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Metal Foams, Nanofluids, and Phase Change Material for Enhanced Heat Transfer and Thermal Energy Storage: A Multiscale Review

Reza Rabani*, **Javad Ghavanini**, **Saeed Shoroei**

Department of Mechanical Engineering, Ka.C., Islamic Azad University, Karaj, Iran
** Corresponding Author: reza.rabani@iau.ac.ir*

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Abstract

Over the past decade, the development of advanced heating, cooling, and thermal energy storage systems has increasingly focused on innovative solutions such as nanofluids, metal foams and phase change materials (PCMs). Through the coordinated use of complementary experimental and modeling approaches. This project systematically assessed the degree of heat transfer and overall thermal performance enhancement achievable in heat exchangers and thermal energy storage systems by integrating nanofluids, metal foams, and PCMs. This article provides an overview of the main aspects of this comprehensive research activity. Particular attention is devoted to the comparison between mesoscopic and macroscopic heat transfer modeling in metal foams and nanofluids, as well as to the experimental datasets acquired and analyzed throughout the research program. Overall, this multiscale review indicates that the combined use of metal foams, nanofluids, and phase change materials can effectively enhance heat transfer characteristics and thermal energy storage performance, while also highlighting the remaining modeling and practical challenges associated with their implementation in engineering systems.

Keywords: Metal Foams; Nanofluids; Phase Change Materials (PCMs); Thermal Energy Storage; Heat Transfer Enhancement; Micro Computed Tomography (μCT); Local Thermal non-Equilibrium (LTNE); Microfin Tubes.

1. Introduction

In recent decades, significant research efforts have been devoted to enhancing heat transfer and thermal energy storage using metal foams, phase change materials (PCMs), and nanoparticles dispersed in fluids or PCMs. These approaches have been widely investigated for the development of advanced heat exchangers and thermal management systems operating over a broad range of characteristic scales, from electronic cooling devices to heat pump and thermal energy storage applications. Also, for various thermal load ranges, from dimensional analyses of 1–3 cm^3 to 0.2–0.6 m^3. In particular, the integration of foams, nanofluids, and PCMs has demonstrated strong potential for improving thermal performance in systems subjected to varying heat loads.

Transport phenomena in fluid-saturated porous media have been extensively studied, with particular emphasis on thermal stability and convection mechanisms. Classical analyses of Darcy–Bénard instability describe the momentum balance using Darcy's law[1], initially considering a quiescent fluid heated from below under uniform boundary conditions. This framework was later extended to include forced through flow configurations, such as the Prats problem, which accounts for the interaction between natural and forced convection. Comprehensive reviews of these instability mechanisms and their implications for heat transfer in porous media are available in the literature. At the microscale, heat transfer within metal foams is strongly influenced by their geometric and morphological characteristics. Previous studies employing tomography-based reconstructions and idealized Kelvin foam models have shown that parameters such as porosity, cell shape, strut geometry, and inclination angle significantly affect effective thermal conductivity, convective heat transfer, and pressure drop[2], while other investigations reported a limited sensitivity of thermal conductivity to strut shape variations [3].

Thermal energy storage systems play a crucial role in a wide range of applications, particularly in renewable energy technologies, where they enable the temporal decoupling of energy generation and consumption[4]. PCMs are especially attractive due to their high latent heat storage capacity; however, their low intrinsic thermal conductivity often limits charging and discharging rates. To overcome this drawback, several studies have proposed embedding PCMs within metal or graphite foams, or within additively manufactured three-dimensional metallic structures, leading to enhanced heat transfer rates and reduced system downtime[5].

Growing environmental constraints and the demand for compact, high-efficiency thermal systems have further stimulated research on innovative heat exchanger designs and advanced working fluids. In refrigeration, air-conditioning, and electronic cooling applications, investigations have focused on enhanced heat transfer surfaces and on flow boiling and condensation processes using novel fluids, aiming to reduce refrigerant charge while maintaining high thermal performance[6]. In parallel, the use of PCMs integrated into heat exchangers has emerged as an effective solution for thermal regulation in both steady and transient operating conditions[7].

Heat transfer augmentation through the combined use of nanoparticles, nanofluids, PCMs, and porous structures has attracted increasing attention. Reliable assessment of the thermophysical properties and stability of nanofluids is essential for their practical implementation[8] , especially in applications such as electronic cooling[9]. Although classical theories, such as the DLVO framework, provide a basic description of colloidal stability[10] , they are often inadequate for capturing nanoscale effects associated with particles with characteristic sizes below 100 nm, highlighting the need for more advanced modeling approaches[11]. The integration of nanofluids with microchannel, foams, or honeycomb structures, as well as hybrid configurations involving Nano-enhanced PCMs and porous media, represents a promising strategy for achieving substantial heat transfer enhancement. However, a comprehensive synthesis of studies addressing the direct coupling of PCMs with metal foams and/or nanofluids, particularly across multiple length scales, remains limited in the open literature. The present review aims to address this gap by providing a unified overview of experimental, numerical, and theoretical investigations on heat transfer and thermal energy storage enhancement using metal foams, nanofluids, PCMs, and their combined implementations, with a focus on underlying mechanisms, modeling approaches, and engineering applications.

In this review, the term multiscale refers to the analysis of heat transfer and thermal energy storage phenomena across different length scales. At the nanoscale, attention is focused on interfacial effects, nanoparticle–fluid interactions, and molecular-level transport mechanisms, which are particularly relevant to nanofluids and Nano-enhanced phase change materials. The mesoscale primarily concerns pore-scale transport processes, including fluid flow and solid–fluid heat exchange within metal foam structures, where local thermal non-equilibrium effects may become significant. At the macroscale, volume-averaged formulations and effective thermophysical properties are commonly employed to describe the overall thermal behavior of engineering systems. Accordingly, mesoscale and nanoscale aspects are mainly discussed in Sections 3 and 4, while macroscale implications are addressed throughout the manuscript.

2. Flow Characteristics at the Mesoscale in Metal Foams Saturated with Fluid

Heat transfer in open-cell metal foams can be analyzed using either pore-scale (mesoscale) or volume-averaged (macroscale) modeling approaches[12]. In the latter framework, the governing equations are formulated through a volume-averaging procedure[13] , whereby the dependent variables are averaged over a representative elementary volume (REV) whose geometrical and physical properties adequately describe the overall porous structure[14] . Mesoscale approaches are particularly suitable when detailed information at the pore level is required, as they explicitly resolve the foam microstructure and the associated local flow and heat transfer phenomena. Conversely, macroscale approaches are generally preferred for large computational domains, where fully resolved pore-scale simulations would lead to prohibitive computational costs. Despite their averaged nature, macroscale models are capable of providing reasonably accurate predictions of key engineering quantities, such as pressure drop across a device or its overall thermal efficiency. It should be emphasized, however, that the closure of volume-averaged governing equations often relies on constitutive parameters or correlations that are most reliably obtained from pore-scale analyses.

2-1. Single-Phase Flow Simulations by Use of μCT Images

Micro computed tomography (μCT) enables the reconstruction of realistic three-dimensional porous structures and has been widely applied in both medical and industrial fields. The tomographic images were processed and meshed using commercial software, and an appropriate grayscale threshold was selected to ensure consistency between reconstructed and measured porosities. An example of the reconstructed foam geometry is shown in Fig. 1.

Heat conduction in open-cell foams reconstructed from μCT scans has been investigated using different modeling strategies. One commonly adopted approach represents the foam as a network of fins, where classical fin equations are applied to describe heat conduction within the solid ligaments[15] . This one-dimensional formulation, in which the axial direction of each ligament is considered, significantly reduces the computational cost compared to finite-element-based methods and is consistent with approaches previously developed within electrochemical fin theory [16]. In this framework, each ligament is modeled as a fin with a variable cross-section, typically assumed to follow an exponential decay law[16], while continuity of heat flux is imposed at ligament junctions. Uniform temperature boundary conditions at the top and bottom of the reconstructed domain allow the evaluation of the effective thermal conductivity of the foam (Fig. 2).

