Phase Change Materials Reinforced with Aluminium Foam for Latent Heat Storage

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DOI: 10.5185/amlett.2021.031612

The structure of aluminium foam is highly porous consisting of aluminium (or its alloy) filling up the space among gas pores. Although pores formed during foaming of aluminium melt are closed, there are always microscopic cracks in the walls of solid foam, so that the porosity is predominantly open. This preference of aluminium foam allows to fill pores with a Phase Change Materials (PCMs) capable repeatedly to store and release a huge amount of latent heat of phase transition from solid to liquid state and vice versa. The excellent thermal conductivity of the aluminium, forming the pore walls, predetermines aluminium foam castings for the production of highly efficient heat exchangers in various industrial sectors, especially in the building industry. The most promising technique for the production of near-net-shaped structural components containing a dense aluminium surface skin and porous inner foamed aluminium structure is powder metallurgical route. Lightweight self-supporting interior ceiling panels impregnated by PCM presented in this contribution, utilize their high mechanical stiffness and their ability to store large amounts of latent heat at a constant temperature. The application of foamed aluminium appears to be very promising also for heat exchangers covering the entire pitched roof of the building which provides not only the better recovery of the heat from the building surroundings but also the dissipation of unwanted excess heat from the interior when needed.

Introduction

The strategy to decelerate global warming involves energy and climate policy including the so-called 20/20/20 targets, namely the reduction of carbon dioxide (CO_2) emissions by 20 %, the share value increase of renewable energy's market to 20 %, and a 20 % increase in energy efficiency. The Paris Agreement negotiated by representatives of 196 state parties at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) signed in 2016 is dealing with greenhouse-gas-emissions mitigation, climate change adaptation, and financial flow management, particularly in relation to companies, organizations and governments. The long-term goal of Paris Agreement is to keep the increase in global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the increase to 1.5 °C, recognizing that this would significantly reduce the risks and impacts of climate change.

The available renewable energy sources are currently incapable of providing continuous coverage of more than just a few percent of humanity's vast energy needs. To overcome this, the solutions have been proposed by combining various Thermal Energy Storage (TES) technologies with renewable energy generation offering thermal energy efficiency enhancement for intermittent heat sources (e.g. solar heating). The need for effective sustainable TES in buildings is ever increasing because it is predicted that over 70 % of the world population will live in urban environments at around 2050 [**1**] despite the ongoing pandemic of COVID-19 disease caused by the coronavirus SARS-CoV-2 and it seems that living in a rural environment would be more advantageous in this respect.

This contribution is focused on possibility to produce highly efficient aluminium foam heat exchangers impregnated by PCM capable repeatedly to store and release a huge amount of latent heat of phase transition and explanation of potential for their industrial application in the building industry. The innovative thermo-active aluminium foam roofing system combined with large-area interior ceiling radiators performs the function of highly efficient heat exchange between surroundings of the building and the heat transfer medium used for maintaining sufficient thermal comfort in interiors as well as for Domestic Hot Water (DHW) preparation required for the operation of future residential as well as non-residential buildings.

Bulk thermal insulation has recently been mistaken considered as one of the best ways of improving the thermal performance of building envelope. The performance of insulation is directly proportional to the insulation thickness in the case that insulated area is isolated from the rest of the building [**3**]. However, cost analysis showed that the conventional thermal insulation cannot be considered as the only system to achieve improved thermal performance in highly insulated buildings due to relatively high cost and diminishing energy benefits. In spite of several alternative systems for building thermal loads reduction, e.g. cool roof coatings, actively ventilated attics, inclined air spaces under roofing, naturally ventilated cavities of façade systems, etc., the most promising material enhancement can be achieved in the case that PCM is impregnated to aluminium foam interior ceilings in order to increase the attic floor insulation. PCM reduces the overall heat flow across the insulation between building interior and attic floor and so increases the time shifting of the peak-hour loads. The lightweight thermal mass components complemented by the feature of latent heat storage to PCM with a melting point in the range from 23 to 28 °C are therefore an unavoidable means contributing to the reduction of costs related to maintaining of sufficient thermal comfort [**4**].

