ISSN: 2754-4915

Journal of Material Sciences & Manufacturing Research

Research Article

Open Access

Aluminium Foam Heat Exchangers for Future Cooling/Heating Systems

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ABSTRACT

Maintaining thermal comfort in residential and industrial buildings remains a significant energy challenge. Traditional Heating, Ventilation, and Air Conditioning (HVAC) systems are energy-intensive, contributing substantially to both operational costs and greenhouse gas emissions. As the building sector seeks to improve energy performance, attention has increasingly turned to heat storage and passive energy management strategies. This contribution goes significantly beyond the current state of the art by introducing a novel, compact, and modular heat storage solution that leverages Phase Change Materials (PCMs) heat exchangers reinforced with aluminium foam skeletons, integrated into an underground water/ice reservoir. The use of various bio-based PCMs offers a low-carbon alternative to petroleum-derived materials. Reinforcement with aluminium foams significantly improves thermal conductivity and prevents leakage, solving two core limitations of conventional PCM systems. A heat exchanger embedded at the base, constructed from PCM-aluminium foam composites, enables the repeatable storage and release of latent heat for ventilation air conditioning. The use of renewable, biodegradable PCMs, combined with low-energy seasonal storage, supports circular economy principles and offers a path to Net-Zero building operation. This contribution addresses a new generation of high-performance, bio-based heat storage systems that offer practical, scalable, and climate-resilient alternatives to current technologies.

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Received: August 18, 2026; **Accepted:** August 24, 2026; **Published:** August 31, 2026

Keywords: Aluminium Foams, Heat Exchangers, Phase Change Materials, Heat Storage

Introduction

Accumulation and short-term heat storage in combination with the possibility of repeatedly storing latent heat in Phase Change Materials (PCMs) is currently considered the best way to ensure generally higher energy efficiency of any technological process in an environmentally friendly manner. Currently, the most advanced commercially used heat storage technology in concentrated solar power plants is the molten salt technology. However, this technology brings many technical and economic disadvantages, such as:

- Limited maximum operating temperature (e.g. up to ≈ 400 °C for parabolic trough power plants);
- High solidification temperatures of the salts used (120 – 220 °C) and
- Relatively high costs of molten salt (≈ 0.70 €/kg).

Therefore, it is economically much more advantageous to focus on technologies that allow the use of at least short-term accumulation of low-potential heat (at temperatures up to 70 °C), which allow the use of water or antifreeze as a heat transfer medium.

To ensure rapid heat transfer from the source through the heat exchanger to the fluid without unnecessary losses, researchers are investigated thermo-physical behaviour of various suitable composite materials. These composites combine excellent thermal conductivity with the ability to store latent heat through phase changes of a substance impregnated in the porous structure of a thermally conductive skeleton. A key factor is also the potential for large-scale production of these composites at an industrially acceptable cost.

This contribution was created based on the authors' many years of experience in the field of aluminium foam manufacturing technology by powder metallurgy and the study of the relationship between the structure and properties of components made from it. In this article, they pointed out the unique thermophysical properties of aluminium foam with an unusually high density (over 1.5 g/cm^3), the structure of which is impregnated with vegetable coconut (lat. Cocos nucifera) oil. This ecological biodegradable natural oil is characterized by a greate ability to repeatedly accumulate and dissipate a large amount of low-potential heat to its surroundings (at a temperature close to the temperature suitable for ensuring good thermal comfort in building interiors, i.e. in the range of ≈ 15 – 30 °C). Coconut oil has a very high potential for use in heat storage systems, mainly due to its low water and free fatty acid content, but also due to its extremely high content of soluble acids. The production process of virgin coconut oil is environmentally friendly, as it does not use any organic chemicals or oil solvents. Organic non-paraffinic PCMs, including in addition to coconut oil, various fatty acids, esters and alcohols, have many properties that make them suitable for use in repeatable latent heat storage systems operating in the ambient temperature range (≈ 10 – 40 °C). Therefore, they can be easily integrated into building materials and structures to mitigate excessive temperature fluctuations, accumulating heat during the phase change from solid to liquid [1]. The accumulated heat can later be dissipated back into the system for space heating when the temperature drops below the freezing point. Saturated fatty acids are naturally occurring PCMs, extracted mainly from renewable plant and animal sources such as tallow, coconut, palm kernel and soybean oil

[2]. A life cycle assessment study of lauric acid ($CH_3(CH_2)_{10}COOH$) showed that the energy spent on its production from palm kernel oil can be recovered within a few months [3].

