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ALUMINUM FOAM HEAT EXCHANGERS FOR FUTURE ZERO-ENERGY BUILDINGS

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Abstract: Zero-energy building energy demands need to be secured to a large extent by renewable sources available in the building or its proximity. The design of the building has to be drafted with a targeted orientation of the glazed windows, exclusion of thermal bridges, controlled ventilation and heat recovery in order to use heat gains efficiently. The energy efficiency of residential buildings is today mostly improved by upgrading the energy performance of the building envelope and facilities. However, huge energy reductions can be achieved also by a focus on new innovative systems enabling to cover natural solar energy fall-outs resulting from generation much excess heat during the peak time (summer, day) which is almost not possible to use during periods of excessive energy consumption (winter, night). This drawback can be very efficiently solved by storing and later evolving of accumulated heat according to the day-night as well as the seasonal, i.e. summer-winter cycle.

This contribution deals with the system of thermo-active aluminium foam cladding for pitched roofs of the buildings covered by innovative coating sufficiently resistant to weathering, frost, intense solar radiation, summer heat, chemicals presented in the air, chemically polluted water vapour and to mechanical damage caused by adverse weather conditions (e.g. heavy rainfall, groats, etc.). The objective is to achieve excellent mechanical and physical properties related to highly energy efficient solar radiation and heat harvesting as well as the ability to dissipate an undesirable heat accumulated in the building interior to the surroundings of building via the roof surface during colder summer nights. This smart roofing system can be easily supplemented with the system of interior aluminium foam heating/cooling ceiling heat exchangers that allow short-term storage of the heat for at least several hours in the form of latent heat of phase transition of <u>P</u>hase <u>C</u>hange <u>M</u>aterial (PCM) impregnated in the porous structure of aluminium foam. This heat can later radiate to the interior or can be removed from panels and dissipated to the building surroundings.

This novel concept allows expanding the use of aluminium foam with a reinforced surface in the building industry thanks to technological options related to the achievement of its excellent surface quality suitable for mechanical load, corrosion, chemical environment, strong solar radiation, large temperature fluctuations between winter and summer season, etc.

Keywords: aluminium foam, heat exchangers, solar radiation, heat storage, phase change materials, zero-energy buildings

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1 Introduction

As the world population continues to grow and the amount of fossil fuels begin to diminish, it will be impossible, in near future, to provide the amount of energy demanded by the world by only using fossil fuels. Even though that there are plenty of ways to obtain renewable energy, and many techniques are already being used, the energy free available in nature is unfortunately not fully exploited. The decreasing availability of fossil fuel in the nearest future combined with requirements to reduce carbon emissions reveals the necessity for more rational and efficient energy use. The European Union, therefore, is urgently developing new solutions to improve energy efficiency and energy savings in the building sector by the 2010/31/EU Directive [13]. The implementation of new technical solutions suitable for construction of new buildings as well as for the restoration of existing ones should be complex, and their production should be industrially viable [9].

According to Europe 2020 strategy for smart, sustainable and inclusive growth to achieve “20-20-20” goal, which was set by EU leaders in 2007, the EU aims to reduce its greenhouse gas emissions by at least 20 %, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of at least 20 % in comparison with the levels in 1990. Reducing heat losses, optimizing energy system and implementing the legislation of EU to the necessity to build exclusively **n**early **Z**ero-**E**nergy **B**uilding**s** (nZEBs), are the activities which can help to gain this goal in the whole Europe (nZEB is a building that has a very high energy performance and in which its low amount of energy required is covered by energy from renewable sources mainly obtained on-site or in its neighbourhood). The thorough optimization of the energy system is therefore mandatory in order to achieve nZEBs targets based on the requirement that total energy consumption of every new building built after 2020 will have to be roughly equal to the amount of renewable energy obtained on-site [14]. The European **E**nergy **P**erformance of **B**uildings **D**irective (EPBD) requires that all new buildings after 31st December 2020 and all new buildings acquired by public bodies even after 31st December 2018 to be nZEBs. This means that every building completed after these dates must achieve this standard. A certificate of compliance with EPBD regulations could not be signed on 1st January 2021 and later, unless it meets the nZEB standard, and the building could not be in that case occupied.