Energy-efficient aluminium foam heat exchangers

Technical solution of heat storage system using PCM shown in **Fig. 1** is based on constantly alternating processes of heat absorption and release when the storage material undergoes a phase change from solid to liquid and vice versa. The high latent heat absorbed and released during phase transition of PCM at almost constant temperature gives PCM the capability of storing and later releasing large amounts of energy. That is why PCMs can store even ten times more heat per unit volume in comparison with conventional sensible storage materials such as water, masonry, rock or concrete (**Fig. 2**) [**4**]. The significant enhancement of heat storage capability of PCM in comparison with conventional building materials is clearly shown in **Fig. 3**, which illustrates the thickness of building material required to store the same amount of heat as concrete panel with a thickness of 240 mm over a 10 K temperature range [**6**].

Despite the fact that PCM appears to be by far the most suitable building material in terms of necessary heat storage capability, PCMs must exhibit synchronously certain desirable thermodynamic (suitable phase-transition temperature, high latent heat of transition, high thermal conductivity, etc.), physical (small volume change, high density, etc.), kinetic (no supercooling, sufficient crystallization rate), chemical (chemical stability, no toxicity, etc.) and economic (abundant, cost-effective) properties unavoidable for their employment as latent heat storage materials for maintaining of sufficient thermal comfort in buildings. However, the PCMs themselves cannot be used as heat transfer medium. The appropriate heat exchanger has to be designed specially, given the extremely low thermal conductivity of almost all PCMs in general. The highly thermal conductive porous aluminium foams with interconnected pores (occurrence of micro-cracks in the pore walls) prepared by powder metallurgy are therefore the best solution for the construction of highly efficient heat exchangers suitable for storage of a large amount of latent heat (**Fig. 4**).

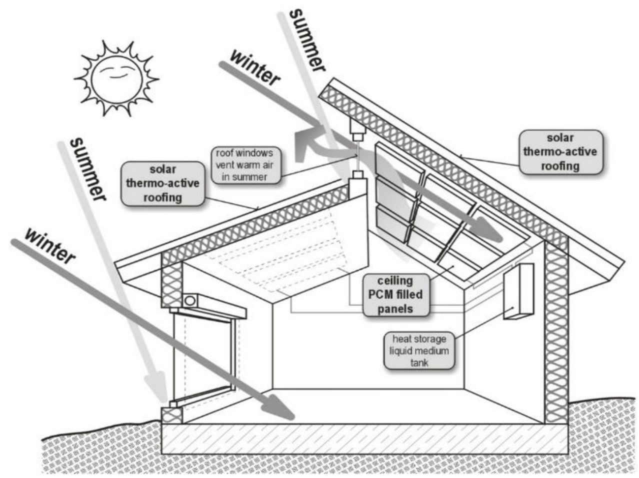

Fig. 1. Design of a novel house for minimum heating/cooling bills characterized by highly efficient solar energy harvesting using thermo-active aluminium foam-based roofing complemented by the advanced system for repeatable short period storage/release of latent heat to/from ceiling aluminium foam heat exchangers impregnated with PCM [5].

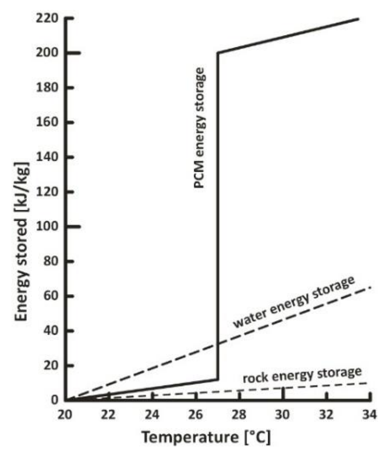

Fig. 2. Performance comparison of PCM, water and rock heat storage systems [**4**].

