. Furthermore, the current body of work is mainly numerical and based on steady-state models. A major drawback is the lack of consideration of the dynamic redistribution of particles under external forces. In practice, when dealing with nanoparticle migration in a rotating UAV propeller, centrifugal and Coriolis forces dominate. This critical behaviour cannot be predicted by existing models, resulting in a significant discrepancy between simulated and real-world performance.

3.1. Limitations of existing models and their physical implications

The models listed in Table 1 are based on assumptions that restrict their ability to predict real-world situations; therefore, it is important to recognize the limitations, interpret the results accordingly, and use the results to inform future research. Single-phase homogeneous models (e.g., Tiwari and Das) consider the nanofluid a uniform medium with effectively enhanced properties; however, their simplifications of radial slip velocity and nanoparticle aggregation and migration do not account for particle movement and the eventual clogging of interconnected channels, thereby failing to capture failure modes such as sedimentation and channel clogging. Two-phase models (e.g., Buongiorno) include transport models, such as Brownian motion and thermophoresis, but ignore the presence of major body forces in real systems (such as centrifugal forces and Coriolis forces in rotating machines), and thus do not predict the nanoparticle distribution, local heat transfer, and long-term stability of real systems accurately. Most studies further assume steady-state conditions, although thermal loads during cycling of electronic systems or manoeuvring of UAVs are very transient; therefore, these models can miss peak temperatures, thermal stresses, and time-dependent migration of particles that dictate actual system reliability. It is often assumed that LTE exists between the solid and fluid matrices; however, this assumption does not hold in high-flux or high-contrast conductivity cases, where LTNE is the driving force and can lead to fundamental and gross errors in the calculation of temperature fields and the velocity of heat transfer, and, ultimately, to the possibility of under-designed cooling systems. All these constraints increase the disparity between the simulated performance and real-system reliability, underscoring the need for a much more advanced, validated, and dynamically aware modelling framework to bridge this gap, which machine-learning-assisted solutions are well positioned to fulfil.

Table 1. Investigation in nanoparticle flow in porous media and modelling

Author	Geometry	Nanofluid	Model	Result / Findings
Sheremet et al.[45]	Square based Cavity	Copper/Water (0.1–0.7% wt.)	Tiwari and Das	Nu $_{ave}$ grows increasing Ra that function then decreases depending on the porous medium's permeability.
Zargartalebi et al.[46]	Horizontal type Plate	Al_2O_3/Water (1.0,2.1,3.4,4.7%vol)	Buongiorno	As the buoyant properties fraction rises, the decreased number calculated by Nusselt falls.
Hossain et al. [47]	Cubic type	Nano PCM Cyclohexane + copperoxide (10%vol)	Buongiorno	As permeability increases, nano-PCM's dissolving velocity drops of various kinds.
Grosan et al.[48]	Square type Cavity	Copper/Water	Expanded Buongiorno	Thermal transportation in fluid with pores is enhanced by particulate enrichment.
Ghalambaz et al.[49]	Parallelogram shaped	Copper/Water	Tiwari and Das	The matrix's heat transport is improved by the addition of nanoparticles.
Sheremet And Pop[50]	Horizontal based cylinder	Copper/Water(2,5%vol)	Tiwari and Das	As the porosity of the porous medium increases, nu $_{ave}$ decreases.
Shermet and Pop[51]	Triangular type cavity	-	Buongiorno	Nu $_{ave}$ increases while Ra and Le quantities rise, and falls as buoyancy ratio, temperatures variables, plus Brown's law of motion all increase.
Rosmila et al.[52]	Vertical kind Plate	Copper/Water Al_2O_3/Water Silver/Water	Buongiorno	The thermal stratification associated with the presence of an electromagnetic field have a good influence regarding Thermal transmission.
Ferdows et al.[53]	Exponentially Type Stretching sheet	- Copper/waterAl_2O_3/water Silver/water	Buongiorno	When the viscous proportion parameter grew, so did the amount of material of the popularity, thermal, and concentrations layer boundaries.
Chamkha and Ismael [54]	Square based domain (Triangular solid wall)	TiO_2/water	Tiwari and Das	Improvement of transport of heat dependent on the number of Rayleigh and barrier thicknesses.
Umavathi et al. [55]	Horizontal type plate	Copper/water	-	When the total percentage as well as Rayleigh quantity of nanocrystals grew, correspondingly rose the speed of heat and mass transport.
Ismael and Chamkha[56]	Square based channel	Silver/water	Tiwari and Das	The openness of the permeable layer impacted the process of conduction heat transfer within the rigid barrier.
Ismael et al. [57]	Triangular kind solid		Tiwari and Das	As the amount present of solution increases, as well the emergence of hysteresis. At little Ray leigh numerals, the temperature velocity of transfer increased with an extension of the wall height.

The synthesis in Table 1 indicates that, in addition to regular patterns, there are fundamental contradictions that pose challenges to these systems. One of the consistent conclusions made by the majority of studies is that the relation between the Nu and the Ra is positive because stronger convection is induced by greater buoyancy [45, 48, and 54]. On the same note, a rise in the nanoparticle volume fraction (ϕ) tends to boost because of the increasing thermal conductivity [45, 49, and 55]. However, a significant contradiction exists regarding the role of porosity. Although Sheremet et al. [45] and Hossain et al. [47] have found a reduction in heat transfer with the increase in the porosity in certain designs, Sheremet et al. and Pop et al. found the reverse in a horizontal cylindric annulus [50]. This inconsistency is not a mistake; rather, the impact of ϵ is not monotonic and depends strongly on both the predominant mechanism of heat exchange and the system's geometry. In porous media, increases in porosity reduce the solid conductive matrix; however, they may increase permeability and fluid flow. The overall impact on Nu is determined by which of the two—conduction by the solid skeleton or convection by the fluid channels—dominates the balance, depending on Da, Ra, and the geometry in question. This presents the danger of extrapolation and the need to design systems optimally.

4. Nanofluid methods to enhance heat transfer in porous media

Different methods of surface roughness modification, lengthy fin, vibration, and electric fields are few of the common passive and active approaches to heat transfer enhancement as expounded by Singh et al. [180,181]. This section focuses on the specific synergies and practices for using nanofluids in porous media that integrate fluid-property engineering with structural alteration.

4.1. Nanofluid properties, dispersion, and performance optimization

Nanofluids have been widely researched by several researchers through modelling, simulation and experimental research to understand their behaviour and performance in more depth [58-60]. Nanofluids were investigated for thermal management. They examined absorptive coolers and impingement jet cooling. Figure 4 is a schematic of nanofluid application in impingement jet cooling. A stream of nanofluid is focused perpendicularly onto a hot target surface. The jet lies immediately beneath the stagnation zone, where heat transfer is predominantly conductive and the zone is highly efficient. The fluid then expands radially to create a wall-jet region with high convective velocity, resulting in high heat transfer. Dispersal of high-thermal-conductivity nanoparticles throughout the base fluid increases heat removal in both regions: it enhances conductive heat transfer in the stagnation region and convective heat transfer in the wall-jet. This renders jet impingement using nanofluids an effective approach to cooling localized high-heat-flux devices, which are widespread in UAV propulsion engine systems. It was found that the results had improved heat transfer and reduced the generation of entropy [61, 62]. The theory of impingement jet cooling is very useful for targeting hot spots on critical components, such as the root of a drone propeller or the motor housing, where a high heat flux can result in failure. Lam et al. and Prakash et al. conducted cooling studies of jet-impingement systems. They added heat transfer performance and thermodynamic behaviour [63].

