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# The Effect of Fresnel Lens Focal Point Location on Heat Transfer in Phase Change Material (PCM) Enhanced Dynamic Solar Facade

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***Abstract*** **– In recent years, the demand for energy-efficient technological solutions in the building sector has risen significantly worldwide. The exploitation of phase change material as a medium for thermal energy storage in building envelopes has increased due to its superior properties. There is still a knowledge gap to cover in the way to the effective solar thermal energy storage in the building envelope – to enhance the heat transfer, to reduce the heat loss, etc. This paper deals with the optimisation of heat transfer using a solar concentrator (Fresnel lens). This study examines the effect of Fresnel lens focal point location on heat transfer in a dynamic solar facade prototype that stores thermal energy in phase change material. Nine different setups (solar façade compositions) were tested in the laboratory – two parameters with three alternatives each. Testing conditions simulate the relevant Northern Europe climate. By changing the air gap configuration and location of the Fresnel lens focal point, the heat transfer to phase change material was observed by measuring temperatures in the phase change material container using five thermocouples. The results show the improved thermal performance in test modules with larger cone diameter by 7.2 % and Fresnel lens focal point positioning closer to the back of the phase change material container by 5.4 %.**

***Keywords*** **– Building envelope; melting temperature; solar thermal energy storage; latent heat; small-scale dynamic solar module**

## 1. INTRODUCTION

The demand for energy-efficient technological solutions in the building sector is significantly rising. The concern about air pollution caused by $CO_2$ and other GHG emissions has been growing worldwide in recent years. The latest data mark the recovery of the building sector after the COVID-19 crisis, as the industry output is 2.5 % higher than in 2019 [1]. The renovation of old buildings and construction of new buildings must be based on green and carbon-neutral technology involvement to reach the EU's climate targets [2]. Hybrid energy systems can be used to reduce the dependency on conventional fuel-based heating and cooling systems. Here, on-site renewable energy utilization is critical in providing clean and green energy for buildings [3].

The building envelope can serve as the energy transformation media - energy available on site is captured and transmitted to the end user directly [4]. The most common in buildings is

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solar energy transformed into electricity or heat. Systems can be free-standing photovoltaic (PV) panels or solar thermal systems, or building-integrated both – photovoltaic panels (BiPV – building integrated photovoltaic panels) and solar thermal systems (BiST Building integrated solar thermal systems). Based on the number of examples gathered in a thorough literature review conducted by Vassiliades *et al.*, it can be concluded that there is significantly more research on BiPV than BiST [5]. There are technological advancements offered to couple BiPV and BiST systems with latent energy storage using phase change materials. However, there are scarce examples of PCM embedded in the thermal envelope itself to store solar energy.

