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Phase change materials in facades of buildings for solar heating and cooling

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Abstract. Phase change materials (PCMs) have already been used in buildings and building services for several decades, mostly integrated into walls or ceilings to passively increase the building's thermal inertia, or integrated into the HVAC system for (pre-)heating or (pre-)cooling fresh air. More recently, the use of PCMs in facades is being explored for solar heating. This paper presents the results of a several years of research into the use of PCMs in rotatable Trombe walls and sun-shading for passive heating and cooling purposes. Simulations used a custom-made model of a room in Matlab/Simulink, in which all relevant heat transfer paths and mass components are accounted for. Once the behaviour of PCM was modelled, the model was connected with the optimisation platform modeFRONTIER to study the (best) performances under different scenarios. The results show that a significant reduction in the energy demand for heating and cooling can be achieved in different climates. The results also show that the shading and insulating effect of the solar wall have the highest impact on the reduction of the cooling respectively heating demand, followed by the thermal mass effect. The paper ends with the development of a prototype of a Trombe wall which was installed in an office at the Green Village (a living lab in Delft).

Keywords. Phase change materials, heating and cooling demand, Trombe wall, solar wall
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1. Introduction

In 2019, buildings and activities inside buildings (households plus commercial and public services) accounted for 41% of the final energy use in the European Union [1]. The built environment will face a daunting challenge to reduce its (fossil) energy use and related carbon emissions to meet the targets set by the Paris Agreement. Besides producing renewable energy, buildings need to become more energy-efficient by among others reducing the demand for space heating and cooling, at the same time maintaining comfort for its occupants. Several strategies can be used like climate responsive design.

One novel group of materials that could work well in conjunction with the principles of climate responsive design are phase change materials (PCMs). PCMs are materials that can store or release significant amounts of heat latently by a change of phase (e.g., solid-liquid) without significant change in temperature. Examples of PCMs are salt hydrates, paraffin, eutectics, and bio-based materials using palm oil or rape seed oil.

PCMs have been applied in buildings and building services for several decades. One of the first documented applications in buildings dates back to 1948 when Glauber's salt was stored in drums inside the Dover house [2]. In recent decades, PCMs have been used to increase the thermal inertia of buildings (walls, floors, ceilings, roofs, sun-shading), or as mass inside ventilation systems to pre-heat or pre-cool fresh air supply, in floor heating systems to stabilise the system, and in heat recovery units [3, 4, 5].

Over the past years, the authors have investigated the application of PCMs in facades of buildings, with one application addressing their use in Trombe walls for passive solar heating and cooling. A Trombe wall is a structure made of a 10-20 cm thick solid wall placed behind a layer of glass with a thin layer of air in-between [6, 7]. Generally, in winter the wall heats up due to insolation and temporarily buffers this heat in its mass. Due to conduction the heat will slowly conduct towards the other side of the wall where it with a time delay will transfer the heat towards the space behind the wall. Many Trombe walls also have grills at their bottom and top which can be opened in the afternoon and at night to allow for a flow of warm air from the cavity to the room further enhancing the heat transfer. As a result of the time delay, the heat is available when occupants are at home at night reducing the energy demand for heating.

These traditional walls, however, have several drawbacks: they are very heavy and thick; they are not suitable for refurbishment projects; they block the admittance of daylight into the building; and they cannot be adjusted to the varying outdoor and indoor conditions. Among the first studies that investigated lightweight thermal storage systems in façades are the studies conducted by Kienzl [8], Manz et al. [9], Weinläder et al. [10] and Fiorito [7]. Although these studies investigated the possibilities for lightweight systems, none of these were adjustable to varying circumstances as they were developed as static building components. Our research into Trombe walls explored a system that can be tuned concerning heat absorption and radiation for both winter and summer using PCM as a lightweight thermal buffering material, and thereby save on energy demand for heating and cooling.

2. Research method

2.1 Trombe wall principle and materials

The Trombe wall is made of phase change material of 10 to 60 mm (as a variable) on one side and of 10 mm translucent aerogel grains on the other side, encased in a thin plastic container, and rotates twice a day at sunrise and sunset. In winter between sunrise and sunset the PCM faces the window and between sunset and sunrise it faces the room; in summer between sunrise and sunset the PCM faces the room and between sunset and sunrise it faces the window. Furthermore, in summer at night vents are opened in the façade which enables a natural flow of outdoor air along the PCM in order to release the stored heat into the outdoor environment (Fig. 1).