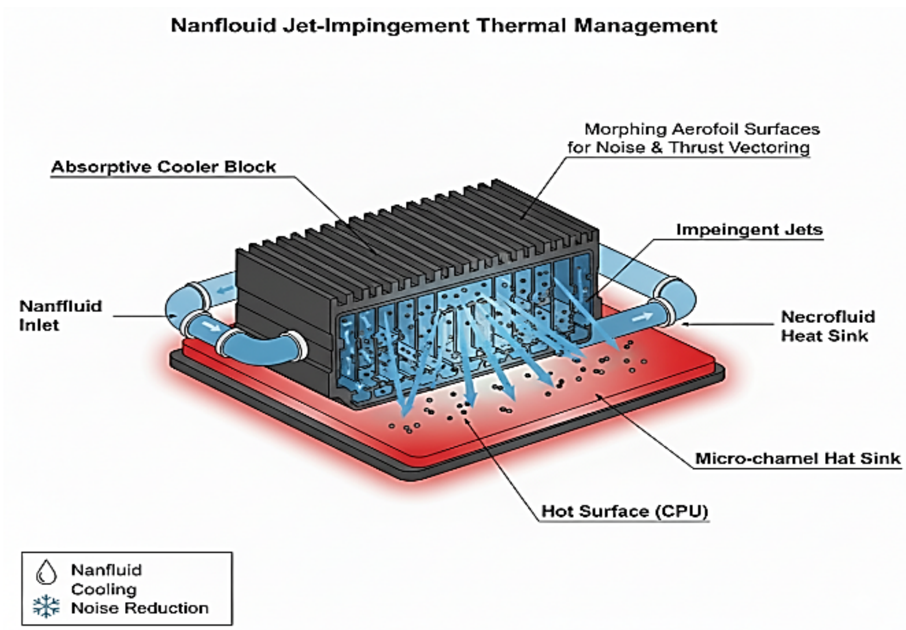

Figure 4. Nanofluid application in impingement jet cooling

Research analysed an absorption chiller that utilises a chiller based on flat plate collectors using nanofluids [64]. The study involved water-copper nanofluids with concentrations of less than 2%. The system was optimized using energy and exergy analysis. The improved system was optimized and resulted in an improvement of 3.99% in performance [65]. Nanofluids are innovative and expensive. Studies that are model based provide an economical method of appreciating their characteristics [66-68]. Research has established that neural networks perform well at predicting noisy data. They were very accurate, with Nusselt number accuracy of 99.76% and relative pressure drop accuracy of 99.54% [69]. This level of predictability is important when simulating the complex multiphysics environment of a rotating propeller, where predictability is not easily measured and physical prototyping is very expensive. The study suspended CuO and Al_2O_3 nanoparticles in water and applied them to the reactor walls [70]. The exergo-environmental evaluation and exergo-economic evaluation concepts are used to model a solar-geothermal CCHP system [71]. Through careful selection, the study identified twelve decision variables that could serve as primary objective functions. Nanoparticle concentrations were more favourable for all objectives in the optimization process. The research employed NSGA-II individually in all applications involving R134a, R423A, R1234ze, and R134yf. It was found that alumina nanofluid was better at cooling a liquid block using multi-objective optimization alongside decision-based strategies [72]. The development of nanofluid-enhanced thermal systems requires the evaluation of conflicting performance measures within an MOO framework. Although the concentration of nanoparticles usually increases with increasing thermal conductivity and the heat transfer coefficient, this process also increases the fluid viscosity, pumping power, and operational costs, and leads to the risk of colloidal instability. A single-parameter optimization may therefore yield practices that are impracticable. To explore this complicated trade-space, MOO techniques, including the Non-dominated Sorting Genetic Algorithm (NSGA-II) using machine-learning surrogates, are employed. They provide a Pareto front of optimal solutions, which displays the optimum compromises between goals, such as maximizing heat transfer (Nusselt number), minimizing hydraulic resistance (pressure drop/friction factor), and minimizing cost or entropy generation. This method is critical to the rational and cost-effective design of high-tech thermal management systems [72, 26].This is similar to the advanced, state-of-art AI solutions, including the application of a combined fuzzy-MCDM (Multi-Criteria Decision Making) to achieve the optimal parameters of sand-coated solar air collectors, which illustrate that AI is capable of handling multi-variable, multi-dimensional design spaces[179].The multi-objective strategies presented are directly relevant to drone propeller design, where conflicting goals such as maximizing heat dissipation, minimizing weight, and reducing pumping power must be balanced simultaneously. Riyadi et al. used two target functions and compared processor temperature and pumping power across three T.W.B. They observed that, compared with concentration and particle size, power did not significantly affect temperature. The Reynolds number influenced both objectives similarly. They experimented on a hybrid nanofluid consisting of CNTs and magnetite in an annulus [73]. To examine the behaviour of the nanofluid, researchers measured its thermal conductivity and viscosity. They found that the higher the levels of the solution, the higher the heat transfer and entropy production were as a result [[21]. The researcher also used compromise programming to obtain optimal solutions under various conditions. They maximized thermal conductivity of TiO_2 nanofluid through Response Surface Methodology (RSM)by the volume concentration, PVP surfactant, and sonication time [74-75]. Appropriate optimization of nanofluid synthesis parameters is a prerequisite for developing a stable, high-performance coolant capable of sustaining the severe operational regime of a UAV. Most studies on heat transfer enhancement employ the first law of thermodynamics. The better heat transfer is usually associated with greater pressure drop penalty of heat exchangers [26]. This represents the primary trade-off in designing a drone's cooling loop: the energy required to operate the pump reduces the aircraft's available flight power and endurance.

The stability of a nanofluid, as measured, also directly depends on the reliability of experimentally reported thermophysical values (e.g., k, μ). Methods will be highly sensitive to aggregation of particles near the probe, which may occur during measurements and result in false or unreliable measurements. Hence, interpretation of measured property data must be accompanied by quantitative stability measurements (e.g., zeta potential > 30 mV; sedimentation balance tests over days to weeks) and an explanation of the preparation and measurement procedures. The lack of such information may render experimental results invalid and unreliable for system design.

4.2. Nanofluid heat transfer: advances, challenges, and future directions

Nanofluids have enhanced thermal properties compared with conventional fluids. Their optimisation was investigated by Buongiorno et al. [76] and Jou et al. [77] which demonstrated that the dependence of natural convection is on Brownian motion, thermophoresis and buoyancy whereas forced convection is determined by Reynolds and Darcy numbers and magnetic fields These mechanisms have a different interaction in the context of a drone propeller, as natural convection and thermophoresis in the porous core of the blade play a vital role since forced convection dominates because of the rotation, but at the same time, effects of natural convection and thermophoresis have a critical impact on the distribution of nanoparticles and local hot spots The challenges encountered in nanofluid development include few experiments, settling of particles and fluctuations in concentration These challenges are especially pronounced in UAV applications, because gravitational and centrifugal forces can rapidly accelerate sedimentation, clogging the porous structure of the channels through which a propeller functions. The review presents the major findings on natural and forced convection, identifies research shortcomings, and suggests future directions to bridge the gap between theory and industry. Various experimental studies, such as those on the natural convection of nanoparticles in porous media that consider the Rayleigh numbers, nanoparticle concentration and the porous parameters, are shown in Figure 5. Buongiorno et al. [76] consider thermophoresis and Brownian diffusion as major processes, whereas Jou et al. [77] focus more on effect of buoyancy and the aspect ratio.

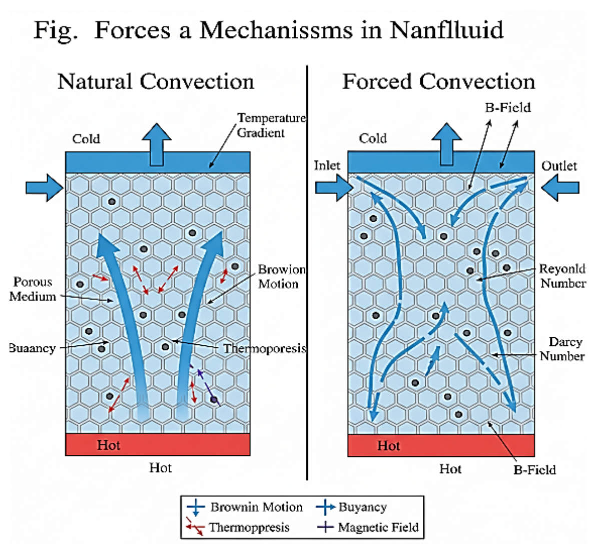

Figure 5. Key convection and transport mechanisms in nanofluids within porous media

