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LOW ENERGY BUILDINGS: MULTIFUNCTIONAL STRATEGIES AND SOLUTIONS

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Abstract. EU directive on the Energy Performance of Buildings states that by 2020 new construction buildings must be Nearly Zero Energy Buildings (NZEB). These are common goals for the EU, however, it creates a challenge for northern countries where climate requests higher energy efficiency materials and respectively the costs. NZEB achieves low energy consumption, solar gains, and reduces heat losses, therefore, has very high energy performance. Passive solar heat gains and its utilization is widely used to reduce energy consumption, especially, through windows in the South façade. Research and experiments of solar simulation models deliver results that allow evaluating potential gains from solar thermal façade systems; in addition, it reduces heat losses for buildings to reach the requirements of NZEB. The goal of the research is to assess latent and sensible energy storage in building envelopes using phase change material (PCM) as a heat accumulator and Fresnel lens as a solar concentrator. A new passive solar thermal façade system model is designed that consists of a Fresnel lens as solar concentrator, PCM as heat accumulator, and copper as heat transfer enhancer to accumulate thermal energy received from the Sun or solar simulator. This research is an example that biology can be integrated with architecture via biomimicry principles and nature has countless multi-functional, complex, and highly responsive mechanisms, strategies, and solutions. Biomimicry in architecture remedies existing errors of efficient system design and products, by taking into the fact that outer shells in nature face the same weather conditions and have the same functions and tasks as reducing heat loss via thermal envelope (insulation, metabolism, hibernation), storing and generating energy, avoiding indoor from overheating.

Keywords: renewable energy; solar energy; biomimicry for façade systems; phase change materials; multifunctional strategies, solutions

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Additional disciplines are physics; ecology and environment; construction engineering; transport engineering; environmental engineering; and energetics.

1. Introduction

During the last decades, low-energy building design has been separated into two alternative strategies: active technologies and passive design. The first approach aims to improve sustainability in the building environment by integrating innovative technical devices most commonly used for decentralized energy systems, energy supply generation from renewable energy sources, or resource conversion at greater efficiency. Passive design is associated with building construction design and building shape. Passive design aims to capture, store, and evenly distribute renewable energy sources mainly wind and solar energy. It also replaces non-renewable energy for indoor heating, conditioning, and lighting. Successful building design is becoming an increasingly complex task, due to a growing demand to satisfy more ambitious environmental, societal, and economic performance requirements. The application of climate adaptive building shell (CABS) has recently been put forward as a promising alternative within this strive for higher levels of sustainability in the built environment. Compared to conventional façades, CABS offer potential opportunities for energy savings as well as improvement of indoor environmental quality. By combining the complementary beneficial aspects of both active and passive building technologies into the building envelope, CABS can draw upon the concepts of adaptability, multi-ability, and evaluability (Aelenei et al. 2016). The energy-efficient external building envelope is key for cold climates to reach NZEB requirements by 2020. The strategy to reach NZEB requirements can involve utilizing low-energy geothermal, solar, and other renewable energy resources to provide heating and cooling for the indoor environment. Full or partial usage of renewables would not only create certain independence from energy suppliers but also cut costs that occur during the heating season in cold climates where the average heating season is 200 days (Ručevskis et al. 2020).

Building shell is a boundary between indoor and outdoor environments and is subject to various conditions. For example, weather changes throughout the day and season, the same applies to indoor environments based on building type, occupancy, and comfort requirements. Static buildings have no capability to act to any changes. Therefore, a shift to CABS would create an opportunity to transform from a manufactured indoor climate to a mediated one. By integrating the CABS principle and combining passive design with active technology, CABS reduces energy consumption, while improving indoor air quality (IAQ), and thermal and visual comfort levels (Aelenei et al. 2016). The switch from static to adaptive building facades is a complex engineering process during the construction and operation phases. Building design nowadays not only means monumental building creation but is an assembly of a complex model that has a certain function. It is not efficient enough to add adaptive features to an existing system, CABS should create a new design to meet the needs and use as much free energy and light as possible. It happens that separate building envelope systems or elements are integrated together to meet a requirement. CABS also should find a balance between various opposites, for example, daylight and glare, overheating heat gains, proper air circulation, and draught (Hayes et al. 2019), (Kannan and Vakeesan 2016).

CABS is only one label of a concept, several synonyms of the term ‘adaptive’ exist as active, advanced, dynamic, intelligent, interactive, kinetic, responsive, smart, etc. Yet the terms have slightly different meanings, they are interchangeably used in the literature. Every CABS influences multi-physical behavior by blocking, filtering, converting, collecting, storing, or passing via various energy fields. To characterize CABS differences and similarities, four domains are distinguished in Table 1.

Table 1. Physical domains description of CABS (Aelenei et al. 2016).

Thermal	Adaptation causes changes in the energy balance of the building via conduction, convection, radiation, and storage of thermal energy
Optical	The adaptive behavior influences occupants’ visual perception via changes in the transparent surfaces of the building shell
Air-flow	A flow of air across the boundary of the façade is present, and adaptive behavior is influenced by the direction and speed of the wind
Electrical	Building-integrated energy generation takes place on the façade level, or electricity consumption is an essential part of the adaptation mechanism

Strong coupling exists between thermal and optical domains. Solar radiation is an environmental factor with high variability and direct consequences for thermal and visual comfort, in addition to daily, monthly, and seasonal weather-related fluctuations. Efficient CABS should be able to perform on these solar radiation fluctuation responses, prevent overheating and glare, and sustain efficient energy operation within the building. CABS involves innovative technology integration that results in challenging and costly projects with relatively high risk. Project creators have the tendency to have more conservative attitudes toward implementing new technology because of the risks that involve disproportionate payback times caused by higher investment, maintenance, or failure costs. Adaptive building envelopes improve building energy efficiency and economic matters because of their ability to change behavior in real-time based on various parameters of materials, components, and systems located indoors and outdoors (Aelenei et al. 2016).

As façade is main parameter that impacts building energy performance, elements of façade should be designed to ensure required flexibility of a building in terms of energy flow and thermal comfort. Existing standards determine that building envelopes act as energy-efficient mechanical systems that can react to non-continuous, non-predictable, and changing external conditions and temperatures. In other words, the façade needs to change and adapt to the environment to fulfill its function and be efficient enough. For this reason, including adaptive façades in building construction plan have the potential to increasingly reduce energy use of building and CO_2 emissions. In the meantime, it ensures thermal and visual comfort. Different adaptive façade concepts have been presented and demand increase has been forecasted for emerging and innovative solutions within the next decade. Adaptive façades consist of multifunctional highly adaptive systems where the physical separator between indoor and outdoor environment (building envelope) can change its functions, features, and behavior over time in response to transient performance requirements and boundary conditions, aimed to improve overall building performance [62]. According to the definition, multi-functional adaptive facades ensure the response to changes indoors and outdoors to improve envelope function of heat, air, IAQ, water vapor flow, rain penetration, solar radiation, noise, fire, strength, stability, and aesthetics. The Façade ensures controlled insulation and thermal mass, radiant heat exchange, ventilation, energy harvesting, daylighting, solar shading, and humidity control. For a building to meet NZEB requirements and be integrated into the smart city concept this type of facade is crucial. Since interest in the design and development of adaptive building materials and dynamic façade systems has risen, they have been classified by different concepts with common features and properties. Review papers published different categories of four adaptive façade concepts adaptive glazing, phase change material (PCM), solar façades, and daylighting systems (Moss et al. 2018). It is vital to characterize and determine adaptive façades purpose, response function, components, degree of adaptability, and other factors as in Fig. 1. before façade material performance evaluation and testing.

