Highly efficient storage of solar gains using aluminum foam heat exchangers

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Abstract

The energy efficiency of buildings is today mostly improved by upgrading the energy performance of the building envelope and facilities. However, huge energy reductions can also be achieved by a focus on the novel systems enabling to cover natural energy fall-outs resulting from generation much excess heat during the peak time (summer, day) which is currently almost not possible to use during periods of excessive energy consumption (winter, night). This main drawback of the solar energy can be very efficiently solved by storing and later evolving of accumulated heat from solar gains according to the day-night as well as the seasonal, i.e. summer-winter cycle. A novel solution described in this contribution is an opportunity to reduce significantly the energy demands for heating/cooling and heating of Domestic Hot Water (DHW). The costs for construction and operation of future buildings are considerable reduced if the heat comfort is maintained by aluminium foam heating/cooling ceiling heat exchangers that allow storage of the heat in the form of latent heat of phase transition of Phase Change Materials (PCMs) impregnated in the porous structure of aluminium foam for later use or, for removal of undesirable heat to the building surroundings during comparatively colder summer nights. Copyright © 2019 VBRI Press.

Keywords: Aluminium foam, phase change material, heat storage.

Introduction

The decreasing availability of fossil fuels combined with requirements to reduce carbon emissions in the world with exponential population growth reveals the necessity for more rational and efficient energy use. The European Union is urgently developing new solutions to improve energy efficiency and energy savings in the building sector by the 2010/31/EU Directive [**1**]. The implementation of novel solutions suitable for construction of new buildings as well as for the renovation of existing ones should be complex and industrially viable.

This contribution describes both the novel thermo-active cladding for pitched roofs and the interior ceiling radiating heating/cooling panels based on the findings from the results of technological experiments related to the production of aluminium foam heat exchangers. This innovative technical solution of roofing combined with large-area ceiling radiators performs the function of highly efficient heat exchangers between surroundings of the building and the heat transfer medium for heating and air conditioning of interiors as well as for DHW preparation required for the operation of future residential as well as non-residential buildings.

Storage of heat from solar gains

The heat storage using PCM is one of the most effective way of storing heat from solar gains. The extremely high energy storage density and the isothermal nature of the storage process are the most significant advantages. The technical solution 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. However, the most promising material enhancement can be achieved in the case that PCM is added to interior ceiling heat exchangers especially in order to increase the attic floor insulation. The high heat of fusion gives PCM the capability of storing and later releasing large amounts of heat. 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 [**2**].

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.

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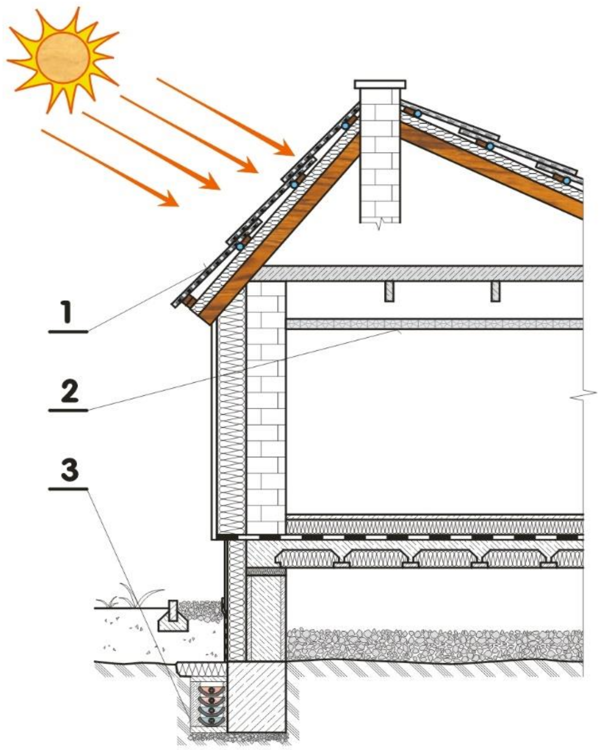

Fig. 1. Sketch of the building thermal storage system which includes: (1) thermo-active aluminium foam roofing performing efficient heat exchange between building surroundings and heat transfer medium for heating/cooling of interiors, DHW preparation, (2) aluminium foam interior heating/cooling ceiling panels impregnated by PCM, and (3) an underground collector incorporated to the underground base plate system of the building allowing the seasonal storage of summer heat surpluses for using them predominantly for heating of the interior and DHW during the winter season.