The most persistent trend seen in the literature is that many numerical studies exploring advanced applications involving hybrid nanofluids, complex porous geometries, or the integrated effects of magnetic fields do not have experimental support. This results in a disparity between the performance predicted in simulated settings and the performance attainable in real systems, especially in dynamic challenges such as nanoparticle movement and durability. In most experimental studies, there is no experimental validation of nanoparticles and dynamic nanoparticle modelling although Motlagh et al. [78] and Alsabery et al. [79, 80] have made their contributions. According to Baghsaz et al. [81], the gap that needs to be filled by future research should focus on transient analysis, experimental verification, and hybrid nanoparticle systems, discussing the ignored aspect of the problem of sedimentation and hybrid nanofluids optimization by Kadhim et al. [82] and magnetic field relationship research by Izazi et al. [83].The need for transient analysis and verification is essential to UAV propulsion because thermal loads on a propeller are highly dynamic, changing with thrust requirements and maneuvering during flight, which is entirely unresolvable using steady-state models**.** Gholamalipour et al. [84]. discovered that natural convection performs better in an annulus that is porous with downward eccentricity which enhances the heat transfers but worsens when the eccentricity is upwards. Al-Amir et al. [85]. examined the influence of Prandtl number on natural convection of air in nanofluids, both Ag/water, which is used to saturate porous media that are layered**.** Torabi et al. [86] used a mix of interrupted and inline patterning to investigate the heat transfer and the generation of entropy in Al_2O_3-water nanofluid convection in square pillar array porous media. These findings regarding geometry-sensitive performance directly inform the positioning of the porous cooling core within an asymmetric propeller blade to exploit favourable flow behaviours. The Lattice Boltzmann Method was used by Sheikholeslami et al. [87] to investigate Al_2O_3-H_2O nanofluid forced convection under a magnetic field in a porous cavity that is subjected to a hot sphere. Findings indicated that the Nusselt number is positively related to the Darcy and Reynolds numbers and negatively related to the Hartmann numbers. Nevertheless, the research did not undergo any experimental validation or transient analysis. The research proves that the Reynolds number and Darcy number increase the rate of heat transfer, whereas Lorentz force lowers the performance of Sheikholeslami et al. [88, 89] and Pordanjani et al. [90]. When a magnetic field is applied, MHD effects are generated, significantly affecting the flow and heat transfer of nanofluids. In an electrically conducting fluid, the interplay between the field and the flow gives rise to Lorentz forces that oppose motion, thereby weakening the convection currents and often decreasing the Nusselt number, as observed in the above studies. Nonetheless, in the case of the nanofluid which consists of magnetic nanoparticles (e.g., Fe_3O_4) the field interacts with the particles directly. This allows active control: particle position can be controlled through the application of a magnetic field; sedimentation can be inhibited; chain formation can be induced to form conductive pathways; and local viscosity can be increased to change flow patterns. The twofold functions of MHD are a convective suppressor and an active nanofluid handling device that is a reliable yet diverse field of smart thermal management [83, 92]. Hybrid nanofluids have been found to elevate Nusselt numbers and pressure drop is a complication as demonstrated by numerical studies conducted by Moghadasi et al. [91] and Aminian et al. [92]. This penalty associated with pressure drop is an important design constraint for a drone's cooling system because the onboard pump should be small and lightweight, making high-pressure circulation infeasible. Benos et al. [93] emphasize the fact that the absence of experimental evidence in the untested turbulent areas is the primary drawback. According to Siavashi et al. [90] hybrid nanofluids can be used to optimize the thermal performance through the addition of porous media. The research revealed that there is an increased heat transfer with an increase in Rayleigh and Darcy number, optimal flow at four corrugations (N=4), and an increase in the good result when the cylinder is mounted at an upright position [94]. Molana et al. [95] discovered that Fe_3O_4-H_2O nanofluid with a magnetic field enhances heat transfer in a novel porous cavity regardless of the blade-shaped nanoparticle at high Rayleigh numbers. Active thermal management in drones can be achieved using a magnetic nanofluid, in which an applied magnetic field dynamically controls nanoparticle location and heat transfer rates, allowing it to switch between heat emission and absorption. Nevertheless, the research of Mohebbi et al. [96] study did not have the experimental validation and application-based tests of solar power plants. Future research must include alternative nanoparticles in the hybrid nanofluids, enhance the cavity design, and incorporate time dynamics and magnetic field analysis. Dogonchi et al. [97] investigated natural convection of Cu-water nanofluid in porous media at an inclined magnetic field between a rectangular hot and a circular cold collector. It was numerically demonstrated in a study by Akhter et al. [98] that the heat transfer in a porous square enclosure using Al_2O_3-water nanofluid increases with the increase in the Rayleigh number. The thermal conductivity properties of kerosene-alumina nanofluids demonstrated by Agarwal et al. [99] are superior, but it becomes unstable when nanoparticles are in large amounts, which are revealed by the numerical analysis studies of both Ghalambaz et al. and Mehryan et al. [100]. Agarwal et al. and Ghalambaz et al. [101] emphasize that the future studies need to be conducted with experimental validation, dynamic property measurement, and scaled testing, that is, regenerative cooling and thermal energy storage systems are to be used in industry. The latter is the key obstacle to the implementation of this technology in UAVs: until verified models and nanofluids can remain stable under high-g flight conditions, the translation of the numerical potential of this technology into a flight-worthy component cannot be achieved. Success requires solving the problems of sedimentation, optimising the ratio of nanoparticles, and identifying cost-effective stabilisers. Ferdows et al. established that MHD induced convection of Cu, Al_2O_3, and TiO_2-water nanofluids between a porous plate at rest and found that the higher the volume fraction of the nanoparticles, the higher the heat transfer in the presence of magnetic fields [102, 103]. Thus, this is illustrated in Table 2.

Table 2. Analysis of nanofluid convection in porous media: findings and identified research gaps

Study Focus	Key Investigators	System & Key Findings	Critical Research Gaps & Limitations
Natural Convection Mechanisms	Buongiorno et al. [76]; Jou et al. [77]	Identified Brownian motion, thermophoresis, and buoyancy as key drivers. Aspect ratio and porous parameters significantly influence flow.	Lack of Dynamic Modelling: Most models are steady state. Transientavior and dynamic nanoparticle redistribution are overlooked.
Geometry & Magnetic Field Effects	Gholamalipour et al. [84]; Dogonchi et al. [97]; Sheikholeslami et al. [87, 88, and 89]	Heat transfer is sensitive to geometry (e.g., downward eccentricity improves it) and magnetic fields (Lorentz forces can reduce performance).	Insufficient Experimental Validation: Findings are predominantly numerical. Lack of experimental setups to validate complex multi-physics (flow, thermal, magnetic) interactions.
Hybrid Nanofluids & Advanced Structures	Moghadasi et al. [91]; Aminian et al. [92]; Torabi et al. [86]; Siavashi et al. [90]	Hybrid nanofluids increase Nusselt numbers. Patterned porous structures (e.g., square pillars, corrugations) can optimize thermal performance and entropy generation.	Pressure Drop & Stability: Increased viscosity and pressure drop with hybrid nanofluids is a challenge. Long-term colloidal stability and sedimentation in complex porous geometries are not adequately studied.
Industrial Application & Scalability	Agarwal et al. [99]; Ghalambaz et al. [101]; Mohebbi et al. [96]	Nanofluids show promise (e.g., kerosene-Al_2O_3) but face instability at high concentrations. Performance in real-world systems (solar plants, storage) is not fully proven.	Scalability Gap: A significant disconnect exists between lab-scale numerical success and industrial application. Missing are cost-benefit analyses, durability tests, and scaled prototypes under realistic operating conditions.
Turbulent Flow & Comprehensive Modeling	Benos et al. [93]; Baghsaz et al. [81]	Highlighted a general lack of data in turbulent flow regimes. Future work should focus on transient analysis and hybrid systems.	Unexplored Flow Regimes: Turbulent flow in nanofluid-porous systems is virtually unstudied. There is a critical need for models and experiments that integrate all relevant forces (magnetic, thermophoretic, Brownian) in dynamic, large-scale systems.

The concise literature review in Table 2 of research on nanofluid convection in porous media demonstrates several key areas that characterize the state of the art and its limitations. Although numerical analyses have spread, a meta-analysis indicates that a remarkable dependence on simplified assumptions a steady-state, laminar flow, which diverges to the dynamic and frequently turbulent nature of industrial practice is witnessed [81, 93]. Moreover, the encouraging outcomes of hybrid nanofluids [91, 92] are always systematically accompanied by reports of a coexistent and occasionally counterbalancing augmentation of pressure drop [26, 91], a concession that is hardly balanced on a case-by-case basis. This trend shows that the field has done well in mapping the parameter space of idealized scenarios but is now confronted with the more difficult task of bridging the simulation-to-application gap. Table 2 presents these findings and the corresponding research gaps.