Based on tomographic reconstructions, a detailed analysis of anisotropy in open-cell foams was performed in [17]. Anisotropy may originate from manufacturing processes influenced by gravity or viscosity effects, or it may be intentionally introduced through additive manufacturing. By characterizing foam cells through their principal axes, computed using Feret diameters, it was shown that cell elongation leads to directional dependence of effective thermal conductivity. In particular, higher ratios between cell diameters result in larger discrepancies between conductivities evaluated along different directions, with cell size ratios reaching approximately 1.4 and corresponding thermal conductivity ratios approaching 1.8. These findings indicate that anisotropy should be explicitly considered when modeling heat conduction in metal foams.

The same copper foams investigated in [18] were experimentally characterized under forced air convection by Mancin et al. [19] using a wind tunnel facility. The foams were assembled in sandwich-like configurations, with metallic plates brazed to the top and bottom surfaces, and tested under different flow conditions. These experiments enabled the determination of pressure drop and convective heat transfer coefficients, as well as the development of empirical correlations for forced convection in open-cell foams.

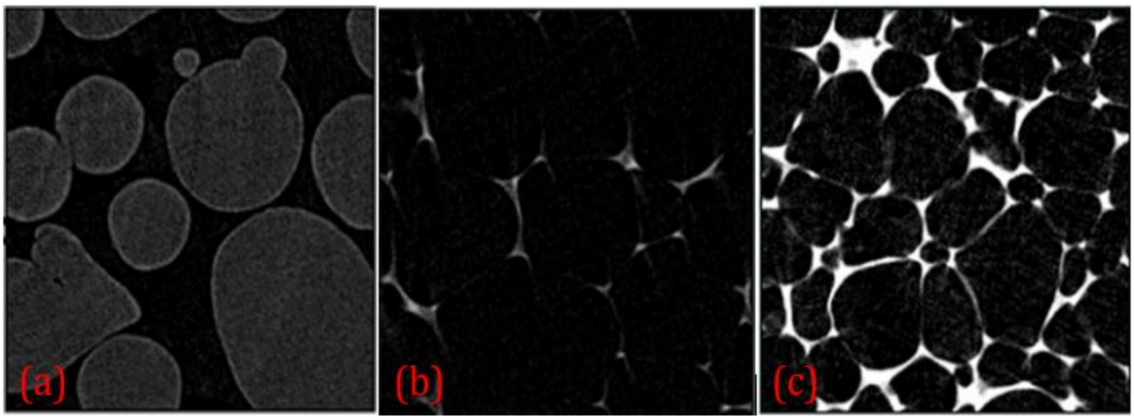


Fig. 1. Examples of μCT scanning. (a: Solid material & b: PU & c: Foams).

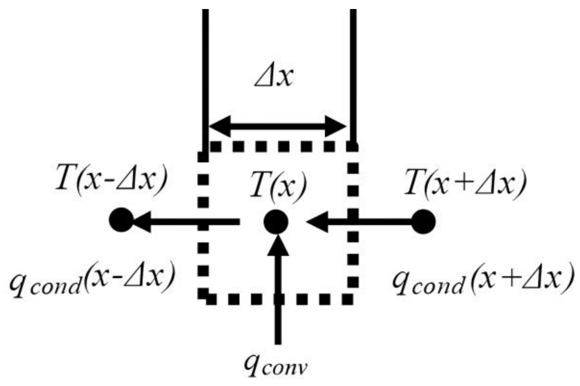


Fig. 2. Energy balance performed on an elementary portion (Δx).

Due to computational limitations, numerical simulations were performed on reduced domains with constant heat flux boundary conditions, after identifying a representative number of pores along the flow direction.

Numerical simulations were carried out using Ansys Fluent, and a direct comparison with experimental data showed good agreement. For all four foam samples, mean relative and absolute deviations in pressure drop of −3.8% and 5.4%, respectively, were reported. Moreover, the interfacial heat transfer coefficients obtained numerically were consistent with those predicted by the empirical correlations developed in [19], both in terms of local heat transfer coefficients and overall foam efficiency. Following the observation of anisotropy effects in thermal conduction [17], similar behavior was identified for convective heat transfer. In [20], heat transfer coefficients were evaluated for airflow aligned with each of the three principal cell directions of the foam. The results showed an inverse relationship between cell elongation and convective heat transfer coefficient, with more elongated cells exhibiting lower heat transfer performance. This behavior was attributed to thermally developing flow effects within the foam structure, in agreement with previous findings [21]. Based on these results, a Nusselt–Reynolds number correlation incorporating anisotropy effects was proposed, where the characteristic length is defined along the flow direction.

2-2. Two-phase heat transfer in micro-finned tubes

Among the various approaches used to model porous materials, capillary models represent the porous structure as a bundle of parallel mini- or micro channels. Beyond their use as idealized representations of porous media, small-diameter channels are widely employed in practical applications such as air conditioning, refrigeration, and electronic cooling systems. It is well established in the literature that the introduction of micro fins on the inner surface of these channels significantly enhances heat transfer, not only by increasing the effective heat transfer area but also by promoting turbulence and flow mixing. In two-phase flows, micro fins further modify flow regime transitions, inducing an earlier shift from stratified to annular flow at lower vapor qualities and mass velocities compared to smooth tubes of equal inner diameter.

Within this framework, Diani and Rossetto [22], Liu et al. [23], and Diani et al. [24] experimentally investigated microfin tubes with outer diameters of 3.0, 4.0, and 7.0 mm under both condensation and flow boiling conditions, using several low–global warming potential (GWP) refrigerants, including R513A, R450A, R515B, and R1234ze(E). The experiments covered a wide range of operating conditions in order to assess their influence on heat transfer coefficients and frictional pressure drops. Specifically, mass velocities ranged from 50 to 800 kg m^{-2} s^{-1}, saturation temperatures were set between 20 and 40°C, and, for flow boiling tests, applied heat fluxes varied from 10 to 60 kW m^{-2}.

When compared to equivalent smooth tubes with the same inner diameter, microfin tubes consistently exhibited superior thermal performance in terms of heat transfer coefficients. This enhancement is commonly quantified through the enhancement factor (EF), defined as the ratio between the heat transfer coefficient of the microfin tube and that of the smooth tube under identical operating conditions. As illustrated in Fig. 3 for condensation tests in a 7 mm outer diameter microfin tube, EF values exceed the corresponding geometric enhancement factor, Rx, defined as the ratio between the heat transfer areas of the microfin and smooth tubes (Rx = 1.63 for the considered geometry). The highest EF values were observed at mass velocities in the range of 100–200 kg m^{-2} s^{-1}, where microfin tubes predominantly operate in the annular flow regime—associated with higher heat transfer coefficients—while smooth tubes under the same conditions remain in the stratified flow regime.

2.3. Metal foams as engineered periodic structures

Metal foams are commonly characterized as random porous media, which makes their virtual reconstruction and experimental reproducibility challenging. Nevertheless, several studies have shown that the pore morphology of metal foams can be effectively represented using periodic structures [25]. In this context, different idealized geometries have been proposed to reproduce the intrinsic periodicity of foam microstructures.

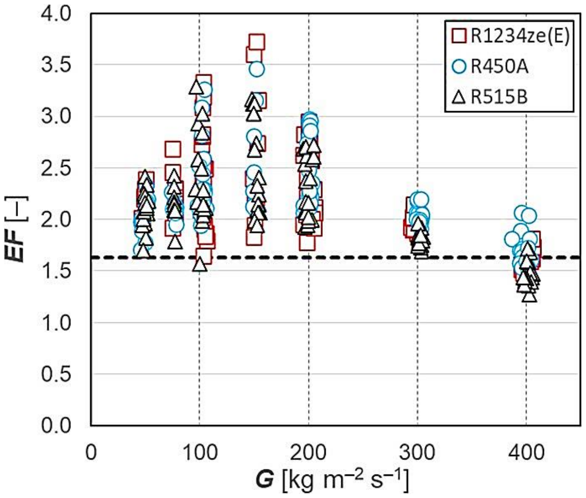


Fig. 3. Enhancement factor vs. mass velocity for the OD 7 mm microfin tube during condensation.