The edge of the building base plate is designed to have the capability for seasonal storage of summer heat surpluses that can be used for heating of interiors and DHW especially during winter season. Previous investigation has shown that excellently heat-conducting aluminium foam heat exchangers with vertical thermal stratification (impregnated by PCMs with various phase transition temperatures) can be a breakthrough solution allowing not only significantly to reduce operating costs of future buildings, but simultaneously also to minimize investment costs for their construction as well as to reduce embodied energy during primary production of building materials and the CO_2 footprint during the whole life cycle of the buildings.

Most existing studies have demonstrated that the dispersion of high thermal conductive nano-sized materials into the PCMs can enhance their thermal conductivity. However, the increase of the thermal conductivity using porous aluminum foam structure is much more efficient and at the same time also economically more advantageous solution compared to all previously known methods.

Maintaining of sufficient heat comfort

The heating and cooling of interiors play an important role with regard to the energy concepts of future buildings. As the energy loads for maintaining of sufficient heat comfort should be in buildings very small, there is a chance to develop totally new system solutions capable of minimizing operational cost and reduce energy consumption by combining the heating and cooling systems. During autumn and spring periods the temperature in south oriented part of building is, due to solar gains usually higher than cooling set point (ca 26 °C) while the operative temperature in the other parts of building is under heating set point (ca 20 °C). The installed water loop system might cool the south zone and simultaneously to heat the north zone, for obtaining the highest possible energy efficiency. Moreover, the above mentioned energy efficient concept, based on the storage of energy obtained through the aluminium foam roof or facade cladding is capable of absorbing the desired as well as take away the excess heat to the surroundings if necessary [**4**]. This allows effectively to distribute the heat by means of heating liquid medium/coolant to interior or dissipate the heat from interior to building surroundings using ceiling heat exchangers made of aluminium foam enabling additionally due to filling by PCM to store the energy required for heating/cooling for a period of at least several hours. An optimal thermal comfort of building interiors is in such a way achieved with minimal costs for energy consumption [**5**].

The highly porous metallic structures with high thermal conductivity containing pores interconnected by micro-cracks in the pore walls such as aluminium foams filled with PCM are the best solution for the construction of highly efficient heat exchangers suitable for storage of a large amount of latent heat. The aluminium foam cell walls with an excellent heat conductivity allow transferring heat uniformly to the large volume of PCM that fills the space of the pores. Paraffin waxes or fatty acids based PCM provides the possibility to store and to release large volumes of latent heat during their phase change from solid to the liquid stage and vice versa (~ 200 – 250 kJ/kg) at a nearly constant temperature. By cooling, this keeps the temperature of the heat exchanger at required level for a longer time without the need to dissipate heat into the building surroundings immediately. The charging of the PCM heat exchanger is possible also by the transport fluid with the temperature only slightly higher than the melting point of used PCM. If the ceiling heat exchanger (**Fig. 2**) 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 ceiling temperature at a required level until all PCM is melted.

This concept allows keeping the air in the room at required comfortable temperature for longer time (up to 4 days in winter) without need to transfer any heat into the room. The charging of ceiling aluminium foam radiators is thus necessary only once in a few days whereas the fluid with the temperature slightly higher than melting point of PCM is sufficient (~ 30 °C). During hot sunny days the ceiling radiators are able to accumulate excessive heat generated in the building

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interior into melting of PCM thus keeping the temperature at comfortable low level. This heat can be later (during the cold night) dissipated on the roof into building surrounding using pipe system embedded in ceiling radiators and directly interconnected with thermo-active aluminium foam roofing covering the entire pitched roof.

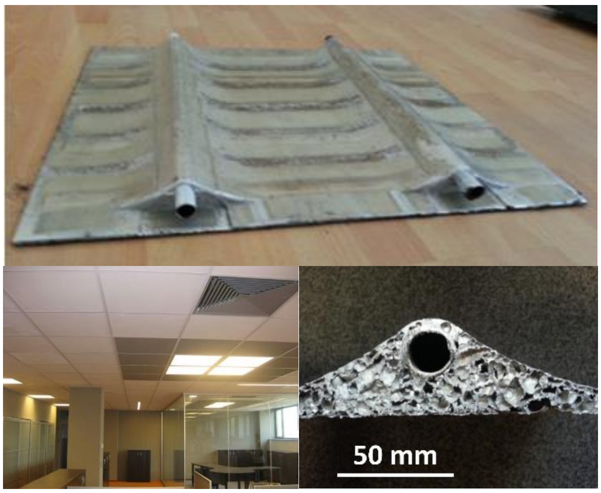

Fig. 2. Ceiling heating/cooling aluminium foam radiators in the open office space area 260 m^2 of company Hydro Extrusion Slovakia JSC in Žiar nad Hronom, Slovakia (bottom right – cross-section of aluminium foam structure with embedded tube distributing heat transfer fluid).

