Energy-Efficient Maintaining of Thermal Comfort in Buildings by Thermo-Active Aluminium Foam Roofing

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Kurzfassung: Thermal comfort in buildings is usually provided through the heat exchangers requiring a relatively high temperature gradient that is most often obtained by conversion from electricity or combustion of coal, gas, resp. biomass. The development is therefore focused on active systems for solar heating in combination with suitable containers for heat storage and distribution systems in order to use emission-free alternative energy for heating of buildings and Domestic Hot Water (DHW). The interior cooling during hot summer days is usually solved independently and is ensured almost exclusively by electrically powered air-conditioning or air-recuperative units. Prospective environmentally attractive solution ensuring the thermal comfort of buildings is the effective use of rarely used heat from a low-temperature difference (15°C), which can be obtained every day from the difference between day and night temperatures without any need for heating/cooling using electric power or combustion of fossil fuels.

The focus of this R&D study is based on describing performance of novel large-scale aluminium foam roofing with integrated function of heat exchanger which is able effectively to obtain low potential heat from the surroundings of building and transfer it through the liquid heat transfer fluid to the interior of the building. The roof cladding made according to this concept is simultaneously able to dissipate excess heat accumulated in the building to its surroundings during hot summer nights when the outside temperature drops below 20°C.

Various technical solutions of surface coating are described in this contribution to explain the appropriateness of most beneficial methods for application of suitable coatings to the surfaces of the aluminium foam castings that lead to obtaining useful characteristics for the optimal interaction with the rain water and water vapour, ensuring colour stability when exposed to sunlight, frost resistance up to a temperature – 15°C, heat resistance up to 60°C, and the ability to achieve efficient heat transfer between the external environment and internal structure of the foam through roofing surface.

Keywords: aluminium foam, heat exchangers, solar radiation, heat storage, energy efficiency

1 Introduction

Heat recovery and storage can be used to increase the energy efficiency in building sector by reducing the mismatch between supply and demand of heat and cold. Short term storage of the heat obtained from solar gains is essential as there is a large mismatch between supply and demand. The development of materials and technical systems for efficient heat storage has become a popular research topic recently as the amount of heat gained from solar gains depends significantly on day and night cycle. That's why the right choice of materials for heat storage directly affects the utilization efficiency of solar energy.

It can be stated that there is no shortage of energy currently in the world around us, although energy is an extremely valuable and precious resource for humankind. Throughout history, technological ingenuity and strategic efforts have been devoted to the extraction of energy from moving water, blowing wind, burning coal, petroleum, or natural gas, uranium subjected to nuclear fission, sunlight, Earth's crust heat and other primary energy sources. It is quite wrong to talk of the rate at which we “consume” energy – to power our cars, heat our homes, manufacture our industrial products, etc. From a scientific point of view, however, energy is not lost when we use it. Indeed, the essence of energy is that it is conserved. The yearly average rate at which solar energy is normally incident at the top of Earth's atmosphere is given by the solar constant ~ 1 361 W/m^2 per second. The total steady rate at which solar electromagnetic radiation hits the Earth every second is therefore roughly 173 000 TW. This is approximately 10 000 times the rate at which the humanity uses energy at the present time. The challenge is therefore to find practical and economical ways of channelling energy to human use from its natural state as effectively as possible [9].

The heat can be stored as a change in internal energy of a material as sensible heat, latent heat, thermo-chemical energy storage or a combination of these. In the case of sensible heat storage system, thermal energy is stored by raising the temperature of a solid or liquid. The amount of repeatedly stored and later released energy depends on the specific heat of the medium, the temperature changes during the process of charging and discharging and the amount of storage medium. The water appears to be thanks to extremely high specific heat (4190 J/(kg·K)) the best available sensible heat storage liquid, however above 100°C, oils, molten salts, etc. are used. For air heating applications rock bed type sensible heat storage solids (unconsolidated, such as sand, clay, or mud, or consolidated, such as granite, limestone, etc.), but also stones, bricks, and concrete are successfully used. The thermochemical energy storage systems rely on the energy absorbed and released by breaking and reforming molecular bonds in a completely reversible chemical reaction [5].

Generally, the water is usually used as the sorbate substance in building applications because it meets the requirements of a safe system with no environmental risks. Therefore, hydrophilic substances such as silica gel, zeolites, $MgCl_2$, $SrBr_2$, KBr, LiBr, LiCl, $CaCl_2$, etc. are suitable sorbents for sorption applications. The energy can be stored during desorption through the breaking of the water–sorbent bond. If needed, water can then be condensed and stored for future use. Heat recovery consists of re-bonding water vapour with the sorbent. This phenomenon is called ad/absorption. **Fig. 1** shows the comparison of heat storage systems based on sorption phenomena and the other heat storage methods (sensible and latent). Thermochemical materials have the advantage of high heat storage density, a significant temperature increase, and the possibility of storing the reactants (sorbent and sorbate) at ambient temperature and with no self-discharge. This a significant advantage can be in nearest future effectively utilized for seasonal heat storage applications [2].