Solar power is used for this purpose because of its wide availability in almost any climate zone. For instance, when solar radiation is available in the daytime, it can be collected in thermal storage appliances and used later in the nighttime for heating purposes while the outside temperature is low. However, a challenge is the collected thermal energy storage systems, as solar radiation is not available at all times [6]. While solar energy can be transferred into electrical energy by using photovoltaic panels and stored in batteries [5], the long-term storage of solar thermal energy is more complex. It requires more financial investments. In climate zones where solar radiation is available for most of the daytime throughout the year, solar thermal power concentrating systems are used for medium heating and generation of electricity [7]. These systems are based on focusing solar heat on one area by using a reflective surface and can be efficiently used in desert areas. Yet, for the northern climate zone with the longer heating season, solar thermal energy must be collected in insulated storage to provide the system's efficiency. Developing innovative solutions for on-site renewable energy, such as solar thermal power conservation, is an absolute necessity to reach the goals of building sector decarbonization by 2050. According to data [8], solar thermal power capacity grew by 3 % in 2021 compared to 2020. Thermal energy storage systems can be exploited to collect energy for later use by stocking energy in a storage medium. These systems can be sorted into two main types - thermal and chemical. While chemical systems collect thermal energy with chemical reactions, thermal systems are based on storing energy in sensible and latent heat. Thermal systems are the most common energy storage systems that are used for heating and cooling purposes in buildings. Some of the conventual sensible heat storages are water tank storage, underground storage (that makes use of the heat or cold from the ground), aquifer storage, and packed-bed storage. Latent heat storage is based on the phase change properties of the medium and has the advantage of storing heat at an almost constant temperature [9]. In recent years phase change materials (PCM) have drawn their attention as a medium for thermal energy storage in building envelopes due to their superior properties [10]. PCM has been incorporated in building envelopes (walls, roof, windows, and floor) to minimize the need for additional heating and cooling systems [11]. In the study [12], a PCM-enhanced gypsum board is installed on the building envelope (retrofitting) to reach higher energy flexibility and power efficiency than the regular building envelope. Another study examined the PCM-enriched hempcrete and concluded that by adding 20 wt% microencapsulated PCM to the concrete/hemp mixture, heat capacity was raised by 70 % [19]. Kalbasi and Kassani, in the study of the effect of PCM presence on comfort, conclude that the building with the addition of PCM can reach a comfortable temperature range (18 °C to 27 °C) up to 82 % of the year without an additional heating system [13]. In many other recent papers [14]–[19], PCM incorporation in building envelopes has been studied and proven successful in reducing additional heating and cooling demand in buildings. Active PCM systems can save up to one-third of the additional energy consumed in heating and cooling systems than passive solutions [20]. Despite the advantageous PCM properties of energy storage capacity, when used in building envelopes, it has to be coupled with insulation material to preserve stored heat for longer periods of time. The insulation is crucial for building envelopes that are used in northern climate zones on account of cold winter and medium spring and autumn seasons, as well as only partial solar radiation availability. To intensify the energy accumulation of the available solar energy in northern Europe climate zones, the application of active building envelopes (ABE) is one of the most reasonable solutions [21] as they interact with the changing environment. By using ABE, which utilizes on-site solar radiation, thermal energy can be stored and released from the building, taking off the load from heating [22] and cooling [23] systems. Conventional building insulation materials do not always meet the needs of ABE applications due to their properties (weight, size, volume, etc.). Here innovative insulation materials such as aerogel can be useful. It is an ultra-light, transparent, ecological material with excellent heat insulation properties [24]. Solar energy is available only partially due to different seasons and dynamic weather changes in the northern Europe climate zone. Such conditions indicate the need to capture available solar heat as much as possible. Additional dynamic elements in ABE, such as reflective blades and light-concentrating lenses, can enhance heat transfer into thermal storage. This study aims to utilize PCM in combination with high thermal performance insulation – aerogel into the dynamic solar facade module; it is possible to accumulate solar thermal energy that can be used for water and space heating. The application in buildings of such facade modules in the northern European climate zone has a great potential to noticeably reduce the dependence on conventional fuel-based energy usage for heating [13].

## 2. METHOD

Our research team is working on developing a dynamic solar facade with solar energy storage in PCM for the northern Europe climate zone. The methodology steps for elaborating the dynamic solar facade are presented in Fig. 1. The overarching research is divided into four large stages to advance through technological readiness levels from TRL2 – evaluating the potential of suitable components; to TRL6 – demonstration in the relevant environment. In this paper Stage 2 of the research is presented – variations of components of solar façade are compared. Particularly, the effect of the Fresnel lens focal point location and cone dimensions on heat transfer in small-scale solar facade modules is tested in laboratory conditions.

