ECOS 2026: Thermodynamic Optimization of Adsorber Beds: Transitioning from Packed Beds to TPMS Structures for Enhanced Hydrodynamics and Efficiency

Lukasz Lasek[a], Marcin Sosnowski[a], Karolina Grabowska[a], Jaroslaw Krzywanski[a], Ania Zylka[a] and Dorian Skrobek[a]

[a] *Jan Dlugosz University in Czestochowa, Czestochowa, Poland, l.lasek@ujd.edu.pl CA*

Abstract:

In response to the rapidly increasing demand for freshwater production and cooling, there is a growing need for more efficient adsorption-based desalination and cooling systems. However, the performance of such systems remains strongly constrained by the design of the adsorber bed, where coupled heat and mass transfer processes limit achievable water production and cooling capacity.

This paper reviews the key structural factors governing adsorber performance, with particular emphasis on limitations of conventional packed beds, including thermal resistance, flow maldistribution, and pressure losses. Advanced adsorber configurations, such as coated heat exchangers and metal-foam-supported beds, are analysed and compared in terms of their thermo-hydrodynamic performance.

Special attention is given to triply periodic minimal surface (TPMS) structures, which are identified as a promising class of ordered geometries capable of addressing the fundamental trade-off between heat transfer enhancement and flow resistance. Finally, the need for systematic structure–property mapping is highlighted, particularly in relation to the influence of TPMS unit-cell geometry on coupled thermal and hydrodynamic behaviour under relevant operating conditions.

Keywords:

Adsorption cooling and desalination systems, triply periodic minimal surface, heat transfer, mass transfer

1. Introduction

Water scarcity and the rapidly increasing demand for cooling represent two global challenges that are closely intertwined. Conventional cooling technologies are heavily reliant on electricity, thereby contributing to rising energy consumption and environmental pressures. In this context, alternative cooling approaches that utilise low-grade thermal energy are garnering increasing attention. [1–3].

Adsorption cooling and desalination (ACD) systems offer a promising pathway to address both challenges simultaneously, as they can be driven by waste heat or renewable sources while using environmentally benign working pairs. However, despite their advantages, their performance remains limited by slow heat and mass transfer processes occurring within the adsorber bed, which directly determine the achievable specific cooling power (SCP) and coefficient of performance (COP) [4,5].

In order to surmount the limitations identified, a broad spectrum of adsorber configurations has been proposed. These include conventional packed beds, coated heat exchangers, metal foams and, more recently, architected porous structures. The majority of these approaches are oriented towards enhancing heat transfer by improving thermal conductivity and contact between the adsorbent and the heat exchanger surface. However, it should be noted that such modifications have the effect of simultaneously affecting vapor transport, pressure drop and flow distribution within the adsorber [6,7]. The hydrodynamic aspects of adsorber operation – including vapor-flow resistance, maldistribution, and transient flow effects – remain comparatively less systematically addressed, particularly under cyclic operating conditions. Consequently, adsorber performance is governed by a fundamental trade-off between heat-transfer enhancement and hydrodynamic resistance, which is not fully captured in many extant design strategies [8–10].

This review examines modern adsorber bed architectures from a coupled thermo-hydrodynamic perspective. Particular attention is given to the interaction between heat transfer and flow behaviour, including pressure losses and transient effects. Advanced configurations such as coated beds and metal foams are critically assessed, followed by an analysis of emerging ordered geometries. In this context, triply periodic minimal surface (TPMS) structures are highlighted as a promising design space for systematic co-optimization of thermal and hydrodynamic performance.

2. Conventional Adsorber Beds

In conventional adsorption chillers, stationary packed beds are predominantly employed: granular material (e.g., silica gel) is packed between the tubes of a heat exchanger or within finned-tube/foam-bed channels, without any forced movement of the particles. However, such systems exhibit fundamental limitations that result in low COP and SCP [8]. These limitations can be characterized within several interrelated domains, including bed porosity, thermal contact resistance, pressure drops, and the lack of control over flow distribution.

2.1. Impact of Porosity

A characteristic feature of conventional packed beds is the significant influence of porosity on the overall mechanisms of mass and heat transfer. Void spaces, typically filled with gas, exhibit low thermal conductivity due to their physical properties and thus effectively act as thermal insulation. Consequently, a high fraction of void space in porous media, including packed beds, leads to reduced process efficiency [11]. However, it should be emphasized that pores within a packed bed also play a crucial role in mass transport. The requirement to maintain an adequate level of porosity, which promotes efficient mass transfer, may conflict with the demands of effective heat transfer, ultimately increasing the overall thermal resistance of the system. [12].

2.2. Thermal Contact Resistance

The thermal resistance of the packed bed itself constitutes a significant limitation to system performance, particularly in the contact regions between the adsorbent and the heat exchanger surface. Such resistances contribute to an increase in the overall thermal resistance of the system, while simultaneously exacerbating the effect of the sorbent's inherently low thermal conductivity. Moreover, loosely packed particles located between the heat exchanger elements substantially reduce the effective contact area, thereby increasing the contact resistance both at adsorbent–adsorbent interfaces and at the adsorbent–metal interface [13].

2.3. Pressure Drop

Particle size is one of the key parameters determining the energy efficiency of the system. A densely packed bed with a high packing degree, composed of small particles, undoubtedly enhances the adsorption capacity. However, this simultaneously leads to an increased pressure drop across the bed.