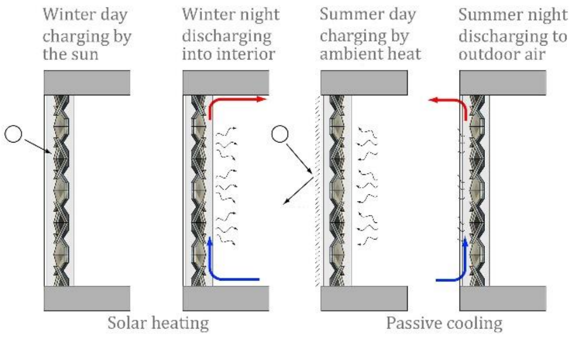

Fig. 1 - Principle of the latent heat storage unit [11].

The thickness of the air cavity between the glass and the wall is considered a variable and varies between 10 and 160 mm. For the façade with window, the window-to-wall ratio is fixed to 80%, whereas the size of the Trombe wall in relation to the window is variable ranging between 40 and 90% (If not mentioned for the specific simulation, it is 90%). The orientation of this façade can vary.

For aerogel the following properties were used: a thermal conductivity of 0.012 W·m^{-1}·K^{-1}, a bulk density of 75 kg·m^{-3} and a specific heat of 1440 J·kg^{-1}·K^{-1}. A layer of 10 mm aerogel transmits and absorbs 91% respectively 9% of the incoming solar radiation.

The PCM used in this study is a salt hydrate with a melting temperature (mid-point of melting range) as a variable ranging between 20 and 26 °C (if not mentioned for the simulations it will be 25 °C). Also the latent heat of fusion is considered a variable ranging between 160 and 240 kJ·kg^{-1} (if not mentioned for the simulations it will be 180 kJ·kg^{-1}); it is modelled as a temperature dependent specific heat capacity, c_p, as shown in Figure 2. The thermal conductivity is set to 0.6 W·m^{-1}·K^{-1}, the bulk density to 1450 kg·m^{-3} and the sensible specific heat capacity to 2000 J·kg^{-1}·K^{-1}. Most PCMs exhibit hysteresis which means that the melting cycle differs from the solidification cycle. A hysteresis dead band of 2 °C was included in the simulations.

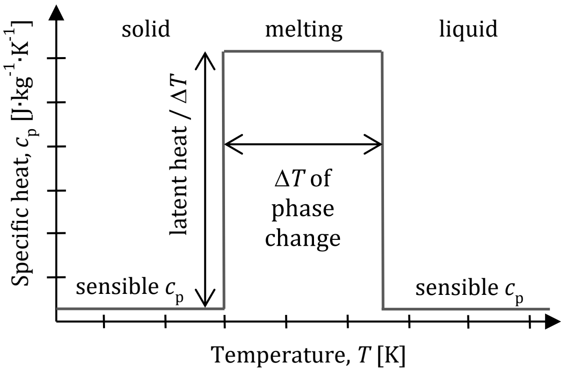

Fig. 2 – Modelling of the latent heat as part of the specific heat capacity.

2.2 Simulation model

For this research an energy performance simulation model in Matlab/Simulink was developed that includes a rotating Trombe wall with latent heat storage properties. Three of our MSc students, Carlos Chang Lara [12], Jeroen van Unen [11] and Kees-Jan Hendriks [13] added features specific for their research. The model is set-up as a multi-nodal model with nodes for the room air, the cavity air, the outdoor environment, the walls, ceiling and floor (two surface nodes and two inner nodes each) and multiple nodes for the Trombe wall. Between these nodes conductive, radiative and/or convective heat transfer and in some case air flow is taking place. Figures 3a and 3b show examples of heat transfer modes between several of the nodes. Air exchange between the nodes of the cavity and the indoor space and between the cavity and the outdoor air (night flushing) is modelled using the stack effect formula for which the relevant coefficients were obtained from an air flow network model.

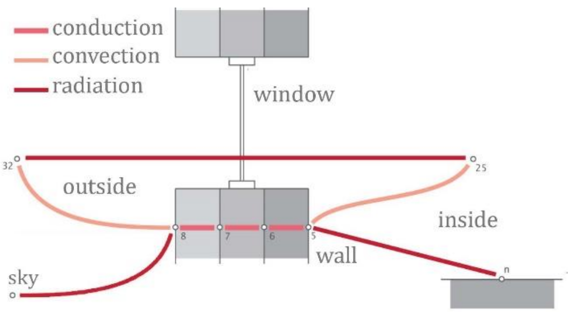

Fig. 3a – Heat transfer between nodes near window without Trombe wall [12].