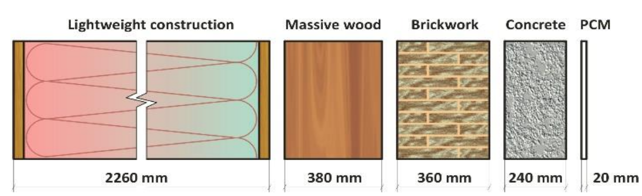

Fig. 3. Comparison of the building material thicknesses needed to store the same amount of heat by heating it from 20 °C to 30 °C as it can be stored in a 240 mm concrete panel [**6**].

Fig. 4. Ceiling aluminium foam radiators in the open office space area 260 m^2 of company Hydro Extrusion Slovakia JSC in Žiar nad Hronom, Slovakia (right – cross-section of aluminium foam structure with embedded tube distributing heat transfer fluid).

The aluminium cell walls allow transferring heat uniformly to the large volume of PCM that fills the space of the pores. The PCMs on the base of organic paraffin waxes provide by this way the possibility to store and to release large volumes of latent heat during its phase change from solid to the liquid stage and vice versa (~ 200 – 250 J/g) at a nearly constant temperature. This allows keeping the temperature of the heat exchanger at required temperature for a longer time without the need to dissipate heat into the surroundings of the exchanger immediately. The heat exchanger is therefore chargeable also by the fluid with the temperature only slightly higher than the melting point of used PCM. In the case that the heat exchanger is used for the purpose of undesirable excessive heat removal from the building interior, the heat is consumed for melting of PCM thus keeping the temperature at a required level until all paraffin wax is melted.

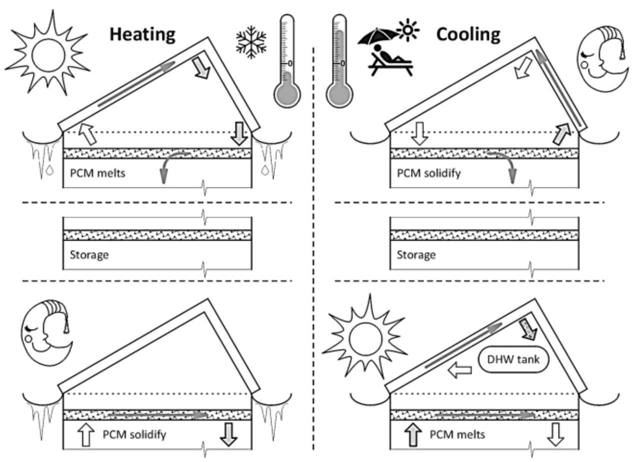

Fig. 5. Behaviour of solar thermo-active roofing combined with large-area ceiling interior aluminium foam radiators impregnated with PCM during winter season – heating (left) and summer season – cooling (right).

The system of aluminium foam-based thermally active roofing supplemented with interior ceiling panels allows to maintain sufficient thermal comfort thanks to their capability to store/release large amounts of latent heat during melting/solidification of PCM impregnated in the structure of ceiling panels. This system can provide heating and cooling following the operating principle shown in **Fig. 5**. PCM with phase transition temperature 28 °C is encapsulated in the structure of aluminium foam-based interior ceiling heat exchangers. During winter mode, the PCM is melted by non-freezing liquid flowing through the structure of south side of pitched roofing in the case that its temperature is above 30 °C and stored until additional heating supply is needed. During summer season, the non-freezing liquid is pumped at night to the ceiling heat-exchangers from north side of pitched roofing to solidify PCM. Moreover, night free cooling mode could be used if the inner environment has a cooling demand, and the external conditions can cover it. The summer heat surpluses can be during hot summer days utilized for DHW preparation. The main advantage of above mentioned concept is that the amount of heat stored in the ceilings is usually sufficient to maintain thermal comfort in the interior satisfactory. This leads to significant improvement of energy efficiency and reduction of operating costs in comparison with conventional technologies used currently in the building industry.