Studies on adsorption in packed beds indicate the existence of a fundamental trade-off between the required sorption capacity of the bed and the permissible pressure drop during fluid flow through its structure [10]. Moreover, forced flow through the bed is associated with an increase in hydraulic resistance, which intensifies with increasing bed length and decreasing porosity. Consequently, the design of such systems requires balancing efforts aimed at improving sorption kinetics and maximizing the adsorption surface area, while maintaining appropriate flow properties of the bed [14].

2.4. Lack of Flow Control

In traditional, conventional adsorption beds, fluid flow is largely uncontrolled and inherently non-uniform. The gas, following paths of lower flow resistance, preferentially moves through larger channels formed by void spaces within the bed structure. This phenomenon leads to an uneven distribution of adsorption zones, particularly those responsible for water vapor uptake, as well as to the formation of local temperature gradients and concentration non-uniformities [17]. CFD-based numerical analyses indicate that porosity variations resulting from particle geometry further intensify flow non-uniformity within the bed. Irregular packing promotes the occurrence of channelling, defined as the formation of preferential flow paths, which results in asymmetric system behaviour [15].

In response to these limitations, contemporary adsorption refrigeration engineering increasingly explores alternatives to conventional packed-bed configurations. These include coated adsorbent layers, hybrid structures combining adsorbents with metal foams, and ordered architectures such as TPMS structures, aimed at improving transport properties and overall system performance [16].

3. Advanced heat exchanger structures

Conventional packed beds suffer from weak thermal conductivity, large contact resistance, and limited control over vapor transport. To address these constraints, a variety of advanced adsorber heat exchanger architectures have been developed, including coated beds, metal foams, and more recently ordered porous structures. These designs primarily aim to intensify heat transfer by increasing solid-phase conductivity and improving thermal contact between the adsorbent and the heat exchanger surface. However, thermal enhancement alone does not guarantee better overall performance, since geometric modification also affects vapor accessibility, pressure drop, and internal flow uniformity.

3.1. Coated Beds

This technology is based on eliminating localized thermal contact resistance between loosely packed adsorbent grains and the metallic surface of the heat exchanger by applying a thin layer of sorption material. Coatings can be formed either through direct crystallization on the substrate (*in situ*) or by using polymeric or inorganic binders (*ex situ*) [11,17]. The transition from conventional packed beds to coated beds enables a significant intensification of heat transfer. In particular, the heat transfer coefficient at the exchanger–bed interface can increase from typical values of 10–50 W/(m²·K) to as high as 1000 W/(m²·K) in the case of directly synthesized coatings [17]. Solovyeva et al. [18] prepared and compared two compact configurations of an MOF-801 bed: grains adhered to a metallic substrate and thin adsorbent coatings. Coatings prepared using polyvinylpyrrolidone achieved a specific power of 1.6–5.1 kW/kg, representing approximately a twofold increase compared to loose grains. Polyvinylpyrrolidone, bentonite, thermal conductive paste, and hydroxyethyl cellulose were found to enhance heat transfer coefficients and accelerate adsorption, whereas polyvinyl alcohol and polyaniline were observed to impede the adsorption process.

Despite their clear thermal advantages, coated adsorber configurations are not free from limitations. The introduction of binder phases and the formation of dense adsorbent layers may reduce pore accessibility and introduce additional mass transfer resistance, particularly for thicker coatings. As a result, the improvement in heat transfer does not always translate directly into proportional gains in overall system performance, especially under conditions where vapor diffusion becomes rate-limiting. Furthermore, the achievable coating thickness is constrained by mechanical stability and adhesion requirements, which limits the total adsorbent loading and thus the system capacity.

These challenges have motivated the development of hybrid solutions in which coated adsorbent layers are combined with highly conductive and porous support structures, such as metal foams. In such configurations, the foam provides structural support and enhanced heat spreading, while the coating ensures effective thermal contact with the adsorbent phase. This synergy aims to overcome the limitations of standalone coated beds, although it introduces additional complexity related to pore structure, permeability, and flow resistance, which must be carefully balanced.

3.2. Metal foam beds

Metal foams are among the most widely studied approaches for thermally enhancing adsorption beds. Their open-cell structure combines high porosity with a continuous conductive solid network, which improves heat spreading and reduces the thermal resistance typical of conventional packed beds. As a result, metal-foam-supported configurations can accelerate adsorption–desorption cycling and improve overall thermal performance. However, the introduction of a foam scaffold also modifies vapor transport pathways, permeability, and pressure losses. For this reason, metal foams should be assessed not only as heat-transfer enhancers, but as structured porous media that influence the coupled thermo-hydrodynamic behavior of the adsorber.

The application of aluminium foams integrated with silica gel enables the composite to achieve an effective thermal conductivity of approximately 6 W/(m·K), which significantly accelerates the thermal response and heat waves propagation [19].