Among these, triply periodic minimal surfaces (TPMSs) have emerged as a particularly attractive modeling option [26]. TPMS geometries are mathematically defined by combinations of trigonometric functions and can be reliably manufactured using metal additive manufacturing techniques, such as selective laser melting (SLM) [27]. These features make TPMS-based structures promising candidates for the design of advanced metal foam heat exchangers.

Beyond thermal performance, the mechanical response of TPMS-based metal foams represents a key design aspect. The mechanical properties of several engineered TPMS foams were numerically investigated in [28], with particular attention to the influence of residual stresses induced by selective laser melting on their thermomechanical behavior. In addition, Novak et al. [29] experimentally and numerically studied the compressive response of tubes filled with diamond TPMS structures. Their results demonstrated a significant enhancement in energy absorption under both axial and transverse loading compared to empty tubes. Moreover, the specific energy absorption of TPMS-filled tubes was shown to exceed that reported for other types of foam-filled tubes in previous studies, highlighting the potential of TPMS-based foams for multifunctional thermal and structural applications.

In addition to their mechanical behavior, the heat and mass transfer performance of TPMS-based metal foams is of primary interest for thermal engineering applications. Numerical investigations of transport phenomena in such engineered structures were reported in [30], where heat and mass transfer in a gyroid TPMS-based channel were analyzed with particular emphasis on the thermal entrance region. The local momentum balance was modeled using the Navier–Stokes equations, while the energy transport was described through a coupled convection–conduction formulation. A schematic representation of the TPMS channel is shown in Fig. 5.

Fig. 4. Gyroid, diamond, and primitive TPMS drawn for an isotropic medium.

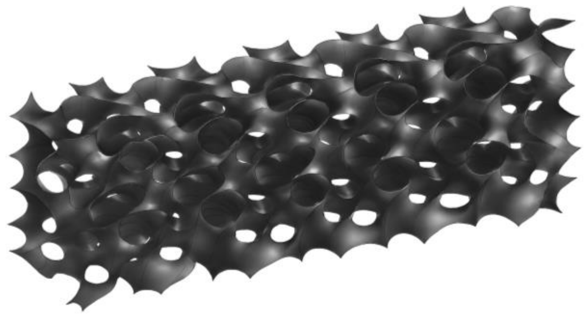


Fig. 5. Square section channel filled with a fluid-saturated engineered metal foam based on gyroid TPMS.

Assuming a high-conductivity metallic structure, the solid phase was treated as isothermal. Under this assumption, the pressure drop and the volumetric interfacial heat transfer coefficient were evaluated as functions of the inlet velocity (Fig. 6). The resulting pressure drop–velocity relationship was found to be consistent with the Darcy–Forchheimer model [1], confirming that TPMS-based structures can be effectively represented at the macroscale as equivalent porous media.

Cell-scale investigations of structured metal foams were further reported in [32], where different working fluids, including water-based mixtures and Al_2O_3 nanofluids, were considered to evaluate both fluid-dynamic and thermal characteristics, such as permeability and local heat transfer coefficients. These analyses provided insight into the interaction between fluid properties, pore-scale flow structures, and heat transfer mechanisms.

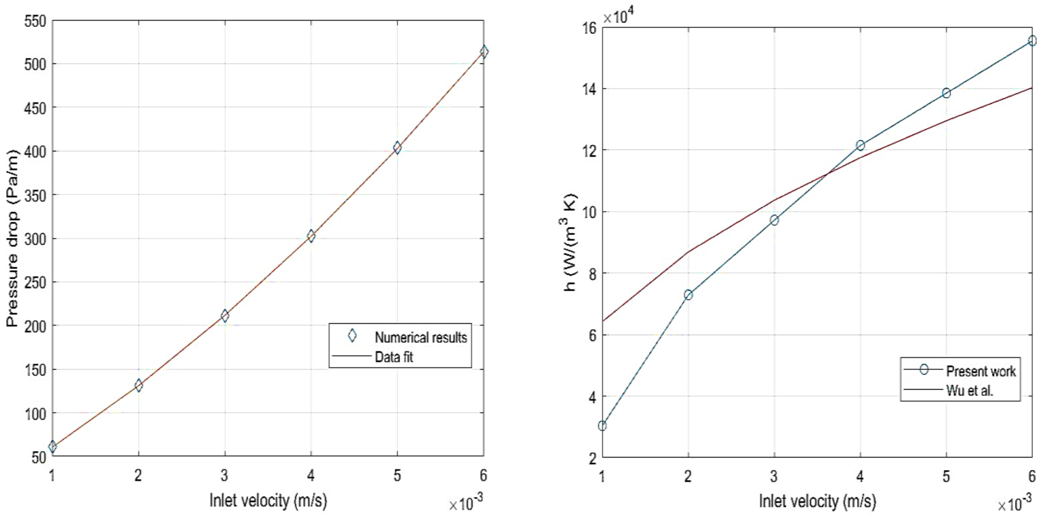


Fig. 6. Pressure drop, left hand side frame; and volumetric interphase heat transfer coefficient, (compared with the paper by [31]) right hand side frame; as functions of the inlet velocity [30].

The thermodynamic performance of cellular metal foams was also examined through entropy generation analyses [33]. Results indicated that thermal irreversibility represents the dominant contribution to entropy production; however, at high pore densities, mechanical irreversibility associated with frictional losses becomes increasingly significant. Additional pore-scale modeling efforts addressed non-classical transport effects, including the introduction of slip boundary conditions in Kelvin cell structures [34], which were shown to influence both permeability and heat transfer coefficients. Furthermore, variable permeability and porosity effects were investigated in [35] by modeling the melting of Kelvin cells to simulate the phase transition from solid to liquid in ice-structured systems.

3. Flow Models at Macro Scale in Metal Foams and Comparison with Mesoscale Data

3-1. Metal Foams and Local Thermal Non-Equilibrium (LTNE)

Metal foams consist of a highly conductive solid matrix saturated by a fluid phase with significantly lower thermal conductivity. Under intense thermal loads, this contrast often leads to the establishment of Local Thermal Non-Equilibrium (LTNE) between the solid and fluid phases [36]. In the context of stability analysis for horizontal flows in saturated porous layers, LTNE has been shown to exert a destabilizing influence on the onset of both convective and absolute instabilities, regardless of the Péclet number associated with the imposed horizontal flow or the aspect ratio of the system [37].

The LTNE condition is commonly described through a two-temperature model, which introduces separate local energy balance equations for the solid and fluid phases. When metal foams are treated as porous media, the term “local” refers to quantities averaged over a Representative Elementary Volume (REV), defined as a volume sufficiently small to capture local behavior while being large enough to ensure meaningful averaged field variables [1].

The applicability limits of the simpler Local Thermal Equilibrium (LTE) assumption have also been examined in the literature. In [38], rectangular porous fins were analyzed under LTNE conditions, and criteria were proposed to assess when the LTE model can still be adopted with acceptable accuracy. These results provide useful guidance for selecting the appropriate thermal model in the analysis and design of metal-foam-based thermal systems.

Under the local thermal non-equilibrium (LTNE) assumption, separate energy equations are employed for the solid matrix and the fluid phase within the metal foam. The general form of the two-energy-equation LTNE model can be written as:

$$\rho_s c_s(1-\varepsilon)\frac{\partial T_s}{\partial t} = k_s(1-\varepsilon)\nabla^2 T_s + h\left(T_f - T_s\right),$$

$$\rho_f c_f\left(\varepsilon\frac{\partial T_f}{\partial t} + \mathrm{u}\cdot\nabla T_f\right) = k_f\,\varepsilon\nabla^2 T_f + h\left(T_s - T_f\right)$$

where the subscripts s and *f* refer to the solid and fluid phases, respectively. Moreover, ρ is the density, c is the specific heat capacity, ε is the porosity of the solid phase (metal foam), T is the temperature, t is the time, k is the thermal conductivity, h is the volumetric interphase heat transfer, and u is the velocity vector.