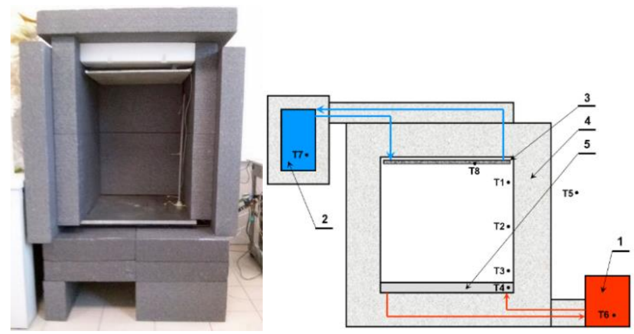

Fig. 6. Experimental climatic chamber designed for measurement of the ability to store latent heat of phase transition by heating/cooling panels of aluminium foam impregnated by PCM and testing their performance under various conditions of cooling and heating (1 – thermostat, 2 – reservoir with 12.6 litres of water, 3 – aluminium foam heat exchanger, 4 – thermal insulation, 5 – aluminium plate with dimensions 700 × 700 × 25 mm stabilizing the temperature in the chamber).

Experimental

Following experiments have been done in order to investigate the ability to store reversibly latent heat of phase transition by paraffin wax impregnated in the porous structure of aluminium foam sample:

An experimental climatic chamber has been used for this purpose. The chamber has been designed for testing of the ability to store the latent heat of phase transition during multiple thermo-cycling of flat-shaped aluminium foam panels impregnated by PCM with the area 600 × 600 mm (**Fig. 6**). The chamber allows to measure and record: T1, T2, T3 – air temperature at a distance of 200 mm, 500 mm and 800 mm from the sample, T4 – temperature of aluminium plate located on the bottom of climatic chamber, T5 – ambient temperature, T6 – temperature of the water in thermostat ensuring the maintenance of the temperature of the climatic chamber at a constant level, T7 – temperature of the water circulating from the reservoir through panel located on the ceiling of climatic chamber and T8 – temperature of the tested panel. The aluminium plate located at the bottom of the chamber was heated and maintained by flowing water stabilized by thermostat at a constant temperature. The temperature was periodically changed every 24 hours between 15 °C and 45 °C during experiments demonstrating the ability of aluminium foam panel inserted in the chamber repeatedly to store and remove the heat from the interior of the climatic chamber. The thermal behaviour of aluminium foam tested sample (**Fig. 7**) with dimensions 290 × 130 × 15 mm and apparent density 0.547 g/cm^3 placed in the upper part of the cavity of the climatic chamber (200 mm from its ceiling) has been investigated. The resulting record of measured temperatures has been compared with the results of a similar experiment by which tested sample was impregnated with 37 g of PCM RUBITHERM® RT28HC produced by German company Rubitherm Technologies GmbH with the melting range 27 – 29 °C.

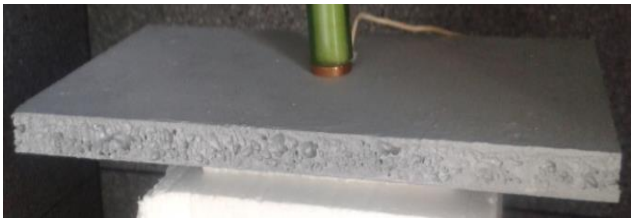

Fig. 7. A tested sample of aluminium foam with dimensions 290 × 130 × 15 mm and apparent density 0.547 g/cm³.