Metal-foam-supported adsorber beds have consistently demonstrated substantial potential for overcoming the thermal limitations of conventional packed configurations. Recent studies indicate that integrating adsorbents with open-cell metallic scaffolds significantly enhances heat transfer and overall system performance. For instance, copper-foam-coated tube configurations employing advanced adsorbents such as SAPO-34 and CPO-27(Ni) have been shown to yield considerable performance improvements, with increases of up to 163% in COP and 223% in SCP compared to reference systems [13]. Similar findings were reported for aluminium-foam-based beds using Maxsorb adsorbents in ice-making applications, where numerical studies identified an optimal foam thickness in the range of 2–5 mm, highlighting the need to balance thermal conductivity enhancement with mass transfer resistance [6,19]. Bruckner et al. [20] modelled water adsorption in SAPO-34-coated aluminium foam and explicitly showed the influence of pore diameter on mass transport limitation — larger pores ease vapor access but reduce the foam's thermal enhancement. Bansode et al. [21] tested 5, 10, 20, and 40 PPI aluminium foams and found that 10 PPI delivered the best overall heat transfer coefficient and lowest thermal resistance, while pressure drop across 40 PPI foam was 1.5–1.8× higher than 5 PPI.

Taken together, these results clearly indicate that while metal foams can substantially enhance heat transfer within adsorption beds, their performance is inherently constrained by competing transport mechanisms. Improvements in thermal conductivity, achieved through increased solid fraction or reduced pore size, are often accompanied by reduced permeability, higher pressure drop, and limited vapor accessibility. Conversely, structures that facilitate vapor transport tend to compromise thermal performance. This fundamental trade-off highlights the limitations of stochastic porous media such as metal foams, where geometric parameters can be adjusted only within a restricted range. As a result, there is growing interest in more controllable and ordered architectures, such as lattice structures and TPMS-based geometries, which offer the potential to systematically tune both thermal and hydrodynamic characteristics within a unified design framework.

3.3. TPMS Structures

The most advanced direction in the topological optimization of adsorption beds involves the use of additively manufactured lattice structures based on TPMS, such as Gyroid and Diamond networks. These structures are characterized by an exceptionally high heat transfer surface area per unit volume and smooth flow pathways devoid of dead zones [22]. In contrast to metallic foams, which exhibit a stochastic architecture and a random pore structure [23]. TPMS structures are defined by precise mathematical functions that ensure zero mean curvature at every point, thereby providing smooth, continuous flow channels without stagnant regions. The geometric predictability of TPMS also enables precise control over surface morphology [24].

TPMS structures additionally eliminate the need for pore-blocking binders, the presence of which—at levels up to 15%—can reduce the coefficient of performance (COP) by approximately 20% and the specific cooling power (SCP) by as much as 55% [11]. Within TPMS structures, the adsorbent can be directly packed into predefined geometric voids without degradation of its diffusion properties, ensuring optimal phase contact without introducing additional thermal or mass transfer resistance associated with a binding layer [7,25].

From the perspective of heat transfer, TPMS-based exchangers generate increased turbulent kinetic energy, which translates into an enhancement of overall heat transfer performance by approximately 15% to 100% compared to conventional compact heat exchangers [26]. Naturally, both heat and mass transfer characteristics are largely determined by the specific TPMS geometry employed; for instance, Primitive-type structures exhibit more uniform flow compared to Diamond or Gyroid configurations [26]. Furthermore, the pressure drop is closely related to the number of flow channels within a given exchanger design [24]. Table 1 presents a comparative summary of the advantages and disadvantages of selected advanced adsorption structures relative to conventional packed beds.

Table 1. *Advantages and limitations of selected advanced adsorber structures relative to conventional packed beds.*

Structure	Heat transfer	Pressure Drop	Advantages	Limitations
Coated heat exchangers [11,17,18,27–30]	High effective conductivity; Improved wall heat-transfer coefficient; SCP increase (up to ~2× vs packed beds);	Relatively low due to open flow channels; Lower than tightly packed bed;	Low thermal contact resistance; Compact design; High specific power; Industrially demonstrated;	Mass-transfer resistance increases with coating thickness; Limited adsorbent loading; Adhesion and cracking issues;
Metal foams [8,13,31]	Strong enhancement of effective thermal conductivity; Improved heat spreading; Reduced cycle time (≈600 → <180 s);	Increased pressure drop for small pore sizes; Dependent on porosity and pore size;	Excellent heat spreading; Supports coatings; high SCP and water productivity	Higher cost; corrosion constraints; Trade-off between permeability and thermal conductivity
TPMS structures [7,16,22,32,33]	High surface area; enhanced convective heat transfer (≈55–149%); Improved effective thermal conductivity	Moderate pressure drop; Can be reduced via geometry optimization (up to ~85%)	Tunable morphology; Controllable trade-off between permeability and conductivity; Suitable for high-performance adsorbers	Manufacturing complexity; Early-stage development; Limited experimental validation

Recent studies on TPMS-based adsorber configurations provide quantitative evidence that geometric topology and porosity have a strong and non-trivial impact on system performance. Variations in TPMS structure, including Gyroid, Diamond, and Primitive topologies, have been shown to significantly influence transport-related parameters such as specific surface area, tortuosity, and permeability, which in turn affect adsorption dynamics and cooling output [7,22].

For instance, increasing porosity from 0.2 to 0.8 can substantially reduce adsorption time and increase the number of daily cycles, leading to marked improvements in cooling energy output. In some cases, TPMS-based structures have demonstrated cooling energy enhancements exceeding 30% relative to conventional finned configurations, while SCP improvements on the order of 5–20% have also been reported depending on topology and structural configuration. At the same time, different TPMS morphologies exhibit distinct trade-offs: structures with higher surface area or tortuosity may enhance heat and mass transfer locally, but can also introduce increased flow resistance or non-uniform transport pathways [7,22].

