VOL. 9, NO. 1 (2023)

TOWARDS A NEW ETHICS IN BUILDING

TEMA
Technologies
Engineering
Materials
Architecture

Journal Director: R. Gulli

e-ISSN 2421-4574
DOI: 10.30682/tema0901

Guest Editors: A. Sanna, G. Di Giuda, L.C. Tagliabue

Assistant Editors: A.C. Benedetti, C. Mazzoli, D. Prati

Cover illustration: Jewish Museum Berlin by Daniel Libeskind, The Garden of Exile, Berlin, Germany, 2001. © Riccardo Gulli (2009)

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
ISBN online 979-12-5477-288-1
DOI: 10.30682/tema0901
Vol. 9, No. 1 (2023)
Year 2023 (Issues per year: 2)

Publisher:
Ar.Tec. Associazione Scientifica per la Promozione dei Rapporti tra Architettura e Tecniche per l'Edilizia
c/o DICATECH - Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica - Politecnico di Bari
Via Edoardo Orabona, 4
70125 Bari - Italy
Phone: +39 080 5963564
E-mail: info@artecweb.org - tema@artecweb.org

Publisher Partner:
Fondazione Bologna University Press
Via Saragozza 10
40123 Bologna - Italy
Phone: +39 051 232882
www.buponline.com

TEMA: Technologies Engineering Materials Architecture
Vol. 9, No. 1 (2023)
e-ISSN 2421-4574

TESTING AND COMPARISON OF AN ACTIVE DRY WALL WITH PCM AGAINST A TRADITIONAL DRY WALL IN A RELEVANT OPERATIONAL ENVIRONMENT

TEMA Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 1 - (2023)

Marco Imperadori, Nicole Di Santo, Marco Cucuzza, Graziano Salvalai, Rossano Scoccia, Andrea Vanossi

DOI: 10.30682/tema0901i

Abstract

As the building stock plays an essential role in meeting Europe's climate target, suitable strategies are necessary for the sector transition. This paper compares two dry-multi-layer walls characterized by different compositions: one applies heat reflective insulation with Phase Change Materials (PCM), while the second uses traditional glass wool batt. The experimental tests were conducted in a retrofitted building, the VELUXlab, a multi-testing laboratory located at Politecnico di Milano University (Italy), as one of the main outputs of the TEPORE project granted by the Lombardy Region. The temperatures and Heat Flux were measured through sensors between the inner and outer surfaces of the traditional wall (Dry Wall) and the false-wall with PCM (Active Dry Wall). The goal was to compare the two technologies evaluating the performance during daytime and nighttime in the winter season. Outcomes showed the advantages of the PCM application on space heating energy needs, revealing that their integration into the false-wall decreases the temperature by 1°C for a 30-40% thermal savings in the building envelope heat losses per week during cold seasons compared to the traditional wall. The study reveals that the PCM layer reduced the peak Heat Flux by 2.67 W/m^2 during the accumulation and release period.

Keywords

PCM, Dry construction technology, Energy efficiency, Thermal inertia, Sensors.

Marco Imperadori
DABC - Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, Milano (Italy)

Nicole Di Santo
DABC - Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, Milano (Italy)

Marco Cucuzza*
DABC - Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, Milano (Italy)

Graziano Salvalai
DABC - Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, Milano (Italy)

Rossano Scoccia
Dipartimento di Energia, Politecnico di Milano, Milano (Italy)

Andrea Vanossi
DABC - Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, Milano (Italy)

** Corresponding author: e-mail: marco.cucuzza@polimi.it*

1. INTRODUCTION

The European Parliament and the Council's request for highly efficient buildings [1] regard not only the near-zero annual balance between produced and absorbed energy (NZEB) [2] but also the reduction of life-cycle-related greenhouse gas emissions [3]. Indeed, almost 40% of in-home energy use is due to occupants' interaction with the building's systems [4, 5], generating an enormous amount of environmental impact [6, 7]. In this perspective, the adoption of Phase Changing Materials, mainly in lightweight technology [8], can be a suitable "carbon-effective" investment to refurbish existing buildings [9] or new constructions [10]. Even though the buying price of PCM is relevant, it has been observed that the payback cycle of the system is efficient thanks to the cost of energy saved [11] by lowering the cooling and heating demand. In active systems, the PCM is a possible heating peak load shifting strategy for buildings to achieve indoor thermal comfort, especially for applications to existing buildings to improve the current installation's performance [12]. On the one hand, auxiliary studies on dynamic energy simulation show that construction solutions with PCMs can cut consumption by flattening the indoor temperature fluctuations and reducing/shifting the load peak [11] due to the heating store capacity of the material (artificial inertia). On the other hand, the monitoring campaign on indoor environmental quality metrics and energy consumption of a building designed with PCM and installed in the second story of the west unit [13] shows that the installation of PCM had a positive effect on thermal comfort, reducing the estimated annual overheating hours from about 400 to 200 and that has a significant impact on the building's energy consumption.

Some other research [14] demonstrated that a suitable storage system capable of accommodating the thermal loads arising within the room during the daytime, a 5 cm layer of microencapsulated PCM (25% by weight of the ceiling material) and gypsum in a ceiling panel are sufficient to maintain a comfortable room temperature in standard office buildings [15]. The addition of a PCM layer to building walls [16] shows that: (i) the PCM-integrated walls are advantageous mostly in moderate climates and when the daily temperature swings should be favorable to permit free ambient cooling/heating; (ii) the transition temperature of the PCM should be optimized to enhance the utilization of the PCM; (iii) the location of the PCM in the wall should be tweaked so that the layer can interact with both the exterior as well as the interior environments. A further study [17] highlighted that incorporating PCMs in buildings' walls, floors, and ceilings can significantly release load management. Indeed, PCM can offer a higher storage capacity [18] associated with the latent heat of the phase change, accumulating and discharging heat and cold on-demand, and controlling humidity in various applications. Additionally, different parameters may influence the performance of PCM, as the location of the PCM layer embedded in walls and the environmental conditions [19] affect the thermal proprieties, as the absorption and release of latent heat can radically change. The study reports that PCM with a transition temperature of 22-24°C, located in the middle of the wall, reduces the annual heat gain by 3.5%-47.2% and the annual heat loss by -2.8% and 8.3%, depending on the location considered in this reference study using USA climate [16].

Although the literature shows many studies related to the PCM effectiveness measurement, only some studies compare their efficiency by analyzing data from case studies instead of digital/theoretical models. Therefore, the need to further investigate the PCM application with a work aiming to compare the behavior of two real false-wall, one with PCM, to assess their inertial capacity in heating mode. The intention is to support the ecological transition to a more sustainable – and ethical – approach to buildings by estimating the amount of energy savings thanks to the combined use of sensors and a thermographic survey. This double method of analysis looks at meliorating not only the quality of life and integrity of buildings but also that of individuals according to climatic zones and comfort requirements.

Accordingly, the obtained results for the winter season could be examined and verified in further development for the summer season, where the artificial inertia capacity of Phase Changing Materials allows for flattening the temperature peak around noon and releasing stored heating during the night.

2. METHODS

The present paper aims to compare two types of portions of multi-layer technology false-walls – the first is called Active Dry Wall with a layer of phase change materials (PCMs) between the gypsum boards, and the second is a traditional Dry Wall [20]. They were installed as two portions of counter wall in VELUXlab, a Politecnico di Milano test building. This work is part of the TEPORE project, a research project supported by the Lombardy region (Italy) that evaluates the application of innovative envelope technology based on the heat sink effect [21] in efficient and intelligent buildings under heating through a sensor-based upgrade approach [22]. The selected technologies were chosen because of their market diffusion as a standard dry wall solution to compare with an efficient PCM layer composition among materials furnished by the project partners. The comparison between various building components and products is carried out through their on-field performance by checking, monitoring, analyzing, and optimizing the energy consumption and comfort in heating mode.