In order to prevent leakage of liquid PCM from aluminium foam sample during its melting, various methods of sealing micro-cracks that are inevitably present in each surface of foam aluminium castings have been suggested and tested. Experiments have shown the suitability of applying a two-component dispersion of a medium molecular epoxy resin, inorganic pigments and fillers, organic solvents with the addition of additives filled with zinc phosphate pigment and aluminium powder, cured by polyalkylene polyamine to the surface of heat exchanger enabling long-term sealing of liquid PCM in the structure of porous aluminium foam maintaining sufficient thermal conductivity of its surface layer. The whole surface of aluminium foam sample has been therefore coated by this coating layer. 12.6 litres of water have been circulating during experiments from the container placed in the room maintained at the temperature 20 °C through aluminium foam panel located on the ceiling of the climatic chamber. The thermal behaviour of tested samples of aluminium foam panels is shown in **Fig. 8** under the conditions described above.

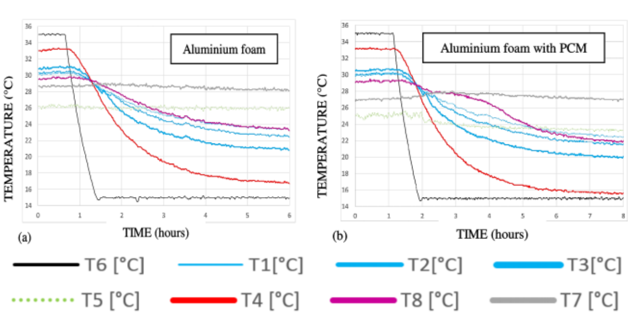

Fig. 8. The thermal behaviour of the tested sample during the experiment by which the interior of the climatic chamber was heated by melted and slowly solidified PCM impregnated in porous structure of aluminium foam panel (T1, T2 and T3 – air temperatures at a distance of 200 mm, 500 mm and 800 mm from the chamber ceiling, T4 – temperature of aluminium plate located on the bottom of climatic chamber, T5 – ambient temperature, T6 – temperature of the water in thermostat ensuring the maintenance of the temperature of the climatic chamber at a constant level, T7 – temperature of the water circulating from the reservoir through aluminium foam ceiling panel and T8 – temperature of the tested sample); (a) Al foam sample 290 × 130 × 15 mm, weight: 309 g, density 0.547 g/cm³, (b) the same sample impregnated by 37 g of PCM RUBITHERM® RT28HC.

Results and discussion

It has been shown, that the value of the PCM investigated in this study is only approximate estimate as no PCM melts and solidifies in the entire volume of the heat exchanger at exactly constant temperature. The heat storage capacity of PCM RUBITHERM® RT28HC is approximately 250 kJ/kg (e.g. ~ 70 Wh/kg) ± 7.5 %. This heat is the sum of latent and sensible heat in a temperature range from 21 °C to 36 °C. The distribution of heat capacity of this PCM during heating and cooling within said temperature range is shown in **Fig. 9**. This graph shows that e.g. 125 J of heat is stored to each 1 g of PCM during heating of the PCM from 27.5 °C to 28.5 °C and during cooling in the same temperature range 1 g of PCM releases 159 J of heat.

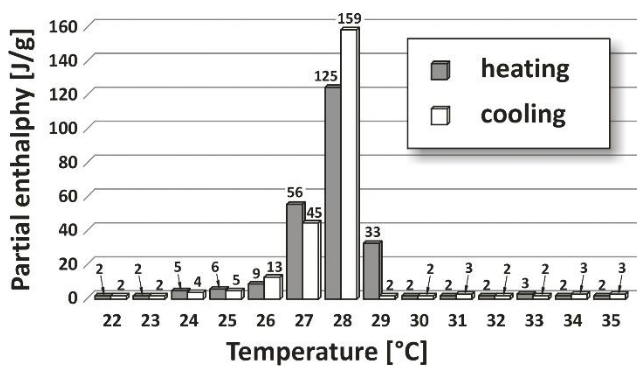

Fig. 9. The distribution of heat storage capacity of PCM RUBITHERM® RT28HC during heating and cooling within temperature range from 21 °C to 36 °C [**8**].