Importantly, these results indicate that there is no universally optimal TPMS geometry. Instead, performance depends on a complex interplay between topology, porosity, and operating conditions. This highlights a key limitation of current approaches, which typically rely on isolated case studies rather than systematic exploration of the design space. As a result, there is a clear need for structured design methodologies capable of linking geometric parameters of TPMS unit cells to their resulting thermo-hydrodynamic performance. Developing such structure–property–performance maps would enable more rational and efficient optimization of adsorber geometries across different operating regimes. As shown in Figure. 1, increasing porosity leads to a significant increase in daily cooling energy for all structures; however, the magnitude of this improvement strongly depends on topology. While TPMS structures underperform conventional fins-based configurations at low porosity, they significantly outperform them at higher porosity levels, with energy gains exceeding 30% for optimized geometries.

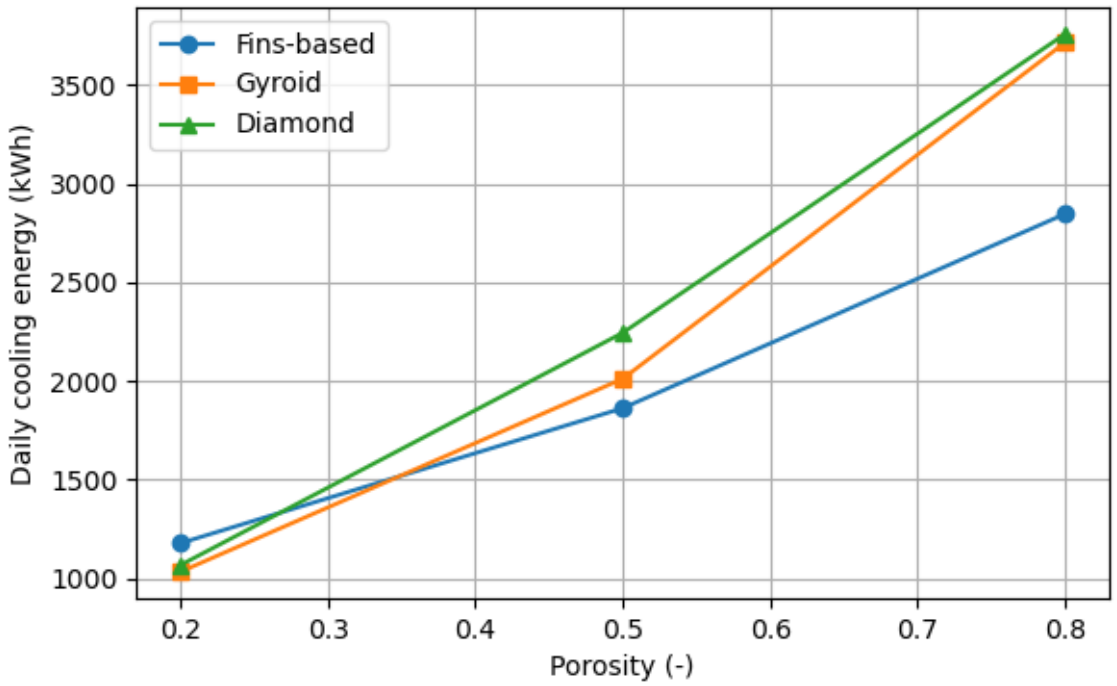

Figure. 1. *Influence of TPMS heat exchanger (Gyroid, Diamond) porosity on daily cooling energy [7].*

4. Thermo-hydrodynamic coupling in adsorption systems

The performance of adsorption cooling and desalination systems is strongly influenced by vapor flow through porous adsorbent structures. Studies indicate that flow resistance within the adsorber bed is one of the key factors limiting SCP and overall system performance, particularly under low-pressure operating conditions [34]. The penetration depth of vapor into the porous matrix is often restricted by pressure losses, which can significantly reduce adsorption kinetics and limit the effective utilization of the bed volume. In many cases,

macroscopic permeability and gas-phase transport resistance govern system behaviour, independently of the intrinsic thermal performance of the adsorbent layer [34–36].
This leads to a fundamental design conflict: reducing particle size improves intra-particle transport and adsorption kinetics, but simultaneously increases flow resistance and pressure drop at the reactor scale [35]. As a result, gains achieved at the microscale may be offset by hydrodynamic limitations at the macroscale. In addition to flow resistance, non-uniform vapor distribution represents a major limitation in packed and structured beds. Spatial variations in porosity and local packing density lead to preferential flow paths and channelling, resulting in uneven utilization of the adsorbent [37].
Regions with enhanced permeability may experience premature saturation, while other zones remain underutilized, effectively forming inactive regions within the bed. Such effects reduce overall system efficiency and negatively impact COP. Studies have shown that tailored porosity distributions, such as graded or spatially varying structures, can improve vapor distribution and enhance system performance without introducing significant additional thermal resistance [15].
Adsorption systems operate under inherently transient conditions, with continuous variations in temperature and pressure throughout the cycle. These fluctuations directly affect fluid properties and flow behaviour, leading to time-dependent changes in pressure losses and transport resistance. Under certain conditions, transient phenomena such as local bed expansion or fluidization-like behaviour may occur, which can temporarily enhance mass transfer by reducing diffusion limitations [1,38–40].
Taken together, these findings demonstrate that adsorption systems must be treated as coupled thermo-hydrodynamic systems, in which heat transfer, mass transfer, and fluid flow interact across multiple scales. Importantly, many existing design strategies focus primarily on thermal enhancement, while hydrodynamic effects are often treated as secondary constraints rather than design variables. This imbalance limits achievable performance improvements and highlights the need for geometries that enable simultaneous control of heat transfer and flow behaviour. In this context, structured and ordered porous media, particularly TPMS-based architectures, offer a promising pathway toward systematic co-optimization of thermal and hydrodynamic performance [22].