Several sensors were installed between the false-walls to detect the surface temperature and heat flow. Realizing two sensor walls with different stratigraphy allows for verifying their efficiency by an on-site survey of a data series derived in a digital environment. The smart control technique is applied to enhance and monitor their performance and make them cost-effective [12] from the sustainable design perspective, i.e., BIM 6D [23].

The research evaluates PCM's energy performance for 69 days within a test facility building to observe the winter seasons' behavior compared to traditional dry wall technological solutions [14, 21]. The progress ensured by the data collected is crucial to understanding the material's behavior in different climate conditions (rainy, cloudy, and clear sky), the humidity of the environment and the radiation level as a parameter of influence for the artificial inertia performance. The survey was taken from 24th November 2018 until 1st February 2019. The results are reported both in a medium-term perspective (Section 3.3. *Weekly Analysis*: 24th–30th November), with a daily focus (Section 3.2. *Daily Analysis*) and on-the-spot comparison, as expected behavior of the technology during the winter period (Section 3.4. *Weekly Comparison of Active Dry Wall and Traditional Dry Wall*). Parallelly, on the 6th and 12th of November 2018, a thermographic survey (Section 3.1. *Thermographic Survey*) analyzed the surface temperature of the wall to check and compare results with analytical data from sensors (Section 3.5. *Temperature Section Analysis*).

2.1. COMPONENTS FEATURES

The energy performances of the two dry wall technologies (Active Dry Wall and Dry Wall) are compared using the monitoring data collected by sensors. In particular, sensors are inserted into different layers of the two false-walls installed on the existing building envelope, as described in Section 2.2 Experimental setup. The stratigraphies of the two false-walls are:

- Active Dry Wall: plasterboard, PCM sachets, plasterboard, reflective honeycomb thermal insulation, air cavity, thermal reflective insulation;
- Dry Wall: plasterboard, air cavity, plasterboard, glass wool insulation, air cavity, thermal reflective insulation.

The main thermal properties of the wall materials are reported in Table 1.

Item	Width x Height (mm)	Thickness (mm)	Density (kg/m³)	Specific Heat Capacity (J/kgK)	Thermal conductivity (W/mK)	Quantity
Laths for fixing Multi-Reflective Insulation	40 x 2,000	15	-	-	-	1 m²
Metal frame	C,U 40 x 2,000	75	-	-	-	7.4 m
Gypsum board	1,200 x 2,500	12.5	680	1,000	0.21	10 m²
Thin Multi-Reflective Insulation	1,220 x 2,000	-	20	1,450	0.04	5 m²
Honeycomb insulation	550 x 2,000	100	9	2,300	0.033	2 m²
Glass wool	550 x 2,000	75	21	1,030	0.33	2 m²
PCM	124 x 122	12.5	14,000	Solid state 5,000 Liquid state 2,000	0.93 0.75	6 sachets

Tab. 1. *Material items referred to Dry Wall and Active Dry Wall installed on the south side of the east wing of VELUXlab. Characteristics of Thermal Capacity and Thermal Conductivity of PCM in the solid and the liquid state.*

Specifically, thermo-reflective insulation is multi-reflective thin insulation based on sheep wool, airtight and watertight. It is positioned to detach the two false-walls from the effect of the external closure behind them. In particular, it preserves results from direct radiation affecting the west wall during the afternoon and avoids heat loss from inside to outside during the night. The honeycomb insulation ensures winter and summer thermal insulation, acoustic insulation, and airtightness of buildings. The glass wool is used for thermo-acoustic insulation of walls, false-walls and false ceilings made with the dry system. Finally, the PCM used is a commercial solution (ClimSel C21©) in salt hydrate-based material in aluminum packets. Its main components are sodium sulphate, water, and additives. The starting melting temperature range is between 21°C (solid) and 26°C (liquid); the latent heat of fusion is 134 kJ/kg for a liquid density of 1.4 kg/l.

The internal false-walls were positioned in contact with the existing vertical closure, detaching the two walls by inserting thin reflective insulation using a galvanized lightweight metal frame with C studs and a U transom to contain the insulation. Different insulation layers characterize the systems because of their diverse behavior: the thermo-reflective insulation has no inertial performance, provided by the PCM sachets, while the traditional Dry Wall provides it through the glass wool. The two systems are selected because they are two conventional dry wall layers available on the market with comparable thermal transmittance.

The two walls are mainly differentiated by the presence of a layer of Phase-Change Material in the Active Dry Wall between two layers of plasterboard, whereas the traditional Dry Wall has an air cavity. The hydrate salt materials accumulate significant amounts of heat while maintaining a constant temperature during the transition phase (between 21°C and 26°C for the PCM material adopted: sodium sulphate, $Na_2 SO_4 \cdot 10H_2O$).

The two walls' comparative performance analysis is based on the PCM characteristic to exploit the cycles of heat release and heat absorption, allowing the regulation of the thermal condition of indoor environments during the heating time. The material allows heat flow while maintaining the same physical state. The material allows heat flow while maintaining the same physical state. The material starts its phase transition during its melting temperature, maintaining a constant temperature until the transition is complete when the heating flux restarts. The heating flux can be considered positive during the day when PCM stores heating by absorbing it from external radiation and negative during the night when the heating absorbed is released. The capability to store thermal energy related to phase transitions, allowing a temporary accumulation of thermal energy at a higher temperature and its release at a lower [21], can be described as "artificial inertia" [24]. According to the comfort temperature setup, the melting temperature of PCM is 21°C, although the inner temperature and the PCM surface temperature can be higher because of their location. The salt-hydrate superficial temperature can come up to 26°C in the winter because they are affected by direct sun radiation from the south window. The temperature can continue to increase once the transition to the liquid state is complete.

The comparative analysis of the performance [25] of the two walls in the facility building of VELUXlab, focuses primarily on the monitoring process through "sensing". The sensorization of walls is functional to collect data through the surface temperature and heat flow of the two technologies in the inner and outermost layers. As the building's nature is an office, comfort temperature is settled at the 20-26°C range and a working schedule of 8:00–18:00. During the winter season, the outside temperature float between -5°C and 10°C, with 2°C–7°C of average temperature in December.

2.2. EXPERIMENTAL SETUP

The case study of this research, which is part of the TEPORE project in collaboration with Smart Living – an initiative to investigate technologies and products application in home buildings – is VELUXlab, a multi-test building of the Politecnico di Milano at Bovisa Campus neighborhood in the northern part of the city (Fig. 1). The false-wall was installed against a portion of the west wall of the east wing of the VELUXlab, near three roof windows that allow light to enter and break down against the new construction (Fig. 2).

The data survey took place from 24th November 2018 until 1st February 2019 with a time step of 15 minutes. It was functional to test the proper functioning of these sensors and design the system of graphic representation