Nevertheless, the following calculations can be used to quantify the amount of heat, which is capable of being stored and later dispersed to the air or heat transfer fluid at a constant temperature by aluminium foam panels filled by PCM. Let us consider the aluminium foam panel with dimensions 600 × 600 × 10 mm, the volume of 3600 cm³, a density of 0.5 g/cm³ and a weight of 1800 g.

The weight of 1 m² of panels is 5.4 kg. They can be fully filled with about 7.24 kg of PCM RUBITHERM® RT28HC with the melting range 27 – 29 °C (PCM density in the solid state is 0.88 g/cm³ and in the liquid stage 0.77 g/cm³). Since 1 kg of PCM can accumulate about 250 kJ of latent heat, and thus even 1810 kJ (e.g. ~ 503 Wh) of latent heat can be accumulated during phase transition of PCM into 1 m² of aluminium foam panels with pores fully filled by PCM in this way. There is enough of heat during winter for keeping sufficient thermal comfort about 9 hours without delivering additional energy from source as an average winter monthly heat demand is ~ 40 kWh/m². The temperature of the ceiling panels does not drop below the phase transition temperature during this time even when they accumulate no more heat from the source. This means that during those days of the heating season that can be obtained from solar gains through a roof at least 500 Wh of heat (by heating the liquid heating medium to a temperature of at least 30 °C) for every 1 m² of living space, sufficient thermal comfort can be assured by the daily charging and discharging of said ceiling heating/cooling panels. The sufficient amount of solar gains is available in the region of Central Europe for this purpose almost throughout whole spring as well as autumn.

Further research work described in this contribution has been focused on the development of such an aluminium foam structure, which allows more efficient heat transfer by conduction through the structure of PCM impregnated in the volume of the heat exchanger. The aluminium foam samples were prepared for this purpose from an aluminium powder of 99.7 % purity with a particle size < 63 µm (median of the powder particle diameter d_{50} = 43 µm, i.e. 50 % particles is smaller than d_{50}). The use of such fine-grained powder for the preparation of a foamable precursor has been shown to contribute significantly to preventing the foam structure from collapsing during foaming during aluminium foam melting. In order to be able to achieve a higher panel density, a foamable precursor was prepared containing only 0.15 wt. % foaming agent – TiH_2 powder. The precursor was hot extruded from the pre-compacted mixture of the aluminium powder (Al 99.7 %) and the powdered foaming agent TiH_2. The sample specimens had been foamed in the steel moulds in an electric resistance furnace in the form of small square plates (40 × 40 × 5 mm) using 4 Pcs of foamable precursor with dimensions 20 × 40 × 2 mm. As can be shown from **Fig. 10**, relatively homogenous pore distribution can be achieved by this way even when the density of aluminium foam from which the heat exchanger will be made reaches the value of 1.624 g/cm^3 (porosity is only 39.86 %).

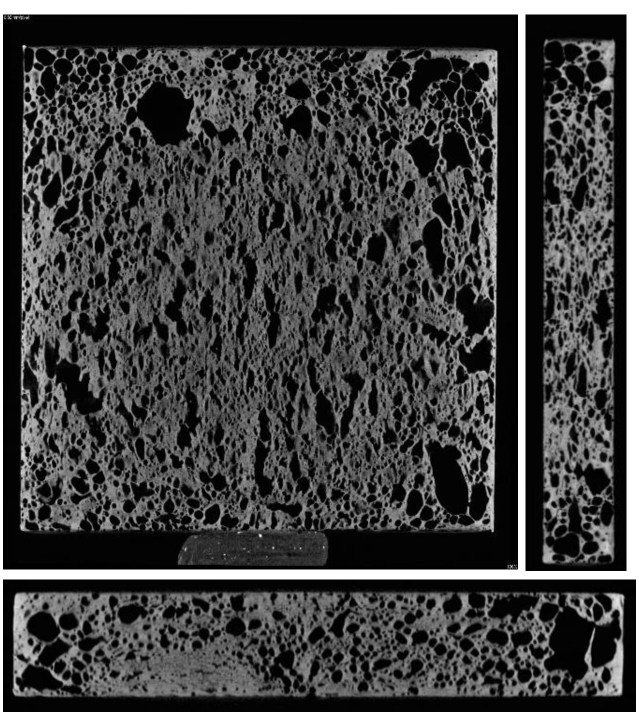

Fig. 10. The cross-sectional images of the aluminium foam sample (40 × 40 × 5 mm) with the density of 1.624 g/cm^3 in three mutually perpendicular sections obtained by X-ray tomography observation (device: Phoenix / X-Ray Nanotom 180).