5. Two-phase flow effects in heat exchanger channels

Two-phase flow, typically introduced through air injection into the liquid stream, has been proposed as an active method for enhancing heat transfer in thermal systems [41,42]. In adsorption cooling applications, where overall performance is often limited by slow heat transfer within the adsorber bed, improving the thermal response of the heat exchanger becomes particularly important [34,43].
The presence of gas bubbles in the liquid flow induces additional mixing and disrupts the thermal boundary layer, leading to enhanced convective heat transfer. Experimental studies have shown that such two-phase flow configurations can significantly increase heat transfer coefficients in both plate and tubular heat exchangers [44–46]. However, these benefits are accompanied by increased pressure losses and potential flow instabilities, which may affect overall system efficiency.
In the context of TPMS-based heat exchangers, the complex three-dimensional channel geometry can further intensify mixing effects by promoting continuous flow redirection and secondary vortices. This suggests a potential synergy between structured geometries and two-phase flow, where enhanced mixing may improve heat transfer performance without requiring higher bulk flow rates [26,32].
At the same time, the introduction of a gas phase introduces additional design challenges. Increased hydraulic resistance may require higher pumping power, while excessive gas fractions can lead to the formation of insulating gas pockets or flow maldistribution within complex structures. These effects may locally reduce heat transfer and counteract the expected performance gains [45,47].
Although this concept remains at a nascent stage of development, it represents a compelling direction for future research. The anticipated enhancement in near-wall boundary layer mixing must be critically weighed against a substantial hydraulic penalty. Furthermore, the complex morphology of TPMS architectures introduces a significant risk of localized gas pocket formation (vapor lock) and flow maldistribution, which could severely offset the thermal gains. Consequently, the viability of this approach necessitates rigorous preliminary validation through advanced multiphase CFD simulations prior to any experimental implementation.

6. Outlook and future directions

Despite the rapid development of advanced adsorber architectures, current design approaches remain largely empirical and case-specific, lacking a unified framework that systematically links geometry to transport behaviour and overall system performance. As demonstrated by recent studies and illustrated in Figure. 2, even simple variations in geometric parameters of TPMS unit cells—such as porosity or characteristic length scale—can lead to significant and non-linear changes in transport properties and cooling performance.
This highlights the need for a more structured approach to adsorber design, based on explicit structure–property–performance relationships. In particular, treating the TPMS unit cell as a fundamental building block

offers a promising pathway toward constructing parametric design maps that relate geometric descriptors to permeability, pressure drop, and heat transfer characteristics under defined operating conditions.
Such an approach would enable systematic exploration of the design space and facilitate the identification of optimal trade-offs between thermal enhancement and hydrodynamic resistance, which are central to adsorption system performance. Importantly, this framework is inherently extensible and can be further supported by numerical simulations, targeted experiments, and data-driven methods to efficiently navigate high-dimensional geometric parameter spaces.

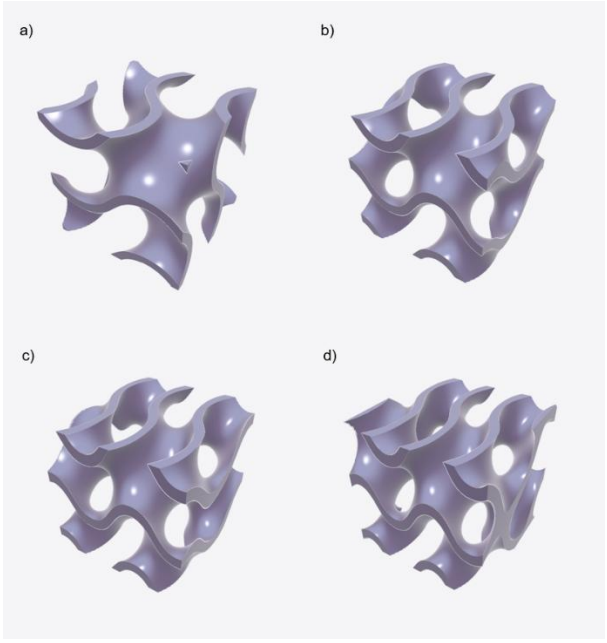

Figure. 2. *Parametric variation of TPMS unit cell geometry with anisotropic spatial frequency scaling. The gyroid surface was generated with increasing wave number along the x-direction ($k_x = 1, 1.4, 1.6, 1.8$; $k_y = 1$; $k_z = 1$).*

The TPMS geometries were generated using an anisotropic formulation of the classical gyroid implicit surface. The standard nodal equation was extended by introducing directional spatial frequency parameters k_x, k_y, and k_z, resulting in:

$$\sin(k_x x)\cos(k_y y) + \sin(k_y y)\cos(k_z z) + \sin(k_z z)\cos(k_x x) = 0 \quad (1)$$

This formulation allows independent control of the spatial periodicity along each coordinate direction while maintaining a constant bounding domain. Increasing the wave number k_i along a given axis effectively reduces the characteristic unit-cell size in that direction, leading to anisotropic scaling of the internal structure without altering the external dimensions of the sample.
As a result, the proposed approach enables systematic control of structural density and morphological anisotropy, providing a flexible framework for investigating structure–property relationships in TPMS-based geometries. This parameterization directly links geometric descriptors to transport-relevant features such as pore size distribution, tortuosity, and hydraulic diameter.
Overall, the development of geometry-based design methodologies represents a key step toward transitioning from empirical adsorber optimization to predictive and scalable engineering of next-generation adsorption cooling and desalination systems.