Materials and Methods

Various scientific studies have focused on investigating heat transfer through heterogeneous porous structures of metallic, ceramic as well as polymeric cellular solids [4-7]. A number of methodologies have been developed to investigate heat transfer through solids in porous structures. In all of them, the morphology of the pore structure is one of the most important factors that can influence the effective thermal properties of these composites. Most simulation models focus on analytical or theoretical modelling that describes the macroscopic properties of cellular composites in order to simplify heat transfer analysis. However, simulation models usually focus on the composition of materials, their relative volume fractions, and the morphology of the internal microstructure is mostly considered to be geometrically simple arranged in order to simplify analytical calculations [8, 9].

That is why we decided to investigate the thermophysical properties of stochastic cellular aluminium foam structure, whose density varies even in such a large range as 0.32 – 2.4 g/cm^3. Composites consisting of aluminium foam skeleton impregnated with coconut oil were investigated based on a simulation model created in the real structure of the aluminium foam sample. The thermophysical behaviour of coconut oil was assumed in the calculations, based on the results obtained from the T-history method investigation by previous study [10].

In the present contribution, we determined the thermal properties of porous aluminium foam impregnated with the coconut oil. The thermal conductivity of coconut oil in the solid state is 0.261 W·m^{-1}·K^{-1} and in the liquid state 0.21 W·m^{-1}·K^{-1}, which is significantly higher than the thermal conductivity of air (≈ 0.026 W·m^{-1}·K^{-1}) [4]. However, compared to the thermal conductivity of aluminium (237 W·m^{-1}·K^{-1}) this value is significantly lower. The Maxwell-Eucken model can be presented as follows [8]:

$$k_{s+g} = k_g \frac{[(1/2) + p] + (k_s / k_g)(1 - p)}{(k_g / 2\,k_s)(1 - p) + [1 + (p/2)]} \tag{1}$$

where k_{s+g} (W·m^{-1}·K^{-1}) is the thermal conductivity of the porous material, k_s is thermal conductivity of the solid component of this material, kg is the thermal conductivity of the gas filling the pores and p is porosity.

We assume in this work the thermal conductivity values according to Eq. (1) calculated for a composite material formed by an aluminium foam matrix impregnated with coconut oil, where instead of the thermal conductivity of the gas, we calculate with the thermal conductivity of solid or molten coconut oil. If the temperature of coconut oil is increased from T_1 = 20°C to T_2 = 30°C, the total heat Q_{CN-O} stored in 1 kg of coconut oil during melting is the sum of the sensible heat and the latent heat of fusion $\Delta_{fus}H$ = 103.25 kJ/kg, and it is calculated from:

$$Q_{CN-O} = \int_{T_1}^{T_{mpt}} m\, c_{p,s}\, dT + m\, \Delta_{fus}H + \int_{T_{mpt}}^{T_2} m\, c_{p,l}\, dT \tag{2}$$

where T_{mpt} = 24.5°C is the temperature at which the phase transition occurs, the heat capacity of solid coconut oil is $c_{p,s}$ = 1.7 kJ·kg^{-1}·K^{-1} and that of the liquid is $c_{p,l}$ = 2.2 kJ·kg^{-1}·K^{-1}. This means that 1 kg of coconut oil accumulates ≈ 125 kJ of heat (latent + sensible) when heated from 20°C to 30°C, while 1 kg of water accumulates in the same temperature range only ≈ 42 kJ of sensible heat [11].

The objective of this work is to analyse thermophysical behaviour of a real experimentally prepared aluminium foam sample with a stochastic porous structure and an apparent density above 1.5 g/cm^3 impregnated with coconut oil.

Samples for Investigation of Heat Storage

The aluminium powder with 99.7% purity and a particle size < 63 μm have been dry blended with 0.05 wt.% of the foaming agent (ultrafine TiH_2 powder). The resulting powder mixture was subsequently compacted by cold isostatic pressing and hot extruded (in solid state) at the temperature of 450°C, obtaining a foamable precursor with the shape of continuous profile with the cross-section 20 × 5 mm^2 that has the particles of foaming agent gas-tightly embedded in the entire volume of the aluminium matrix. This avoid the premature release of the hydrogen at heating of the foamable precursor to its melting temperature. The aluminium foam samples were prepared by melting of this precursor inserted in the cavity of steel foaming mould. The molten foam expands during melting due to the thermal decomposition of the foaming agent, the released hydrogen creates bubbles in the melt, the foam fills the entire mould cavity in such a way that it copies its shape, and the remaining aluminium melt flows out of the mould through small leaks. The mould with the foam is after filling the mould cavity suddenly cooled down and after solidification of the foam is the solid porous aluminium sample removed from the mould.