Conclusion

The experiment described in this contribution demonstrated the capability of PCM with the trademark RUBITHERM® RT28HC produced by German company Rubitherm Technologies GmbH with the melting range 27 – 29 °C impregnated in the structure of tested aluminium foam sample to store repeatable large amount of latent heat during phase transition of PCM from solid to liquid and vice versa. That is why such composite structure consisting of PCM reinforced with an aluminium foam skeleton is suitable for the construction of extremely energy efficient heat exchangers for building industry.

The thermophysical properties of said heat exchangers can be significantly improved if the aluminium foam is made from powder-metallurgical foamable precursor prepared from fine-grained aluminium powder of 99.7 % purity with a particle size < 63 µm containing only 0.15 wt. % of TiH_2 powder as a foaming agent.

Acknowledgements

The financial support by the Slovak Research and Development Agency under the contract APVV-17-0580 (project: Research of roofing with integrated function of heat exchanger, acronym: RoofFoam) is gratefully acknowledged.

Conflicts of interest

There are no conflicts to declare.

Supporting information

Supporting informations are available online at journal website.

Keywords

Aluminium foam, heat exchangers, phase change materials, heat storage, energy efficiency.

Received: 07 July 2020
Revised: 10 November 2020
Accepted: 27 November 2020

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Authors biography

Dr. Jaroslav Jerz has completed his PhD from Vienna University of Technology (Austria) with dissertation dedicated to the development of aluminium foam by powder metallurgy. He is a scientist at the Institute of Materials & Machine Mechanics, Slovak Academy of Sciences in Bratislava (Slovakia). His work is devoted mainly to the field of materials engineering and related investigation of efficient management of production and consumption of energy from renewable sources. He performs also development, testing and industrial commercialization of novel ceiling aluminium foam heating/cooling panels as well as thermally active aluminium foam based roofing systems. His scientific work is devoted to advanced metallic materials, development of technologies for their industrial production and transfer of knowledge gained by material research into industrial practice.

Arun Gopinathan is a PhD student working at the Institute of Materials & Machine Mechanics, Slovak Academy of Sciences in Bratislava (Slovakia) and currently pursuing his doctoral studies from Slovak University of Technology (Slovakia) with dissertation dedicated to the development of aluminium foam composite panels by powder metallurgy which is impregnated with PCM for developing Thermal Energy Storage (TES) system. He is working under the supervision of Dr. Jerz and involved in the project of developing and testing thermally active aluminium foam based roofing systems. His dedicated work involves the investigation of the porous structural aluminium foam in enhancing the heat transfer process and the possibility of its application in the future based TES systems.

Dr. Jaroslav Kováčik is senior researcher at Institute of Materials & Machine Mechanics, Slovak Academy of Sciences in Bratislava (Slovakia). He is involved in investigation of metallic foams – measurement and modelling of mechanical and physical properties. His work is devoted to metal matrix composites, focused on physical and mechanical properties of copper – graphite materials. He deals also with using of concentrated solar power for powder metallurgical preparation of Ti and Ti composites and solar nitridation of Ti.

Graphical abstract

Design of a novel house concept for minimum heating/cooling bills (a) characterized by highly efficient solar energy harvesting using thermo-active aluminium foam-based roofing (b) complemented by the advanced system for repeatable short period storage/release of latent heat to/from ceiling PCM based aluminium foam heat exchangers (c).