Roofing which reduce energy costs

The possibility to accumulate large amounts of latent heat in the ceiling panels in order 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 so as to efficiently use heat surpluses from solar gains that the current building industry does not use almost at all. The construction of roofing utilized benefits of an efficient heat storage system for novel buildings described in this contribution, allows not only the heat accumulated at a time when heat from solar gains is sufficient (during hot summer days) to use preferably for heating of DHW, seasonal heat accumulation underground in close proximity to the foundations of the building, but also very energy efficient heat dissipation of large amount of excess heat accumulated during whole day in the interior through the roofing to the building surroundings during cooler summer nights.

The main requirements for thermo-active roofing of pitched roofs (**Fig. 3**) which reduce the energy consumption of a building designed according to this concept can be summarized as follows:

- ✓ roofing must be sufficiently resistant to weathering, frost, intense solar radiation, summer heat, chemicals presented in the air, chemically polluted water vapor and to mechanical damage caused by adverse weather conditions (e.g. heavy rainfall, groats, etc.),
- ✓ roofing must provide considerable heat gains even when the temperature around the building is low, but the sunshine on the roof is sufficiently intense,
- ✓ the amount of the heat accumulated by roofing during hot summer days is low enough to dissipate it to the building surroundings during summer nights as efficiently as possible together with the heat of the liquid heat transfer medium flowing through the pipelines integrated into the structure of aluminium foam from which the roofing is made,
- ✓ the manufacturing cost of a thermo-active roofing for pitched roofs of buildings must be only slightly higher compared with the manufacturing cost of classic roofing used in the current building which fulfills together with an additional heat insulation layer in particular only the functions of thermal insulation of the roof and the protection against the penetration of rainwater and water vapor into the interior,
- ✓ thermo-active roofing must be architecturally designed so that it is the part of the roof without being possible to recognize at first sight the places from which the heat of solar gains is gained from the rest of the roof.

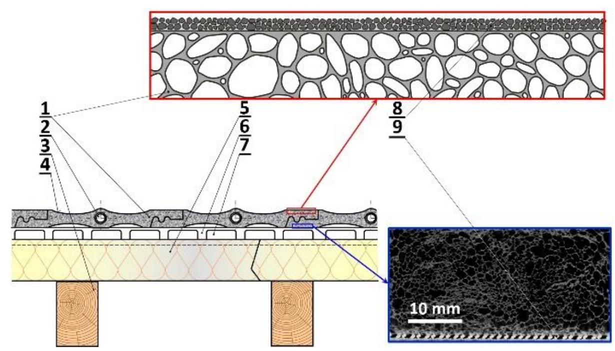

Fig. 3. The design of thermo-active ultra-light aluminium foam solar roofing appropriate for subtropical climatic conditions shown in the cross-section perpendicular to the direction of the pitched roof rafters: 1 – roofing made of aluminium alloy foam, 2 – corrugated tubes made of corrosion-resistant chromium-nickel austenitic steel used for distribution of liquid heat-transfer fluid, 3 – wooden rafters (supporting structure of pitched roof), 4 – aluminium foam roofing surface ensuring a high solar heat absorptivity, 5 – the thermal insulation layer above the rafters of pitched roof ensuring its waterproofing and creating a barrier to water vapor, 6 – rails of galvanized steel integrated into the insulation layer above rafters, 7 – venting air gap between the top layer of aluminium foam roofing and waterproof insulation with vapor barrier above the rafters of pitched roof, 8 – coating of polymer-based matrix composite containing bitumen roofing sealant reinforced by basalt granules, protecting surface layer of aluminium foam casting against mechanical damage caused by adverse weather conditions and providing highly efficient heat transfer, 9 – expanded stainless steel sheet reinforcing tensile loaded surface of thermo-active ultralight aluminium foam roofing.

The roofing surface has to be adapted so that the heat exchange between the ambient air and the heat transfer fluid flowing through the corrugated stainless steel pipes embedded inside the structure of the heat conducting aluminum foam roofing is as efficient as possible. The use of various composite systems with an aluminum alloy matrix which is able to impregnate the free space between particles (ultra-fine basalt granules, aluminium scrap granules, crushed natural stones, crushed recycled foam glass, any other metallic or ceramic particles, etc.)