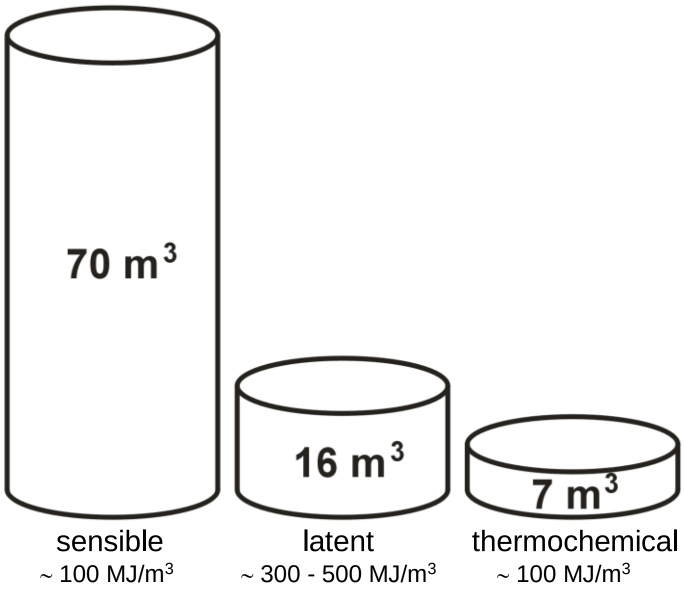


Figure 1. *Approximate estimate of the volume needed to full cover the annual heat storage need of an average sized passive family house (6 480 MJ) [1].*

2 Energy-efficient maintaining of sufficient thermal comfort

Nevertheless, the heat storage using Phase Change Materials (PCM) is nowadays one of the most effective way of storing heat from solar gains. The high energy storage density and the isothermal nature of the storage process are the most significant advantages. The technical solution shown in **Fig. 2** 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 most promising material enhancement can be achieved in the case that PCM is added to interior ceiling heat exchangers. The high latent heat of phase transition gives PCM the capability of storing and later releasing large amounts of energy. The heat is absorbed and released during phase transition of PCM at almost constant temperature. PCM is therefore able to reduce the overall heat flow across the insulation between building interior and attic floor and so to increase 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 energy consumption for space conditioning by a time shift of peak-hour loads [11].

The time shifting of the peak-hour loads during air conditioning using PCMs for ceiling boards in an office building has been previously examined in [1]. As can be seen from **Fig. 3**, during overnight thermal storage time (~ from 2 a.m. to 7 a.m.), the cool air from the Air Handling Unit (AHU) flows into the ceiling chamber space and chills the PCM ceiling board, thus removing the thermal energy from this space (**Fig. 3a**). During the normal cooling time (~ from 7 a.m. to 1 p.m.), the cool air from the AHU flows directly into the room (**Fig. 1b**). During the time of big heat load (~ from 1 p.m. to 6 p.m.), the air from the room returns to the AHU via the ceiling chamber space passing through the cooled-down PCM ceiling on its way back to the AHU (**Fig. 1c**). The maximum thermal load, as well as the capacity of the heat source, can thus be significantly reduced.

Moreover, the novel thermo-active reinforced aluminium foam roofing system is able to get heat from the solar gains and from heat around the building for heating of the interior and DHW as well as also to take away an undesirable heat to the surroundings during cooler summer nights.