An sample of aluminium foam with dimensions of 40 × 40 × 5 mm^3, prepared by powder metallurgy for the purpose of a thorough investigation of its pore structure by high-resolution Computed Tomography (CT) is shown in Figure 1.

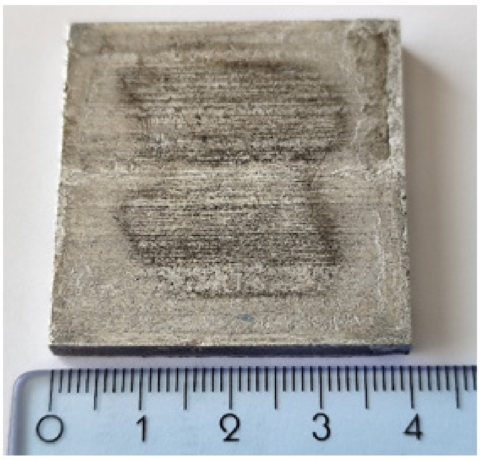

Figure 1: Aluminium foam sample with a continuous aluminium layer covering its entire surface (dimensions: 40 x 40 x 5 mm^3; weight: m = 13.855 g; apparent density: ρ = 1.732 g/cm^3)

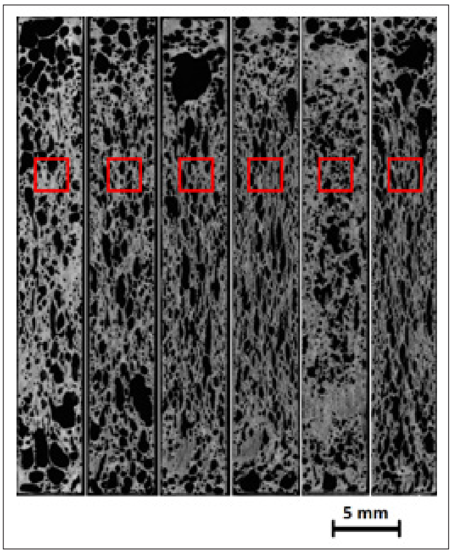

Figure 2: Cross-sections of an aluminium foam sample in 6 mutually parallel planes (in plane XY) spaced 0.5 mm apart obtained by CT method (The red squares indicate a part of the sample with dimensions 2.5 x 2.5 x 2.5 mm^3, which was subjected to a thorough structural analysis in order to obtain a simulation model for investigating thermo-physical behaviour during heat transfer through the sample.)

The porous structure of aluminium foam was investigated by high-resolution CT using a Phoenix/X-ray Nanotom® 180 manufactured by General Electric Company Ltd. This method of structural analysis is the most appropriate for investigating the morphology of pores in metallic structures. Its main advantage is the ability to recognize details of the shape of the pore surface at the nanometric level. A nanometer corresponds to one billionth of a meter, so the nanometer scale allows the observation of surface contours of 1 – 100 nm, i.e. 10^{-9} – 10^{-7} m in size.). The cross-sections of a foamed aluminium sample were made in all three (XY, YZ and XZ) mutually perpendicular planes. The distance between every two parallel sections was 2.5 µm.

Figure 2 shows 6 mutually parallel cross-sections of a foamed aluminium sample obtained by the high-resolution CT method at a distance of 0.5 mm from each other. As can be seen the structure of aluminium foam sample is highly inhomogenous. Simulating heat transfer through such a structure impregnated with coconut oil is therefore a relatively challenging task. The methodology used in this study is described as follows.