3-2. Porous Media Fabricated via Additive-Manufactured with PCMs

Phase change materials (PCMs) are widely employed for latent thermal energy storage, as they absorb and release heat at nearly constant temperatures. Among available PCMs, paraffin waxes—mixtures of hydrocarbon molecules—are particularly attractive due to their tunable melting temperatures, which can be selected according to the target application. Their main limitation is the low thermal conductivity, which may lead to high operating temperatures and long melting or solidification times. To mitigate this drawback, high-conductivity metallic inserts, such as metal foams or engineered porous structures, can be integrated within the PCM to enhance the effective thermal conductivity. Recent advances in additive manufacturing have enabled the fabrication of customized porous architectures specifically designed to be impregnated with PCMs.

In this context, Diani et al. [39] experimentally investigated modified body-centered cubic (BCC) structures fabricated via selective laser melting. Two cell sizes were considered, with edge lengths of 5 mm (BCC5) and 10 mm (BCC10). The samples were made of AlSi10Mg, an aluminum alloy with a measured thermal conductivity of approximately 175 $W\ m^{-1}\ K^{-1}$ [57]. The additively manufactured porous structures were integrated with aluminum plates to allow temperature measurements through embedded T-type thermocouples, while Bakelite plates and a Teflon housing completed the experimental setup. Three commercial paraffin waxes supplied by Rubitherm—RT42, RT55, and RT64HC—were tested during melting under laterally applied heat fluxes of 10, 15, and 20 $kW\ m^{-2}$, with the samples oriented vertically. A transparent frontal window enabled direct visualization of the melting front, and heating was interrupted once complete melting of the PCM within the structure was achieved.

Experimental observations indicated that natural convection effects within the molten PCM were negligible. This finding enabled the validation of a purely conductive numerical model developed using Ansys Fluent [39], in which the transient nonlinear heat conduction equation was solved by means of the apparent specific heat method to account for latent heat effects. Compared to the standard enthalpy–porosity formulation available in Fluent, this approach allows for a more accurate representation of the temperature-dependent enthalpy variation during phase change.

The numerical domains were defined as representative repeating units extracted from the experimental modules (Fig. 7). To better reproduce the experimental thermal response, convective boundary conditions were applied to lateral surfaces corresponding to symmetry planes, and the thermal inertia of insulating components not explicitly modeled was accounted for by adjusting the effective heat capacity of the Teflon parts. The resulting model showed excellent agreement with experimental measurements for all investigated conditions. As an example, Fig. 8 compares temperature histories at the heated surfaces and midplanes for BCC5 and BCC10 structures impregnated with RT42 paraffin.

From an engineering perspective, the availability of a validated simplified conduction-based model is particularly advantageous, as it enables rapid evaluation and comparison of the thermal performance of PCM-impregnated porous structures with significantly reduced computational effort. Using this model, Diani et al. [39] assessed the thermal energy storage rates of BCC5 and BCC10 structures filled with RT42, also comparing different metallic materials (AlSi10Mg and copper) under imposed temperature boundary conditions. Nonino et al. [40] later extended similar analyses to RT55 and RT64HC paraffin's.

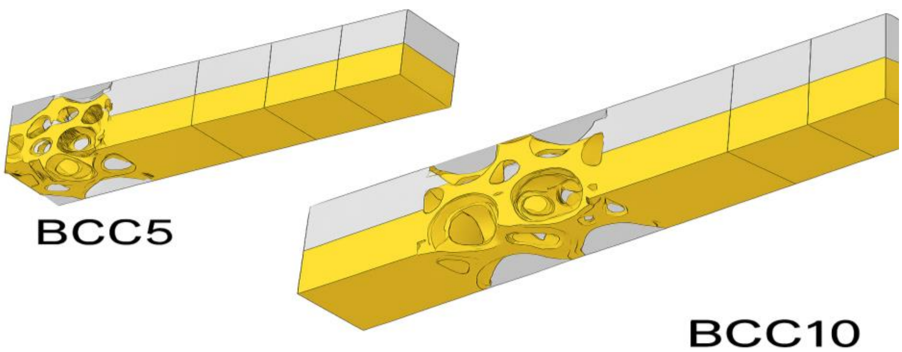


Fig. 7. Computational domains (orange) used for numerical simulations concerning the BCC5 and BCC10 structures [39] (reproduced from [39] with permission from Diani et al., Applied Thermal Engineering; published by Elsevier, 2022).

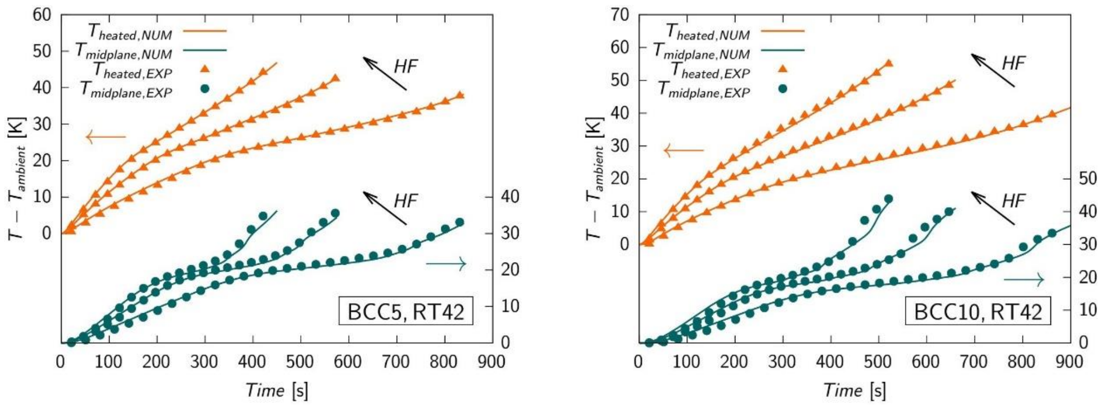


Fig. 8. Sample comparisons of experimental and numerical results for three values of the heat flux *HF*[39].

Finally, the influence of system size on PCM melting dynamics was investigated numerically in [41] for structures based on Kelvin cells with different pore densities. The results highlighted a clear volume effect on the melting rate: for a given cell density, larger volumes exhibited faster melting, whereas for smaller volumes the melting rate decreased with increasing cell density.

4. Nanofluids: Models and Experimental Data from Nanoscale to Macroscale Physical Properties of Nano Fluids

This section reviews recent modeling approaches for predicting the thermophysical properties of nanofluids, including density, specific heat, thermal conductivity, and viscosity. Among the governing parameters, the local concentration of nanoparticles in the base fluid plays a primary role, while additional effects such as temperature, particle size, shape, and aggregation state must also be considered. A critical challenge for practical applications is nanofluid stability, since nanoparticle concentration may evolve due to gravitational sedimentation, agglomeration, and surface interactions [42]. Numerous models have been proposed to describe nanofluid thermophysical properties, ranging from classical formulations based solely on nanoparticle volume fraction to more advanced models incorporating Brownian motion, particle morphology, and temperature dependence. A comprehensive overview of classical theoretical models is provided in [43], while the intrinsic difficulty in experimentally and theoretically evaluating reliable thermophysical properties is emphasized in [44]. Owing to their multiscale nature, nanofluids exhibit non-trivial dependencies on particle composition, shape, agglomeration phenomena, and surfactant effects. Traditional theoretical and empirical correlations [45] are often insufficient to capture this complexity, motivating the development of multiscale modeling strategies capable of linking nanoscale interactions to macroscale behavior.