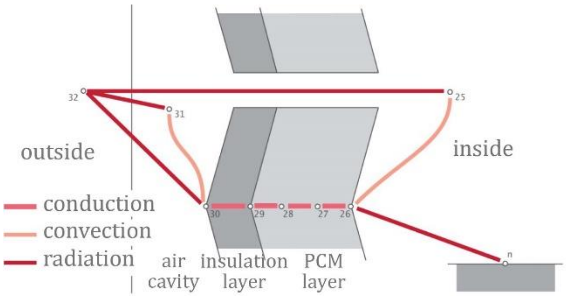

Fig. 3b – Heat transfer between nodes near window with Trombe wall [12].

The basic room (Fig. 4) has three adiabatic walls, an adiabatic floor and ceiling, and one façade which exchanges heat with the outdoor environment via infiltration, transmission and solar radiation gains. Balanced mechanical ventilation with heat recovery is implemented providing fresh air to the occupants of the space. Besides, a simplified heating and cooling system (COP=1) is implemented in the model that provides a stable temperature inside the room based on a set-point temperature and PID controller for the times the space is occupied. The set-point for heating is 20 °C and for cooling 26 °C. The output of the model thus is the energy demand. A complete description of the model is provided in [11], [12] and [13].

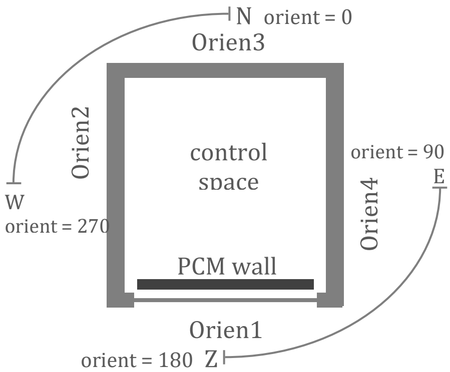

Fig. 4 – Floor plan model of the simulated room. The orientation may vary in the model.

Table 1 provides an overview of the most important properties and settings of the simulation model for both the offices and housing simulated.

2.3 Optimisation model and settings

For running the optimisations, the Matlab/Simulink model was connected to the optimisation platform modeFRONTIER. ModeFRONTIER creates a direct connection between the two platforms. Once the optimisation is set with optimisation objectives, design variables, eventual constraints and other relevant features, modeFRONTIER drives the optimisation process through simulations in Matlab/Simulink. Several optimisation objectives were defined of which only here are shown:
1.) Minimisation of the energy demand for cooling;
2.) Minimisation of the energy demand for heating;
3.) Minimisation of the year round energy demand.

The self-adaptive multi-strategy optimisation algorithm pilOPT [14] in modeFRONTIER was used to drive the optimisation process. This algorithm combines Response Surface Methodology (RSM) with a Genetic Algorithm (in our case NSGA-II), which increases the robustness of the process and the quality of the optimisation. Around 4000 generations were sufficient to have good convergence of the results towards a Pareto front.

2.4 Climates

Several climates were included in these studies: Cold (Stockholm), temperate (Milan), dry (Cairo) and tropical (Singapore) [13]. Weather data for these cities were extracted from the website of EnergyPlus. Also the town De Bilt was included in another optimisation run for which weather data based on the Dutch standard NEN5060: 2018 was used [11]. This standard includes a reference meteorological year for the Netherlands for energy simulations.

Tab. 1 – Settings and properties of simulation model.

variable	value	
building function	offices	housing
room size	small: 3.6 x 5.4 x 2.7 m^3 big: 7.2 x 10.8 x 3.0 m^3	
façade orientation	North, East, South or West	
radiat./convect. (ins./outs.) surface heat transfer coef.	5.0 / 2.7 /25 $W{\cdot}m^{-2}{\cdot}K^{-1}$	
%openings in Trombe wall	10%	
U-value / SHGC of glass	double: 1.6 $W{\cdot}m^{-2}{\cdot}K^{-1}$ / 0.7 triple: 0.7 $W{\cdot}m^{-2}{\cdot}K^{-1}$ / 0.5	
R_c-value opaque facade	old buildings: 2.0 $m^2{\cdot}K{\cdot}W^{-1}$ new buildings: 4.5 $m^2{\cdot}K{\cdot}W^{-1}$	
Infiltration rate	old buildings: 0.8 ach new buildings: 0.2 ach	
total internal heat load	office: 25 $W{\cdot}m^{-2}$	housing: 6 $W{\cdot}m^{-2}$
Occupancy, intern. heat load and vent. schedule	8.00-18.00 h (Mon-Fri)	18.00-8.00 h (Mon-Fri) 0.00-24.00 h (Sat-Sun)
heating set-point temperature	20 °C	
cooling set-point temperature	26 °C	
mech. vent. rate	2.0 ach	0.7 ach
efficiency of heat recovery	90% bypassed: $T_{int,op}>T_{ext}$ & $T_{int,op}>24$ °C	
nat. vent. (rate) at night to flush PCM	$A_{in} = A_{out} = 0.025{\cdot}A_{facade}$ $C_d = 0.8$ (stack eff. formula) on: $T_{int,op}>T_{ext}$ & $T_{int,op}>24$ °C	
sun-shading operation	closed: $T_{ext}>24$ °C & $q_{sol}>100$ $W{\cdot}m^{-2}$ [13] or 22 °C & $q_{sol}>100$ $W{\cdot}m^{-2}$ [11]	
SHGC sun-shading	0.25	