4.3. Combining SVM and ANN with CFD improves predictions and cuts computing costs

The combination of ML and CFD represents a paradigm shift in the design and analysis of thermal systems. The rationale is that high-fidelity, but computationally expensive CFD simulations create an extensive dataset of input parameters and measures of output performance. One then uses this dataset to train a fast surrogate ML model, e.g., an ANN or SVM. After training and validation, the ML model can sample new input sets with predicted system performance within milliseconds, allowing rapid and efficient exploration of the design space, enabling multi-objective optimization, sensitivity analysis, and, in applied cases, inverse-design tasks that are particularly intractable to simulate directly with CFD across a set of candidate design variations. This synergistic combination can decouple the costs of analysis and optimization, enabling thermal high-performance systems to be developed substantially faster. Heat transfer, thermal conductivity, and system performance are effectively enhanced by using base fluids containing nanoparticles [104, 105]. Nanofluids have found extensive applications in air conditioning [106-108], power plants [109, 110], and heat exchangers [111-113], with important increases in efficiency. These established efficiency advantages in traditional systems provide a solid basis for the use of thermal management in high-power drone propulsion systems, where the ability to dissipate heat generated by the motor and propeller is constrained. Modelling and optimisation algorithms such as ANNs are now of importance in refining and modelling nanofluid applications through enabling the fast simulation of systems and fine-tuning of thermophysical parameters by decoding the complex behaviour of the systems [114].This is a great improvement of the previous rule-based fuzzy logic and expert systems to more advanced data-driven ANN and SVM models [177-178].This is particularly important in the design of drone propellers, where the multi-physics problem, which is a combination of rotating aerodynamics, porous media flow, and conjugate heat transfer, is too complicated and computationally prohibitive to attempt with traditional CFD alone. Tafarroj et al. [115] exemplified the critical use of ANNs to predict heat transfer coefficient and Nusselt number in a microchannel heat sink (MCHS), which is TiO_2/water nanofluid flow. ANNs were presented in their work as an inexpensive alternative to expensive experiments. Similarly, a trained ANN surrogate model might provide faster estimates of the thermal performance of a nanofluid-cooled porous propeller blade across thousands of design variations, substantially reducing the development cycle. They used a 40-channel MCHS with a bottom heater to analyse data on nanoparticle volume fractions down to 2 per cent and Reynolds numbers below 1700, demonstrating that ANNs are highly predictive. The k-nearest neighbours (k-NN) performed better than the GPR, RF, and MLP models. It reduced the maximum temperature when active synthetic jets (SJs) and staggered dimples were used. The test outcomes also revealed that the heat transfer coefficient increased by 104.8% with inline dimples under the off condition of SJs. Additionally, the conductive heat transfer was enhanced by 54.9% when the in-phase configuration was used. The combination of CFD and machine learning increased the validity of the findings and reduced computational cost. It began by simulating geometric and operational parameters using CFD, followed by applying ML models such as MLP, which customized hidden layers to make individual predictions, as shown in Figure 6.

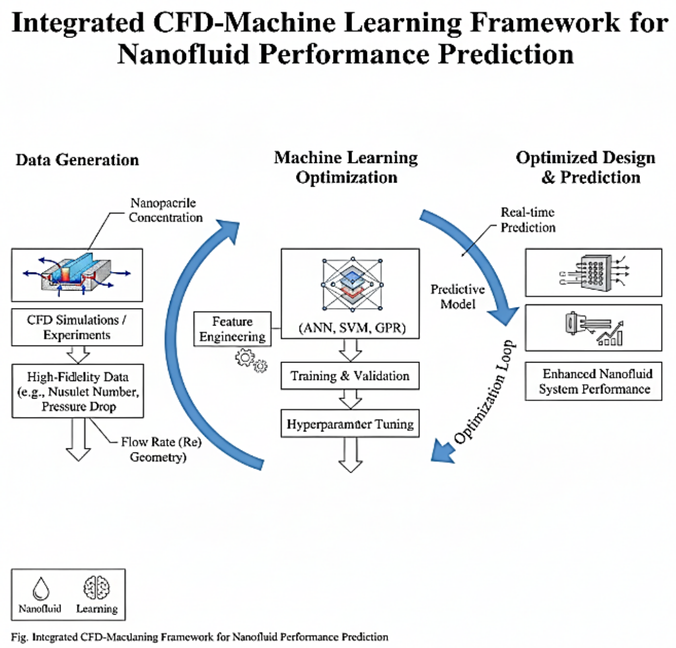

Figure 6. AI-driven design and optimization loop for nanofluid-porous media systems

Baghban et al. [116] applied ANFIS, LSSVM, and MLP-ANNs to study water-carbon nanofluids in heat exchangers. Among the 72 data points, LSSVM was the most predictive. Similarly, ANNs were used to model the hydrothermal properties of the SiO_2/water nanofluids in turbulent flow. A 2-6-6-2 network best predicted pressure drop and Nusselt number, with Reynolds number, volume fraction, and inlet temperature as key factors for optimisation[117]. The comparison of ANN with the polynomial model indicated that ANN had superior forecasting ability, with an R^2 of 0.9996 and an average relative deviation of only 0.88%, a negligible error; thus, it could be considered reliable for predicting the thermal conductivity of a CuO-based nanofluid. Since nanofluids are highly thermally conductive, they are necessary to enhance heat transfer in thermal systems. Baghban et al. conducted a sensitivity analysis and applied machine learning to determine the heat-transfer efficiency in CNT/water flow in coils. The use of nanofluids in power plants, air conditioners, heat exchangers, and other engineering systems is increasing. Machine learning, particularly ANNs, has revolutionised research on nanofluids by enabling accurate prediction and optimisation. This prompts new developments in heat exchangers, solar thermal technology and more energy efficient uses [118-120]. Nanofluid technology, combined with computational modelling, provides cost-effective and scalable heat-management solutions for industry by mitigating cost and experimental challenges. Heat transfer in porous media is a complicated thermal interaction within interlaced pores present in both bio-tissues, geological structures or engineered structures such as porous heat exchangers [121 - 122]. This is a process in which conduction takes place in the solid phase, convection in the liquid phase and thermal radiation [123]. These theories are applicable to underground reservoirs and biological tissues. Heat exchangers play an important role in industrial processes. They allow the heat to be transferred between fluids which are separated by solids in a controlled manner [124]. The confluence of these disciplines has attracted interest; in particular, nanofluids and machine learning have been applied to enhance thermal analysis. Alizadeh et al. [125] demonstrated this synergy by predicting thermodynamic and transport processes in in Cu-Al_2O_3/water hybrid nanofluid flow using machine learning, through porous media. They used CFD data to model temperature, velocity, Nusselt number, and entropy generation effectively by combining it with SVM and particle swarm optimization (PSO). Theirs was an approach that reduced the computational cost compared with the classical analysis and clearly demonstrated the impact of parameters on shear stress and heat transfer. Sajjadi et al. [126] simulated the convection of nanofluid in the form of MWCNT-Fe_3O_4/water in porous media using Lattice Boltzmann technique. They realized that Nusselt numbers were proportional to the nanoparticle concentration, whereas increases in the magnetic field (Hartmann number) decreased Nusselt numbers. The combination of machine learning and homotopy analysis created new methods of computation used by Hayat et al. [127]. Their case under study was the impinging flow on porous, stretched plates. They analysed more than 1,200 computational cases using BBML and CFD. Their experiment demonstrated the usefulness of their method for maximizing heat transfer at low Reynolds numbers in complex geometries, such as catalytic membranes. The approach used to determine the optimum balance between porous matrix density, nanofluid concentration, and channel geometry can be directly applied to the optimisation of a drone propeller, where PSO could be used to determine the optimal design to maximize cooling and minimize weight. Abad et al. [128] further demonstrated that AI has great predictive capabilities when used to analyse reactive Al_2O_3-Cu/water nanofluid flow around bluff bodies in porous media using ANN-PSO hybrid models, showing how a slight variation in nanoparticle concentration could significantly change the dynamics of thermal and chemical reactions, hence supporting the sensitivity of nanoparticle concentration highlights the importance of careful nanofluid preparation in a drone application, where a slight variation in nanoparticle concentration can cause the difference between stable flight and overheating-induced failure as illustrated in Figure7(a), Figure7(b) and Figure7(c) respectively. They used one hidden layer in their multilayer perceptron (MLP) model. It was superior to conventional approaches. It forecasted Nusselt and Sherwood numbers more accurately and with less error. These computational approaches address problems in porous media systems. traditional approaches have difficulty handling numerous variables. In more recent work, AI models that predict hybrid nanofluid flow around cylinders in porous media have been developed [125]. These models have been found to estimate temperature fields, Bejan numbers, and shear stress profiles using supervised learning on simulation data. Collectively, these investigations demonstrate that machine learning has disruptive potential for heat transfer in porous media. They provide precise estimates and minimize computational expenses. They have precise estimates and minimize the computational expenses. Combining ANN, SVM, PSO, and other AI methods with CFD offers a new opportunity to optimise thermal systems. This enables rapid analysis of complex parameters in nanofluid-enhanced porous media; such applications include heat exchangers and catalytic reactors.