Recent advances have focused on explicitly resolving nanoscale mechanisms such as nanoparticle self-assembly, surfactant adsorption, and interactions with complex structures. These phenomena are fundamental for understanding nanofluid behavior at the molecular level but remain challenging due to the wide range of spatial and temporal scales involved. A notable multiscale framework was introduced in [46], aiming to bridge nanoscopic and macroscopic descriptions of nanoparticle suspensions in aqueous media. In this approach, all-atom molecular dynamics (MD) simulations were employed to compute the potentials of mean force (PMFs) between nanoparticles. These PMFs were subsequently used to define tailored coarse-grained force fields, enabling stochastic and Langevin dynamics simulations to predict suspension stability and aggregation kinetics across extended time and length scales (Fig. 9).

The results demonstrated that classical DLVO-based descriptions, relying on van der Waals and electrostatic interactions, may fail to accurately represent nanoparticle interactions due to neglected molecular-level effects. Atomistic simulation-based strategies were therefore shown to be more reliable, as they naturally incorporate entropic contributions that are particularly relevant at the nanoscale (Fig. 9c). Langevin dynamics simulations based on the computed PMFs revealed that the height of the potential energy barrier critically controls dispersion stability. The introduction of surfactants or the tuning of nanoparticle surface charge density significantly enhanced suspension stability, whereas purely attractive interactions led to rapid aggregation. Moreover, lower nanoparticle volume fractions were associated with increased stability (Fig. 9d)

Focusing on alumina nanoparticles, the same framework was employed to estimate the effective thermal properties of nanofluids through cluster analysis, without imposing *a priori* assumptions on aggregate size or shape. This strategy enabled the prediction of nanofluid thermal conductivity and provided a foundation for rational nanofluid design based on microstructural features rather than empirical fitting. The methodology was subsequently extended to Titania nanoparticles in [47]. In this case, nanoparticle atomic structures were obtained from quantum calculations, and MD simulations combined with Umbrella Sampling were used to compute PMFs. Significant discrepancies were observed when comparing these results with DLVO-based predictions, further supporting the need for atomistic approaches. The computed PMFs were then used in Brownian Dynamics simulations involving tens of thousands of nanoparticles at relatively low computational cost. Aggregation kinetics were compared with classical Smoluchowski theory, revealing increasing deviations for smaller particles at higher volume fractions. A modified, time-discretized Smoluchowski formulation incorporating two fitted coefficients successfully reproduced the simulation results. Another key factor governing nanofluid stability is the presence of amphiphilic molecules acting as surfactants. In [48], a novel framework coupling steered molecular dynamics with Langmuir adsorption theory was proposed to predict surfactant adsorption isotherms (Fig. 9a). The model showed good agreement with experimental data in the dilute regime, where surfactant self-assembly is negligible. The analysis highlighted the combined role of enthalpic and entropic contributions in surfactant–nanoparticle interactions, revealing that repulsive interactions between sodium dodecyl sulfate (SDS) and coated nanoparticles are predominantly entropic in nature. Furthermore, nanoparticle curvature and surface heterogeneity were shown to induce multiple adsorption sites and asymmetric adsorption patterns, effectively translating nanoscale interfacial phenomena into a continuum adsorption framework suitable for engineering design.

In line with these studies, the self-assembly of biomolecules on nanoparticles—representing interactions with complex structures—was investigated in [49]. Atomistic MD simulations of gold nanoparticles (AuNPs) in aqueous environments demonstrated that PLGA oligomers first form clusters in solution and subsequently adsorb onto the nanoparticle surface. Machine-learning techniques confirmed that higher PLGA concentrations accelerate cluster formation (Fig. 9b). The adsorption process was found to be anisotropic, with the {111} crystallographic plane of AuNPs being more favorable than the {100} plane, an effect attributed to enthalpic contributions quantified via Umbrella Sampling. These results conceptually demonstrate that surfactant and biomolecule adsorption mechanisms can be controlled through a rational design of nanoparticle topology and surface structure.

5. Using Metal Foams, Microchannel, and Nanofluids to PCM Thermal Energy Storage Devices and Heat Exchangers

5-1. Metal Foams Applications

Metal foams are increasingly employed in engineering applications where enhanced heat transfer is required. Their effectiveness mainly stems from their porous-medium nature, which enables a transition from surface-dominated heat transfer to a quasi–volume-based heat transfer mechanism. This characteristic leads to a substantial increase in heat transfer rates, making metal foams attractive for applications such as heat exchangers, electronic thermal management, and thermal energy storage systems. When addressing engineering devices operating at relatively large spatial scales, a volume-averaged (macroscale) modeling approach becomes necessary. This framework is particularly suitable when the quantities of interest—such as global heat transfer rates or pressure drops—are weakly dependent on the local pore-scale details. Within this context, metal-foam-based heat sinks for electronic cooling have been numerically investigated and optimized using genetic algorithms, allowing for reliable performance predictions within reasonable computational times. An example of such an approach is provided in [50], where an impinging-flow heat sink combining metal foams and fins was optimized (Fig. 10). The governing equations were formulated within a volume-averaged framework. Due to the lack of specific closure correlations for impinging flows through metal foams, the required closure coefficients were calibrated against experimental data by assuming an analogy with the Žukauskas correlations originally developed for cross-flow over tube banks. A multi-objective optimization was performed, targeting the simultaneous minimization of pumping power and maximization of the heat dissipation rate, the latter being evaluated under the assumption of a uniform plate temperature. The design variables included the heat sink geometry—subject to a fixed base size—and the foam morphological parameters. The results demonstrated that, at a fixed pumping power, the finned-foam configuration was capable of dissipating approximately 3.3–3.5 times more heat than a configuration based solely on metal foam. Furthermore, comparison with similar studies reported in the literature [51] showed that the heat dissipation enhancement ranged between a factor of 2.5–3 for foam-only devices and 5–6 for finned-foam configurations. These findings clearly emphasize the importance of multi-objective optimization strategies in the design of foam-based thermal management systems. Additional performance improvements for impinging jet configurations were reported when nanofluids were employed as the working fluid [52].