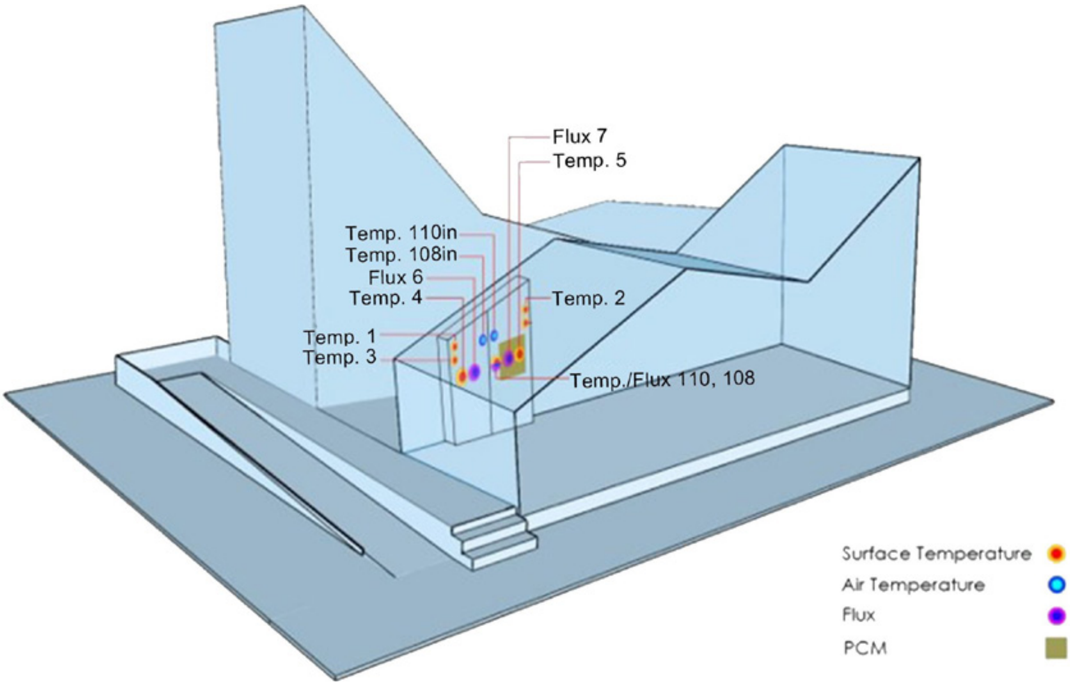


Fig. 1. *The 3D view of the east wing monitoring system: the Dry Wall, on the left side, and the Active Dry Wall, on the right one, installed on the south side of the east wing of VELUXlab.*

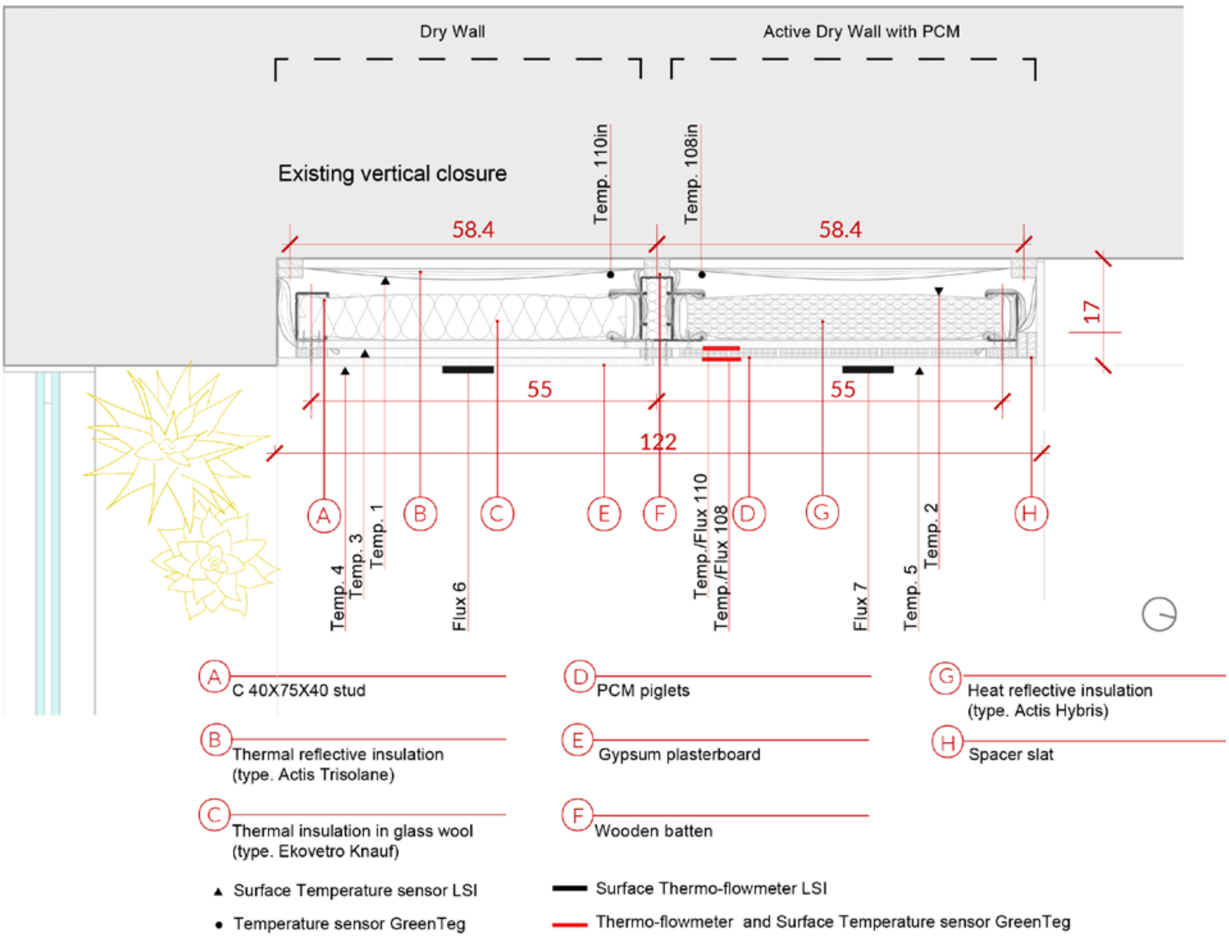


Fig. 2. *The horizontal section of the Dry Wall on the left side and the Active Dry Wall on the right one, installed on the south side of the east wing of VELUXlab, highlighting the sensor's location and the technology layers' composition. The two false-walls are detached from the existing vertical closure thanks to a vertical insulation layer (B) and the wooden batten (F).*

of the data collected. As described in Figure 2, the fully sensorized wall was equipped with the following:

- five surface temperatures and two flow sensors: LSI-LASTEM type (Temp.1_Dry Wall, Temp.2_PCM, Temp.3_Dry Wall, Temp.4_Dry Wall, Temp.5_PCM, Flux6_Dry Wall, Flux7_PCM).

  [The LSI-LASTEM features for Temperature (T) and Heat Flux (HF) are, respectively: Operational temperature range (°C), -50 to +70 (T), -30 to +70 (HF); Accuracy measurement, +/-0.1°C (T), +/-5 kW/m^2 (HF); Resolution sensors, 0.01°C (T)].
- two aerial temperatures and two flow and surface temperature sensors: GreenTEG type (Temp.110_Dry Wall, Flux.110_PCM, Temp.108_Dry Wall, Flux108_PCM, Temp.108int_PCM, Temp.110int_PCM).

  [The GreenTEG features for combined Temperature and Heat Flux are: Operational temperature range (°C), -40 to +80; Accuracy measurement, +/-0.1°C (T), +/-3 % (HF); Resolution sensors, 0.01°C (T), 0.09 W/m^2 (HF)].

The technology of materials and layers is defined as "invisible" because of the high performance achieved in small thicknesses. The use of multi-reflective materials and the high thermal capacity of PCM turn the building into "active" and even more "reactive" to external climatic stimuli in a shorter time. The experiment is conducted by creating two new false-wall portions instead of modifying the existing vertical closure. Sensors installed in the smart dry walls have constantly monitored the real performance of the envelope-plant-interior environment system (indoor comfort). The montage was carried out over the two half-days on the 10th and 11th of July 2018 (Tab. 2).