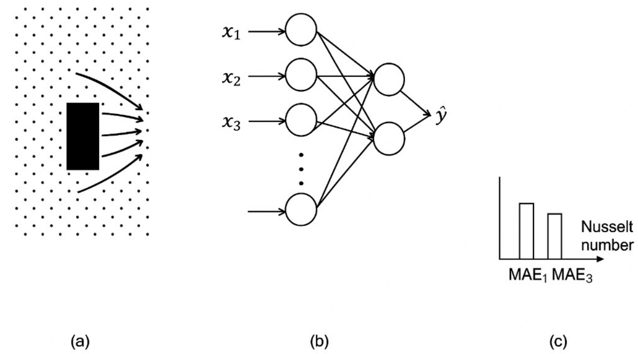

Figure 7. (a) Bluff body under radial impinging flow in porous media, (b) a standard three-layer ANN structure, and (c) the mean absolute error (MAE) method used to calculate the Nusselt number for each model

Most importantly, such a combined CFD-ML system is the only conceivable entry point to the design of the next generation of multi-purpose drone propellers, with blades that are actively cooled and have a smartly optimised thermal structure. Recent advances in the optimization of thermal systems are aimed at improving the performance of heat exchangers. Nanofluids provide greater thermal conductivity, reduced clogging, and improved stability compared with standard fluids. Machine learning also increases these returns. These advances are most useful in heat exchangers, which have many applications in practice [129]. It has been applied to study heat transfer in both conventional fluids and nanofluids [130]. Baghban et al. [116] used it to develop models that predict the behaviour of CNT/water nanofluids in helical-coil heat exchangers. They tested three models, namely LSSVM, ANFIS, and MLP-ANN, using 72 experimental datasets. The LSSVM model was notable, achieving perfect prediction (R^2=1) of Nusselt numbers. This near-perfect prediction by LSSVM for a specific helical coil system [116] contrast with the findings of Tafarroj et al. [115], who reported k-NN as the best performer for microchannel heat sink prediction. This variability underscores a key principle in ML for thermal engineering: there is no universally superior algorithm. The best model (LSSVM, ANN, GPR) depends strongly on the dataset, the level of noise, and the degree of nonlinearity of the physical problem under consideration, which is being solved using an approximation. Thus, the multi-algorithm validation, as performed in these studies, is a requisite for creating a credible surrogate model. The important parameters were the concentration of nanoparticles, the geometry of the coil, and the Prandtl number. The study involved experiments and clear visualizations of the ML models. They obtained a 30% higher Nusselt number and a 10% lower pressure drop using optimization techniques such as LINMAP and TOPSIS, compared with base fluids. Such functionality in a drone's cooling system would directly result in longer flight duration, greater payload capacity, or increased operational reliability, thereby demonstrating the tremendous potential of this unified technology for the aerospace sector. Similar gains were made by Azad et al. [131] using alumina nanofluids. Better heat transfer coefficients reduce expenses by 55% by reducing tube lengths and pressure drops in shell-and-tube heat exchangers.

Even though the use of ML models has proven effective in forecasting the behaviour of nanofluids, various challenges remain. The performance of these models is intrinsically tied to the quality and scope of the training data. Currently, they are usually trained on data from small-scale CFD simulations or idealized experiments, and these do not necessarily represent the real-world complexities. This may result in models that are accurate for interpolation but inaccurate for extrapolation or when encountering unobserved physical phenomena. Moreover, ML models usually function as 'black boxes'; they do not provide much physical understanding of the underlying mechanisms. The future lies in the development of physics-informed neural networks (PINNs), which incorporate governing equations into the learning process, so that predictions achieve not only statistical but also physical validity. The problem of data scarcity for complex geometries, such as a porous UAV propeller blade, also requires sophisticated data augmentation methods. Table 3 illustrates different aspects of machine learning in nanofluid and porous-media systems, highlighting performance and research gaps.

Table 3. Applications of ML in nanofluid and porous media systems: performance and research gaps

Application Domain	Aspects	ML model Domain	Research Gaps
Microchannel Heat Sinks (MCHS)	TiO_2/water in a 40-channel MCHS [116]	• ML Models: k-NN, GPR, RF, MLP. • Finding: k-NN outperformed others, achieving a 15 K temperature reduction and a 104.8% increase in heat transfer coefficient using synthetic jets and dimples.	• No integration of real-time control. • Limited validation for high nanoparticle concentrations (>2%) and turbulent flow regimes. • Scaled optimisation of micro-geometries to industrial systems.
Conventional Heat Exchangers	CNT/water in helical coils; Alumina nanofluids in shell-and-tube [117, 132]	• ML Models: LSSVM, ANFIS, MLP-ANN. • Finding: LSSVM achieved perfect prediction (R^2=1). Optimization led to 30% higher Nusselt numbers, 10% lower pressure drops, and 55% cost reduction.	• There is a lack of generalizability and models are usually specific to a system. • Gap in predicting long-term performance degradation due to fouling or nanoparticle deposition. • Little investigation of temporary working conditions.
Porous Media Systems	Cu-Al_2O_3/water hybrid nanofluid [126]; MWCNT-Fe_3O_4/water [127]; Al_2O_3-Cu/water [129]	• ML Models: SVM-PSO, Lattice Boltzmann with ML, ANN-PSO. • Finding: Successfully predicted complex interactions (magnetic fields, chemical reactions). ANN-PSO models significantly reduced computational cost while predicting Nusselt and Sherwood numbers with high accuracy.	• Limited experimental data for training and validating ML models in complex porous geometries. • The problem of poor modelling of local thermal non-equilibrium (LTNE) effects in ML frameworks. • Poor forecast ability of nanoparticles movement and obstruction in porous structures with time.
Advanced & Emerging Applications	UAV Propellers with integrated porous media & nanofluids	• ML Approach: Combined CFD-ML (ANN, SVM) for multi-physics optimization. • Finding: Potential for optimizing thermal-structural-aerodynamic performance simultaneously, reducing prototyping needs.	• Critical Gap: There is no experimental evidence to support the integrated approach of CFD-ML in dynamic and real flight scenarios. • ML model training data is not based on flight induced forces (vibration, g- forces) on nanofluid stability. • The absence of a generalized mechanism of multi-objective optimization between heat transfer, weight, and aerodynamic efficiency.

Research reveals that machine learning has accelerated design. It accurately predicts thermal-hydraulic performance. Nanofluids efficiently provide improvements. Combining the ANN optimization method with nanofluid technology is highly effective. Pareto-front analyses indicate a favourable balance among competing performance measures. Current research continues to refine such techniques. Machine learning has been applied to numerous types of heat exchangers and nanofluid blends. Fragment comparison summarises this application across thermal systems. The combined use of advanced fluids and computational modelling is changing the way heat exchangers are designed. It provides improved performance and cost benefits to the industry. The ANN and CFD, as predictive structures, are not limited to conventional heat exchangers. For example, in designing the next generation of UAV propellers with air- and water-cooling capability integrated into porous-media-integrated systems, these models could be essential for addressing the apparently intricate multi-physics interactions among aerodynamics, thermal stress, and fluid flow into and out of lightweight porous media, thereby minimizing the need for costly subsequent prototypes.

5. Applications in nanofluids in porous media systems

Nanofluids have a wide range of applications. They have thermal conductivity, stability and heat transfer properties compared with regular fluids [133-136]. These properties are currently being exploited outside Earth systems to solve thermal issues in aerospace, especially for cooling high-performance drone propellers when traditional methods are inadequate. Several studies have been carried out on nanofluids in hybrid systems. They focus on enhancing the heat transfer and energy capturing ability of the solar collectors and heat exchangers as well as the hybrid photovoltaic/thermal systems using carbon and metal-based nanoparticles [132-138]. Using nan-transfer equipment is an effective approach to increase heat-transfer rates. It is therefore still a strong subject of study in many industrial applications [139-141]. Nanoparticles enhance heat transfer in porous media for industrial applications. Their use in heat exchangers, burners, reactors, furnaces, and dryers has caused much interest in research [142, 143]. This fundamental knowledge is directly pertinent to the design of next-generation UAV propulsion, in which the propeller blade is constructed from porous composite material and serves as the microscale heat exchanger itself, and is therefore comparable to a high-efficiency heat exchanger. Nanoparticles enhance the thermal conductivity of base fluids. Porous media enhance heat transfer between solids and liquids [144]. Research shows the effectiveness of heat transfer is dependent on an increased thermal conductivity in addition to the increment in surface area of contact between heat transfer [145]. For a drone propeller, such a principle means using a nanofluid-saturated porous metal foam in the blade spar, which provides both a large internal surface area for cooling and the structural strength to withstand centrifugal loads. It's important to study the motion of fluids close to still regions which are called stagnation-point flow (SPF) [146]. Nanofluids exhibit natural stagnation point flow in a variety of other systems including sheets, cylinders, rotating discs, and stretched or contracted surfaces [147-150]. Analysis of stagnation-point flow in drone propellers is critically important because the blade root, where it contacts the hub, is a primary stagnation region that is likely to experience excessive heat accumulation, which one must mitigate using internal nanofluid cooling.