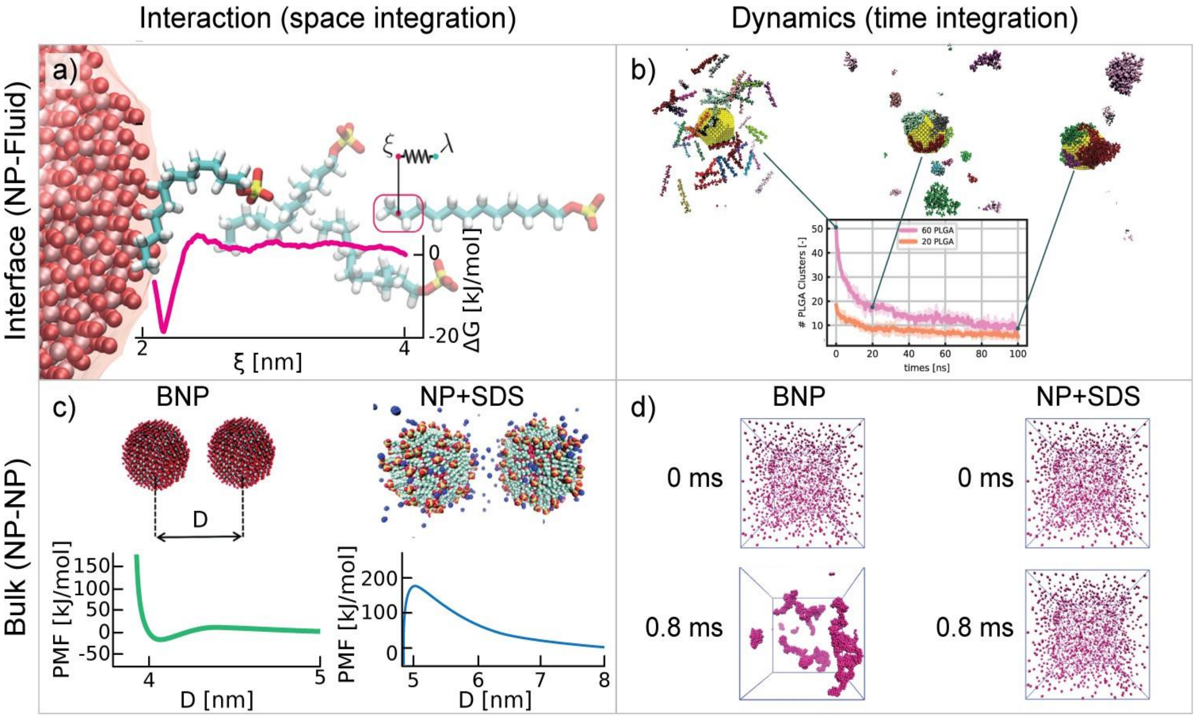


Fig. 9. The multi-panel figure depicts multiscale modeling of nanofluids and outlines the various steps involved in nanoscale characterization and macroscale properties of nanoparticle suspensions, namely: (a) the study of nanoscale interactions with nanoparticle interfaces from De Angelis et al. [48] (Reprinted/adapted with permission from Ref. [48] Copyright 2019, American Chemical Society); (b) the analysis of interaction with nanoparticles in a fluid at the absorption scale from Cappabianca et al. [49] (Reprinted/adapted with permission from Ref. [49] Copyright 2022, American Chemical Society); (c) the study of particle–particle interaction; and (d) finally coarse-grained modeling to predict the behavior of several nanoparticle suspensions from Cardellini et al. [46].

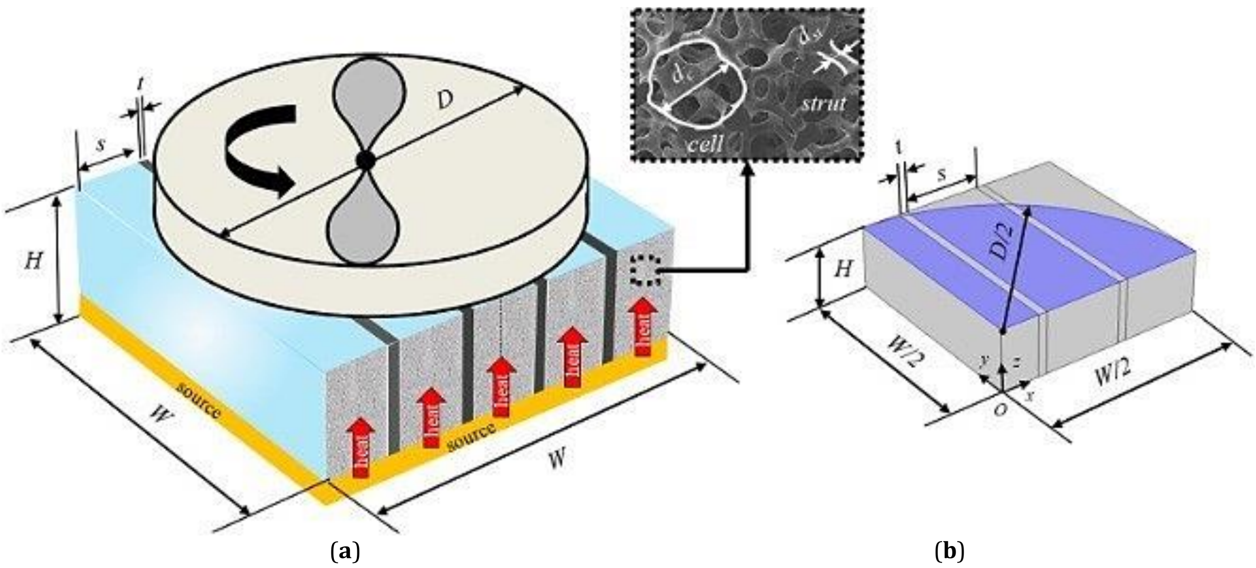


Fig. 10. (a) Finned-foam heat sink under impinging flow conditions (reproduced from [50] and (b) domain used for computations.

Metal foams also exhibit promising behavior in heat exchanger applications. A comprehensive review of crossflow heat exchangers incorporating metal foams is presented in [53], highlighting their distinctive thermal and fluid-dynamic characteristics. A numerical model aimed at evaluating both the hydraulic and thermal performance of compact aluminum-foam heat exchangers was developed in [54]. More recently, metal foams have been proposed for heat recovery applications along automotive exhaust lines, where they are used to enhance the thermal performance of thermoelectric generators (TEGs), thereby improving overall energy conversion efficiency [55].

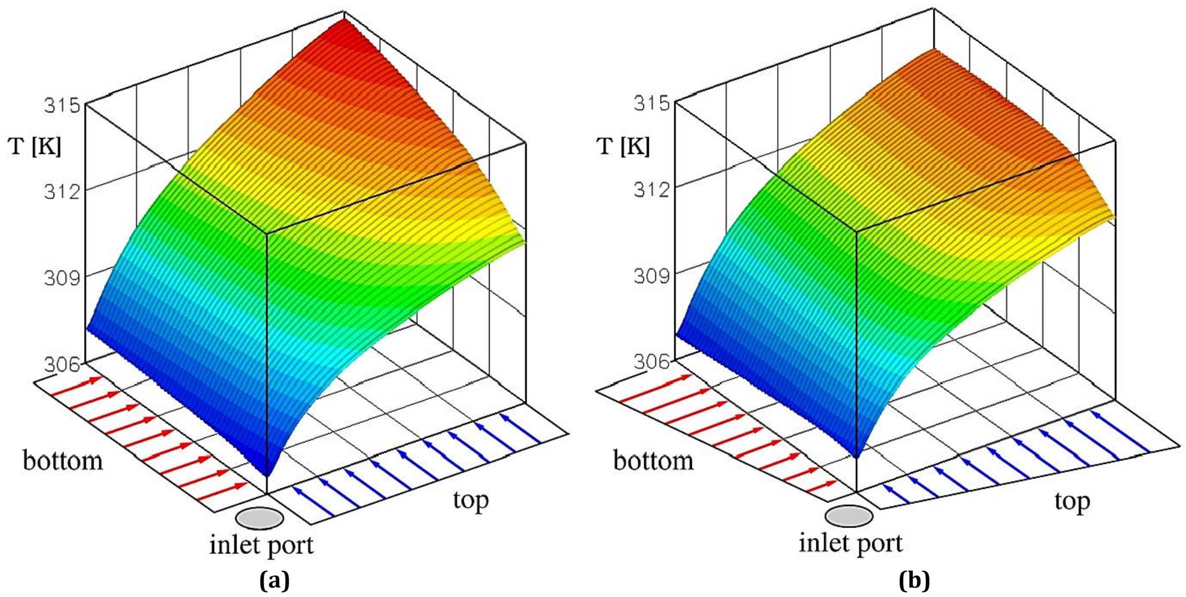
5-2. Effects of Non-Uniform Flow Distribution in Cross-Flow Double-Layered Microchannel Heat Sinks

Liquid-cooled microchannel heat sinks (MCHSs) are a well-established solution for the thermal management of electronic components. Over the past decades, these devices have evolved from single-layer (SL-MCHS) configurations to counter-flow double-layer (DL-MCHS) layouts, the latter offering improved temperature uniformity at the cost of increased complexity in header design due to the need for two inlets and two outlets. A comprehensive review of MCHS technologies is provided by He et al [56]. Despite their potential advantages in terms of simpler piping arrangements, two-layer cross-flow MCHS configurations have received very limited attention in the literature. To the authors' knowledge, only Nonino has systematically investigated their performance and Savino, who employed an in-house finite element method (FEM) code originally developed for the thermal and hydraulic analysis of cross-flow micro heat exchangers [57].

The study in highlighted that a characteristic drawback of the cross-flow DL-MCHS configuration is the formation of a localized hotspot on the heated surface, occurring at the corner where the microchannel outlets are located. This behavior, illustrated in Fig. 11a, emerges under idealized conditions assuming a uniform velocity distribution among the microchannel.