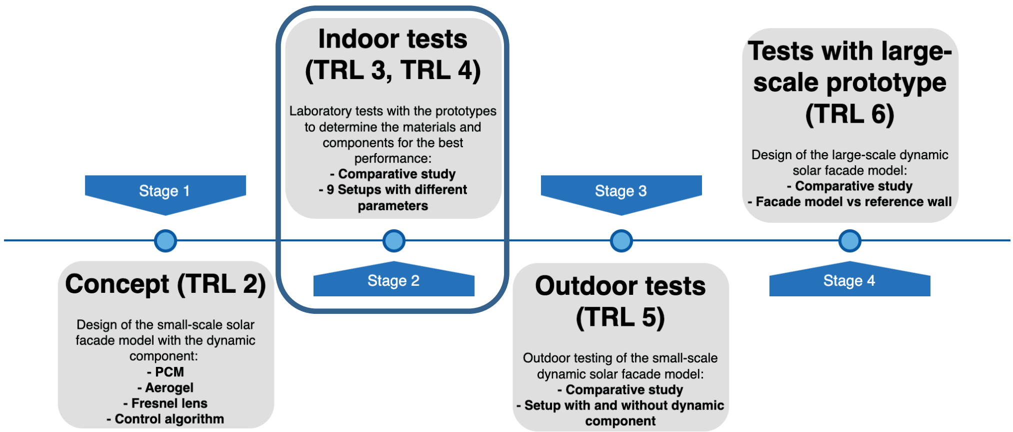


Fig. 1. Scope of the research (Stage 2) within the framework of the whole study [25].

The terminology used in this paper is illustrated below in Fig. 2. The setup is a tested composition of a solar façade module (left). Nine different composition variations are compared and described here in the paper. The test stand is an arrangement and equipment of the experiment (middle). Large-scale solar façade module will be tested in the relevant environment and composed of several small-scale solar façade modules (right).

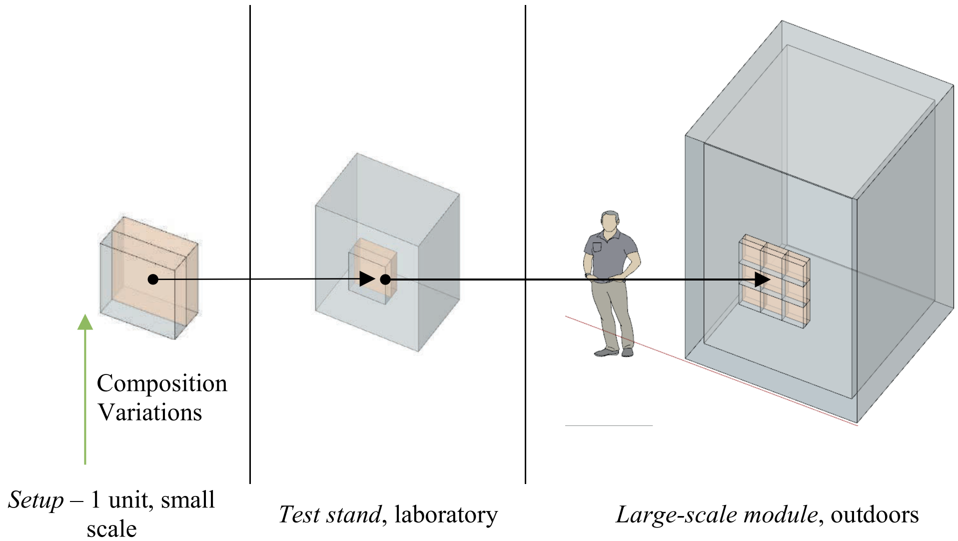


Fig. 2. The terminology used in paper.