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 **D**omestic **H**ot **W**ater (DHW) preparation required for the operation of residential and non-residential buildings.

2 Energy efficient heating and cooling of nZEBs

In any case, especially the heating and cooling of interiors play an important role within energy systems of current buildings. As the heating and cooling loads are in nZEBs very small, there is a chance to develop totally new system solutions capable of minimizing operational

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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 efficiently. Moreover, the energy efficient concept of nZEBs presented in [1], 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. 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 [3].

2.1 Latent heat storage of solar gains in the built environment

Thermal insulation of the building has been recently 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 [4]. The cost analysis demonstrates that the conventional thermal insulation, due to relatively high cost and diminishing energy benefits, cannot be considered as the only system to achieve improved thermal performance in highly insulated buildings. That is why several alternative systems have been developed recently to reduce building thermal loads, e.g. cool roof coatings for reducing exterior solar radiation, actively ventilated attics or various inclined air spaces under roofing, increased thermal mass of building structure (by conventional building materials or PCM), radiant barriers and foil-faced insulations, air spaces and naturally ventilated cavities, etc.

The heat storage system using PCM is one of the most effective way of storing heat from solar gains. The main advantages are the extremely high energy storage density as well as the isothermal nature of the storage process. This system is based simply on permanently alternating processes of heat absorption and release when the storage material undergoes a phase change from solid to liquid or 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].

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2.2 Energy efficient system for heating/cooling of future nZEBs

EU sets ambitious targets for increasing the efficiency of buildings, deployment of renewable energy sources and reduction of CO_2 emissions in short and medium term periods. State-of-the-art for new buildings throughout Europe can be currently expressed by specific non-renewable primary energy demand 160 to 200 kWh/(m²·a). Legislation requirements for all new nZEBs after 2020 in Europe differs from 30 kWh/(m²·a) to quite high values 120 kWh/(m²·a) in Czech Republic, with average between 40 and 50 kWh/(m²·a) in oceanic zone. On the other side the recommendation of EU 2016/1318 has expressed the vision of much strict values about 15 to 30 kWh/(m²·a) as a guideline.

The most advanced buildings that are built in Europe today are passive houses with primary energy about 60 kWh/(m²·a). They use extremely expensive heat pumps for heat delivery and the roofs are covered with PV panels. Significant portion of the obtained renewable electricity in summer is fed into grid without reasonable use of it for space heating and DHW preparation in the house. While for family houses such solution can apparently achieve the zero balance of energy although at an incredibly high manufacturing costs, multi-storey family houses and office buildings do not have enough roof area for PV panels. Moreover, volatility of electricity from PV leads to grid stability problems. Most of EU countries have their own politics for subsidizing and supporting such solutions with different legislation. Reward from such politics is, nevertheless, questionable.