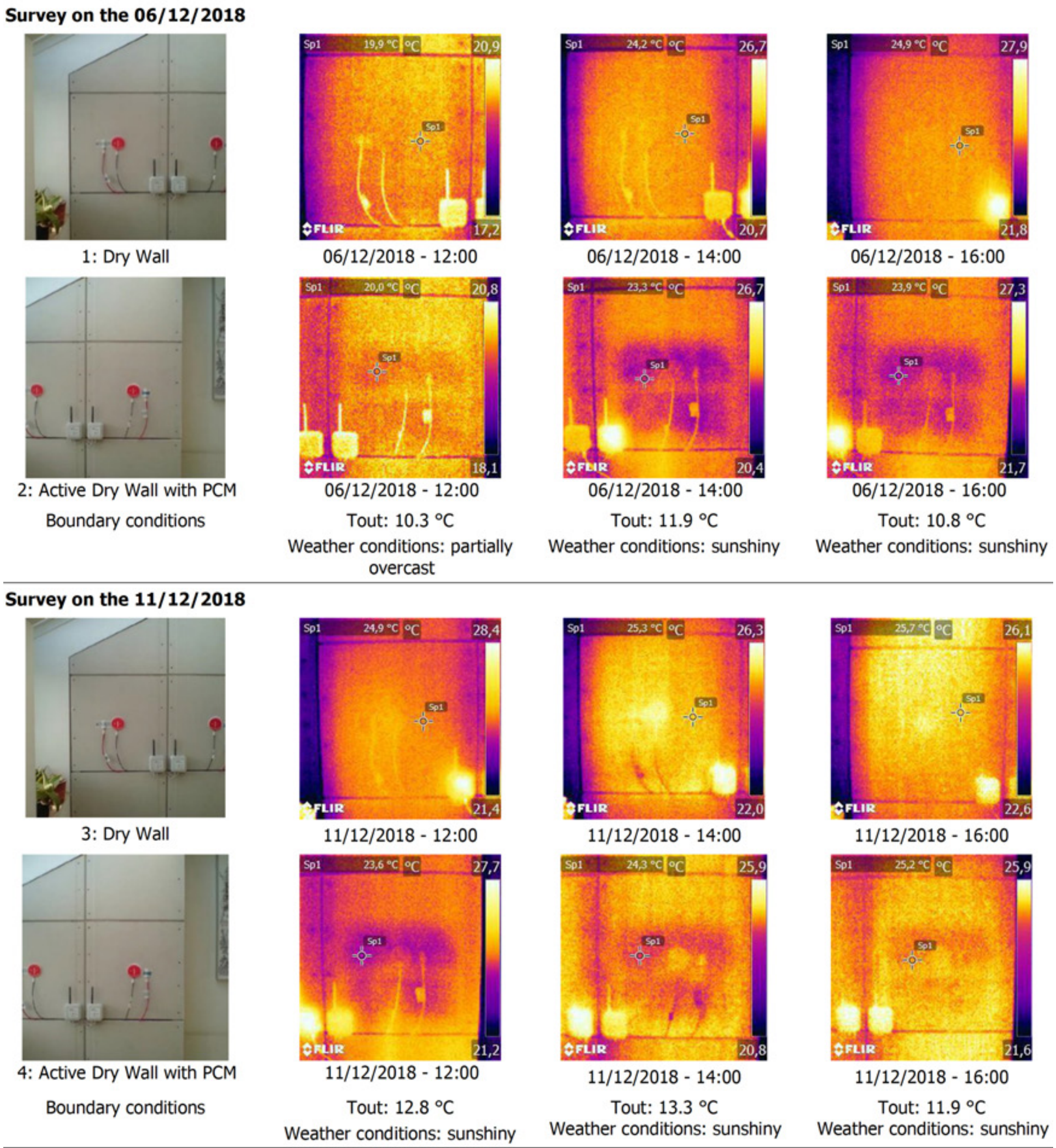
Tab. 2. *The installation phases with eight steps of the Dry Wall on the left flank and the Active Dry Wall on the right one, installed on the south side of the east wing of VELUXlab.*

The two Dry Walls are identically sensorized (Tab. 2 phases 6, 7 and 8) to collect and retrieve data. Data collected are analyzed from generic data (thermographic survey) to specific (sensors analytical values) and from the instantaneous moment to weekly behavior to extend the results to the whole winter season. This approach follows incremental knowledge progress by understanding the global effect of the PCM compared to a simple dry wall at first with lower precision data coming from the thermographic survey and then validating the results by quantifying the effective benefits of heating flux savings by the analytical sensor data collection.

3. RESULTS

3.1. THERMOGRAPHIC SURVEY

A thermographic survey campaign was conducted with the support of a FLIR T400 thermal camera. This survey aims to verify the thermal operation of the two technologies by observing the radiation emitted in the infrared range of the electromagnetic spectrum. The external temperature and weather conditions are collected by the closest weather station located in the northern area of Milan because of the influence of direct radiation and environmental temperature on the results.



Tab. 3. *The thermographic survey performed from 06/12/2018 to 11/12/2018 on the Dry Wall on the left flank and the Active Dry Wall on the right one, installed on the south side of the east wing of VELUXlab.*

The analysis was carried out simultaneously in three hours steps (12:00, 14:00 and 16:00), selecting days with similar weather conditions (sunshiny) to avoid the influence of environmental and climatic conditions of the place under analysis. The two chosen days are the 6th and the 11th of December (Tab. 3).

The results show a constant difference between the surface temperature of the Dry Wall insulation and the Active Dry Wall for both surveys: around 1°C higher for the glass wool insulation due to PCM's most significant heat absorption by its phase change. In the first survey (Tab. 3) on 6th December, the surface temperatures of the PCM and the glass wool insulation are similar (19.9°C and 20°C, respectively) because there is no direct sunlight affecting the wall (partially overcast weather conditions). In the second survey on 11th December, the initial delta at noon is higher (1.3°C, resulting from 24.9°C of the Dry Wall and 23.6°C of the Active Dry Wall) because of the radiation affecting the false-wall throughout the morning.

The higher reduction of the outside temperature from 13.3°C to 11.9°C accelerates the PCM inertial capacity reversion. It released the heat accumulated to the internal environment, having a similar surface temperature to the Dry Wall (0.5°C of the delta at 16:00 on 11th December instead of 1°C on 6th December).

3.2. DAILY ANALYSIS

The proposed analysis realized through fully sensorized walls aims to estimate their energy performances. The heat flow graphs measured on the Dry Wall (sensor Flux6_Dry Wall in Fig. 3a) and the Active Dry Wall with PCM (sensor Flux7_PCM in Fig. 3b) highlight the effect of both walls from the radiation metrics (the blue bar in the charts) as general behavior, with positive values when the sun is present. As a result of the solar radiation intensity peak (6.53 W/m^2 at noon), the surface temperature of the two walls (Temp.4_Dry Wall and Temp.5_PCM) increases together with the inner temperature, reaching the same temperature around 11:00 (21.22°C and 21.24°C respectively for the Dry Wall and the Active Dry Wall).

Instead, the different inertial capacity produces an effect on solar radiation: the Dry Wall closes the gap by approaching the values between the inner air temperature and its surface temperature after the solar radiation intensity peak (0.17°C at 15:00, 0.8% of the indoor temperature), while the Active Dry Wall saves 0.88°C, that is 4.1% of the inner temperature. This delta is constantly maintained during the whole day (0.76°C as the daily average value, around 3.8%), while the Dry Wall release more energy during the night, having at midnight a delta of 1.68°C (7.5% of the inner temperature), compared to 0.62°C (only 2.7% of losses) of the Active Dry Wall.

The difference between the delta daily average value for PCM (1.28°C, 0.6% minor than the inner temperature) and Dry Wall (0.76°C, 3.5% lesser than the internal temperature) is 0.52°C. Therefore, it is 2.5 times higher than the traditional solution, which reflects the superior attenuation capacity of the artificial inertia of the PCM material compared to the traditional one and results in a higher surface temperature during the night, levelling the peaks.

The Heat Flux analysis shows some delays between the two solutions: the accumulation period of Dry Wall starts at 6:00 (Fig. 3a), two hours before the PCM (8:00 in Fig. 3b), and finishes at 16:30, half an hour before the active Dry Wall. The peaks also confirmed the delay: PCM peak is 13.7 W/m^2 at 14:00, while the dry false-wall is 11.1 W/m^2 at 13:00 with a delta of 2.6 W/m^2 between the two maximum values. Comparing the area under the curve, the PCM Heat Flux is 20-30% higher in the accumulation period because of the delta of peaks, despite 1.5 hours less of accumulation. The trend is again confirmed during the night: the negative peak is 1.9 W/m^2 for the dry false-wall at 19:00, while the Active Dry Wall is -4.4 W/m^2 at 1:00. The discharger phase (highlighted in blue) is 2.3 times higher for the PCM due to its (artificial) inertial capacity. The global heating energy transfer for a single day (30th December) results in a reduction of 40%.