The authors of the study analyzed a representative sample of 130 buildings most of which were in warm and maritime temperate climates. Considered external factors were solar radiation, outdoor temperature, wind, humidity, precipitation, and noise. Authors highlighted that a great challenge for adaptive façade is to do both – respond to external factors and ensure a comfortable and stable internal environment that includes thermal comfort, energy performance, indoor air quality, acoustic performance, visual performance, and durability. It was found that the most common external factors are solar radiation coupled with outdoor temperature. These factors have the most direct influence on thermal and visual comfort and on the energy performance of buildings (Moss et al 2018).

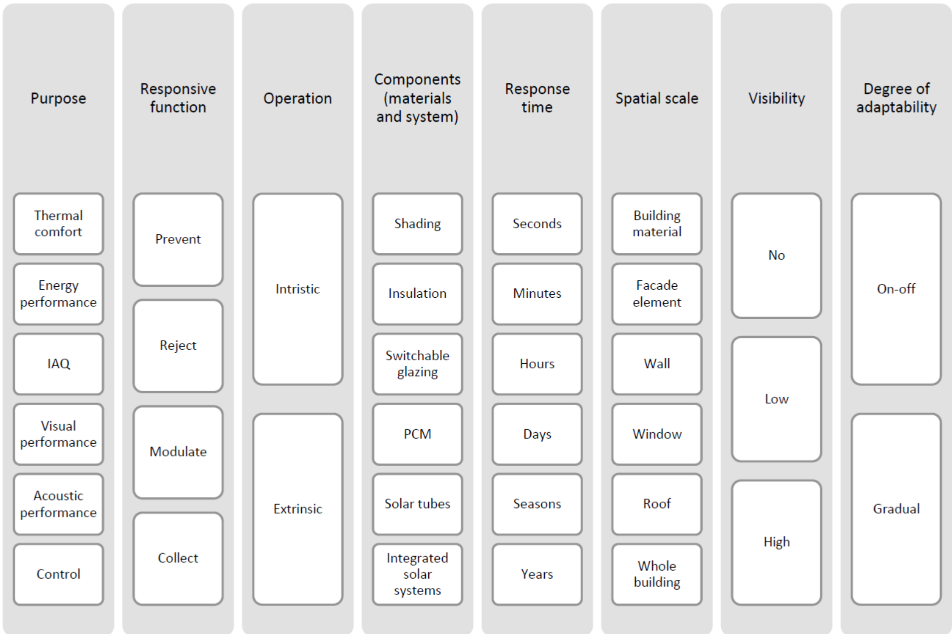

Fig. 1. Overview of characterization concepts for envelope adaptivity
Source: Moss et al. 2018

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Recent trends in envelope system design has evolved using dynamic systems to adapt layered building facades. Each of this layer has a specific function, therefore, the layered façade has a certain level of complexity. Dynamic and kinetic systems are automatically controlled shutters, adaptive skin, climate-adaptive building shells, interactive architecture with robotic and kinetic design, acclimated kinetic envelope, adaptive building skins, and kinetic systems in architecture. They all improve energy efficiency and occupant flexibility for controlling non-static buildings. Most building skins are a system that reacts and performs based on the user's need and adapts to weather conditions by automatic control concepts that are also adjusted by users (Kuru et al. 2019). Lopez (López et al. 2015) is of strong opinion that learning from nature is the answer. Biology has always presented new paradigms in numerous areas, including engineering and medicine. Worth mentioning, that it is also a novel basis for technological thinking. Biology can be integrated with architecture via biomimicry principles that consider nature as countless mechanisms and strategy databases for design. Solutions that are based on biology are multi-functional, complex, and highly responsive; they replace conventional static building envelopes and in a new adaptive form improve energy performance. The biological solution approach helps for building envelope to be more responsive and adaptive to indoor and outdoor environments and satisfy thermal, light, and air quality comfort. Biomimicry has countless opportunities to adopt sustainable building design, however, it creates a challenge to transfer knowledge from biology to engineering, architecture, or technology (Al-Obaidi et al. 2017). In recent biomimetic research on building, thermal envelopes are compared to outer shells that exist in nature. Outer shells in nature face the same weather conditions and have same functions and tasks as reducing heat loss via thermal envelope (insulation, metabolism, hibernation), storing and generating energy, and avoiding indoor overheating (Erebor et al. 2021), (Sommese et al. 2023).

Nature solves various mechanical and structural problems, most notably it does not generate residual and active wastes. To mimic nature, it requires a high level of understanding between biological and technical systems. Even their evolution is similar. As we know biological systems have been evolving for millions of years and are based on genetic codes that are governed by natural selection. Meanwhile, technical systems have been developing for only a few centuries and are developed based on human design to perform and ensure functions (Cohen et al. 2014). Kennedy (Kennedy 2017) defines biomimicry as a new field in science that combines sustainable solutions and innovation with research and industry development by evaluating invention suitability with ecologically based criteria. The author also states that understanding nature as a mentor, measure, and model will be crucial to successfully implementing biomimicry applications (Kennedy 2017). Biomimicry levels are categorized into three phases: form, process, and ecosystem. The first phase is copying attributes and features from any existing organism as appearance, shape, materials, etc. The second phase is on a deeper level to replicate biological systems to mimic natural processes. The third phase is a set of processes that tries to duplicate the ecosystem from a combination of forms and processes. Mazzoleni (Mazzoleni 2013) stated that biomimicry follows certain analogies and performs on diverse stages as organisms, behavior, and ecosystems.
Biomimicry as emerging research in architecture faces some issues that limit its further progress. Biomimicry implementation in areas of engineering and technology is limited due to limited knowledge transfer of technological aspects from biology to design. Nature has various mechanisms and strategies that can be adopted via biomimetic approach and types of biomimetic designs available, however, it creates a great challenge to obtain the most successful architectural design (Al-Obaidi et al. 2017).

Biomimicry in architecture tries to remedy existing errors when designing efficient systems and products. Biomimicry integration in architectural design has diverse directions and classifications and the most common depends on obtained outcomes from research. The basic design approach that has also been widely utilized by researchers and practitioners are the bottom-up and top-down approaches. The bottom-up approach applies as an indirect and solution-based approach and it refers to biology to design where the biological principle is the source for design ideas. It relies on biological property adaptation to human technology to find answers and then identify human design problems. Specific characteristics or behaviors are searched in existing organisms or ecosystems after that the characteristic or behavior is shaped and used as a guideline for developing either architectural designs or industrial products. The top-down approach seeks answers from nature for a specific problem based on analogy or a problem-based direct approach. The approach is based on challenges to biology design problems and finding answers in other organisms or ecosystems with similar problems to solve human problems. An advantage of this approach is that searching for a suitable solution does not require in-depth

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scientific understanding and makes it easier to translate biological information into technical systems (Kuru et al. 2019), (Sommese et al. 2022).