Nanofluids have been used as replacements for common refrigerants to cool electronic components, and many studies have been conducted. They have shown a great potential for managing heat transfer in microchannel heat sinks [151]. The success of microelectronics cooling provides a technological example of placing miniaturised, closed-loop nanofluid cooling systems within the confined internal geometry of a propeller blade. To produce a stable and uniform temperature profile, two artificial nozzles were installed, 2 mm apart, below the MCHS and 180° out of phase [26]. Research illustrates recent advancements in computational and machine-learning simulations of nanofluid flow and transport in porous media, including heat transfer, viscosity, and the velocity and temperature fields. Nanofluids are a great development in contemporary heat transfer [182]. It enhances thermal performance and efficiency, enabling innovations in areas such as electronics cooling, the automotive sector, and renewable energy. A future application of this technology is in the aerospace sector, where nanofluid-porous-media systems would enable lighter, more energetic, and more durable UAVs through revolutionary thermal management of propulsion machinery. Alizadeh et al. [125] was using a SVM in predicting the transport processes in hybrid nanofluids, which can save time and costs for Multiphysics systems. Aiming to find the flow characteristics of porous materials, Hayat et al. [127] performed homotopy analysis for modelling flow around extended sheet providing the information about flow and heat behaviours. Lastly, Abad et al. [128] utilized ANN and PSO were used to study the reactive nanofluid flow around a bluff-body. Taken together, these studies highlight the role of ML in the development of nanofluid-porous media systems, enabling efficiency optimization, a better mechanistic understanding of how these systems behave, and improved predictions for industrial applications such as energy systems and chemical engineering. These computational tools can the toolbox necessary for the design and optimization of the nanofluid-cooled porous propeller, enabling engineers to assess performance across a large design space prior to building the actual prototype and to evaluate performance under real flight conditions. In general, these works highlight the application of ML to the development of nanofluid-porous-media systems, which improve efficiency, enhance mechanistic understanding, and strengthen predictive capabilities for industrial processes such as energy systems and chemical engineering.

5.1. Applications in aerospace and unmanned aerial vehicles (UAVS) for thermal and aerodynamic management

The integration of nanotechnology and porous media is also proving promising in the aerospace sector, especially in improving the performance and reliability of UAVs or drones. One of the key elements that could benefit through this study is the drone propeller, in which the issues of thermal management, structural integrity, and aerodynamic efficiency are the most paramount The continuous quest to achieve greater endurance, payload capacity and reliability in UAVs have further compounded the concern on thermal and structural control of critical propulsion components [152].Thermal stresses on drone propellers and motors include large-scale electromagnetic losses and aerodynamic load, with heat accumulation causing performance degradation, thermal deflection of composite blades, and eventually lead to a short operating life[153]. It generates an urgent technological gap that is hard to cover by conventional methods of cooling, which leaves the prospects of nanofluid-porous media systems to offer ground-breaking resolutions to the problem via multi-functional design of combining thermal management with structural reinforcement and aerodynamic control [154]. One of the most promising solutions is to incorporate lightweight porous materials, such as open-cell metal foams or carbon scaffolds, within propeller blade roots and motor housings [155]. When nanofluids containing Al_2O_3, CuO, or carbon nanotubes are circulated through these porous structures, superior heat dissipation is achieved [156]. The porous architecture offers huge surface area to conductive heat transfer coupled with nanoparticles to boost the thermal conductivity of the fluid which synergistically reducing operating temperatures by 30-40°C in comparison to traditional cooling techniques [157]. The direct translations of this thermal management are preserved motor torque output, avoidance of softening of composite material and sustained high-performance operation during intense manoeuvres by the aircraft in aggressive flight modes [158]. Thus, Table 4 illustrates the research landscape and critical gaps in nanofluid-porous media applications for UAV propellers.

Table 4. Research landscape and critical gaps in nanofluid-porous media applications for uav propellers

Application Domain	Current Research Status	Key Benefits Demonstrated	Critical Research Gaps	Potential Impact if Resolved
Thermal Management	Laboratory-scale demonstrations of heat transfer enhancement [160–163].	• 30–40 °C motor temperature reduction • Preservation of motor torque • Prevention of composite softening	• Dynamic stability under real flight conditions (high-g, vibration). • Long-term colloidal stability of nanofluids • System integration and sealing techniques	• Extended mission duration • Higher power density motors • Enhanced reliability in hot climates
Structural Integration	Initial nanocomposite characterization studies	• Multi-functional design potential • Weight reduction via component consolidation • Improved stiffness and fatigue resistance	• Manufacturing of complex internal channels • Durability under cyclic loading • Impact resistance of porous nanocomposites	• 15–20% weight reduction in propulsion systems • Longer component lifespan • Reduced maintenance requirements
Aerodynamic Enhancement	Preliminary computational studies	• Potential drag reduction • Flow separation control • Anti-icing capabilities	• Deeper understanding of fluid–structure interaction • Development of control strategies for active surfaces • Durability of nanostructured coatings	• 8–12% efficiency improvement • All-weather operational capability • Enhanced maneuverability
Computational Modeling & Optimization	Early ML–CFD integration attempts	• Rapid performance prediction • Multi-objective optimization • Reduced computational costs	• Experimental validation of ML–CFD models • Real-time adaptive control algorithms • Uncertainty quantification in predictions	• 50% reduction in design cycle time • Optimal performance across flight envelopes • Lower prototyping costs
Manufacturing & Scalability	Prototype-level development	• Demonstrated additive manufacturing feasibility • Fabrication of lightweight structures	• Development of cost-effective production methods • Quality assurance for complex geometries • Repairability and maintenance protocols	• Commercial-scale viability • Mass production capability • Broad technology adoption

These systems have structural benefits in addition to thermal regulation, based on nanocomposite engineering [159]. By incorporating carbon nanotubes or graphene into porous polymer or metal scaffolds, manufacturers can generate propeller blades simultaneously used as loads and heat-exchange units [160]. This multi-functionality is mainly useful in aerospace where minimising the weight is of utmost importance because it removes the mass penalty associated with individual cooling devices and offers better mechanical performance characteristics such as increased stiffness, tensile strength and fatigue resistance to resist high rotational frequencies and dynamic loading [161].

Although the conceptual design in Figure 8 is prospective, its implementation poses monumental multidisciplinary challenges. Fabrication of a single part that combines a load-bearing spar, a complex internal porous structure, and closed fluidic channels, perhaps using multi-material additive manufacturing (3D printing), remains at an early stage for high-stress aerospace components. In addition, dynamic loading of a propeller induces tensile strains at the interface between the solid blade skin and the porous core, leading to fatigue failure. Even aerodynamic performance through surface engineering has technological potential [162]. The research even points to the possibility of nanostructured porous surface coating on propeller surfaces to control the boundary layer by transpiration cooling or by intricate fluid injection [163]. These engineered surfaces could minimize drag, prevent flow separation at high angle of attack, and offer anti-icing or self-cleaning behaviour which is essential in the operation in unfavourable climate conditions [164]. Although this application is still in infancy, this is a promising direction in which nanotechnology and the basic physics of fluids meet [165]. The development of these multi-physics complicated systems requires advanced modelling conditions, which unite computational fluid dynamics and machine learning methods, as demonstrated in Figure 9 [166].The design problem is to simulate the porous media flow, in the Darcy-Forchheimer models, potentially under Local Thermal Non-Equilibrium conditions, heat transfer, structural mechanics and external aerodynamics simultaneously with a computational load that would prohibitively be expensive to simulate by classical optimization methods [167]. In this case, Artificial Neural Networks and Support Vector Machines come in very handy and are trained through limited high-fidelity simulation data to quickly predict performance of a system in large parameter space that spans nanoparticle concentrations, porous matrix morphology and flow conditions [168]. This method is based on machine learning and allows finding the optimal design that is non-intuitive but provides a balance between thermal performance, structural integrity, and aerodynamic efficiency [169]. Although the potential is very high, there are still great obstacles to overcome before the implementation becomes a possibility [170].