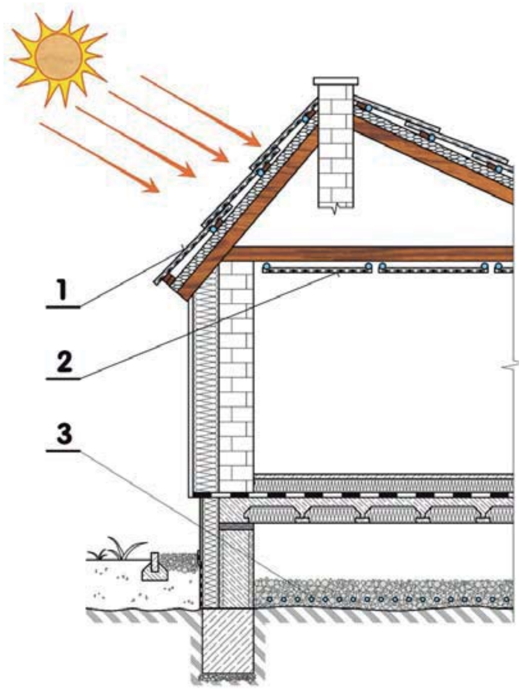

Figure 1. *Sketch of nZEB which includes:*
1 – thermo-active aluminium foam roofing performing efficient heat exchange between building surroundings and heat transfer medium for heating/cooling of interiors, DHW preparation and seasonal heat storage,
2 – aluminium foam interior heating/cooling ceiling panels impregnated by PCM,
3 – an underground collector situated under the base plate 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.

Application of following new technical solutions, therefore, represents a great opportunity to reduce significantly the energy demands for heating/cooling, preparation of DHW, leading to reduction of costs for construction and operation of future buildings (Fig. 1):

- the heat comfort of the interior is maintained during the whole year round by stabilization of the temperature using the system of aluminium foam heating/cooling ceiling heat exchangers (Fig. 2) that allow short term storage of the heat for at least

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several hours in the form of latent heat of phase transformation of PCMs impregnated in the porous structure of aluminium foam for later use or, for removal of undesirable heat to the building surroundings (at the time when it is possible, e.g. during comparatively colder nights),

- the base plate of the building 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,
- the thermo-active roofing which can not only catch the heat from the solar gains as well as from building surroundings and use it for heating of the interior and DHW but also take away an undesirable heat from the interior to the surroundings during cooler summer nights.