Hayes and others (Hayes et al. 2019) address six principles how ecosystems function and it could be translated to any system, as an example taking building skins:

- Dependence on contemporary sunlight: usage of renewable and contemporary energy from solar light based on spatial and time mechanisms.
- Optimisation of the system instead of its components: energy is transferred efficiently between systems and components as form follows the function. Energy and materials used in the same system are applied for multiple functions.
- Dependency on local conditions and situations: materials are sourced locally and adapt to specific environments.
- Diversity in components, relationships, and information: obtaining resilience and diversity is required. Relationships are complex and operate in various hierarchies which lead to self-organization and distribution; as a result, emergent effects occur.
- Creation of conditions favorable to sustained life: Systems are functioning and from an environmental perspective begin improving the biosphere.
- Adaptation and evolution at different levels and at different rates: obtaining the balance of non-equilibrium from constant flux. An ecosystem produces creative mechanisms when limited and ecosystems achieve self-heal capability.

Reichert identified five principles for biomimicry adaptation effectiveness: adaption, material systems, evolution, form and behavior, and emergence. In addition, the author classified biomimicry levels in architecture into nine types: concept, process or behavior, morphology, form, structure, skin, material, expression, and symbolism (Reichert et al. 2015). One of the methods is introduced by Garcia-Holguera et al. (Garcia-Holguera et al. 2016) called Ecomimetic. Conceptual approach or theoretical framework based on previous methods. The approach is a helix model capable of obtaining interactive exercises to integrate feedback. The method focuses on two levels –abstraction and transference of biological principles and is divided into six phases: architectural design goals, ecological solution searching, abstraction and ecological systems representation, the correlation between ecological and architectural systems, transference from ecosystem's principles to the architectural system, and modeling and benchmarking.

Lebdioui (Lebdioui 2022) in research classified biomimicry-based materials into four clusters:
• smart materials that change and react in response to external stimuli,
• surface modifications with innovative surface structures and improved functions,
• nature-inspired material architectures that are focused on innovative forms and structural arrangements,
• technologies that improve current systems by deploying specific adaptive parameters

Smart, responsive, and adaptive concepts are terms that have been used interchangeably and have caused confusion to many professionals. Firstly, smart building skins are referred to as fully or partially automated self-monitoring systems and deploy integrated instruments within a building. Smart building skins can be regarded as self-aware and grid-aware mechanisms that have embedded smart sensors that operate in four main areas user's comfort during different times of the day and year, building use changes, occupancy characteristics variations, and variations in external weather conditions based on collected yearly averages. Responsive building skins on the other hand are defined as a simple form of adaptation with functional and performance characteristics that are similar to smart building skins. The meaning of responsive proposes that environmental conditions are controlled with the usage of computational algorithms. The third term, adaptive building skin refers to a morphogenetic evolution and real-time physical adaptation of a design to its surrounding environment. It is more complex because adaptivity is combined with multi-scalar factors to reach a symbiotic energy-efficient design solution. Adaptive walls ensure a breathing envelope and influence air pressure on the surface to imitate the inhaling–exhaling process. Thermo-regulating envelope maintains an adequate balance between heat gain and heat loss without seeking air-tightness and water-tightness. Light-regulating envelope improves the visual comfort of the indoor environment (Al-Obaidi et al. 2017).

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While designing adaptive building skin it requires low-technology and low-energy adaptive material systems. Consequently, the selected materials should require physical properties and structures that generate movement and adapt to real-time environmental changes. Various criteria should be considered in adaptive systems design as workability, responsiveness to stimulus, durability, resistance to corrosion, and achievable movements to impress force. Furthermore, materials should possess performative and self-actuating abilities, adapt to the system, and react to changes in the environment. Many adaptive materials are mimicked from nature, for instance, conifer cones that have repetitive opening–closing cycles and structural properties to respond to humidity. Civioc et al (Civioc et al. 2022) classified the materials into four areas: temperature-reactive materials, light-reactive materials, humidity-reactive materials, and carbon dioxide-reactive materials. The author classifies 13 smart materials, and 13 adaptive materials and lists their stimulus. Smart materials differ from adaptive materials. Smart materials in order to function, require external stimuli based on conventional energy sources, while adaptive materials function naturally in existing environmental conditions as in nature does plants. In this material classification combination of custom optics and PCM is a smart material with a heat source provided by solar radiation stimulus. Meanwhile, PCM as a material is listed as an adaptive material with temperature-reactive stimulus (Al-Obaidi et al. 2017).

2. Methodology and laboratory test

The main goal of the experimental study is to evaluate solar simulation experiment results and assess latent and sensible energy storage in the building envelope. Another goal is to evaluate 6 material combinations of solar models and determine the most efficient combination of solar façade systems. To reach the goals and test certain materials additional experiments were carried out to test aerogel transparency (Experiment 1) and mechanical (Experiment 2) properties.

It is always of great importance how heat losses can be maximally reduced. Heat loss reduction from sunlight receivers is considered for many applications; it also is meaningful for solar power concentration and converting sunlight into heat.

The volumetric radiation shield needs to be spectrally selective and should allow sunlight to pass while absorbing or reflecting IR radiation. Additionally, low thermal conductivity would be needed and the outer surface would have a significantly lower temperature than the absorber. The material that describes these properties is aerogel. Heat losses are greatly reduced while keeping high solar transparency. This means that aerogel allows the system to run at higher efficiency or receiver efficiency is obtained at lower optical concentrations (Aghabararpour et al. 2018). Silica aerogel has a cross-linked internal structure of SiO_2 chains with many air-filled pores. Due to high porosity, aerogel is the lightest solid material – skeleton density is approximately 2200 kg/m3. Pores are microscopic from 5–70 nm and take up to 85–99.8 % of total volume, depending on purity and fabrication method. Because of microscopic pores and high porosity, aerogel has advantageous physical, thermal, and optical properties. Even more, because of the combination of as low thermal conductor and high daylight and solar energy transmitter, aerogel is a qualitative transparent insulation material (Westgate et al. 2018). Aerogel's low thermal conductivity results from low solid skeleton conductivity, low gaseous conductivity, and low TIR of 0.85 (McEnaney et al. 2017).

Two laser pointers were located on a box 8.5 cm in height, both facing Fresnel lens (poly-methyl methacrylate (PMMA) (127x127 mm) with focal point 71 mm). The distance between lasers was 5 cm and the distance between lasers and lenses was 13 cm. Fresnel lens and its construction has a width of 7 cm. The focus point is located outside the Fresnel lens construction, approximately, 8 cm behind the lenses. The distance between the back of the lens construction and the screen (white A4 paper) is 15 cm.