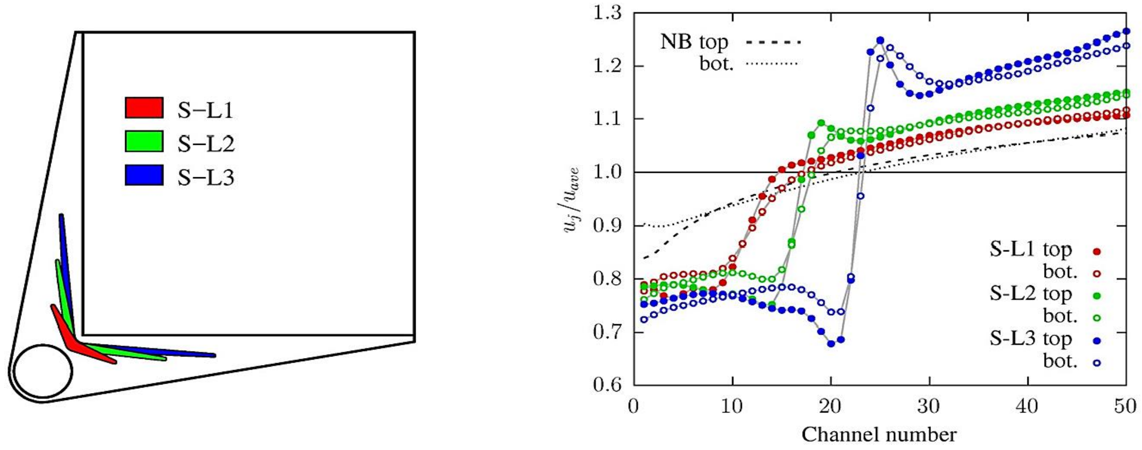
In practical applications, however, perfectly uniform flow distribution is unlikely to occur. While flow maldistribution is generally regarded as detrimental to the performance of thermal systems, in cross-flow DL-MCHSs it can be deliberately exploited to improve temperature uniformity and reduce overall thermal resistance. Specifically, if the velocity non-uniformity leads to increased flow rates in the hotspot region, the resulting temperature distribution becomes more uniform, as shown in Fig. 11(b).

Strategies to induce a controlled non-uniform velocity distribution were investigated by Savino and Nonino [58]. They proposed the introduction of an angled baffle within the inlet header to preferentially enhance the flow rate in the microchannel closer to the outlet header (Fig. 12). Their numerical analysis, performed using Ansys Fluent (release 17.0, 2016), examined multiple configurations obtained by varying baffle length and height, including cases in which the baffle was partially or entirely made of porous material.



(a) **(b)**

Fig. 11. Examples of temperature distributions on the heated base of square cross-flow DL-MCHSs: (a) uniform microchannel velocity; (b) microchannel velocities varying linearly along the sides [58].



(a) (b)

Fig. 12. Inlet header with a baffle: (a) schematic representation of baffles of different lengths; (b) examples of non-uniform normalized microchannel velocity distributions [58].

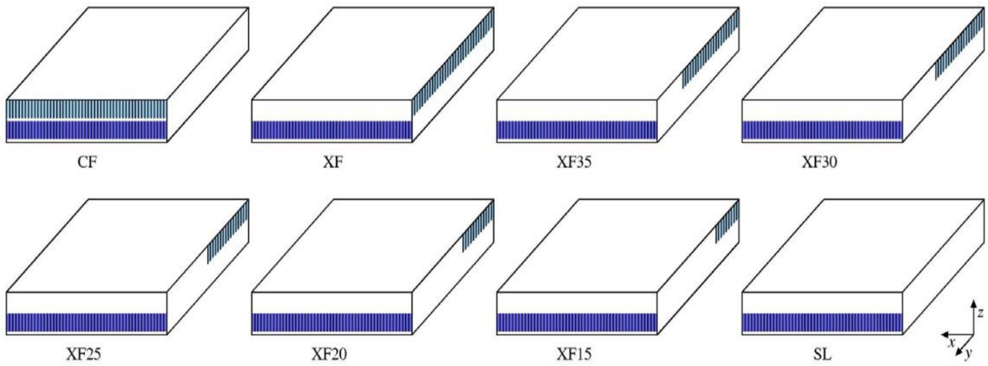


Fig. 13. Schematic representations of the MCHS configurations considered in [59].

An alternative approach to achieve similar thermal performance was proposed in [59], where cross-flow DL-MCHSs with different numbers of microchannel in the upper and lower layers were analyzed. In the investigated configurations, the lower layer always consisted of 50 microchannel, while the upper layer contained between 15 and 50 channels (Fig. 13). Using the same FEM-based numerical framework as in, the authors demonstrated that several of these asymmetric configurations could provide acceptable temperature uniformity and thermal resistance while requiring a significantly simpler collector design compared to counter-flow DL-MCHSs. Moreover, in cases where the applied heat flux on the heated surface is spatially non-uniform, an appropriate orientation of the cross-flow DL-MCHS was shown to enable more effective thermal management than alternative configurations.

5-3. Effects of Nanofluids in Heat Transfer

Applications of nanofluids for heat transfer enhancement span a wide range of engineering fields, with specific objectives, modeling approaches, and optimization trade-offs that strongly depend on the targeted application. In the following, some representative examples are briefly reviewed.

A comprehensive overview of nanofluids for automotive cooling applications is presented in [60]. The review provides an extensive discussion of the state of the art, including nanofluid synthesis techniques, thermophysical properties, and their dependence on key parameters such as nanoparticle material, size, shape, volume fraction, base-fluid pH, and surfactant concentration. The authors highlight that future research should increasingly focus on identifying optimal nanoparticle aggregate morphologies capable of achieving a favorable compromise among enhanced thermal conductivity, limited viscosity increase, and long-term stability. Beyond conventional thermal management applications, nanofluids also offer interesting opportunities in solar energy systems through the engineering of their optical properties. In this context, Moradi et al. [61] investigated the use of nanofluids for direct solar absorption in thermal collectors intended for residential and small commercial applications. Owing to their high absorption coefficients and adequate stability at moderate temperatures, nanofluids were shown to be promising working media. In particular, the study focused on carbon nanohorns, which are expected to exhibit lower toxicity compared to other carbon-based nanoparticles. A three-dimensional numerical model was developed to describe the absorption process of solar radiation in nanofluids flowing inside a cylindrical tube.

The potential toxicity of nanomaterials remains a critical issue for the widespread adoption of nanofluids. To address this concern, Alberghini et al. [62] introduced, for the first time [63], a sustainable, stable, and low-cost colloidal nanofluid based on coffee for direct solar energy collection. The proposed Nano-colloid, composed of distilled water, Arabica coffee, glycerol, and copper sulphate, was designed to improve both photo thermal performance and biocompatibility. The results demonstrated that coffee-based colloids exhibit optical and thermal properties competitive with those of conventional indirect solar absorption systems employing selective surfaces, thereby representing a promising eco-friendly alternative for solar thermal applications.

5-4. Application of Phase Change Materials (PCM) in Thermal Control and Thermal Energy Storage

In the field of thermal energy storage, the incorporation of Nano-additives into phase change materials (PCMs) or microporous sorbents for latent and thermochemical energy storage has attracted increasing attention, as highlighted in recent reviews [64]. The addition of nanoparticles to PCMs is recognized as an effective strategy to enhance their thermophysical properties, particularly the effective thermal conductivity. However, the optimal design of Nano-enhanced PCMs remains an open issue, mainly due to the limited understanding of heat transfer mechanisms at the filler–matrix interface, where interfacial thermal resistances may significantly hinder heat transport. Consequently, further experimental investigations and theoretical modeling efforts are required to rationally design PCMs with tailored thermal properties [64]. From a future perspective, enhanced heat transfer and thermal energy storage technologies could strongly benefit from the combined use of Nano fluids and/or nano-additivated PCMs with emerging and flexible manufacturing techniques, such as additive manufacturing, laser etching, and advanced metal printing processes [65].