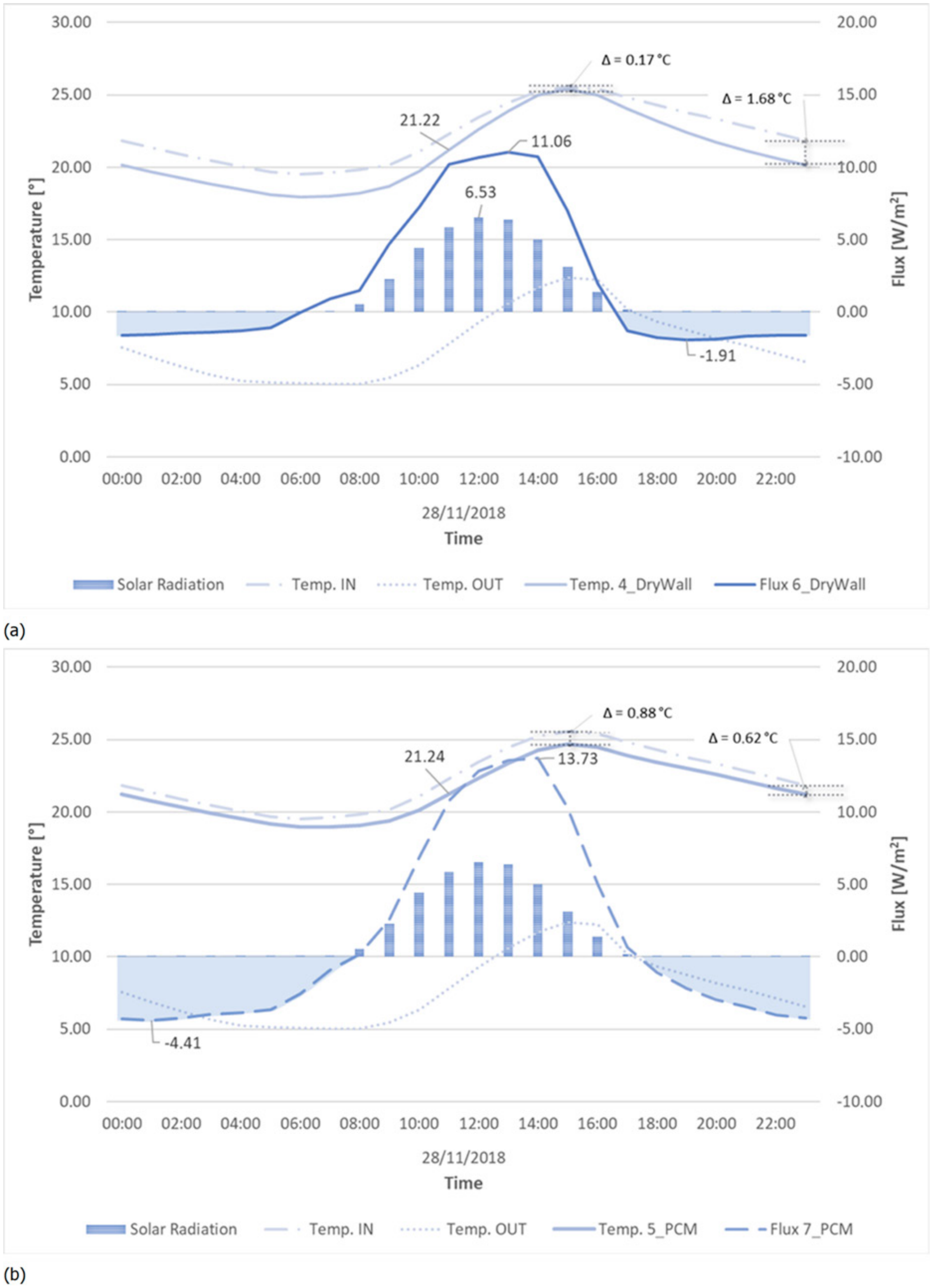


Fig. 3. *The Daily Analysis (28/11/2018) realized. (a) The Heat Flux (sensor Flux6_Dry wall) and the Internal Surface Temperature (sensor Temp.4_ Dry wall) of the Dry Wall – related to Inner and Outer Temperature (Temp.IN/Temp.OUT) and the Solar Radiation. The surface temperature (Temp.4_Dry wall) is close to the Inner Temperature peak at 15:00, while the discharger phase is relatively small compared to the accumulation period. (b) The Heat Flux (sensor Flux7_PCM) and Internal Surface Temperature (sensor Temp.4_PCM) of the Active Dry Wall with PCM – related to the Inner and Outer Temperature (Temp.IN/Temp.OUT) and the Solar Radiation. The surface temperature (Temp. 5_PCM) is constantly 0.9°C lower than the Temp.IN, while the accumulation and the discharger phases are similar in embodied energy thanks to the heat sink effect of PCM (artificial inertia).*

3.3. WEEKLY ANALYSIS

The weekly analysis (Fig. 4) shows a close to zero Heat Flux exchange for November 24th and 25th because the office was not populated, with closed shadings preventing radiation from acting on the false-walls and a set-point for the heating system of 17°C minimum. From Monday 26th to Friday 30th, the general path described is confirmed, showing a flux delay of 1 hour, a higher accumulation capacity of 20-30% and a similar gap of 2.7 W/m^2 in the negative peak. The accumulation peak shrinks when the radiation is lower: both are around 2 W/m^2 lower on the 29th and 30th, while the heating release is unrelated to the radiation path.

Besides, specific analysis for the portion of the wall with PCM (Fig. 5) compares the Heat Fluxes measured on the inner face of the plasterboard before the PCM (sensor Flux110_PCM) and on the exposed surface in the room after the PCM (sensor Flux7_PCM). The two surfaces have opposite Heat Flux curves due to the PCM heat shield effect. In the morning, salt and paraffin collect heat from the external surface – thanks to the direct sunlight – oppositely, the PCM releases the stored heat to the inner space during the night. The honeycomb reflecting insulation avoids heat loss to the external side, directing it to the inner side and coming to zero flux.

The global accumulation flux is 4.5 times larger than the discharger peaks; the proportion between the sunlight hours (13.73 W/m^2 on the 28th) and the night release (-4.31 W/m^2) is also confirmed on the 27th, as highlighted in the graph (Figure 5). On this day, the delta between accumulation (+15.31 W/m^2) and the release peak (-5.88 W/m^2) is also higher (21.19 W/m^2 on the 27th; 19.44 W/m^2 on the 28th) because of the high level of the outer temperature (14.5°C on 27th and 12.3°C on 28th).

Similarly, the releasing period shows the same path: the discharger delta at night (around 1:00) is about 4.71 W/m^2 on the 27th and 4.5 W/m^2 on the 28th, respectively,