The experiment was carried out in 2 parts – laser light ray projection on the screen without aerogel and ray projection filling Aerogel LUMIRA® LA 1000 CABOT (Civioc et al. 2022) (translucent and hydrophobic aerogel granules ranging in size from 70 µm to 4 mm, thermal conductivity 18 mW/(mK)) in Fresnel lens construction with 7 cm aerogel layer between Fresnel lens and focus point.

What mechanical exposure can be on aerogel? The advantages of aerogel are its very low density, nanostructure, and characteristics as amorphous and mesoporous. Because of its structure, the material has remarkable physical, thermal, optical, and acoustical properties. Silica aerogels are load-bearing with a high compression strength of up to 3 bars, however, the disadvantage is very low mechanical strength and fragility (McEnaney et al. 2017). Aerogel has high strength to mass ratio – it can support up to 1600 times its own mass. A downfall is that this brittle material has a fracture toughness of only 0.8 kPa m1/2.

Experimental setup. 25 ml of Aerogel LUMIRA® LA 1000 CABOT (Civioc et al. 2022) (translucent and hydrophobic aerogel granules ranging in size from 70 μm to 4 mm, thermal conductivity 18 mW/(mK)) was measured and placed in a glass jar. An example of aerogel was taken for testing under the microscope with 40 x zoom to take pictures of aerogel before mechanical exposure (Guo et al. 9021).

Even though aerogel can be easily crushed, mechanical exposure does not destroy its porous structure. Meaning, the material grounds into powder and occupies approximately the same space as the original sample (Tafreshi et al. 2022).

The experiment demonstrates that mechanical exposure to aerogel did not damage the material and validates that the pore structure of the material does not change significantly. No critical volume changes occurred during the experiment. A loss of 3 ml appeared due to material placement from the measuring glass to the jar. It was observed that between the tests aerogel became electrified, complicated to capture and to make precise measurements. Aerogel was not drastically damaged by mechanical exposure – it can be explained as it is a light and durable material that did not split into small pieces. Even though the pictures show that aerogel particles have split of various sizes. Different-sized aerogel particles were found in each microscope viewing – from large aerogel parts to small size dust. One observation was that with each mechanical exposure, aerogel became more and more electrified, and aerogel particles pushed against one another. Another observation was that small dusty particles of aerogel that had split off the material greased the surface and the material was abrasive after mechanical exploration. It leads to the conclusion that aerogel after certain mechanical exposure could smudge the surface and lower ray transmittance.

3. Results and discussion

Ray's position in the screen located a certain distance from the Fresnel lens was captured without aerogel fill in Fresnel construction but they were not captured when the Fresnel lens construction was filled with aerogel. The focus point exists at a certain distance from the Fresnel lens without aerogel filling in Fresnel construction. Experiment results prove aerogel's opaque and transparency properties as no focus point exists and aerogel breaks light rays. As mentioned in the literature, aerogel has small pore sizes and high porosity. The experiment demonstrated that the material has high thermal and optical properties. In addition, because of its combination of low thermal conductivity and a low transmittance of daylight and solar energy (including IR spectrum), the material is a remarkable translucent and transparent insulator.

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Solar radiation is kept constant at 560 W/m^2 for 6 hours and 10 minutes. Fig. 2 below shows solar radiation values read by a pyrometer that was located between the boxes at the same distance of 1520 mm from halogen lights. During solar radiation, outside temperatures reached 29 ºC in front of the boxes and 26.2 °C at the back of the boxes, data logger temperature measurements for outside temperatures are very inconsistent experiencing about 1-degree differences between 2 readings in 2–5 minutes period time. This was especially noticed after the lights were turned off and outdoor temperatures were varying due to cooling cycle. The highest value in conus is reached with variation aerogel and PMMA acrylic glass of 71.91 ºC. The next higher temperature of 55.2 °C is reached in conus with PMMA acrylic glass. This in the only variation where conus reaches its peak temperature before solar radiation is turned off. The temperature of 55 ºC was reached on the 330th minute and kept constant for 25 minutes, experiencing a temperature drop after the lights were turned off. Reference box insulation reached the temperature of 42.3 °C and was the first one to reach 13.2 °C after 7 hours (1270th minute) while other temperatures in conus was between 14.5–17.7 °C. In the 1440th minute reference box insulation had reached 13 °C, while other temperatures in conus was between 14.3–14.9 °C and 17.3 °C in the model of conus shape and Fresnel lens.

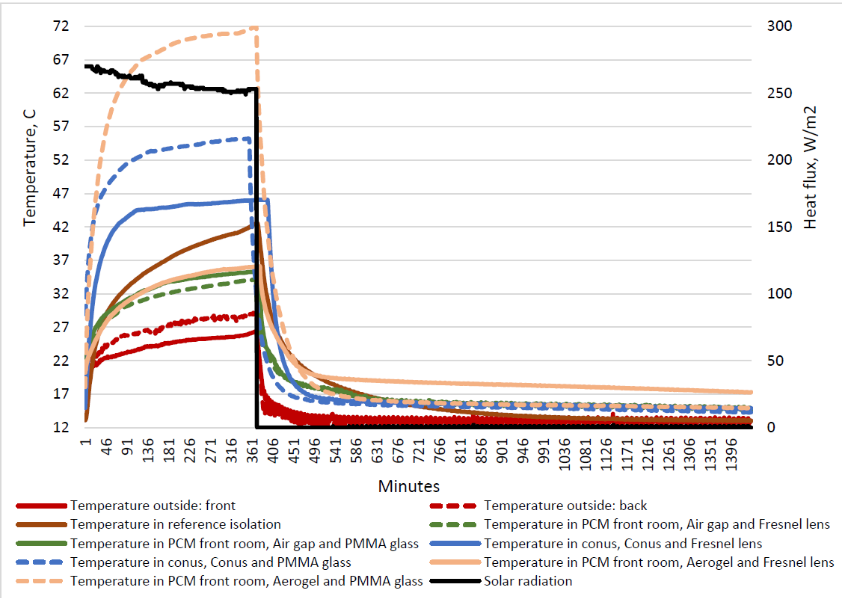

Fig. 2. Solar radiation and temperatures in PCM cone and reference insulation

Both air gap variations results are described below, and graphs are illustrated in Fig 3 of the air gap model with Fresnel lens and Fig 4 of the air gap and PMMA acrylic glass.

Temperature and heat flux results of the first variation with air gap and Fresnel lens can be read in Fig. 3. Temperatures in reference box insulation reach the maximum value of 41.9 °C and the reference room is heated up to 27.7 °C. During solar radiation heat flow in the reference box rises and heat moves inwards the room, overheating it up to 27.7 °C, while the outside temperature is 29 °C. The heat flow rate in the reference box rises within the first 100 minutes after that it reaches the peak of 5–5.7 W/m^2 till the 380th minute when solar radiation is switched off. 110 minutes later, in the 450th minute, heat flow has reached an equilibrium of 0 W/m^2 that continues till the 1440th minute. After solar radiation has stopped opposite process is happening, meaning that heat in the room and insulation gradually evens until room temperature and insulation have similar temperatures and heat flow is zero. Worth mentioning, that heat flow values even reach negative values slightly below zero, respectively, reference insulation receives heat from the reference room due to temperature changes. No heat is accumulated, and the reference box room reaches an outside temperature of 13 °C in the morning.