2.3 Aluminium foam heating/cooling ceiling panels

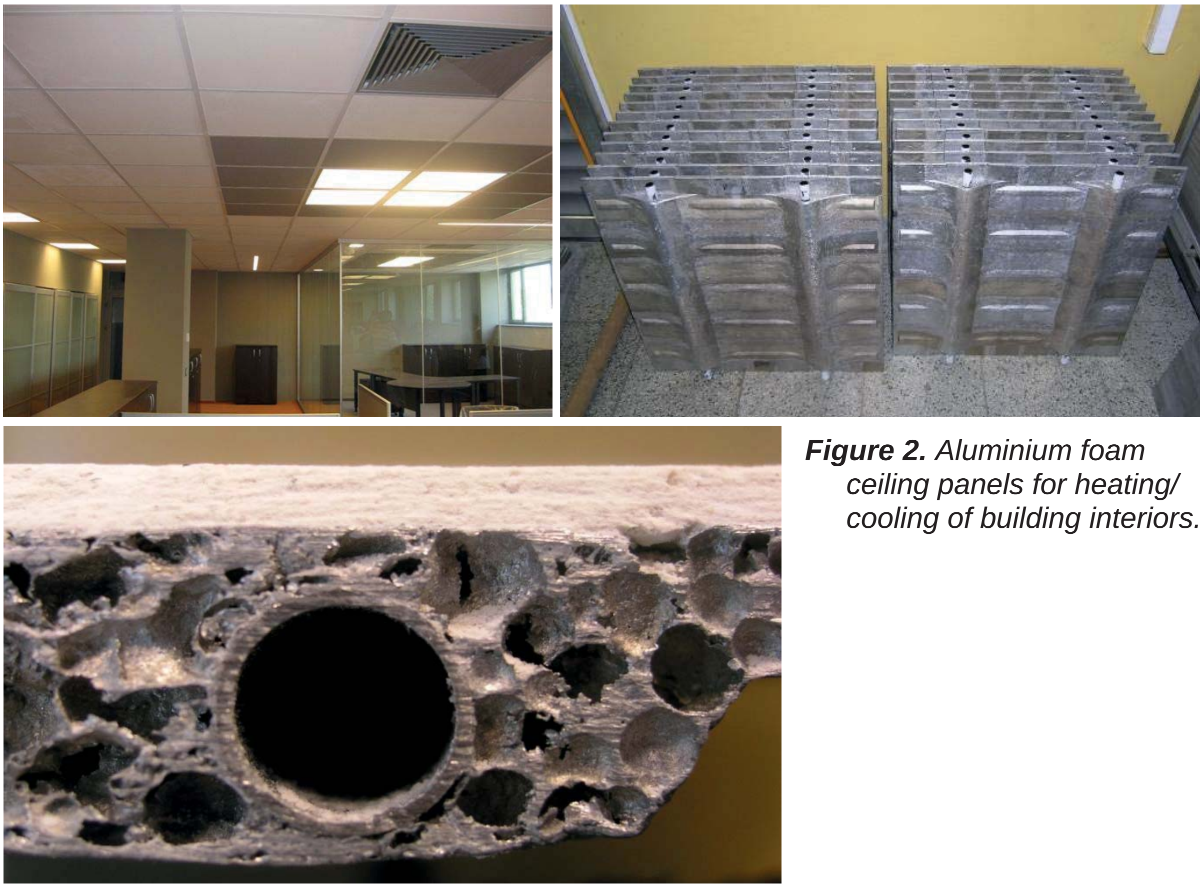

Figure 2. *Aluminium foam ceiling panels for heating/ cooling of building interiors.*

The highly porous metallic structures with high thermal conductivity and interconnected pores (with 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 based PCM provides 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 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

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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 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.

3 Roofing of pitched roofs reducing energy consumption of nZEBs

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 nZEBs presented 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 under the base plate 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 reducing the energy consumption of a building constructed 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 roof covering 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.

The structural design of innovative thermo-active aluminium foam roofing capable of efficient recovering the heat from solar gains also during spring, autumn, and sometimes even winter sunny days is shown in Fig. 3. When the sun shines intensively during the sunny day through

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the translucent glass sheet creating the surface layer of the south-facing pitched roof, it heats very intensively not only the radiation-absorbent surface layer of aluminium foam roofing but also the whole volume of the air enclosed in the space under the glass cover of the roofing. Moreover, the huge advantage of this roofing design is that the surface between the individual glass sheets can be covered by polycrystalline photovoltaic (PV) cells. This modification changes the roof to hybrid PV/solar thermo-active roofing suitable especially for covering the southern pitched roofs of nZEBs in cold and mild climatic regions.