### *2.1. Small-scale solar facade module*

The proposed solar façade is a complex system; it consists of different components that provide the system's operation. To ensure optimal operation and heat transfer into the energy storage (phase change material), it is necessary to configure the components and their combinations for relevant border conditions. Small-scale solar facade module consists of several components (see Fig. 3): dynamic component, which includes moving reflective blades filled with aerogel insulation; Fresnel lens; cone-shaped air gap; aerogel (semi-transparent) insulation layer; PCM container and transparent glass shell that encloses the aerogel layer. The size of the small-scale module is 250 mm in width and 250 mm in height. The depth is dependent on the composition. The dynamic component supports the energy transfer from solar radiation to phase change material and reduces heat losses. Fresnel lens operates as an energy transfer enhancer into the PCM storage unit. A previous study [25] concluded that the aerogel layer thickness and cone diameter directly affect the temperature changes in PCM. These two variables are directly responsible for heat transfer between indoor and outdoor environments as the cone diameter determines the air gap volume between the Fresnel lens and PCM container. However, the aerogel insulation layer sets the focal point location of the Fresnel lens and insulates the heat storage around the cone. It was observed that the location of the focal point on the surface of the PCM container in some compositions was not beneficial. Therefore, as the next, the question of the impact of the focal point location in the phase change material on heat transfer in the proposed solar façade was raised. The experiment plan was designed to test the advanced versions of the solar façade module and evaluate the effect of focal point location and the size of cone diameter on heat transfer.

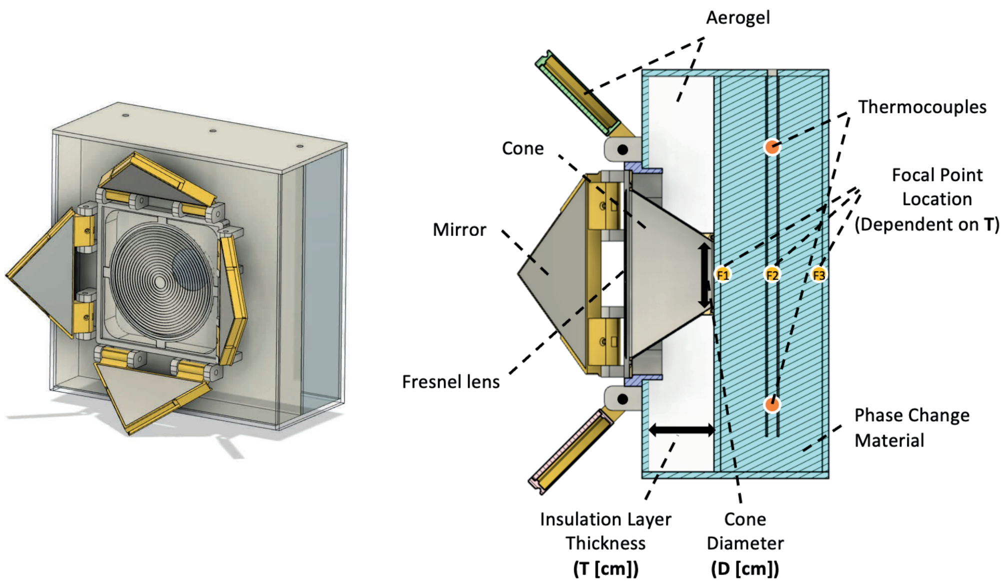


Fig. 3. Design of the small-scale solar facade module and its cross-section (TRL4).

### *2.2. Experimental testing stands and measurements*

Nine different setups (solar façade compositions) of solar façade module were elaborated based on three variations of two parameters – the location of the Fresnel lens focal point (defined as the insulation layer thickness) and the size of the cone diameter. The focal point has been described with three different values that reflect its location on the inner and outer surfaces and in the middle of the PCM container. The values for cone diameter are selected from two to four centimeters. The variations of the setups are listed in Table 1.

TABLE 1. VARIATIONS OF THE EXPERIMENTAL SETTINGS IN TEST SETUPS

| **Insulation layer thickness T, cm** / **Cone diameter D, cm** | **3** | **5** | **7** |
|---|---|---|---|
| 2 | Setup F1 D2 | Setup F2 D2 | Setup F3 D2 |
| 3 | Setup F1 D3 | Setup F2 D3 | Setup F3 D3 |
| 4 | Setup F1 D4 | Setup F2 D4 | Setup F3 D4 |

For the testing rounds, a test stand was created. Small-scale solar facade module setups were enclosed into the extruded polystyrene (XPS) layer and plywood case (350×350×250 mm) to limit the impact of the surrounding environment on the heat transfer processes in the setup (see Fig. 4). The thickness of the insulation layer all around the tested module is 100 mm.