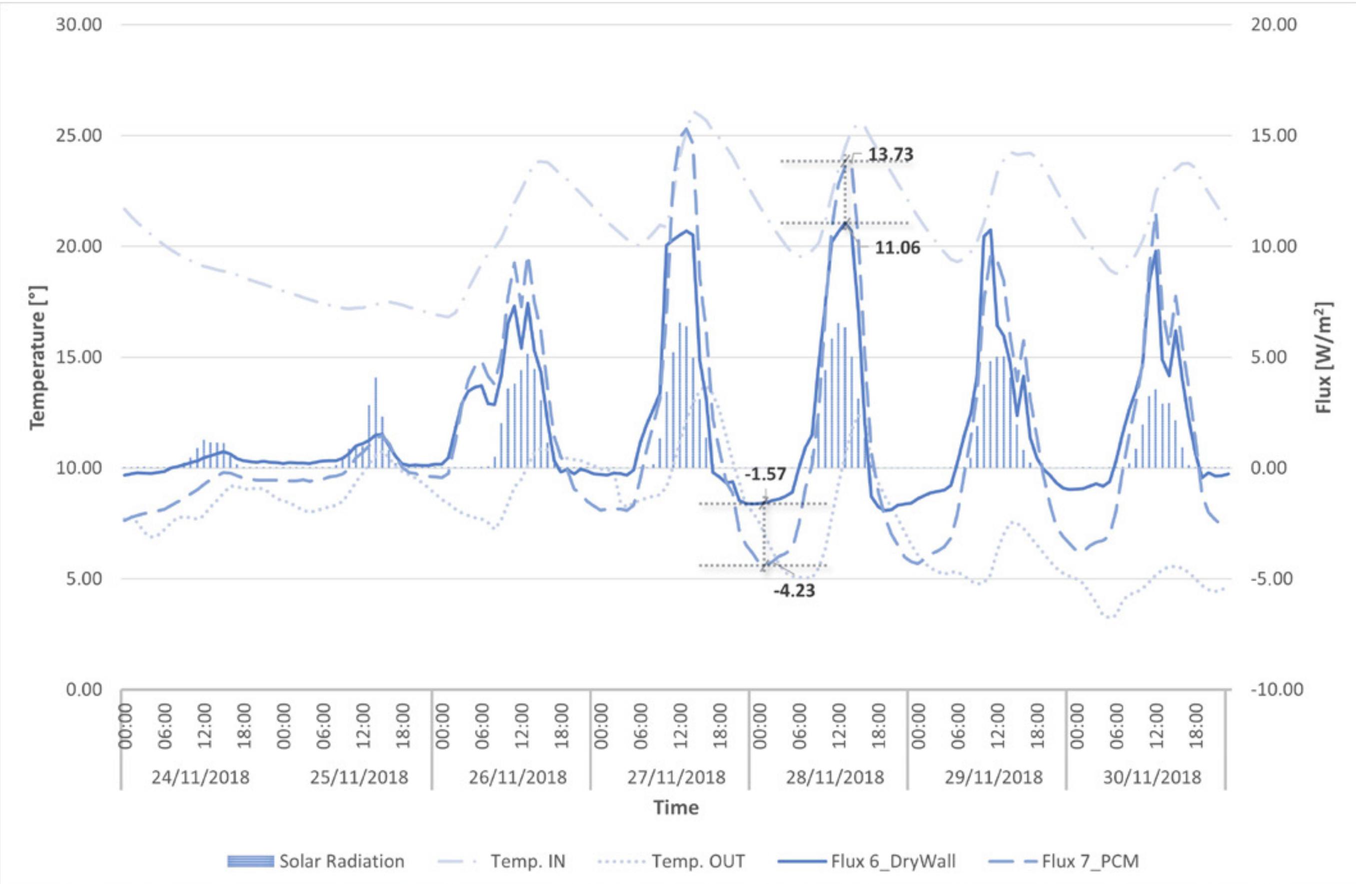


Fig. 4. *The image shows the Heat Flux path during the week for the Dry Wall (Flux6_Dry Wall) and the Active Dry Wall with PCM (Flux7_PCM). The Active Dry Wall heat flux follows the Radiation flow during the day: the accumulation peak is lower, and the radiation during cloudy days on 29/11/2018 and 30/11/2018.*

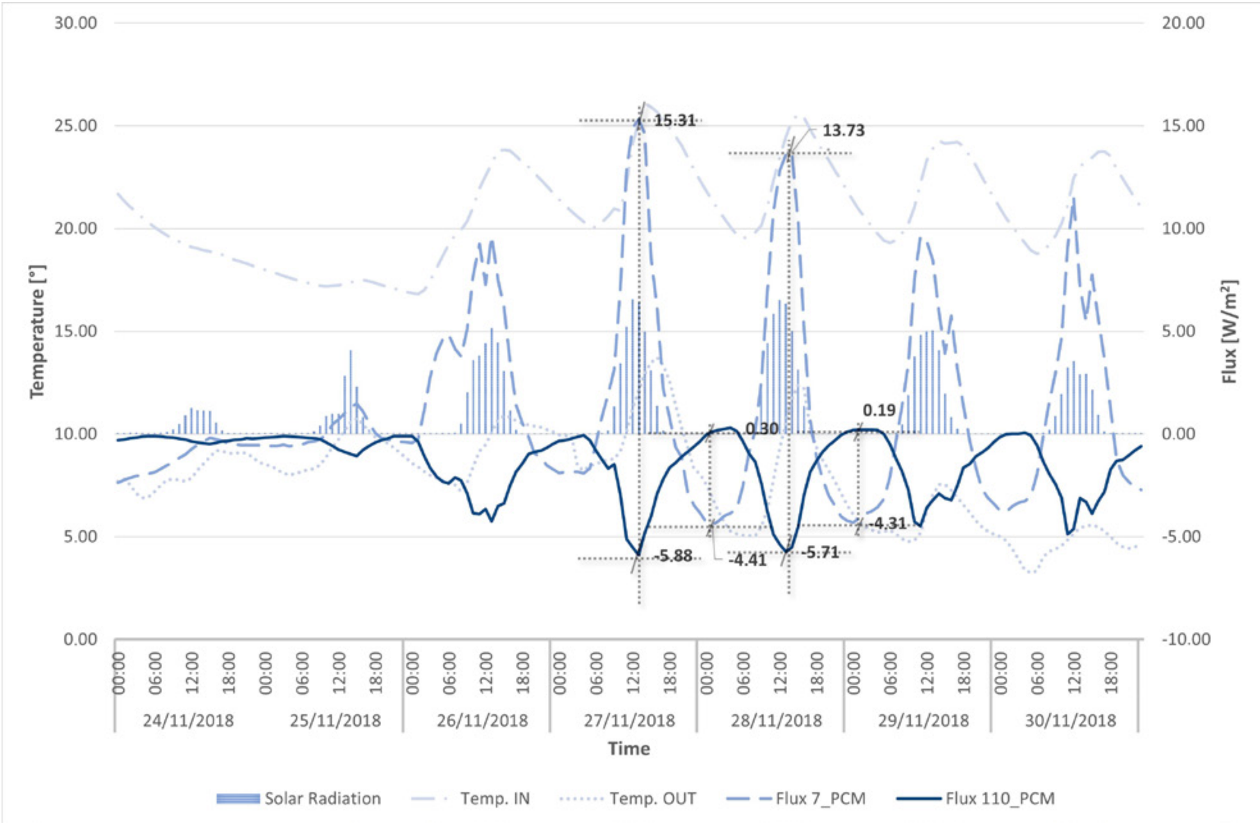


Fig. 5. *The comparison of Heat Flux measured on the plasterboard behind the PCM (sensor Flux110_PCM) and the external surface of the Active Dry Wall (sensor Flux7_PCM). Fluxes are inverted during the day and the night: the deep blue line displays the PCM absorption during the day and its release during the night toward zero. The dotted line displays how the false-wall surface releases heat during the night.*

4.5 and 4.32 times the accumulation. Regarding the absolute value, the absorption peak (15.31 W/m^2 and 13.73 W/m^2) and releasing peak (-5.88 W/m^2 and -5.71 W/m^2) proportion is 2.4 on both days, 27th and 28th, respectively.

3.4. WEEKLY COMPARISON OF ACTIVE DRY WALL AND TRADITIONAL DRY WALL

The overlapping of the two graphs previously analyzed (Figs. 4, 5) supports the parallelism of the two opaque envelope technology thermal hour-by-hour behavior per week.

The comparison (Fig. 6) between the flux and temperature measured on the Dry Wall (Flux6_Dry Wall and Temp.4_Dry Wall) and the Active Dry Wall with PCM (Flux7_PCM and Temp.4_PCM) highlights that the Active Dry Wall works as a "solar collector with artificial inertia". The Active Dry Wall with PCM has a similar surface temperature during the sun hour, while the Heat Flux is considerably higher, with a zenith around 14:00 when the direct sunlight stops affecting the wall. From this moment, there is a reversion in the Heat Flux, having a negative peak at midnight: the heat stored during the day is released during the night, allowing better indoor comfort for the users, as shown by the 1°C higher surface temperature for PCM false-wall.