7. Conclusions

This review has examined the evolution of adsorber bed architectures, demonstrating that modern adsorption systems are fundamentally governed by coupled thermo-hydrodynamic effects rather than isolated thermal limitations. Performance improvements require balancing competing transport mechanisms. The main conclusions and future directions are drawn as follows:

- Inherent Limitations of Stochastic Media: While advanced configurations like coated beds and metal foams provide significant thermal enhancement, their macroscopic performance is inherently constrained by the fundamental trade-off between effective thermal conductivity and vapor permeability
- TPMS as a Paradigm Shift: Architected geometries, particularly TPMS, offer a promising mathematical framework to decouple thermal and hydrodynamic resistances. By ensuring smooth flow pathways and

high surface-to-volume ratios, they enable greater control over internal morphology compared to random porous media

- Need for Systematic Design Maps: The effective implementation of TPMS structures requires transitioning from empirical, case-by-case studies to the development of robust structure–property–performance frameworks. This will allow for the rational optimization of adsorber unit cells under specific cyclic operating conditions.
- Exploration of Complex Flow Phenomena: Several transient and multiphase transport phenomena remain insufficiently explored within complex structured domains. In particular, localized fluidization-like behaviour and high-risk strategies such as two-phase flow integration require rigorous preliminary validation. This highlights the critical need for integrated experimental, numerical, and data-driven approaches to comprehensively capture these multi-scale effects prior to physical implementation.

Acknowledgements

This work was co-financed by the Minister of Science under the “Regional Initiative of Excellence” Programme (contract no. RID/SP/0035/2024/01).
This work was also performed within project No. 2018/29/B/ST8/ 00442, “Research on sorption process intensification methods in modified construction of adsorbent beds” and within project No. 2024/08/X/ ST8/01676 "Development of guidelines for building computational models of fluidized beds", supported by the National Science Centre, Poland. The support is gratefully acknowledged.

References

[1] Krzywanski J, Skrobek D, Zylka A, Grabowska K, Kulakowska A, Sosnowski M, et al. Heat and mass transfer prediction in fluidized beds of cooling and desalination systems by AI approach. Appl Therm Eng 2023;225:120200. https://doi.org/10.1016/j.applthermaleng.2023.120200.
[2] Choudhury B, Saha BB, Chatterjee PK, Sarkar JP. An overview of developments in adsorption refrigeration systems towards a sustainable way of cooling. Appl Energy 2013;104:554–67. https://doi.org/10.1016/j.apenergy.2012.11.042.
[3] She X, Li X, Xu M, Zhou J, Chen J, Huai X, et al. Thermodynamic analysis for new solutions of data center cooling with adsorption refrigeration and heat pipe. Int J Refrig 2024;160:341–56. https://doi.org/10.1016/j.ijrefrig.2024.01.016.
[4] Krzywanski J, Sztekler K, Lasek L, Kalawa W, Grabowska K, Sosnowski M, et al. Performance enhancement of adsorption cooling and desalination systems by fluidized bed integration: Experimental and big data optimization. Energy 2025;315:134347. https://doi.org/10.1016/j.energy.2024.134347.
[5] Alsaman AS, Askalany AA, Harby K, Ahmed MS. Performance evaluation of a solar-driven adsorption desalination-cooling system. Energy 2017;128:196–207. https://doi.org/10.1016/j.energy.2017.04.010.
[6] Elsheniti MB, Al-Ansary H, Orfi J, El-Leathy A, Eissa MS, Elsamni O. Enhancing Adsorption Ice Maker Productivity using Beds of Aluminium Foam Packed with Activated Carbon. IOP Conf Ser Earth Environ Sci 2022;1026:012005. https://doi.org/10.1088/1755-1315/1026/1/012005.
[7] Gado MG, Ookawara S, Hassan H. Utilization of triply periodic minimal surfaces for performance enhancement of adsorption cooling systems: Computational fluid dynamics analysis. Energy Convers Manag 2023;277:116657. https://doi.org/10.1016/j.enconman.2023.116657.
[8] Rezk M, Elsheniti MB, Rezk A, Elsamni OA. Multi-objective optimisation of MOF-801 adsorbent packed into copper foamed bed for cooling and water desalination systems. Appl Therm Eng 2023;229:120642. https://doi.org/10.1016/j.applthermaleng.2023.120642.
[9] Mohammed RH, Radwan A, Rezk A, Olabi AG, Sharma V, Kalam Hossain A, et al. Energy and exergy study of the integrated adsorption-absorption system driven by transient heat sources for cooling and desalination. Energy Convers Manag 2023;277:116614. https://doi.org/10.1016/j.enconman.2022.116614.
[10] Amponsah J, Archibong-Eso A, Fiagbe Y, Opoku DOA, Apatika A, Adorkor E, et al. Coupled Transport and Reaction Modeling of Sorbent Particle Size Effects in Nonisothermal Packed-Bed CO_2 Adsorption. ACS Omega 2025;10:35988–6002. https://doi.org/10.1021/acsomega.5c03466.
[11] Boruta P, Bujok T, Mika Ł, Sztekler K. Adsorbents, Working Pairs and Coated Beds for Natural Refrigerants in Adsorption Chillers—State of the Art. Energies 2021;14:4707. https://doi.org/10.3390/en14154707.
[12] Krzywanski J, Grabowska K, Sosnowski M, Zylka A, Kulakowska A, Czakiert T, et al. Heat Transfer in Adsorption Chillers with Fluidized Beds of Silica Gel, Zeolite, and Carbon Nanotubes. Heat Transf Eng 2021;43:172–82. https://doi.org/10.1080/01457632.2021.1874174.