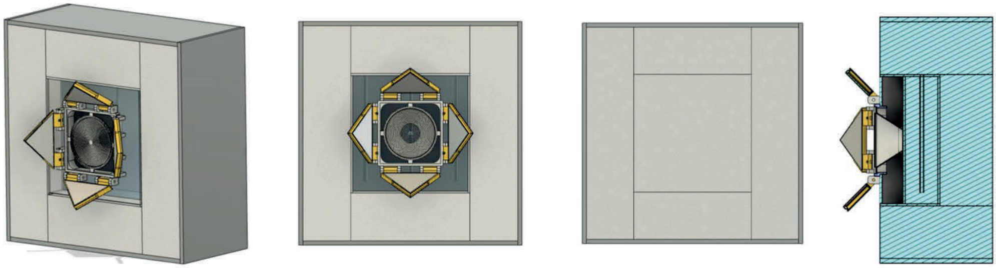

Fig. 4. Experimental stand of small-scale solar facade module.

The material characteristics of the components used in the small-scale solar facade module setups and test stand are listed in Table 2.

TABLE 2. COMPONENTS OF THE SMALL-SCALE SOLAR FACADE MODULE

| **Component** | |
|---|---|
| PCM | RUBITHERM RT21HC<br>Melting area: 20–23 °C<br>Congealing area: 21–19 °C<br>Density 15 °C: 0.88 kg/l<br>Density 40 °C: 0.77 kg/l<br>Heat storage capacity ± 7.5 % 190 kJ/kg |
| PCM glass container | Dimensions: 242 × 242 × 62 mm<br>Thickness: 4 mm |
| Plywood | Thickness: 9 mm<br>λ = 0.13 W/mK |
| XPS | 100 mm<br>λ = 0.037 W/mK |

Experiments were conducted in the climate chamber under the same conditions. Two setups were tested simultaneously using two halogen lamps to simulate solar irradiance. The application of halogen lamps for solar radiation simulation was based on studies [26] and [27] that describe lamps' characteristics and properties and indicate their similarities to the sun's light. Comparison of setups is based on the analysis of temperature changes in phase change material. Temperature is registered in the PCM container with five thermocouples labeled according to their location in the PCM container (see Fig. 5(b)): the letters L, M, and R stand for their place on the x-axis (L – left, M – in the middle, R – right) and the numbers represent the location on the y-axis (1 – lower, 2 – upper). The measurements were registered once a minute using multipurpose data logger CR1000 Campbell Scientific. Solar irradiance was measured with the pyranometer CMP3, Kipp & Zonen. Type T thermocouples were used to measure the temperature in the PCM. Fig. 5(a) shows the layout of the test stand in the climate chamber and the spots of temperature measurements in the PCM container.

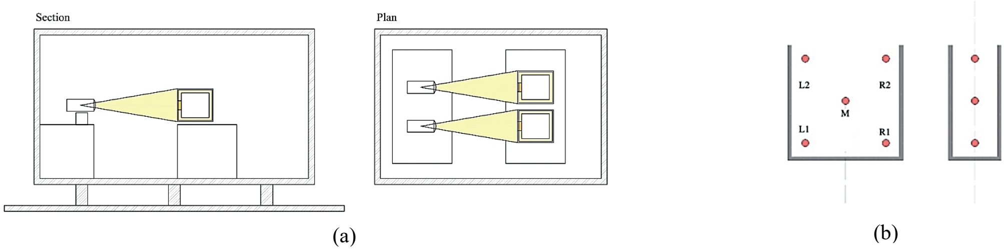


Fig. 5(a) Layout of the test stand in the climate chamber and (b) temperature measurement spots inside the PCM container.