Location, inner and outer temperature, relative humidity, and radiation are the same for both technologies, and the results clearly show the reverse behavior of the two false-walls: the Dry Wall with traditional insulation causes higher temperature variation on the external surface (Temp.4_Dry Wall) with lower flux variation. At the same time, the Active Dry Wall with PCM has a stable surface temperature (Temp.4_PCM) delta of 1°C from the internal temperature by a more extensive range in positive and negative heating flux (20–30%). However, the weekly global heating energy transfer of Active Dry Wall saves 29% thanks to artificial inertial technology.

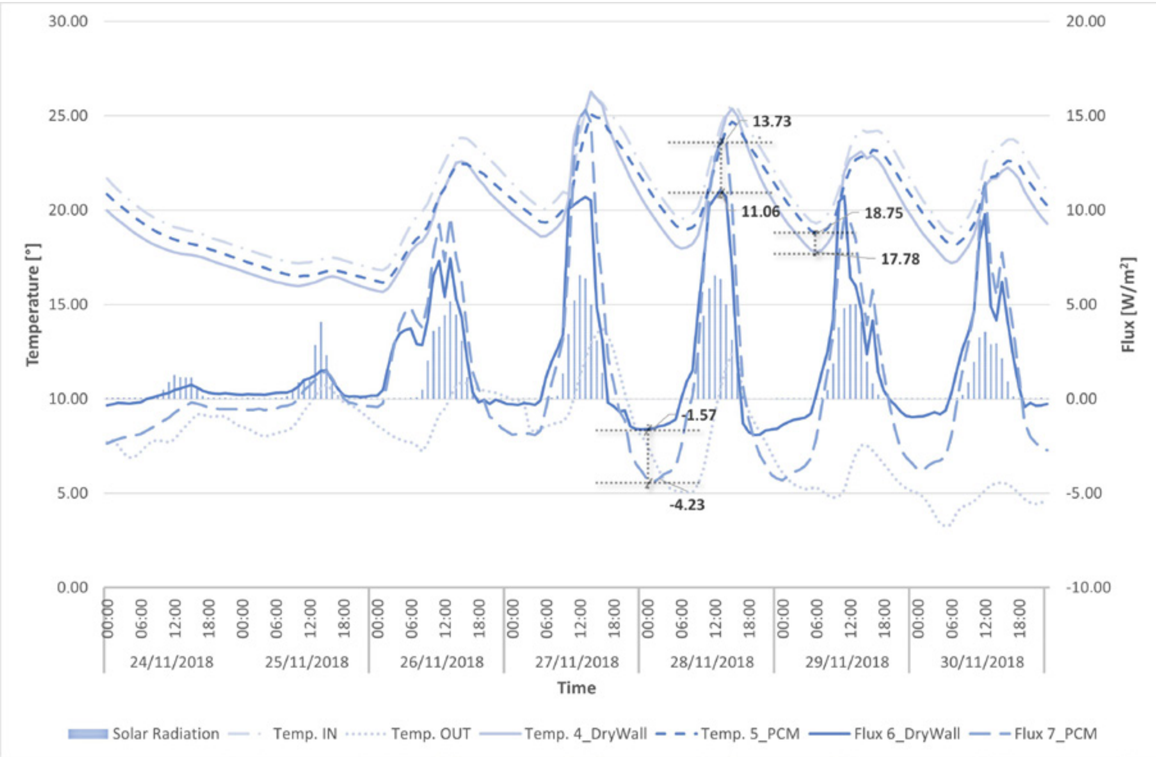


Fig. 6. *The comparison of the Heat Flow (sensor Flux6_Dry Wall and Flux7_PCM) and Internal Surface Temperature (sensor Temp.4_ Dry Wall and Temp.4_PCM) of the Dry Wall and the Active Dry Wall installed on the south side of the east wing of VELUXlab. The weekly sum of the accumulation and the release of heating results is 18.1 W/m² lower for the Active Dry Wall one.*

3.5. TEMPERATURE SECTION ANALYSIS

The weekly comparison of the two technologies analyses the temperature trends section (Fig. 7) at every layer of both technologies during the day (black dot line) and night (red dot line). The comparison is on the level recorded at 14:00 on 26/11/2018 and 2:00 on 28/11/2018.

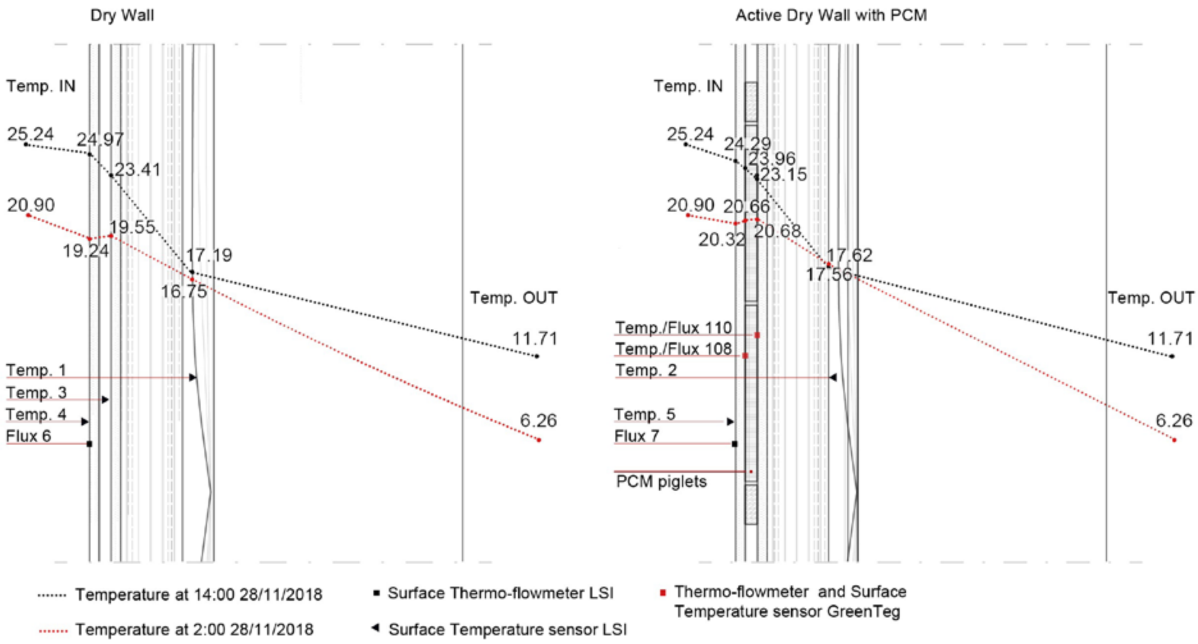


Fig. 7. *The temperature trends of the walls installed on the south side of the east wing of VELUXlab. The comparison of the measurements was recorded at 14:00 (black dot line) and 2:00 (red dot line) on 28/11/2018 on the wall with the Dry false-wall (sensors Temp.1_Dry Wall, Temp.3_Dry Wall, Temp.4_Dry Wall) and the Active Dry Wall with PCM addition (sensors Temp.110_PCM, Temp.108_PCM, Temp.2_PCM, Temp.4_PCM.*

On the left side, the surface temperature of the dry wall is higher (+0.7°C) as well the one measured on the second plasterboard (0.26°C); on the reverse, during the night, the PCM shows a 20.66°C temperature, 1.11°C more than the dry wall (19.55°C). Its artificial inertia causes the temperature turnaround, having a higher temperature on the thermo-reflective layer at night (17.62°C against 16.75°C).