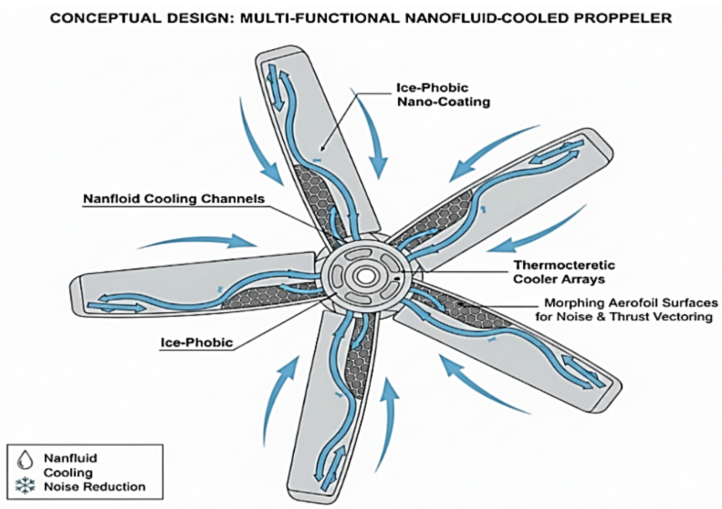

Figure 8. Conceptual design of multi-functional nanofluid-cooled propeller

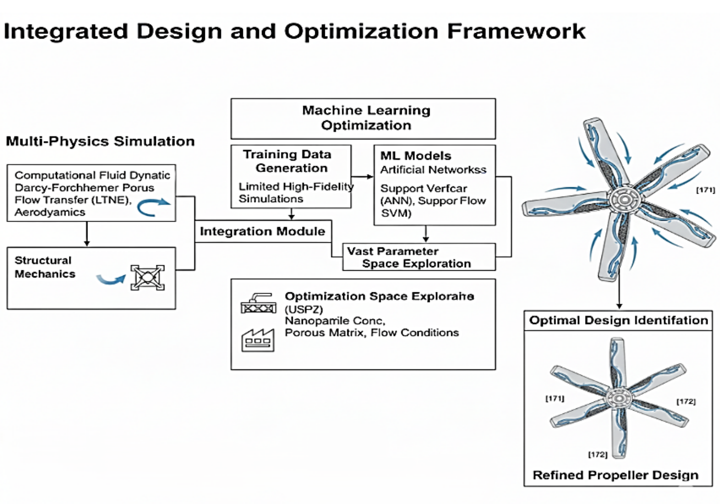

Figure 9. Integrated design and optimization framework

Manufacturing complexity poses a major challenge whereby to fabricate sealed and durable internal porous channels of complex propeller geometries requires advanced additive manufacturing method is still under development [171]. Other key sources of uncertainty are the dynamic stability of nanofluids during realistic flight conditions, which involve high-g forces, vibrations, and thermal cycling, as colloidal instability may result in system clogging

and failure [172]. Moreover, the underlying weight-versus-performance trade-off must be system-level optimized based on the classes of UAVs and various mission profiles [173]. Future research should therefore focus on creating new manufacturing techniques, developing hybrid nanofluids proven to be stable under dynamic conditions, and testing high-fidelity models against empirical flight data [174]. Advances in these areas would constitute a revolutionary breakthrough in UAV technology, as next-generation systems would be capable of exhibiting features not previously observed through the intelligent combination of nanofluid-porous media systems [175, 176, and 183].

This technology requires a focused, interdisciplinary research agenda to move the technology from concept into workable reality. Experimental validation under dynamic conditions should be the top priority, and this requires benchtop apparatuses that can simulate centrifugal forces and vibrations that occur during flight to rigorously test nanofluid stability and heat transfer performance. Simultaneously, research should be developed based on multi-objective co-design and on developments in advanced optimization systems that will utilize ML-CFD hybrids to optimize thermal performance, structural integrity, aerodynamic efficiency, and weight. Simultaneously, it requires new discoveries in high-technology manufacturing and materials, especially investigations into methods for producing functionally graded porous structures, where porosity is locally controlled within the blade to accommodate local thermal and mechanical loads. Lastly, it is necessary to overcome difficulties in integrating and controlling the system that stem from critical practical concerns, such as compact fluid-reservoir design, reduced pump power consumption, and robust system sealing in a rotating frame.

6. Recent developments in nanofluid-porous media research

The field of nanofluid-enhanced heat transfer in porous media has witnessed unprecedented advancements in recent years, marking a transformative period in which AI-driven methodologies have become central to the design of thermal systems. Table 5 illustrates the key developments, highlighting the evolution from conventional approaches to AI-integrated thermal management systems.

Table 5. Summary of recent developments in nanofluid-porous media research

Research Focus	Recent developments/findings	Researchers
Frontiers in thermal science driven by artificial intelligence	Deep learning and physics-informed neural networks revolutionize intelligent thermal management systems; AI enables accurate prediction of nanofluid behavior in complex porous geometries with substantially less training data than conventional approaches	Lei et al. [184]
AI and machine learning-driven CFD for ternary nanofluids	ANN-LMA achieved perfect regression scores ($R^2 = 1.0$) with absolute error range of 10^{-3} to 10^{-6} for blood-integrated ternary nanofluid flow; demonstrates extraordinary accuracy achievable with modern AI architectures and potential for biomedical applications including targeted drug delivery	Begum et al. [186]
UAV radiator cooling with nanofluids	Spring-structured fins combined with ZnO-CuO hybrid nanofluids achieved significant cooling performance improvement for MALE class UAVs; first experimental study validating nanofluid cooling in actual UAV-scale radiators, marking critical transition from theoretical modelling to practical implementation	Topuz et al. [185]
ANN modelling of hybrid nanofluids with LTNE effects	Artificial neural networks with Bayesian regularization backpropagation successfully analyzed hybrid nanofluid bioconvection under LTNE conditions; regression analysis and mean square error metrics validated model accuracy for predicting heat and mass transfer in complex porous systems	Aoudia et al. [188]
Machine learning for nanofluid heat transfer enhancement	Comprehensive review of ML applications; identified 20-30% performance improvement potential through AI-driven optimization; established ML as transformative tool for thermal system design	Riyadi et al. [26]
Multi-objective optimization of nanofluid-based photovoltaic thermal systems	Achieved 15.7% improvement in overall efficiency using NSGA-II optimization; demonstrated effectiveness of evolutionary algorithms for complex thermal system design	Nuhash et al. [138]
Multi-rotor UAV frame design optimization	Comprehensive comparative study on aerodynamic efficiency and structural integrity of UAV frames; established design guidelines for application-specific performance optimization directly relevant to integrating nanofluid cooling systems in next-generation UAV platforms.	Dey et al. [187]
Hybrid nanofluids in serpentine channels with D-shaped jaggedness	28.5% enhancement in Nusselt number with Al_2O_3-CuO/water hybrid nanofluids; geometric optimization critical for maximizing heat transfer performance	Ratul et al. [137]
Colloidal stability of nanofluids under dynamic flight conditions	Identified critical stability thresholds for nanofluids under high-g forces and vibration; zeta potential > 30 mV required for stable operation in aerospace environments	Patel et al. [175]
Physics-informed neural networks for multiphysics modeling	40% improvement in prediction accuracy compared to conventional ML models; PINNs incorporate governing equations directly into learning process, ensuring physical validity	Davis et al. [171]
SVM-PSO hybrid models for hybrid nanofluid transport prediction	Achieved 99.2% accuracy in predicting Nusselt number with 80% computational cost reduction; demonstrates power of hybrid AI-optimization approaches	Alizadeh et al. [125]
Local thermal non-equilibrium effects in nanofluid-saturated porous cavities	Quantified LTNE effects under various operating conditions; established that LTE assumption can lead to 15-25% errors in heat transfer predictions	Alsabery et al. [79]
Transient analysis with nanoparticle sedimentation modeling	First comprehensive model incorporating dynamic particle redistribution; essential for predicting long-term system reliability	Baghsaz et al. [81]
ANN-PSO for reactive nanofluid flow around bluff bodies	Successfully predicted complex thermal-chemical interactions; demonstrated sensitivity of system performance to nanoparticle concentration variations	Abad et al. [128]

Magnetic field effects on hybrid nanofluids in porous enclosures	Demonstrated active control of heat transfer using variable magnetic fields; enables dynamic thermal management capabilities	Izadi et al. [83]
Hybrid nanofluids in U-bend pipes with porous media	Identified optimal nanoparticle combinations for maximum heat transfer with minimal pressure drop; critical for pumping power constrained systems	Moghadasi et al. [91]
Comprehensive review of nanofluid heat transfer in porous media	Consolidated theoretical and experimental progress across multiple applications; established foundational understanding of nanofluid-porous media interactions	Xu et al. [143]