The conditions for all the setups are listed in Table 3. The climate conditions in the autumn and spring seasons provide the most significant potential for the proposed solar facade system to reduce energy consumption for heating. These two seasons in northern Europe's climate are similar in average temperature and amount of available solar radiation. Parameters such as solar irradiance, ambient temperature, and the duration of daylight were set for experimental conditions according to a typical autumn/spring day in Riga (Latvia). They were identified by data analysis from the local metrological station (see Fig. 6). Average solar radiation and average ambient temperature was calculated based on measured data. In the period of observation, it is 300 W/m$^2$ and 10 °C, respectively.

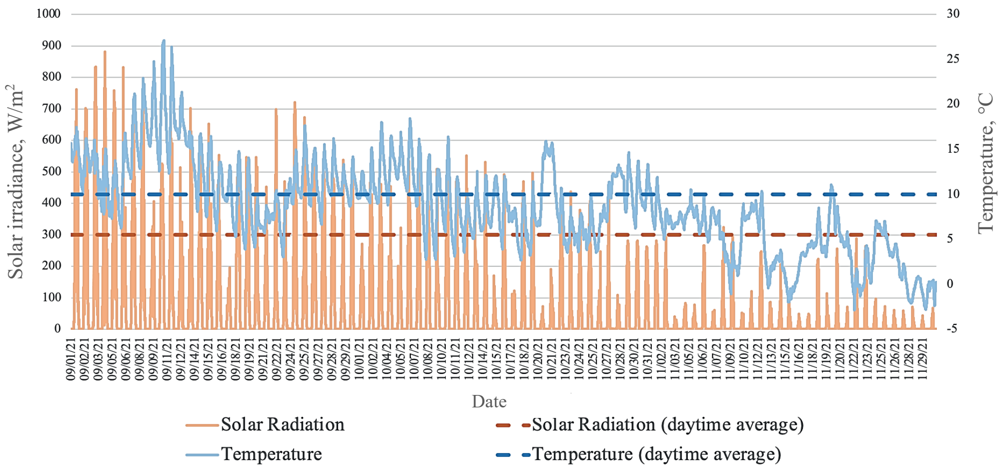


Fig. 6. Data from the Riga Technical University metrological station from September to December 2021.

The experiments were conducted in the climate chamber where the ambient temperature was set to 10 °C. The experiment takes place for 16 hours – 8 h with solar radiation simulation (‘daytime’ phase) and 8 h without solar radiation (‘nighttime’ phase). The blades of the dynamic component were static in this experiment. Two positions were set – during the ‘daytime’ blades were open and concentrated the light from the lamps to the center of Fresnel lens, but in the nighttime, blades were in a closed position, to reduce heat losses from PCM to the surroundings. Test conditions are summarised in the Table 3.

TABLE 3. CONDITIONS OF THE TEST SETUPS

| Condition | Value |
|---|---|
| 'Daylight' duration (solar simulation is switched on) | 8 h |
| 'Night-time' period (solar simulation is switched off) | 8 h |
| Irradiance (solar simulator) intensity | 300 W/m$^2$ |
| Outdoor (ambient) temperature | 10 °C |

## 3. RESULTS

Nine test rounds were performed (one for each setup). The obtained results of the average temperatures in PCM containers in all setups are presented in Fig. 6 and Fig. 7, and sorted by focal point location and cone diameter.

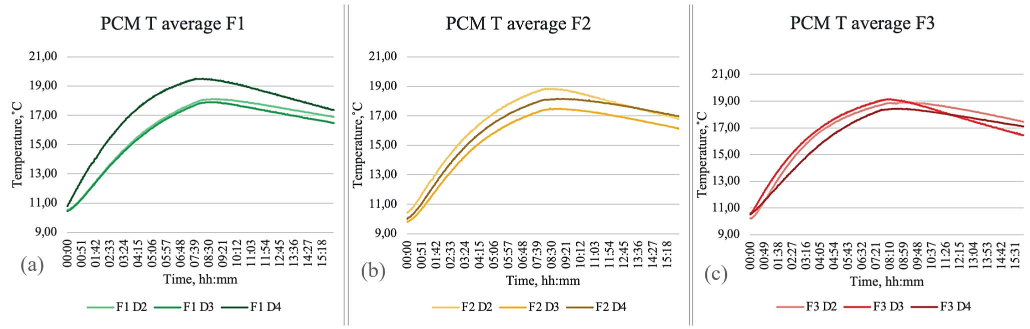


Fig. 6. Average temperatures in PCM container in all the Setups by focal point location: (a) – F1, (b) – F2 and (c) – F3.