[13] Shaaban M, Elsheniti MB, Rezk A, Elhelw M, Elsamni OA. Performance investigation of adsorption cooling and desalination systems employing thermally enhanced copper foamed bed coated with SAPO-34 and CPO-27(Ni). Appl Therm Eng 2022;205:118056. https://doi.org/10.1016/j.applthermaleng.2022.118056.
[14] Stampi-Bombelli V, Mazzotti M. Exploring Geometric Properties and Cycle Design in Packed Bed and Monolith Contactors Using Temperature-Vacuum Swing Adsorption Modeling for Direct Air Capture. Ind Eng Chem Res 2024;63:19728–43. https://doi.org/10.1021/acs.iecr.4c02303.
[15] Li M, Zhao Y, Long R, Liu Z, Liu W. Computational fluid dynamic study on adsorption-based desalination and cooling systems with stepwise porosity distribution. Desalination 2021;508:115048. https://doi.org/10.1016/j.desal.2021.115048.
[16] Dharmalingam LK, Aute V, Ling J. Review of Triply Periodic Minimal Surface (TPMS) based Heat Exchanger Designs. Int Refrig Air Cond Conf 2022.
[17] Riaz N, Sultan M, Noor S, Sajjad U, Farooq M, Khan M, et al. Recent developments in adsorption heat pumps for heating applications. Adv Mech Eng 2022;14. https://doi.org/10.1177/16878132221089444.
[18] Solovyeva M, Gordeeva L. Water Adsorption Dynamics on Metal–Organic Framework MOF-801: Comparative Study of Loose and Glued Grains, and Coatings. Nanomaterials 2023;13. https://doi.org/10.3390/nano13172442.
[19] Elsheniti MB, Eissa MS, Al-Ansary H, Orfi J, Elsamni O, El-Leathy A. Examination of Using Aluminum-Foam/Finned-Tube Beds Packed with Maxsorb III for Adsorption Ice Production System. Energies 2022;15:2757. https://doi.org/10.3390/en15082757.
[20] Bruckner S, Demmer T, Ganswind M, Bathen D. Modeling of Water Adsorption in SAPO-34-Coated Aluminum Foam. Chem Ing Tech 2017;89:757–64. https://doi.org/10.1002/cite.201600035.
[21] Bansode PV, Gupta G, Nair VC, Pundla SA, Saini S, Shahi P, et al. Experimental Analysis of Heat Transfer and Pressure Drop in Aluminum Metal Foams Immersed in Dielectric Synthetic Fluid. 2024 23rd IEEE Intersoc. Conf. Therm. Thermomechanical Phenom. Electron. Syst. ITherm, Aurora, CO, USA: IEEE; 2024, p. 1–13. https://doi.org/10.1109/ITherm55375.2024.10709574.
[22] Gado MG, Ookawara S, Nada S, Elkady MF, Hassan H. Adsorbent beds packed in triply periodic minimal surface-derived structures and their performance in adsorption desalination/cooling systems. Int Commun Heat Mass Transf 2024;150:107205. https://doi.org/10.1016/j.icheatmasstransfer.2023.107205.
[23] Andreozzi A, Asinari P, Barletta A, Bianco V, Bocanegra J, Brandão P, et al. Heat Transfer and Thermal Energy Storage Enhancement by Foams and Nanoparticles. Energies 2023. https://doi.org/10.3390/en16217421.
[24] Cheung S, Kang J, Lin Y, Goodson KE, Asheghi M, Gu XW. Triply periodic minimal surfaces for thermo-mechanical protection. Sci Rep 2025;15:1688. https://doi.org/10.1038/s41598-025-85935-x.
[25] Padrão D, Hancock D, Paterson J, Schoofs F, Tuck C, Maskery I. New structure-performance relationships for surface-based lattice heat sinks. Appl Therm Eng 2024;236:121572. https://doi.org/10.1016/j.applthermaleng.2023.121572.
[26] Yan K, Wang J, Li L, Deng H. Numerical investigation into thermo-hydraulic characteristics and mixing performance of triply periodic minimal surface-structured heat exchangers. Appl Therm Eng 2023;230:120748. https://doi.org/10.1016/j.applthermaleng.2023.120748.
[27] Gordeeva L, Aristov Y. Adsorbent Coatings for Adsorption Heat Transformation: From Synthesis to Application. Energies 2022. https://doi.org/10.3390/en15207551.
[28] Amari I, Chahbani M. Modeling and Simulation of Combined Heat and Mass Transfer in Zeolite SAPO-34 Coating for an Adsorption Heat Pump. Adv Mater Sci Eng 2021. https://doi.org/10.1155/2021/3706981.
[29] Grabowska K, Krzywanski J, Zylka A, Kulakowska A, Skrobek D, Sosnowski M, et al. Implementation of Fluidized Bed Concept to Improve Heat Transfer in Ecological Adsorption Cooling and Desalination Systems. Energies 2024;17:379. https://doi.org/10.3390/en17020379.
[30] Calabrese L, Mittelbach W, Bonaccorsi L, Freni A. An Industrial Approach for the Optimization of a New Performing Coated Adsorber for Adsorption Heat Pumps. Energies 2022. https://doi.org/10.3390/en15145118.
[31] Banos O, Bergmann U, Glorius M, Ohmann S, Seidel T, Breitkopf C. New preparation methods for coated heat exchangers in adsorption refrigeration and heat pumps applications. Sci Rep 2022;12. https://doi.org/10.1038/s41598-022-11548-3.
[32] Attarzadeh R, Attarzadeh-Niaki S-H, Duwig C. Multi-objective optimization of TPMS-based heat exchangers for low-temperature waste heat recovery. Appl Therm Eng 2022;212:118448. https://doi.org/10.1016/j.applthermaleng.2022.118448.
[33] Oh S-H, An C-H, Seo B, Kim J, Park CY, Park K. Functional morphology change of TPMS structures for design and additive manufacturing of compact heat exchangers. Addit Manuf 2023;76:103778. https://doi.org/10.1016/j.addma.2023.103778.