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reinforcing the surface layer during foaming of roofing tiles, appears to be greatly beneficial for this purpose (**Fig. 4**). From a technological point of view, however, it is easier and substantially cheaper to cover the surface layer of as-casted aluminium foam roofing tiles by composite coatings with a thermosetting polymeric matrix (e.g. epoxy resin, polyimide, polyurethane, etc.) or most preferably by a layer of bitumen-based sealant reinforced by fine-grained basalt granules (**Fig. 5**) appropriately corresponding to the assumed weather conditions in the regions for which the roofing tiles are intended.

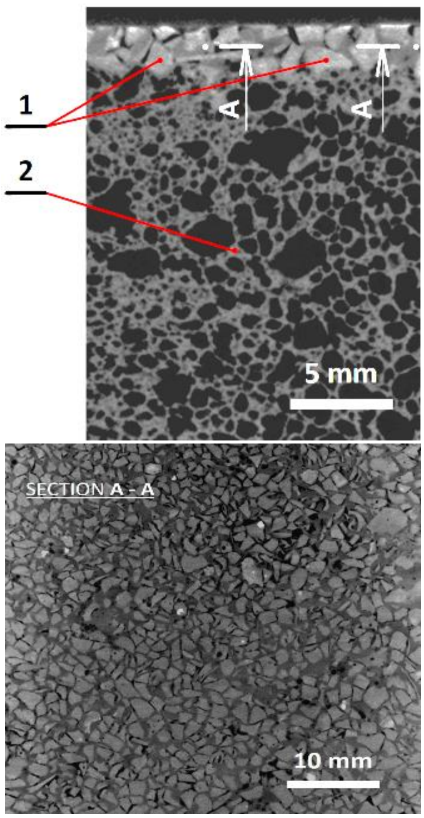

Fig. 4. The structure of aluminium foam-based roofing surface reinforced by fine-grained basalt granules integrated directly to the surface layer exposed to weather conditions: (a) cross-section perpendicular to the roofing surface, (b) longitudinal section through aluminum matrix formed by expansion of aluminium foam during casting – at a depth of 1 mm below the roofing surface.
(1 – basalt granules, 2 – aluminum foam).

The variability of different surfaces opens up the possibility to accomplish appropriate aesthetic appearance of the coating layer, its color fastness, and simultaneously to maintain high mechanical and chemical resistance to atmospheric agents in a wide range of different climatic zones. In order to achieve simultaneously both the high stiffness and the ultra-lightness of the roofing, it is very advantageous to reinforce the bottom roofing surface by perforated expanded stainless steel sheet (as shown in the **Fig. 3**) which significantly improves the bending stiffness of the roofing loaded not only by its own weight but during cold winter season also by gravitational force of the excessively thick snow cover [**5**].

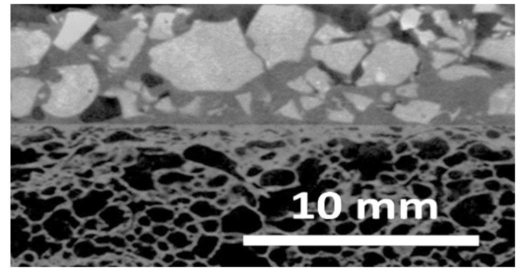

Fig. 5. The detail of aluminium foam roofing surface layer coated by a polymer-based matrix composite coating containing bitumen and reinforced by basalt granules.

Conclusion

This contribution highlights the advantages of innovative ultralight aluminium foam heat exchangers with integrated corrugated stainless steel pipes for the distribution of the heat transfer fluid. These novel heat exchangers can be designed to cover entire pitched roofs of the buildings as well as to ensure very energy efficient cooling/heating through interior ceilings. The roofing is able very effectively to gain low potential heat from (or dissipate it to) the building surroundings. Ceiling aluminium foam panels impregnated by PCM are able even to store the large amount of heat in order to ensure the constant temperature for several hours without necessity to transport it to/from roofing during this time. 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 heat comfort for their users.

However, the principles analyzed in this paper can generally 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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Author's contributions

Conceived the plan: FS, JJ; Performed the expeirments: PT; Wrote the paper: JJ (JJ, SF, PT are the initials of authors). Authors have no competing financial interests.

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