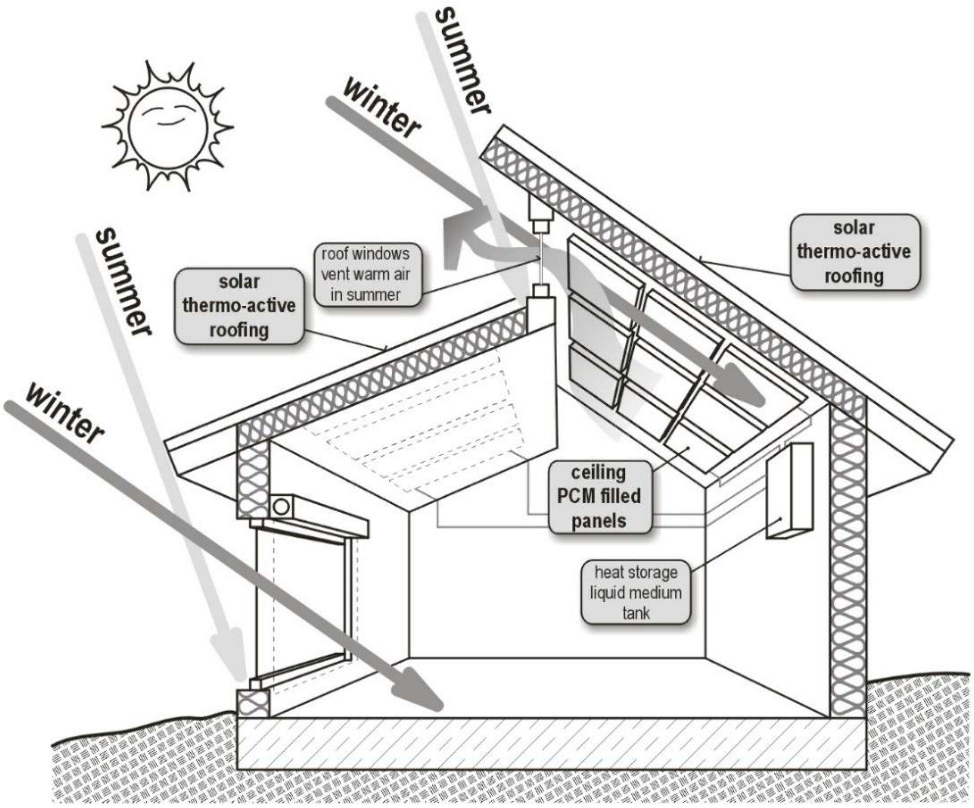
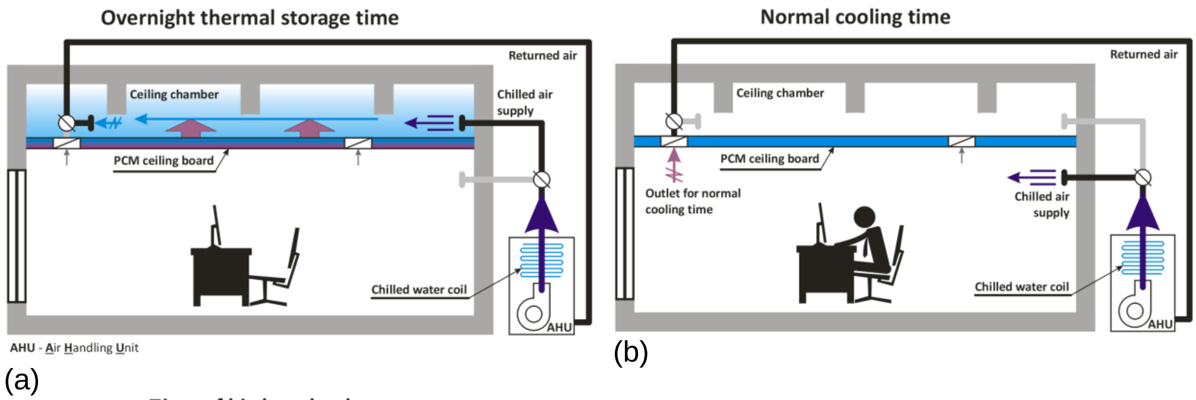


Figure 2. *Design of a novel house for minimum heating/cooling bills characterized by highly efficient solar energy harvesting using thermo-active aluminium foam-based roofing complemented by the advanced system for repeatable short period storage/release of latent heat to/from ceiling aluminium foam heat exchangers impregnated with PCM [11].*

2.1 Effective use of summer energy surpluses

The energy efficiency of building can be significantly improved by incorporating thermo-active heat exchangers covering the entire pitched roof of the building. The novel aluminium foam-based roofing can be supplemented with a system of interior ceiling panels allowing to maintain sufficient thermal comfort thanks to their capability to store/release large amounts of latent heat during melting/solidification of PCM impregnated in their structure. The thermo-active cladding of entire pitched roof with integrated function of heat exchanger can provide heating and cooling following the operating principle shown in **Fig. 4**. 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 day utilized for DHW preparation, or they can be stored in an underground storage system with the possibility of long-term storage of heat for DHW preparation purposes eventually. The main advantage of above mentioned concept is that the amount of heat simple stored in the ceilings is usually (especially during periods when there is no need to store heat from solar gains into the ceiling panels or to transfer heat from the ceiling panels to the surroundings of the building) 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.