Let us consider the elements as shown in Figure 3. The elements have dimensions $a_{i=1\div5} = b_{j=1\div5} = c_{k=1\div5} = 0.5$ mm and are located at coordinates x, y and z, respectively within the cube with dimensions 2.5 × 2.5 × 2.5 mm^3. We can obtain images of all surface layers of each of 125 cubes with a volume 0.125 mm^3. A cross-section of this cube divided to 25 squares 0.5 × 0.5 mm^2 is shown in Figure 4. The volume fraction of pores in the aluminium forming the pore walls ranges from 86.38% to 13.25% in this cross-section, which corresponds at an aluminium density of 2.7 g/cm^3 to the apparent density of the aluminium foam from 0.368 g/cm^3 to 2.342 g/cm^3. In order to create a model of the cube over the whole cube volume, the pseudo-random apparent density distribution of 125 individual cubes from which this cube is composed was used.

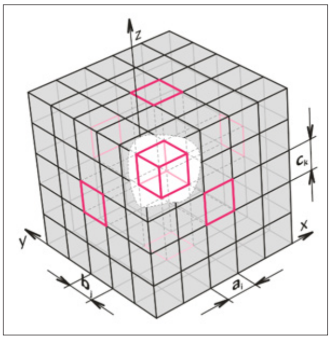

Figure 3: A model of the cube with dimensions 2.5 x 2.5 x 2.5 mm^3 divided to 125 cubes created to the purpose of investigating therophysical behaviour during heat transfer

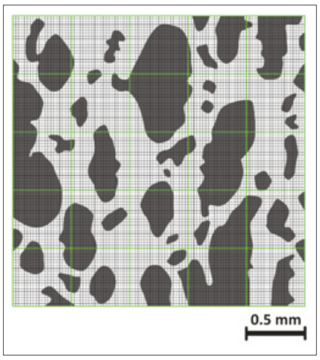

Figure 4: A cross-section through a model of the cube divided into 25 squares with dimensions of 0.5 x 0.5 mm^2

Results

As can be seen from comparison of heat transfer simulation results, the heat is transferred significantly faster through the investigated model of high-density aluminium foam (apparent density of the aluminium foam $\rho_{Al\text{-}foam} = 1.478$ g/cm^3) impregnated with coconut oil (Figure 5) than through a cube model of the same geometry made of bulk non-porous copper (Figure 6) with density $\rho_{Cu} = 8.945$ g/cm^3. The red curves represent in both graphs average temperature of all 25 cubes with side a_1 (× b_j × c_k), blue – a_2, yellow – a_3, green – a_4 and black – a_5, during simulation.

Conclusion

A numerical computational approach was developed and investigated based on simulation model created from the real structure of the aluminium foam sample impregnated by coconut oil. It has been shown that this methodology is sufficiently suitable for obtaining an approximate estimate of the relationship between structure, thermal conductivity, and the amount of accumulated heat during repeatable heating of the investigated composite [12].

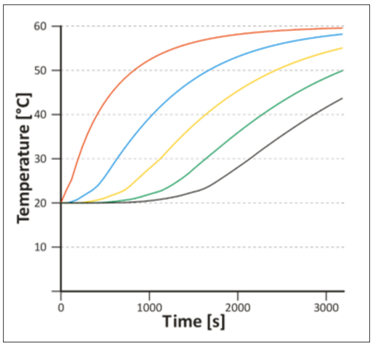

Figure 5: The thermal behaviour of investigated model of high-density aluminium foam impregnated with coconut oil during simulation of the heat transfer

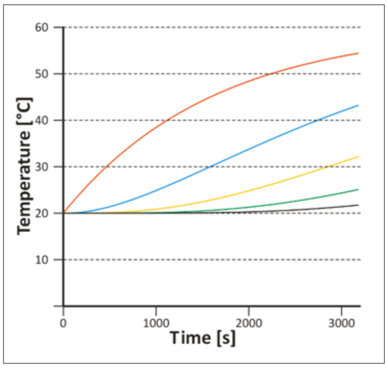

Figure 6: The thermal behaviour of bulk copper cube during simulation of the heat transfer

Author Contribution Statement

Designed Research: J. J.; **Performed Research:** J. J., J. K.; **Writing Original Draft:** J. J.; **Review & Editing:** J. K. Both authors have read and agreed to the published version of the manuscript.

Acknowledgments

The financial support by the Slovak Grant Agency for Science under the contract VEGA 2/0102/25 (project: Aluminium foam reinforced bio-based phase change materials for latent heat storage) is gratefully acknowledged.

Data Availability Statement

Data generated during this study are available from the corresponding author on reasonable request.

Conflict of Interest Statement

The authors declare no conflict of interest.

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