4. CONCLUSIONS

The theme addressed in this paper emphasizes the importance of promoting research, development, innovation, and the "home system" for achieving the EPBD Directive 2010/31/EU request for NZEB buildings. The research was developed within the TEPORE project, performed at Velux Lab, a Politecnico di Milano test building, analyzing PCM's energy performance and efficiency concerning traditional Dry Wall technologies for heating sink effect. The sensorization of the various envelope layers has shown how Active Dry Walls with PCM materials inside can accumulate considerable heat during winter sunlight hours and release this heat at night. This process leads to a weekly global heating energy transfer saving of 29%, resulting in an energy balance cost reduction. The thermal mitigation of the heating peak around noon is 2.6 W/m^2 lower for the PCM material due to the 20–30% higher heating flux during the accumulation period, while the thermal peak delay is one hour later than the Dry Wall.

Symmetrically, the discharger peak is 4.4 W/m^2: 2.3 times higher for PCM at night. Furthermore, the surface temperature analysis shows a reduction of 1°C for PCM Active Dry Wall compared to a glass wool insulation Dry Wall due to the salt heating absorption by its phase change, resulting in a higher environmental comfort for users.

Subsequently, the results open a window to support the meliorating of life and integrity of buildings and individuals according to climatic zones and comfort requirements. Thanks to the advantages of adding artificial inertia to an existing envelope, the performance can be improved by shifting the heating peak load and flattening the indoor temperature. The meliorating of the quality of a space concurs with the ecological transition creating a context where also individuals increase their quality of life, under the possibility of also reducing energy costs. However, some implications can be related to the summer season, which this study did not verify, even though artificial inertia could act as heating storage during the day and as a radiator that releases heat during the night. The summer behaviour can be verified as further research development through advanced digital monitoring and predictive instruments in the perspective of cognitive buildings. It, together with a Life Cycle Cost (LCC) analysis, can answer the question of the more convenient solution from the construction and management point of view.

Acknowledgments

Smart Living and TEPORE project (project ID 379389) are funded by Regione Lombardia DGR X/5520 of 02/08/2016 supplemented by DGR X/6811 of 30/06/2017. The authors would like to thank Regione Lombardia for founding the project and Plasmati E., Vecchi C., Borzone M., Simone R. for the data collection.

Authors contribution

M. Imperadori: conceptualization, funding acquisition, methodology, project administration, resources, supervision. N. Di Santo: data curation, formal analysis, investigation, visualization, writing original draft. M. Cucuzza: data curation, formal analysis, investigation, visualization, writing original draft. G. Salvalai: conceptualization, methodology, project administration, supervision, validation. R. Scoccia: conceptualization, data curation, validation. A.Vanossi: conceptualization, data curation, funding acquisition.

Funding

Regione Lombardia for the TEPORE project (project ID 379389).

5. REFERENCES

[1] EED (2012) Directive 2012/27/EU of the European Parliament and of the Council of 25th October 2012 on energy efficiency

[2] Toftum J, Baxter V (2016) Nearly-zero energy buildings. Sci Technol Built Environ 22:883–884. https://doi.org/10.1080/23744731.2016.1217137

[3] Kyriaki E, Konstantinidou C, Giama E, Papadopoulos AM (2018) Life cycle analysis (LCA) and life cycle cost analysis (LCCA) of phase change materials (PCM) for thermal applications: A review. Int J Energy Res 42:3068–3077. https://doi.org/10.1002/er.3945

[4] Brambilla A, Brunone F, Sangiorgio A, Imperadori M (2018) Inter-ActiveHouse: users-driven building performances for Nearly Zero Energy Buildings in Mediterranean climates. In: Healthy, Intelligent and Resilient Buildings and Urban Environments. International Association of Building Physics (IABP), Syracuse, New York, pp 679–684

[5] Imperadori M, Brunone F (2019) Active House and user-friendly visualisation of sensors' monitored data: VELUXlab, a real cognitive and smart NZEB prototype. IOP Conf Ser Earth Environ Sci 296:012042. https://doi.org/10.1088/1755-1315/296/1/012042

[6] AEN/CTN 198 (2010) UNE-EN 15643-1:2011: Sustainability of construction works - Framework for assessment of buildings and civil engineering works

[7] Laskari M, de Masi R-F, Karatasou S, Santamouris M, Assimakopoulos M-N (2022) On the impact of user behaviour on heating energy consumption and indoor temperature in residential buildings. Energy Build 255:111657. https://doi.org/10.1016/j.enbuild.2021.111657

[8] Salvalai G, Sesana MM, Brutti D, Imperadori M (2020) Design and Performance Analysis of a Lightweight Flexible nZEB. Sustainability 12:5986. https://doi.org/10.3390/su12155986

[9] Al-Yasiri Q, Szabó M (2021) Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis. J Build Eng 36:102122. https://doi.org/10.1016/j.jobe.2020.102122

[10] Röck M, Saade MRM, Balouktsi M, Nygaard Rasmussen F, Birgisdottir H, Frischknecht R, Habert G, Lützkendorf T, Passer A (2020) Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Appl Energy 258:114107. https://doi.org/10.1016/j.apenergy.2019.114107

[11] Soares N, Costa JJ, Gaspar AR, Santos P (2013) Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. Energy Build 59:82–103. https://doi.org/10.1016/j.enbuild.2012.12.042

[12] de Gracia A, Cabeza LF (2015) Phase change materials and thermal energy storage for buildings. Energy Build 103:414–419. https://doi.org/10.1016/j.enbuild.2015.06.007

[13] Sage-Lauck JS, Sailor DJ (2014) Evaluation of phase change materials for improving thermal comfort in a super-insulated residential building. Energy Build 79:32–40. https://doi.org/10.1016/j.enbuild.2014.04.028

[14] Koschenz M, Lehmann B (2004) Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings. Energy Build 36:567–578. https://doi.org/10.1016/j.enbuild.2004.01.029

[15] Salvalai G, Pfafferott J, Jacob D (2010) Validation of a low-energy whole building simulation model. In: Fourth National Conference of IBPSA-USA New York City, New York, 11–13 August, pp 32–39

[16] Kishore RA, Bianchi MVA, Booten C, Vidal J, Jackson R (2020) Optimising PCM-integrated walls for potential energy savings in U.S. Buildings. Energy Build 226:110355. https://doi.org/10.1016/j.enbuild.2020.110355

[17] Stovall TK, Tomlinson JJ (1995) What are the Potential Benefits of Including Latent Storage in Common Wallboard? J Sol Energy Eng 117:318–325. https://doi.org/10.1115/1.2847868

[18] Sarbu I, Sebarchievici C (2018) A Comprehensive Review of Thermal Energy Storage. Sustainability 10:191. https://doi.org/10.3390/su10010191

[19] Jin X, Medina MA, Zhang X (2016) Numerical analysis for the optimal location of a thin PCM layer in frame walls. Appl Therm Eng 103:1057–1063. https://doi.org/10.1016/j.applthermaleng.2016.04.056

[20] Feifer L, Imperadori M, Salvalai G, Brambilla A, Brunone F (2018) Active House: Smart Nearly Zero Energy Buildings. Springer International Publishing, New York

[21] Bony J, Citherlet S (2007) Numerical model and experimental validation of heat storage with phase change materials. Energy Build 39:1065–1072. https://doi.org/10.1016/j.enbuild.2006.10.017

[22] Vanossi A, Imperadori M (2015) BIM e optioneering in edifici S/R di piccola scala BIM and optioneering in dry technology small-scale building. https://doi.org/10.13140/RG.2.1.2353.0400

[23] Wang X (2012) BIM Handbook: A guide to Building Information Modeling for owners, managers, designers, engineers and contractors. Constr Econ Build 12:101–102. https://doi.org/10.5130/AJCEB.v12i3.2749

[24] Arcuri N, Mazzeo D, Reda F (2013) Impiego dei PCM per interventi di riqualificazione energetica in edifici a bassa inerzia termica. In: 7° Congresso Nazionale AIGE, Rende (Cosenza), Italia, 10-11 giugno 2013

[25] Marin P, Saffari M, de Gracia A, Zhu X, Farid MM, Cabeza LF, Ushak S (2016) Energy savings due to the use of PCM for relocatable lightweight buildings passive heating and cooling in different weather conditions. Energy Build 129:274–283. https://doi.org/10.1016/j.enbuild.2016.08.007