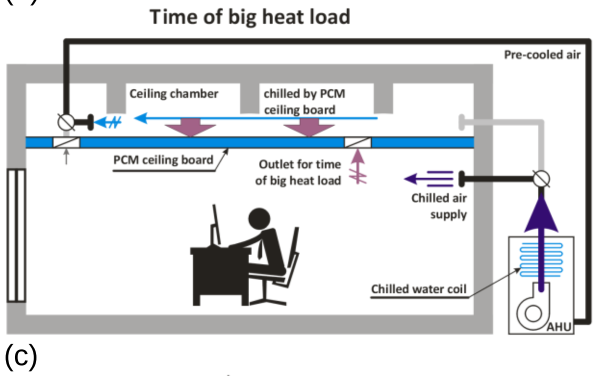


Figure 3. *The system of ceiling board containing PCM with the function of latent heat storage during (a) overnight thermal storage time, (b) normal cooling time and (c) time of big heat load [1].*

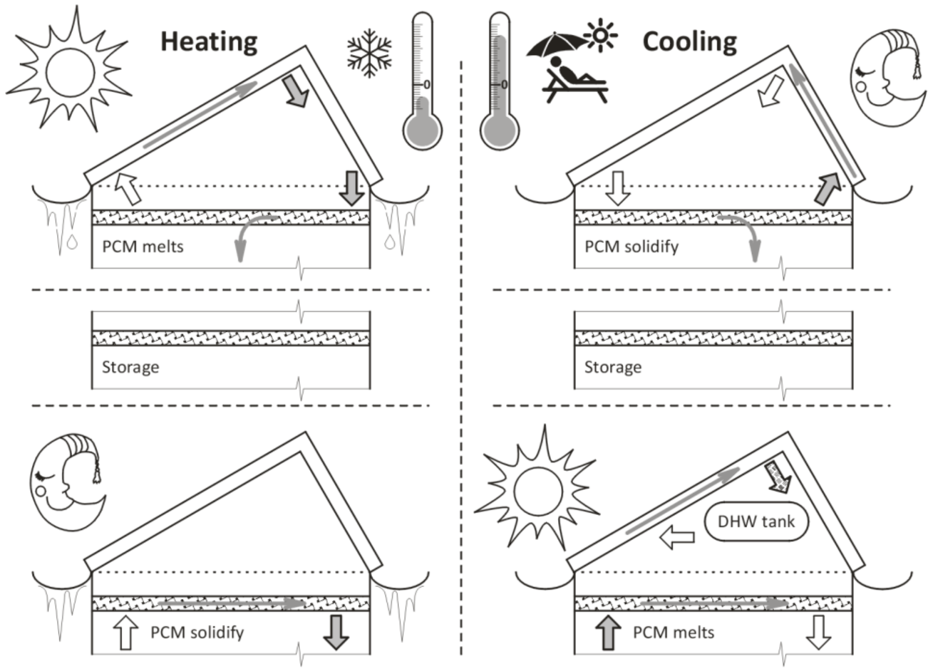


Figure 4. *Operation principle of the system with solar thermo-active roofing combined with large-area ceiling interior radiators during winter season – heating (left) and summer season – cooling (right).*

3 Thermo-active aluminium foam solar roofing

The accumulation of the latent heat in the ceilings to reduce energy demands for maintaining sufficient thermal comfort in the interiors of buildings brings a huge opportunity to adapt the requirements prescribed on the properties of the roofing. The heat surpluses from solar gains which are currently not utilized almost at all can be therefore very efficiently used to reduce the energy needs of residential as well as non-residential buildings.

Conventional active solar systems operate with forced liquid or air heat transfer fluid circulating through the external collector converting radiation into heat. The medium passing through the collector is heated, and heat is used for heating of interior, DHW or is transiently stored in suitable heat storage units such as e.g. water boilers or tanks, thermally activated building structures (concrete cores), etc. Conventional vacuum collectors with a liquid heat transfer medium can reach nearly the boiling point of the liquid medium. However, their major drawback is the relatively high cost, large mass, the necessity of placing on the sunny side of the building and the relatively short-term usability only when the sun shines. The collector installed on pitched south roof of the building is able in the region of Central Europe to provide an annual energy gain of approximately 525 kWh/(m^2·year), but paradoxically it is the most efficient when heat is not required, e.g., during hot sunny summer days. However, the building can accumulate throughout the year all necessary heat to provide sufficient thermal comfort and heat to DHW preparation in the case that the energy could be managed appropriately, stored for the short as well as the long term and used at the low-temperature gradient.