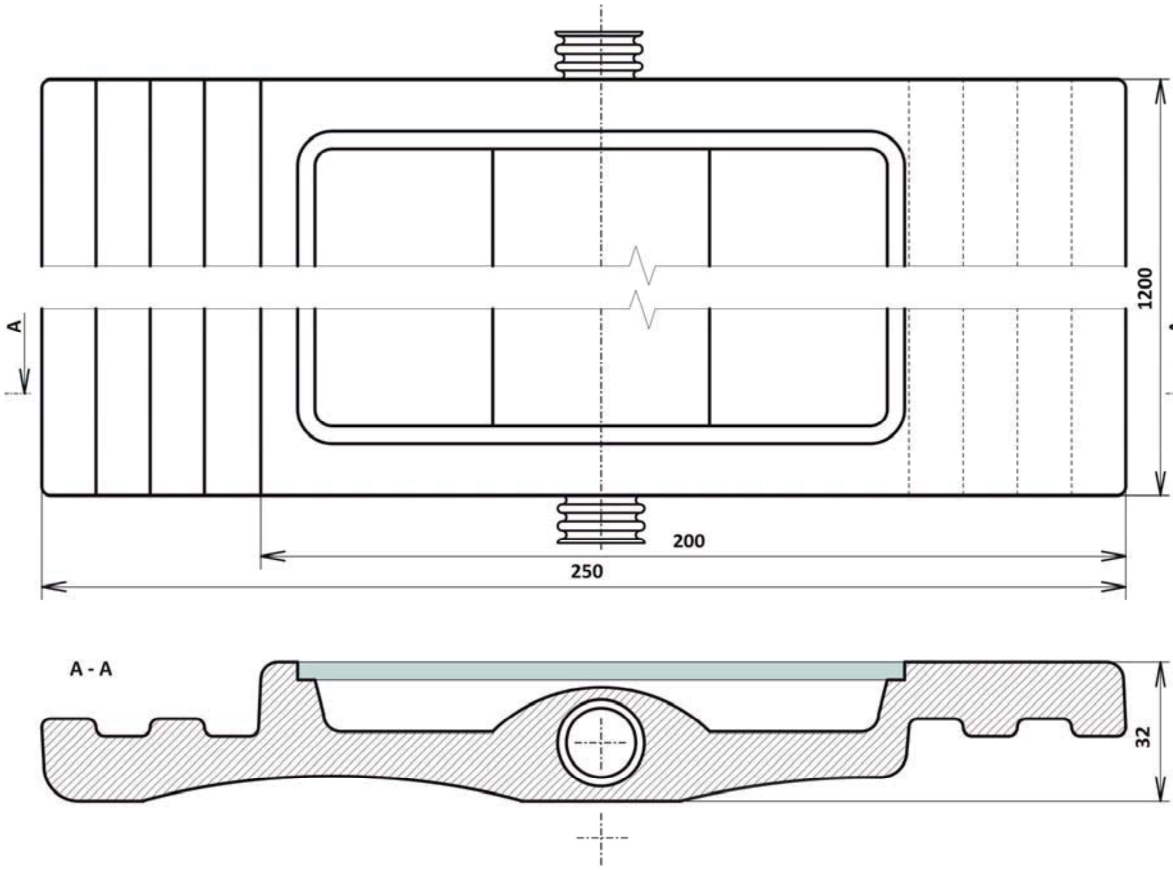

Figure 3. *The thermo-active aluminium foam roofing appropriate for moderate climatic zone, which is able to efficiently recover the heat from solar gains even during colder sunny days, when the sun shines through the translucent glass panel, heats both the absorption surface layer of aluminium foam roofing and the air enclosed in the space under the glass cover.*

In regions where the sun is intensively shining on the surface of the southern pitched roofs for almost the whole year long, it is much more advantageous to use roofing design as shown in Fig. 4. The main advantage of this roofing is that the excess heat accumulated in the interior can be intensively removed during each cooler night by the liquid heat transfer medium and dispersed in the surroundings of the building. The roofing surface has to be adapted for these reasons so that the heat exchange between the ambient air and the heat transfer fluid flowing in the tubes embedded in the structure of the heat-conducting aluminium foam roofing is as intense as possible. The covering of the roofing by various composite systems based on thermosetting polymer matrix (e.g. epoxy resins, graphite filled polyimide, polyurethane, etc.) composites reinforced by particles (metallic or ceramic particles, basalt granules, aluminium scrap granules, crushed natural stones, glass foam splinters, etc.) seems to be very beneficial as the roofing surface must be sufficiently resistant also to any mechanical

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damage caused by heavy rainfall, groats, and any other adverse weather conditions. 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 for the different climatic zones for which this roofing is intended. To achieve both the high stiffness and the ultra-lightness of the roofing, it is very advantageous to reinforce the bottom roofing surface with perforated expanded stainless steel sheet which significantly improves the bending stiffness of the roof loaded by its weight or by snow cover during cold winter season (Fig. 5).