An example of an integrated thermal management solution is provided in Fig. 14, where a finned metal foam heat sink combined with a PCM was analyzed and optimized. The numerical model employed the enthalpy–porosity approach to describe the liquid PCM motion during melting. A multi-objective optimization problem was formulated by considering cost and operation time as objective functions, while foam morphology and fin geometry were treated as design variables. The optimized configurations exhibited costs in the range of EUR 200–250 and operation times—defined by a base-plate survival temperature of 90°C—between approximately 2000 and 6000 s.

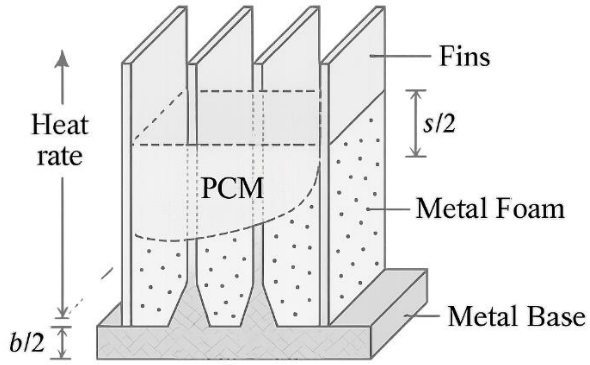


Fig. 14. Finned-foam heat sink equipped with a phase change material for thermal management.

For simpler engineering configurations, such as channels or box-shaped domains, several studies have focused on optimizing foam morphology distribution and characterizing PCM melting dynamics. In [66], the distribution of foam morphology inside a heated rectangular channel (Fig. 15a) was optimized using a volume-averaged modeling approach. Both multi-objective (e.g., Nusselt number versus friction factor) and mono-objective optimizations based on performance evaluation criteria (PEC) [67] were conducted, considering power-law variations of porosity and/or cell size. The results demonstrated that, compared to a uniform foam, a PEC as high as 1.51 could be achieved, corresponding to a 51% enhancement in thermal performance at fixed pumping power.

A combined numerical and experimental investigation of a foam/PCM composite box was presented in [68] (Fig. 15(b)). The numerical model relied on volume-averaged equations coupled with the enthalpy–porosity method, while experiments were conducted using insulated enclosures and monitored via LCD and infrared (IR) cameras.

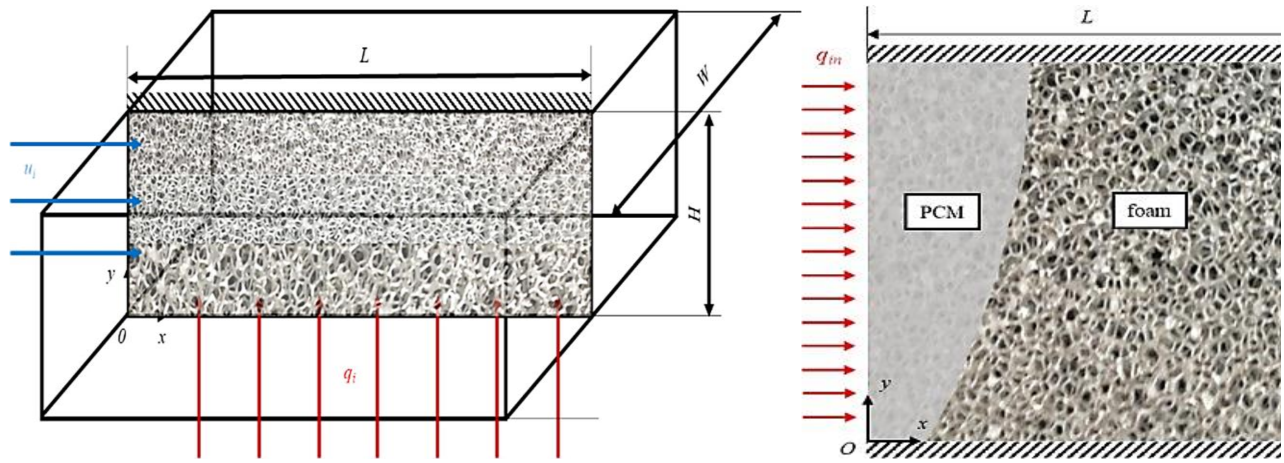


Fig. 15. Graded-foam channel for an optimization analysis (a) and PCM/foam composite box (b) investigated in [66] and [68] (reproduced from [95] with permission from Iasiello et al., Applied Thermal Engineering; published by Elsevier, 2021), respectively.

The melting front evolution captured by IR imaging showed excellent agreement with numerical predictions, confirming the suitability of IR thermography for tracking phase change dynamics. Parametric analyses revealed that lower porosities significantly enhance the melting front velocity, whereas foam orientation and PPI exert a comparatively minor influence. The effectiveness of metal foams in accelerating PCM melting in thermal energy storage (TES) systems has been widely recognized and recently reviewed by Sehrawat et al. [69]. Representative applications include shell-and-tube latent heat TESs partially filled with metal foams, investigated under both adiabatic conditions [70] and with external heat losses [71]. Furthermore, latent heat TES systems incorporating metal foams have also been proposed in combination with solar-based technologies, such as solar chimneys for building applications [72].

6. Conclusions and Future Developments

Metal foams, nanofluids, and phase change materials (PCMs) represent complementary and highly effective solutions for enhancing heat transfer and thermal energy storage. Their performance can be reliably assessed only through a multiscale framework that consistently links pore- and nanoscale phenomena to macroscale, volume-averaged models. This approach enables accurate prediction of key parameters such as permeability, interfacial heat transfer coefficients, and effective thermal conductivity.

Metal foams provide large surface areas and high convective heat transfer rates with limited pressure penalties, while nanofluids enhance thermal transport through increased effective conductivity, enabling compact and efficient thermal devices. PCMs further contribute by enabling high-density thermal energy storage, and their integration with metal foams and nanofluids significantly improves charge–discharge rates and system efficiency. From an application-oriented viewpoint, the main advantages and limitations of the considered heat transfer enhancement and thermal energy storage techniques can be summarized as follows:

- Metal foams provide high surface area and enhanced convective heat transfer, although their use may be accompanied by increased pressure drop and manufacturing complexity.
- Nanofluids offer improved effective thermophysical properties and flexibility in performance enhancement; however, issues related to stability, agglomeration, and cost remain critical.
- Phase change materials enable high thermal energy storage density and temperature regulation, while challenges such as low thermal conductivity, leakage, and supercooling need to be addressed.

Future developments are expected to benefit from the convergence of advanced manufacturing techniques—such as additive manufacturing and laser-based processes—with Nano-enhanced fluids and PCM-based systems. At the same time, further progress requires improved modeling and experimental understanding of microscale and nanoscale transport phenomena, including particle dynamics, interfacial effects, and anomalous diffusion. Addressing stability, cost, and sustainability issues will be essential to promote large-scale adoption. Overall, the combined use of metal foams, nanofluids, and PCMs offers a promising pathway toward next-generation thermal management and energy storage technologies.

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Biography

Reza Rabani is an Assistant Professor in the Faculty of Mechanical Engineering at the University Islamic Azad University, Karaj Branch in energy conversion. He earned his PhD in Mechanical Engineering with a focus on Energy Conversion from Tarbiat Modares University. He has supervised numerous students in the areas of thermal systems and heat transfer, and has published extensively in leading academic journals.

Javad Ghavanini is an M.Sc. Student in Energy Conversion Engineering at the Faculty of Engineering, Islamic Azad University, Karaj Branch. He holds a B.Sc. in Mechanical Engineering with a focus on Fluids from the same university. His academic and professional activities span the fields of energy systems and automotive engineering, with particular interest in thermal management, heat transfer enhancement, and sustainable energy technologies.

Saeed Shoroei is a graduate of Mechanical Engineering from Islamic Azad University, Karaj Branch. He also studies methods for increasing efficiency in energy storage systems.