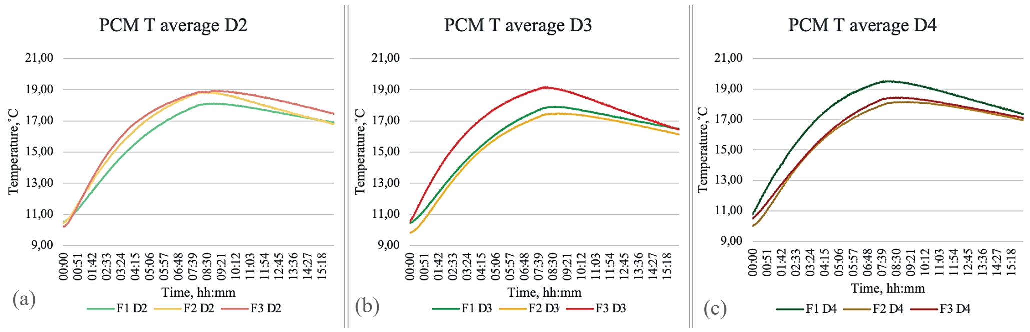


Fig. 7. Average temperatures in PCM container in all the Setups by cone diameter: (a) – D2, (b) – D3 and (c) – D4.

In the Setups with focal point location F1, the highest average temperature in PCM is reached with the widest cone diameter – D4. However, moving the focal point closer to the center of the PCM container gains higher average PCM temperatures with cone diameters D3 and D2. The graphs of setups F2 D2 and F3 D3 indicate a steeper temperature drop during the 'nighttime' period compared to other setups with the same focal point location. A similar tendency can be observed in Fig. 7 diagrams, where steeper 'nighttime' period curves (i.e., temperature drop) appear by enlarging the cone diameter.

Fig. 8 represents the maximum average PCM temperature during the test cycle and average PCM temperature at the end of the test cycle. The maximum temperature is reached in setup F1 D4; however, at the end of the experimental cycle, it drops lower than in setup F3 D2. The highest average PCM temperature at the end of the test cycle is in The most significant temperature drop during the test cycle is observed in setup F3 D3 – it has the second highest maximum average PCM temperature, and at the end of the experimental cycle, temperature decreases almost by 3 °C.

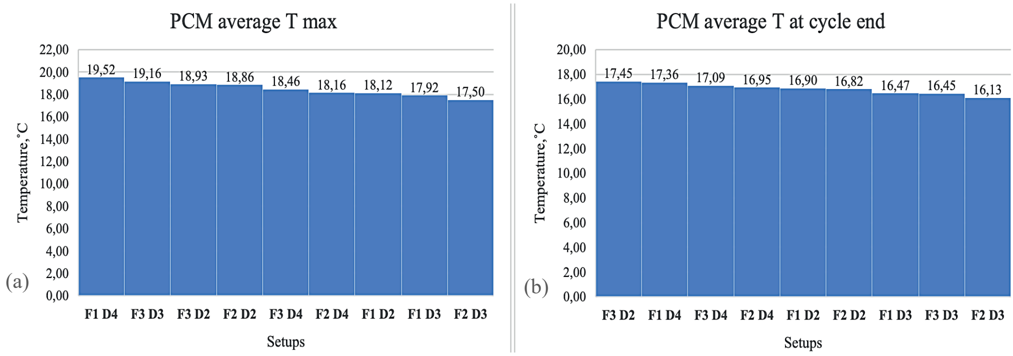


Fig. 8. Maximum average PCM temperature (a) and average PCM temperature at the end of the test cycle (b).