Temperatures and heat flow in PCM boxes operate differently and have more gradual heating and cooling processes. Starting with temperatures, in an air gap room Fresnel lens concentrates light and heats it up to 34 °C. During solar simulation, the PCM box room is heated up to 23.3 °C, and PCM has melted and reached a maximum temperature of 23 °C. PCM box room heats up very gradually as when temperature raises PCM by

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endothermic reaction changes its chase from solid to liquid when it reaches 21 °C and absorbs excessive heat. After lights are turned off opposite process happens, PCM cools down from 23 °C and starts to solidify at 21 °C, by exothermic reaction PCM starts to release heat, reaching a maximum value of 11.9 W/m^2 in the morning. This process is seen in heat flow measurement results, at the start heat flow in the solar facade model increases and has a direction from outside to the indoor room. In the 100th-minute inward heat flow growth rate decreases, in the 180th minute the heat flow direction from the indoor room to the outdoors. In the 380th minute heat flow reached its peak of -6.1 W/m^2 and PCM has maximally absorbed heat energy. In the 500th minute heat flow reaches an equilibrium of 0 W/m^2 and PCM starts to release heat and continues till reaching the peak of 11.9 W/m^2 in the 1100th minute.

It is observed that reference and PCM box heat flows have different cycles. The reference box does not have heat storage, while PCM accumulates heat by reducing overheating and undercooling processes. In the morning, PCM managed to ensure a gradual temperature drop and the room temperature was 16.8 °C, unlike the reference room that has the same temperature as outside of 13 °C.

Temperature and heat flux results of the second variation with air gap and PMMA acrylic glass are shown in Fig. 4. Reference box has similar values as in the first variation. Reference insulation is heated to 42.4 °C, reference room accordingly is overheated during the day to 28 °C and cools to outdoor temperature during the period of night. Temperatures in the PCM box are the following: temperatures in conus reach 35.4 °C, PCM room reaches 23.4 °C while PCM heats to 22.9 C on this day. PCM and PCM rooms are heated to the same temperature. Even though, PMMA acrylic glass managed to heat conus room at 1.5 °C higher temperature, heat fluxes are similar to the first variation and reach 11.8 W/m^2 in the morning and the PCM room has the same 16.8 °C.

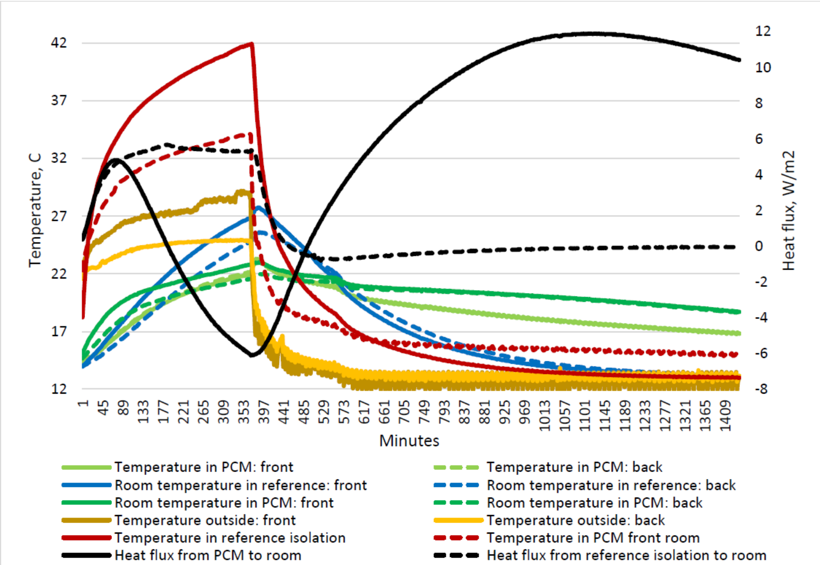

Fig. 3. Air gap and Fresnel lens temperature results

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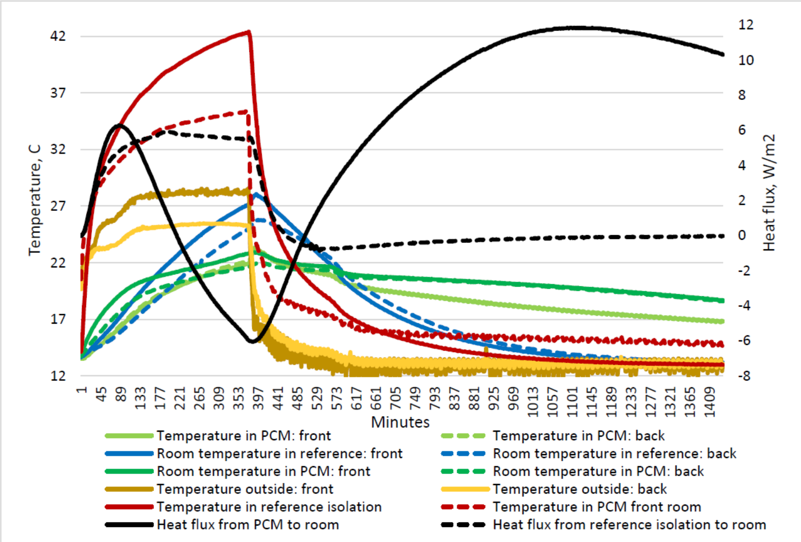

Fig. 4. Air gap and PMMA acrylic glass temperature results

Both conus shape front room variations results are described below, and graphs are illustrated in Fig 5. Of conus shape front room and Fresnel lens and Fig 6. of the shape front room and PMMA acrylic glass.

Temperature and heat flux results of the third variation with conus shape front room of the solar model and Fresnel lens are shown in Fig. 3.4. Reference insulation reaches 40.5 °C while conus room has been heated to 46 °C. The outside temperature of this test reached only 26.8°C, reference room was heated to 25.6 °C, on the contrary PCM room had a maximum temperature of 20.7 °C. The PCM room has optimal room temperature. The reasons why PCM room temperature has dropped is because of lower outside temperatures and PCM temperatures. In this test PCM did not heat to 21 °C, thermocouples measured a maximum temperature value of 20.6 °C in PCM front and 20.2 °C in PCM back. Of the low temperatures, PCM did not manage to melt; yet, heat flux reached 9.5 W/m^2 keeping the temperature in the PCM room in the morning at 16.4 °C which is only 0.4 °C less than for the previous test of air gap. Conus-shaped front room with aerogel managed to reduce heat loss.