[34] Mohammed RH, Mesalhy O, Abdelkareem M, Chow LC. Performance enhancement of adsorption beds with silica-gel particles packed in aluminum foams. Int J Refrig 2019;104:201–12. https://doi.org/10.1016/j.ijrefrig.2019.03.013.
[35] Manila RM, Mitra S, Dutta P. Studies on dynamics of two-stage air cooled water/silica gel adsorption system. Appl Therm Eng 2020;178:115552. https://doi.org/10.1016/j.applthermaleng.2020.115552.
[36] Bujok T, Boruta P, Mika Ł, Sztekler K. Analysis of designs of heat exchangers used in adsorption chillers. Energies 2021;14. https://doi.org/10.3390/en14238038.
[37] Jareteg A, Maggiolo D, Sasic S, Ström H. On the roles of interstitial liquid and particle shape in modulating microstructural effects in packed-bed adsorbers. Chem Eng Res Des 2022;177:682–93. https://doi.org/10.1016/j.cherd.2021.11.031.
[38] Lasek L, Zylka A, Krzywanski J, Skrobek D, Sztekler K, Nowak W. Review of Fluidized Bed Technology Application for Adsorption Cooling and Desalination Systems. Energies 2023;16:7311.
[39] Alahmer A, Ajib S, Wang X. Comprehensive strategies for performance improvement of adsorption air conditioning systems: A review. Renew Sustain Energy Rev 2019;99:138–58. https://doi.org/10.1016/j.rser.2018.10.004.
[40] Skrobek D, Krzywanski J, Sosnowski M, Kulakowska A, Zylka A, Grabowska K, et al. Prediction of Sorption Processes Using the Deep Learning Methods (Long Short-Term Memory). Energies 2020;13:6601. https://doi.org/10.3390/en13246601.
[41] El-Said EMS, Alsood MMA. Experimental investigation of air injection effect on the performance of horizontal shell and multi-tube heat exchanger with baffles. Appl Therm Eng 2018;134:238–47. https://doi.org/10.1016/j.applthermaleng.2018.02.001.
[42] Mahdi Heyhat M, Abdi A, Jafarzad A. Performance evaluation and exergy analysis of a double pipe heat exchanger under air bubble injection. Appl Therm Eng 2018;143:582–93. https://doi.org/10.1016/j.applthermaleng.2018.07.129.
[43] Yaïci W, Entchev E. Coupled unsteady computational fluid dynamics with heat and mass transfer analysis of a solar/heat-powered adsorption cooling system for use in buildings. Int J Heat Mass Transf 2019;144:118648. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118648.
[44] Lasek L, Krzywanski J, Skrobek D, Zylka A, Nowak W. Review of Micro- and Nanobubble Technologies: Advancements in Theory and Applications and Perspectives on Adsorption Cooling and Desalination Systems. Energies 2023;16:8078. https://doi.org/10.3390/en16248078.
[45] Ghashim SL, Flayh AM. Experimental investigation of heat transfer enhancement in heat exchanger due to air bubbles injection. J King Saud Univ - Eng Sci 2021;33:517–24. https://doi.org/10.1016/j.jksues.2020.06.006.
[46] Marouf ZM, Fouad MA, Hassan MA. Experimental investigation of the effect of air bubbles injection on the performance of a plate heat exchanger. Appl Therm Eng 2022;217:119264. https://doi.org/10.1016/j.applthermaleng.2022.119264.
[47] Flayh RAER, Flayh AM. Experimental Analysis of Heat Transfer Enhancement in Double Tube Heat Exchanger with Air Injection. Iraqi J Chem Pet Eng 2024;25:41–8. https://doi.org/10.31699/IJCPE.2024.2.4.
[48] Hasan SS, Baqir AS, Mahood HB. Improvement of Thermal Performance of Coiled Tube Heat Exchanger Utilizing Air Bubble Injection Technique. IOP Conf Ser Earth Environ Sci 2021;877:012040. https://doi.org/10.1088/1755-1315/877/1/012040.