Fig. 9 illustrates the temperatures in PCM different layers measured by thermocouples. The temperature in Setup F1 D4 gradually rises in similar inclination in all the layers of PCM during the daytime cycle; on the contrary, the same temperature curves in Setups F2 D3 and F3 D2 are in broader amplitude. The central layer T M of PCM in all the Setups reaches the highest temperature at the end of the experimental cycle.

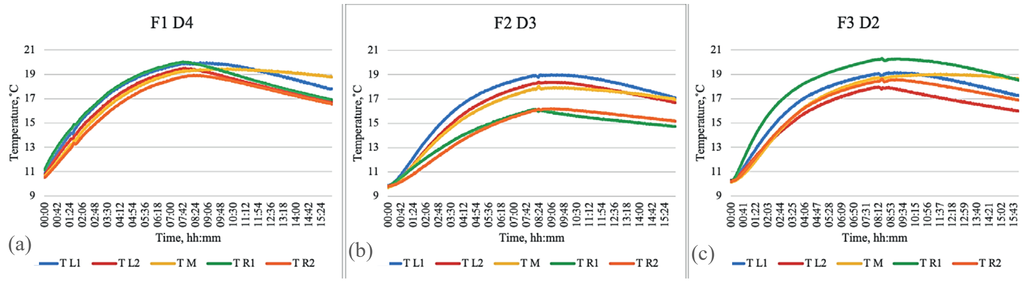


Fig. 9. Temperatures in PCM different layers (L1, L2, M, R1, R2) in Setups F1 D4 (a), F2 D3 (b) and F3 D2 (c).

## 4. CONCLUSIONS

The obtained results of temperatures in PCM indicate several conclusions:

1. The most significant amount of heat transferred into the phase change material is reached with setup F1 D4; during the 'daytime' cycle, the highest maximum temperature of 19.52 °C is gained in this setup.
2. The highest average temperature in PCM at the end of the test cycle is observed in the setup with the smallest cone diameter, which differs by 7.5 % compared to the setup with the lowest average PCM temperature. The lowest amount of heat was lost in setup F3 D2.
3. Moving the focal point location from the place on the PCM container's surface closer to

the PCM container's center means faster heat transfer with smaller cone diameters. Comparing setups F1 D4 and F3 D2, the results show that the average PCM temperature is 3 % higher in setup F1 D4.

4. Heat transfer enhancement can be achieved with a large cone diameter and thin aerogel layer (F3) in the 'daytime' cycle, yet the heat loss in 'nighttime' cycle reduces the total benefit. In setups F3 D3, the average PCM temperature is the second highest – 19.16 °C, however at the end of the cycle temperature drops to the second lowest 16.45 °C.
5. Both – focal point location and cone diameter significantly affect heat transfer enhancement in PCM. Comparing setups F1 D2 and F1 D4, the average PMC temperature increase is observed by 7.2 %. Similarly, comparing setups F3 D4 and F1 D4, the temperature increase is 5.4 %.

The experiments show that the best-performing test setup is Setup F1 D4. However, by implanting the module into the dynamic solar envelope, the focal point distance should be selected considering the aerogel insulation layer thickness. The aerogel insulation layer prevents the system from heat losses when ambient temperatures are low, and solar radiation is not enough. Obtained results show that by selecting a wider cone diameter, the heat transfer can be enhanced; therefore, for the studied solar facade, the most suitable setup is with an aerogel insulation layer of 7 cm and focal point location F1.

This paper reviews the laboratory testing stage of the complete dynamic solar facade development research. The effect of Fresnel lens focal point location and cone diameter on heat transfer enhancement in PCM has been evaluated. In a further study, it is planned to incorporate small-scale modules presented here into a large-scale façade and test it in relevant conditions. A PASLINK-type experimental setup will be used to conduct a comparative analysis – the proposed solar energy storage technology will be compared to the performance of a conventional facade such as a triple-glazed window.

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