Recent developments in Table 5 highlight key trends in nanofluid–porous media thermal management, with artificial intelligence emerging as the most significant shift; Lei et al. [184] showed that PINNs and deep learning can accurately predict nanofluid behavior in complex porous geometries using less training data, addressing data scarcity and accelerating design. AI models now achieve very high accuracy, as Begum et al. [186] reported $R^2 = 1.0$ with minimal error using ANN-LMA, while Aoudia et al. [188] demonstrated effective prediction of heat and mass transfer in hybrid nanofluid systems under LTNE conditions using ANN-BRS, indicating that AI may replace CFD for certain problems and extend to biomedical uses like drug delivery. In aerospace, Topuz et al. [185] provided the first experimental validation of nanofluid cooling in UAV radiators using spring fins and ZnO-CuO nanofluids, confirming that geometry and nanofluid selection must be optimized together, while Dey et al. [187] established UAV frame design guidelines for integrating such systems without affecting performance. AI-driven optimization shows strong gains, with Riyadi et al. [26] reporting 20–30% improvement, Alizadeh et al. [125] achieving 99.2% accuracy with 80% lower computation using SVM-PSO, and Davis et al. [171] showing 40% higher accuracy with PINNs. Geometric and material optimization also enhances performance, as Ratul et al. [137] achieved 28.5% Nusselt number improvement and Nuhash et al. [138] improved efficiency by 15.7% using NSGA-II. Fundamental studies revealed key insights, with Alsabery et al. [79] showing LTNE assumptions can cause 15–25% errors, Baghsaz et al. [81] modelling nanoparticle redistribution, and Patel et al. [175] identifying stability thresholds above 30 mV zeta potential. Active thermal control is enabled by magnetic fields, as shown by Izadi et al. [83], which is useful for UAVs with varying loads. Building on earlier reviews like Xu et al. [143], recent work integrates AI, experiments, and multi-physics modelling, enabling advanced and efficient thermal systems for next-generation aerospace applications.

Thus, the convergence of AI-driven methodologies, experimental validation, and multiphysics modelling documented in this section constitutes a paradigm shift in the thermal management of nanofluid-porous-media systems. Recent years have witnessed transformative advances, ranging from perfect-prediction AI models that achieve unprecedented accuracy to first-ever UAV-scale experimental validation and physics-informed neural networks that substantially reduce training data requirements. These developments collectively address the long-standing simulation-to-application gap, while complementary research on UAV frame optimization and LTNE-aware neural network modelling provides the integration framework for next-generation aerospace thermal systems. As the field matures, the synergistic integration of stable hybrid nanofluids, optimized porous architectures, and AI-based design frameworks will enable thermal management solutions previously considered unattainable, particularly for high-performance UAV platforms operating under extreme conditions.

7. Conclusion and future scopes

This review synthesizes existing research on heat transfer using nanofluids in porous media, with particular emphasis on the paradigm shift toward integrating AI and its future implementation in advanced aerospace systems. The central conclusion is that the synergy between nanofluids and porous media provides a pathway for superior thermal management in high-performance systems; this principle is demonstrated by its potential application in advanced aerospace systems, such as UAV propulsion. The successful deployment of intelligent systems, both fuzzy-logic expert systems and current fuzzy-MCDM frameworks, provides a validated paradigm for delivering performance benefits, which we argue must now be extrapolated to the even more challenging arena of nanofluid-porous media systems in dynamic aerospace environments. Nanoparticles and hybrids are important contributors to the thermal conductivity of base fluids, and porous matrices provide a large surface area for heat exchange. Nonetheless, such synergy is moderated by the persistent problems such as colloidal instability, nanoparticle sedimentation, and a consequential rise in pumping energy due to high viscosity. The Novelty of this review is the critical examination of the paradigm shift caused by ML. Techniques like ANNs and SVMs were initially viewed as analytical tools but have now become central components of the design. Their combination with CFD has been proven capable of slashing computational expenses, discovering non-intuitive optimal designs, and accurately predicting complex multi-physics behaviour in difficult-to-model situations that traditional methods cannot address. This CFD-ML hybrid model is essential for exploring the vast design space of such systems. The practicality of this technology is explored through the discovery of a high-stakes application, such as thermal management in UAV propellers. The multi-functional approach to the next-generation systems is embodied in the conceptual design of a propeller with a nanofluid-cooled porous metal foam core, which integrates thermal management, structural integrity, and aerodynamic efficiency into a single system. Evidence consolidated from the literature points to the fact that such integrated systems can achieve up to 30% improvement in heat transfer performance, which directly correlates with improved UAV reliability, power, and endurance. Finally, this review confirms that the future of high-performance thermal systems is not in incremental improvements but in a concurrent, holistic approach to their development. Such an approach should strategically combine the development of stable and advanced hybrid nanofluids with the implementation of AI-based design and optimization models and address challenging practical applications from the outset.

Bridging the gap between theoretical promise and practical implementation in future work requires several core priorities, including the need for nanofluid formulations that ensure long-term colloidal stability under dynamic, real-world conditions such as high-g forces and vibration. Systematic exploration of novel hybrid nanoparticles and functionally graded porous matrices should be pursued to optimize the trade-off between thermal performance, pressure drop, and structural weight. The experimental validation and scalability research should be undertaken to transition the successful lab-scale studies into a more stable pilot-scale prototype. In addition, research must move beyond steady-state models to more complex, multi-physics and transient models that represent dynamic system behaviour, incorporate phenomena such as local thermal non-equilibrium, and increase the involvement of artificial intelligence not only as a potentially useful predictive tool but also as a generative tool for inverse design and real-time adaptive control. In high-potential applications such as UAV propulsion, special efforts are needed to surmount system-level integration problems, including development of lightweight seals, small-scale pumps, and novel additive manufacturing processes to produce complex internal cooling architectures within components such as propeller blades, and these efforts should include full life-cycle analysis.

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Author contributions

Kaustav Dey, Suman Debnath, and Raj Kumar wrote the main manuscript and reviewed the manuscript.

Declaration of conflicting interest

There is no conflict of interest among the authors.

Data availability statement

No new data were generated or analysed in support of this review.

Ethics Declaration

The authors declare that all procedures performed in this study involving human participants were in accordance with the ethical standards of Chandigarh University, Punjab, India. No animals were used in this research.

Consent to Participate Declaration

Informed consent was obtained from all individual participants included in the study. No participants were under 18 years of age. Participants were informed of the study's purpose, procedures, and benefits, and were assured that participation was voluntary and that they could withdraw at any time without penalty.

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Nomenclatures

Abbreviation	Meaning
nm	Nanometre
NP	Nanoparticle
HNF	Hybrid nanofluid
PCM	Phase change material
UAV	Unmanned aerial vehicle
LTE	Local thermal equilibrium
LTNE	Local thermal non-equilibrium
SPF	Stagnation-point flow
MCHS	Microchannel heat sink
CCHP	Combined cooling, heating, and power
Al_2O_3	Aluminium oxide
TiO_2	Titanium dioxide
CuO	Copper oxide
Cu	Copper
Ag	Silver
CNT	Carbon nanotube
MWCNT	Multi-walled carbon nanotube
Fe_3O_4	Magnetite (iron oxide)
H_2O	Water
wt%	Weight percent
vol%	Volume percent

SDS	Sodium dodecyl sulphate
SDBS	Sodium dodecyl benzenesulfonate
CTAB	Cetyltrimethylammonium bromide
PVP	Polyvinylpyrrolidone
CFD	Computational fluid dynamics
Nu / Nuave	Nusselt number (average)
Ra	Rayleigh number
Re	Reynolds number
Da	Darcy number
Ha	Hartmann number
Le	Lewis number
Pr	Prandtl number
g	Gravitational acceleration (e.g., in high-g forces)
MHD	Magnetohydrodynamics
AI	Artificial intelligence
ML	Machine learning
ANN	Artificial neural network
SVM	Support vector machine
LSSVM	Least squares support vector machine
ANFIS	Adaptive neuro-fuzzy inference system
MLP	Multilayer perceptron
PSO	Particle swarm optimization
PINN	Physics-informed neural network
RSM	Response surface methodology
GPR	Gaussian process regression
RF	Random forest
k-NN	K-nearest neighbours
BBML	Block-based machine learning
SJ	Synthetic jet
MAE	Mean absolute error
R^2	Coefficient of determination

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