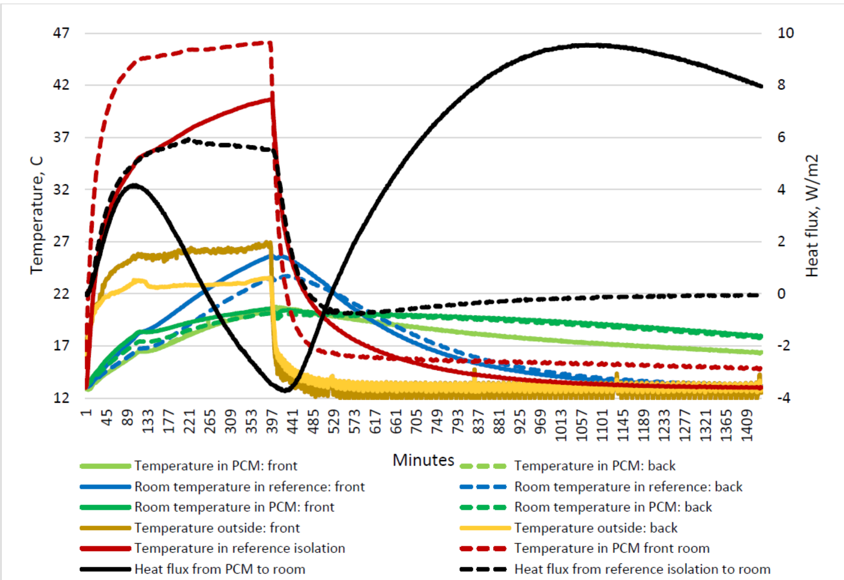

Fig. 5. Conus with aerogel and Fresnel lens temperature results

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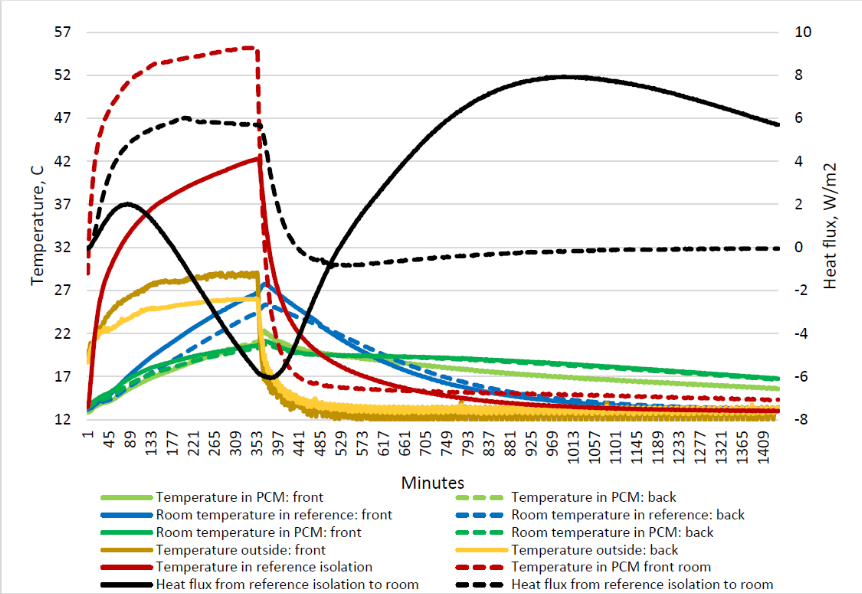

Fig. 6. Conus with aerogel and PMMA acrylic glass temperature results

Temperature and heat flux results of the fourth variation with conus shape front room of the solar model and PMMA acrylic glass are shown in Fig. 6. Reference insulation reaches 42.1 °C and conus room is heated to 55.2 °C. Outside temperatures of this test reached 29o C, the reference room was heated to 27.7 °C, while the PCM room reached 22.3 °C. In this test PCM was heated to 21 °C, however, thermocouples measured 21 °C in the PCM front for only 20 minutes. Meanwhile, PCM back heated up to 20.7 °C. Due to insufficient and low temperatures, PCM did not manage to melt and heat flux reached only 7.9 W/m^2 keeping the temperature in the PCM room in the morning at the lowest value of 15.6 °C.

Both aerogel-filled variations results are described below, and graphs are illustrated in Fig 7. of aerogel fill and Fresnel lens and Fig 8. of aerogel fill and PMMA acrylic glass.

Temperature and heat flux results of the fifth variation with aerogel fill in the front room of the solar model and Fresnel lens are shown in Fig. 7. Reference insulation reaches 42.8 °C and aerogel room is being heated to 36 °C. The outside temperatures of this test reached 29.8 °C, the reference room was heated to 27.8 °C, while the PCM room reached 22.7 °C. This solar simulation also did not manage to heat PCM to 21 °C, however, thermocouples measured 20.9 C in the PCM front for 50 minutes. Meanwhile, PCM back heated up to 20.5 °C. Of the low temperatures, PCM heat flow reached only 9.5 W/m^2 keeping the temperature in the PCM room in the morning value of 16.4 °C that are the same value as the variation with conus shape front room of the solar model and Fresnel lens.

Temperature and heat flux results of the sixth variation with aerogel fill in the front room of the solar model and PMMA acrylic glass are shown in Fig. 8. Reference insulation reaches 42.6 °C and aerogel room is heated to 71.9 °C. The outside temperatures of this test reached 29.3 °C, the reference room was heated to 27.1 °C, while the PCM room reached 21.6 °C. This solar simulation managed to heat PCM to 21 °C, however, thermocouples measured 21 °C in PCM front only for 30 minutes. Even though, the PCM back heated up to 20.8 °C, PCM heat flow reached 10.2 W/m^2 keeping the temperature in the PCM room in the morning value of 16.8 °C that are the same value as variation with conus shape front room of the solar model and Fresnel lens.

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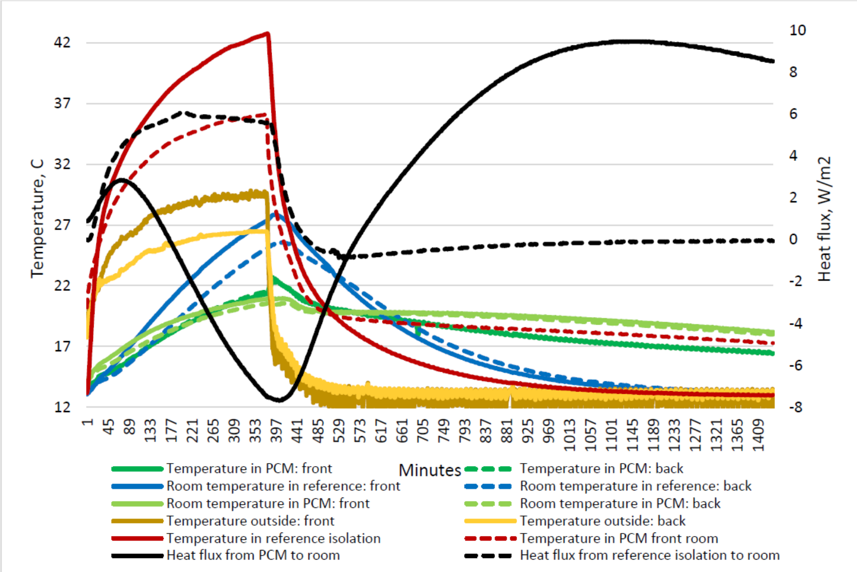