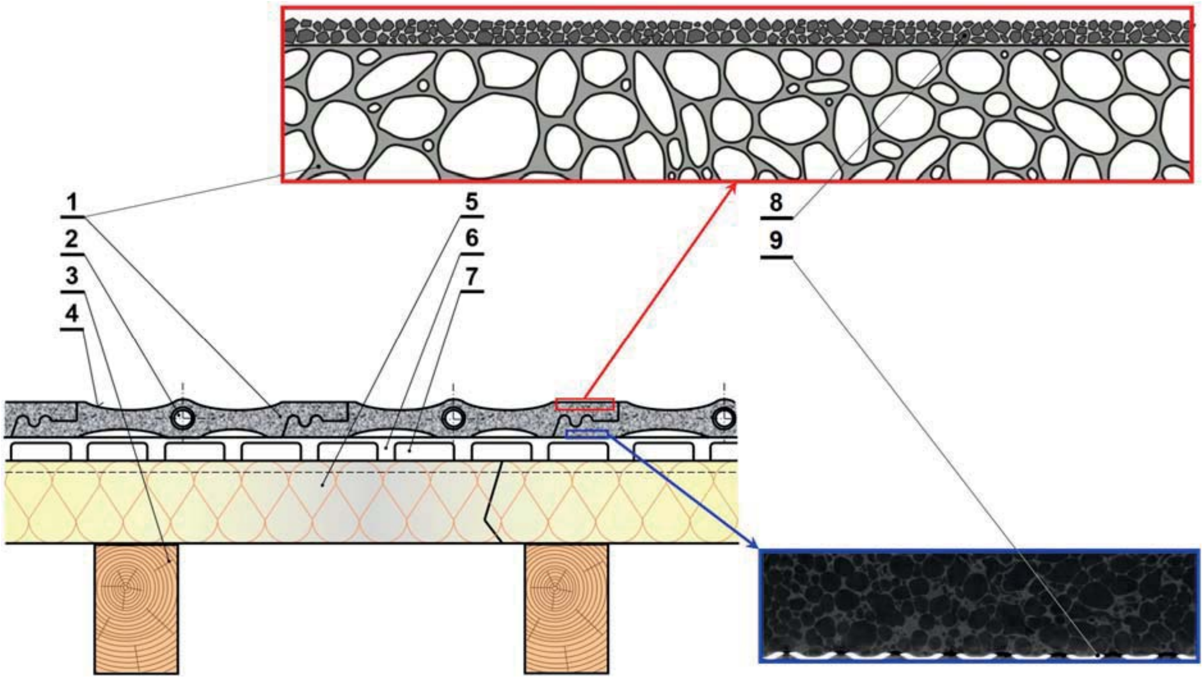

Figure 4. *The design of thermo-active ultra-light aluminium foam solar roofing appropriate for subtropical climatic conditions shown in the cross-section perpendicular to the direction of the pitched roof rafters.*

1 – roofing components 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 – supporting structure of pitched roof made from wooden rafters,

4 – surface layer of aluminium foam roofing 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 vapour,

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 vapour barrier above the rafters of pitched roof,

8 – coating of polymer matrix composite reinforced with 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 solar aluminium foam roofing.

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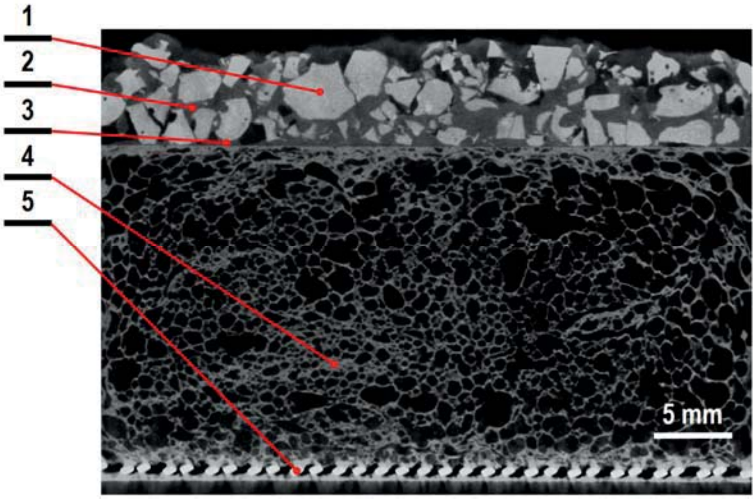

Figure 5. *The cross-sectional area of ultralight aluminium foam roofing obtained by X-ray tomography observation of testing sample:*
1 – basalt granules,
2 – polymer-based roofing sealant containing bitumen,
3 – epoxy-based adhesive,
4 – aluminium foam core of the roofing,
5 – expanded stainless steel sheet reinforcing tensile loaded surface of the roofing.