The surface of thermo-active roofing has to be adapted so that the heat exchange between the ambient air and the heat transfer fluid flowing through the pipes embedded inside the structure of the heat-conducting aluminium foam roofing is as efficient as possible. The use of various composite surface layers of aluminium based roofing tiles appears to be hugely beneficial in order to improve the resistance of roofing surface to weathering frost, intense solar radiation, summer heat, chemically polluted water vapour and to mechanical damage caused by adverse weather conditions (e.g., heavy rainfall, groats, etc.). The composites with bitumen-based sealant or thermosetting polymeric matrix reinforced by fine-grained basalt granules (**Fig. 5**) can be most preferably used for this purpose. However, as can be seen from **Fig. 6** a surface layer of roofing tiles can be reinforced by basalt granules fully embedded in an aluminium matrix. The abrasion and corrosion resistance of roofing tile surface is in this case significantly improved as the aluminium melt fills the free space between the reinforcing basalt granules directly during foaming of the aluminium foam core of the roofing tile.

Figure 5. *Aluminium foam samples (dimensions 105 x 75 x 6 mm) coated by bitumen-based matrix composite reinforced by fine-grained basalt granules (size of basalt granules: 2 – 4 mm – left, 1 – 2 mm – right).*

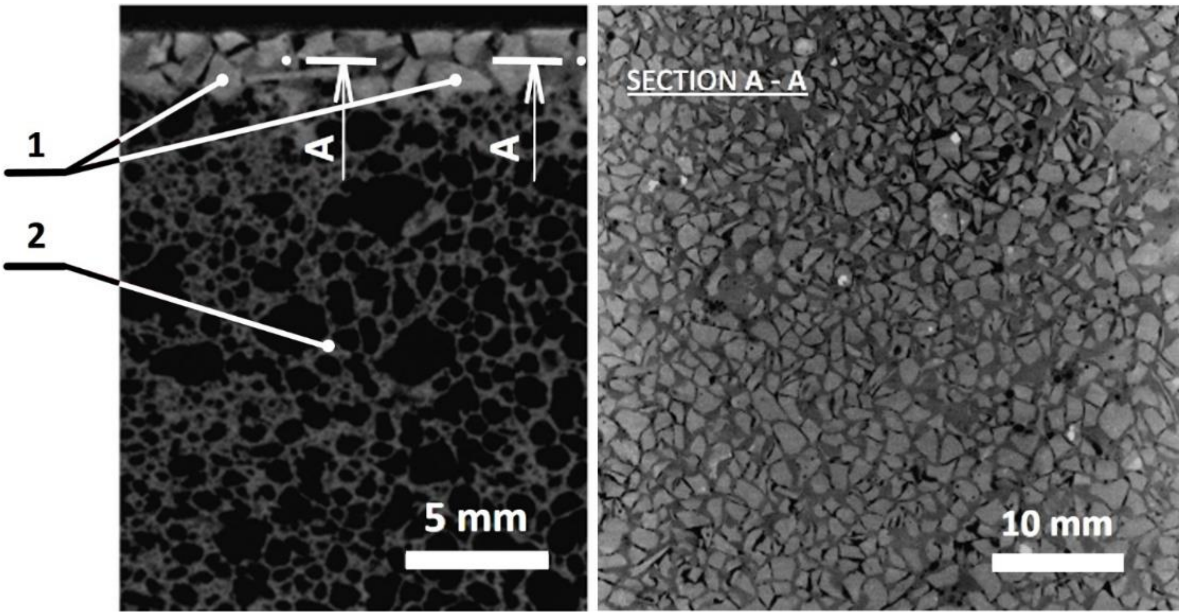


Figure 6. *The structure of aluminium foam-based roofing surface reinforced by fine-grained basalt granules integrated directly to the surface exposed to weather conditions: (a) cross-section perpendicular to the roofing surface, (b) longitudinal section through aluminium matrix formed by expansion of aluminium foam during casting – at a depth of 1 mm below the roofing surface (1 – basalt granules, 2 – aluminium foam).*

4 Conclusion

The ideas presented in this paper highlight the novel aluminium foam roofing system with integrated function of heat exchanger. This roofing can be designed to cover entire pitched roofs of the buildings and by this way to ensure energy efficient cooling/heating through interior ceilings impregnated by PCM. The roofing is able effectively to gain low potential heat from (or dissipate it to) the building surroundings. The aluminium foam ceilings are therefore able to store the large amount of heat to ensure the constant temperature for several hours without necessity to transport it to/from roofing. The aluminium foam heat exchangers are able not only to reduce the building and operation costs of future buildings but simultaneously to increase significantly the thermal comfort for their users. The principles analysed in this paper can be used in the building sector for designing of any structural part forming an outer building envelope with an integrated function of energy efficient heat exchanger.

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