Fig. 7. Aerogel and Fresnel lens temperature results

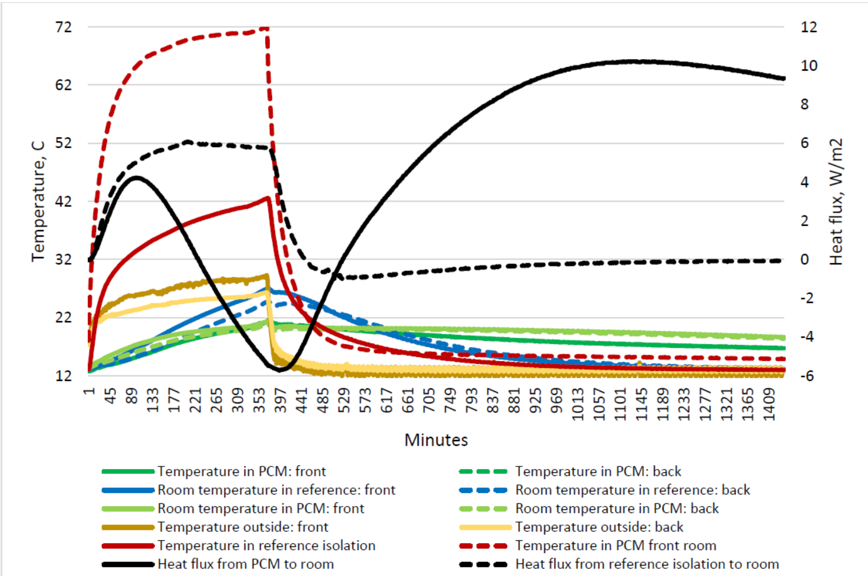

Fig. 8. Aerogel & poly-methyl methacrylate acrylic glass temperature results

Heat flux results of all six variations and reference boxes are illustrated in Fig. 8. At the beginning of solar simulation all boxes and variations experience heat flow growth rate in direction from outdoors to indoors. The reference box reached its peak heat flow of 5.5 W/m^2 in the 150th minute and stabilized till the 370th minute when the solar simulation is turned off. After 70 minutes in the 450th minute, the reference box flow reaches the equilibrium of 0 W/m^2. During solar simulation, heat flows in a direction from outdoors to indoors, after solar simulation is switched off, temperatures in reference box insulation and room drop by reducing heat flow towards the room and changing heat flow direction towards the outdoors. Four out of six test variations reach peak heat flow rate within the first 70 minutes those are air gap with Fresnel lens and PMMA acrylic glass, aerogel with Fresnel lens, and conus with PMMA acrylic glass. Conus with Fresnel lens and aerogel with PMMA acrylic glass reach heat flow peak at the 90th minute. Each of the test variations has different heat flux values.

Both air gap tests with Fresnel lens and PMMA acrylic glass in the solar simulation started reaching heat flux peaks of 4.8 and 6.2 W/m^2 and had 11.9 and 11.8 W/m^2 heat flow peaks at the time PCM released latent heat.

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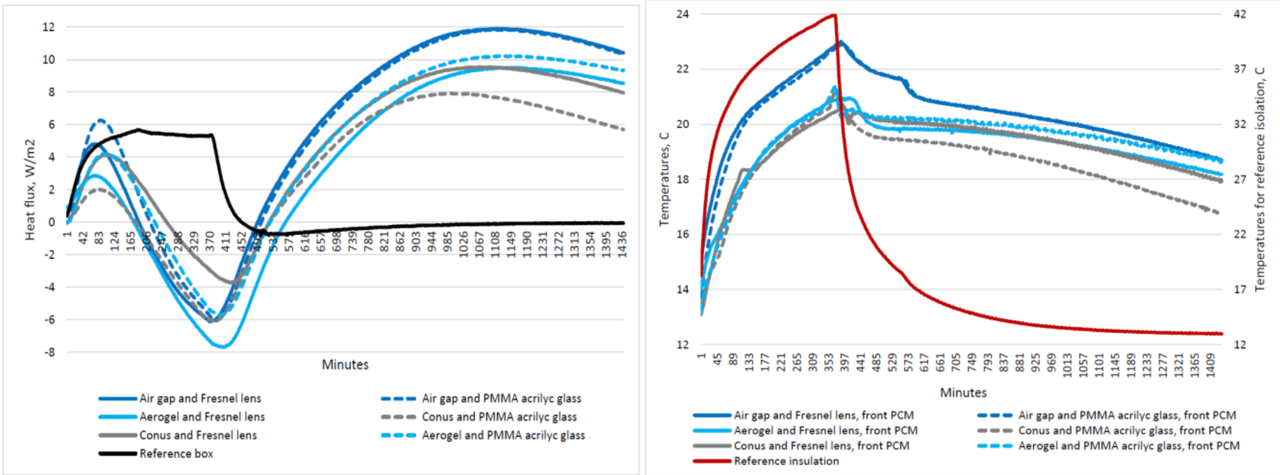
Both conus shape tests with Fresnel lens and PMMA acrylic glass had at the beginning heat flow of 2 and 4.1 W/m^2 and when PCM released heat it managed to have 7.9 and 9.5 W/m^2. Because of the low heat flow rate conus shape model with PMMA acrylic glass fails to accumulate heat in PCM and has the lowest room temperature. Aerogel fill model with Fresnel lens and PMMA acrylic glass had different heat flow rates at the start of 2.8 and 4.2 W/m^2. Even though the Fresnel lens test had a low heat flow rate, it managed to accumulate the appropriate amount of heat to release latent energy to 9.5 W/m^2 and maintain PCM room temperature to 16.4 °C. Aerogel with PMMA acrylic glass had a heat flow of 4.2 W/m^2 and released latent heat up to 10.2 W/m^2 to remain at room temperature to 16.8 °C.

Temperatures in PCM of all six variations and reference box insulation are illustrated in Fig. 9(a). This graph illustrates mineral wool and paraffin thermal properties. Reference box insulation experiences temperature changes that range from a peak of 42.8 °C to an outdoor temperature of 13 °C.