4 Conclusions

This contribution highlights the possibility of using aluminium foam for both the novel roofing as well as the smart system of aluminium foam ceiling for interior heating/cooling. The roofing is able to effectively gain low potential heat from, or dissipate it to the surroundings. The transport fluid transfers heat to or from the building interior ceiling. Ceiling Al-foam panels impregnated by PCM can store the heat in form of latent heat to secure constant temperature for several hours without necessity to transport it to/from roofing. The roofing is designed to cover entire pitched roofs of future nZEBs. 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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References

[1] J. Jerz, F. Simančík, J. Šebek, J. Kováčik, J. Španielka, Application of aluminium foam for heat exchangers on building facades and interior ceilings. In: *6th International Conference Mechanical Technologies and Structural Materials 2016*. – Split: Croatian Society for Mechanical Technologies (2016) 61-66. ISSN 1847-7917.

[2] J. Jerz, P. Tobolka, V. Michenka, T. Dvorák, Heat storage in future zero-energy buildings. In: *International Journal of Innovative Research in Science, Engineering and Technology* (2015), vol. 4, iss. 8, 6722-6728. ISSN 2319-8753 (http://www.ijirset.com/upload/2015/august/3_Heat.pdf).

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

[3] A. Sharma, V. V. Tyagi, C. R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications. In: *Renewable and Sustainable Energy Reviews 13* (2009), 318-345.

[4] J. Kośny, A. Fallahi, N. Shukla, E. Kossecka, R. Ahbari, Thermal load mitigation and passive cooling in residential attics containing PCM-enhanced insulations. In: *Solar Energy 108* (2014), 164-177.

[5] T. Kodo, T. Ibamoto, Research on using of PCM for ceiling board, IEA ECESIA, Annex 17, 3rd workshop, Tokio, Japan, October 1-2, 2002.

[6] M. Kenisarin and K. Mahkamov, Solar energy storage using phase change materials. In: *Renewable and Sustainable Energy Reviews 11* (2007), 1913-1965.

[7] T. F. Whiffen and S. B. Riffat, A review of PCM Technology for thermal energy storage in the build environment: Part I. In: *International Journal of Low-Carbon Technologies* (2012), 1-12.

[8] T. F. Whiffen and S. B. Riffat, A review of PCM Technology for thermal energy storage in the build environment: Part II. In: *International Journal of Low-Carbon Technologies 8* (2013), 159-164.

[9] J. Jerz, F. Simančík, J. Kováčik, J. Španielka, Aluminium foam for thermo-active pitched roofs of nearly zero-energy buildings. In: *7th International Conference Mechanical Technologies and Structural Materials 2017*. – Split: Croatian Society for Mechanical Technologies (2017), 49-58. ISSN 1847-7917.

[10] J. Kováčik, Ľ. Orovčík, J. Jerz, High-temperature compression of closed cell aluminium foams. In: *Kovove Mater. 54* (2016), 429-440.

[11] Ľ. Orovčík, M. Nosko, J. Kováčik, T. Dvorák, M. Štěpánek, F. Simančík, Effect of chemical composition on the pore structure and heat treatment on the deformation of PM aluminium foam 6061 and 7075. In: *Kovove Mater. 54* (2016), 463-470.

[12] J. Kováčik, J. Španielka, T. Dvorák, P. Oslanec Jr., J. Jerz, Closed Cell Aluminium Foams with Phase Change Material, In: *Metallic foams 1* (2017), 42-48.

[13] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

[14] Jerz, J. – Simančík, F. and Orovčík, Ľ. Advanced solution for energy storage in net zero-energy buildings. In: *Mechanical Technologies and Structural Materials 2014.* – Split: Croatian Society for Mechanical Technologies, 2014, pp. 47-54. ISSN 1847-7917.