At the same time, in all six variations paraffin heats up to 20.6–23 °C and cools down to 16.6–18.7 °C. In both air gap models with Fresnel lens and with PMMA acrylic glass PCM is heated to 23 °C and paraffin manages to melt. In the air gap model with Fresnel lens thermocouples measured the PCM front is heated to 23 °C and the back of PCM to 22 °C, as a result, PCM cools down to only 18.7 °C and 18.6 °C. The air gap model with PMMA acrylic glass has similar results of 22.9 °C in the PCM front and 22 °C in the PCM back. In conus shape models PCM did not manage to melt properly and for that reason, PCM cools down at 1 °C compared to air gap models. In the conus shape model with Fresnel lens PCM reaches temperatures of 20.6 and 20.1 °C and cools down to 17.9 °C and 17.8 °C, While with PMMA acrylic glass PCM heats to 21 °C in front of PCM and 20.7 °C in back. However, this variation does not bring worthy results and PCM is cooled to the lowest values of 16.7 °C. In variations of aerogel fill paraffin also did not manage to melt, however, room temperatures are better than in cone-shaped variations. In aerogel with Fresnel lens front of PCM is heated to 21 °C, back to 20.6 °C and PCM cools to 18.2 °C and 18 °C. Aerogel with PMMA acrylic glass heats to 21.4 °C in front and 20.8 °C in back and paraffin cools down to 18.6 °C and 18.4 °C.



a) b)

Fig. 9 (a) Heat flux and (b) temperature measurement in 6 variations and reference box results

Temperatures of all six variations of the PCM room and reference box room are illustrated in Fig. 9 (b). During tests reference box room was heated to 28 °C and in the climate chamber cooled to outdoor temperature to 13 °C, meanwhile PCM box room was cooled to temperatures in the range of 15.5 °C to 16.8 °C. As explained earlier, PCM melted only on test with an air gap, for this reason, PCM box room has both highest values within solar simulation and after reaching 23.3 °C and 23.4 °C and cooled to 16.8 °C for both Fresnel lens and PMMA acrylic glass. In variation of the conus shape model Fresnel lens PCM room was heated to only 20.7 °C, however, it managed to cool down on average as all other tests of 16.4 °C, unlike PMMA acrylic glass this variation also did not perform. Room temperature is heated to 22.7 °C. However, the room is cooled to the

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lowest value of 15.5 °C. Aerogel filled with Fresnel lens heated up room is 22.7 °C and cooled to 16.4 °C, while aerogel filled with PMMA acrylic glass is heated only to 21.4 °C and cooled to 16.8 °C. °C

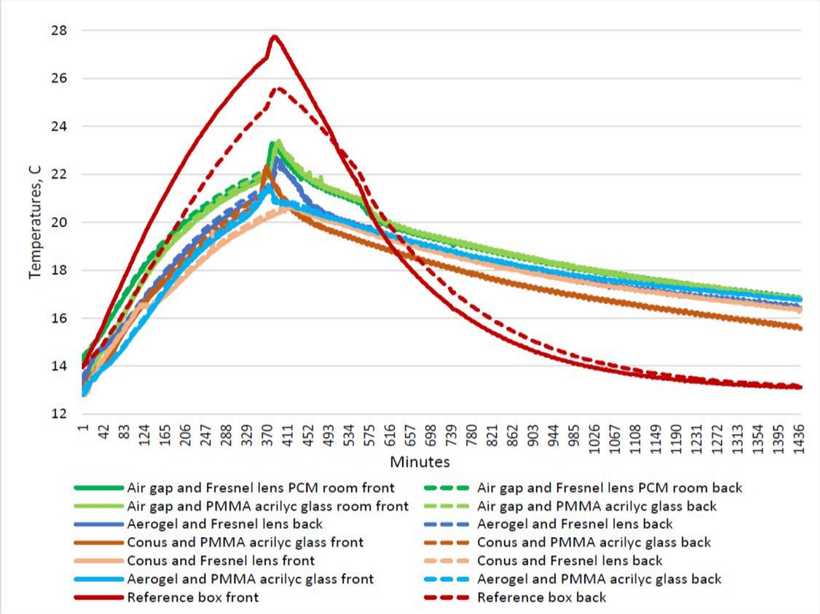

Fig. 10. Temperatures of PCM room in 6 variations and reference box

More detailed results of phase change during the solidification process of PCM are shown in Fig. 10. When the phase change process is over, the temperature continues to fall down at the previous rate which is higher. The green area is the melting temperature region and the purple area is the solidification temperature area given by the material producer (Noroozi et al. 2019).

All 6 variations compared to the reference box give certain level heat gains. As a result, this proves that solar façade systems with integrated PCM are energy-efficient solutions to incorporate in building facades. However, it was observed during the result analysis that paraffin should be heated at least to 21 ºC to ensure the endothermic reaction that absorbs heat that is later released as latent heat. As PCM managed to melt only on the first 2 test days, not all six variations can be analyzed within each other. Air gap models can be compared with each other as for these tests PCM managed to melt. Another comparison is between the other four variations of conus shape and aerogel fill.

Conclusions

Aerogel is considered an essential material of this model. The four experiment variations that included aerogel as a component material, proved thermal and optical properties. It is concluded that thermal insulation as energy conservation and energy loss reduction are vital for this solar façade model. Thermal insulation applications in buildings maintain a comfortable indoor climate even at low ambient temperatures and reduce heat losses through thermal bridges. Aerogel is a reasonable choice to isolate thermal transfer. The basic principle applies to enclosing motionless air in material structure thermal insulation material. Heat is absorbed by aerogel and re-emitted back to the absorber, reducing radiation loss. Conduction loss through aerogel is very small due to the low solid thermal conductivity. Part of the heat is lost to the environment and conducted through the glass via radiation and convection.

Result analysis proves that using a Fresnel lens or poly-methyl methacrylate acrylic glass in solar energy concentration technology is an effective way to fully use sunlight. Results of the experimental study also uncover that the variations with Fresnel lens and poly-methyl methacrylate acrylic glass show similar results and light-gathering performance. It is concluded that the use of a Fresnel lens as a solar concentrator does not give any thermal improvements in this technical solution compared to poly-methyl methacrylate acrylic glass.

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For this reason, the Fresnel lens as a solar concentrator can be substituted with poly-methyl methacrylate acrylic glass which would also reduce costs for material.

As mentioned in the literature, biomimicry is an innovative approach to adapting sustainable solutions by imitating nature's time-tested patterns and processes. Correspondingly, the natural process of heat absorbing is adapted to solar façade model design to manage heating. Basic natural processes and main heat transfer methods, radiation, conduction, and convection, are used in solar façade model solutions.

This research and solar model is an example that biology can be integrated with architecture via biomimicry principles and nature has countless multi-functional, complex, and highly responsive mechanisms, strategies, and solutions. Biomimicry in architecture remedies existing errors of efficient system design and products, by taking into the fact that outer shells in nature face the same weather conditions and have the same functions and tasks as reducing heat loss via thermal envelope (insulation, metabolism, hibernation), storing and generating energy, avoiding indoor from overheating.

Scientific novelty/practical value of the findings

Solar energy has great potential in all continents and locations in the world. The solar model proposed in this thesis is an effective way to collect solar energy with a concentrated lens and efficiently transfer heat via a building envelope. Materials used in the model are tested previously to suit the model and have compatible mechanical, chemical, electrical, optical, and thermal properties.

Results gained from the experiment show improvements in energy efficiency and reduction of heat losses, consequently, reducing CO_2 emissions. This model proves solar thermal façade system efficiency and suitability for domestic heating embedded in building envelopes.

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