3. Results

3.1 Different climates

Figures 6a/b show the effect of the PCM based rotatable Trombe wall on the heating respectively cooling demand of all simulated offices and homes for cold, temperature, warm dry and tropical climates. In cold climate the Trombe wall mostly impacts the heating demand, in warm dry and tropical climates the cooling demand and in temperate climates both the heating and cooling demand. Since the different spaces simulated were of different sizes, the absolute differences also depend on room size. Percentile differences show that energy demand reduction of 5 to 100% can be achieved using this type of Trombe wall, the exact amount depending on the available thermal mass in the room, the thermal quality of the façade, the window-to-wall ratio, the internal heat loads, the amount of ventilation, etc.

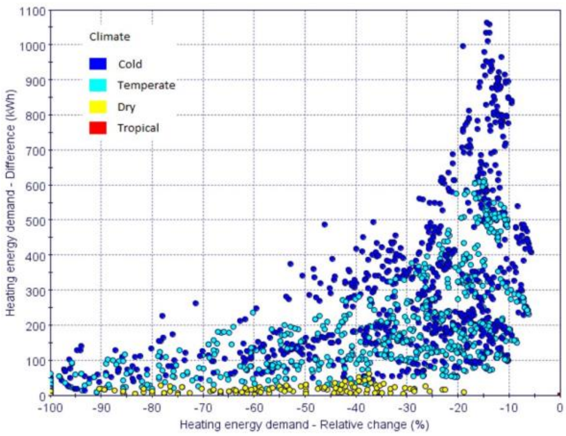

Fig. 6a – Difference in heating demand (absolute and relative) between room without and with Trombe wall for different climates [13]. Positive absolute values / negative percentages denote that the Trombe wall leads to an energy saving.

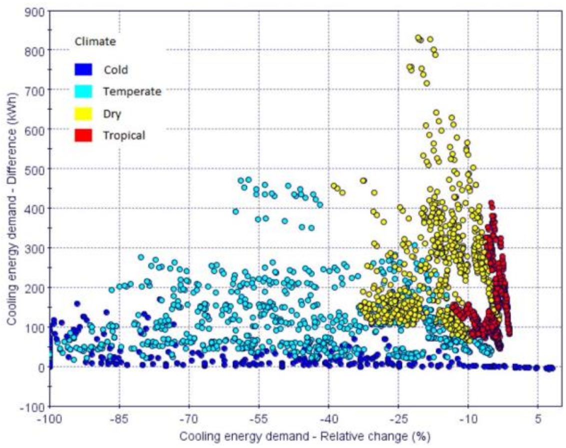

Fig. 6b – Difference in cooling demand (absolute and relative) between room without and with Trombe wall for different climates [13]. Positive absolute values / negative percentages denote that the Trombe wall leads to an energy saving.

3.2 Offices versus housing

Figures 7a/b show the difference between housing and offices for all simulated cases. For both offices and housing the heating demand reduction of the PCM based Trombe wall is of the same order of magnitude looking at all cases as a whole. However, in summer the cooling demand reduction in general is higher for residences than for offices.

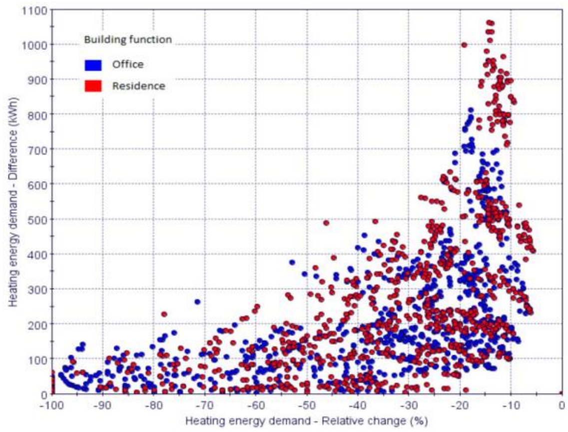

Fig. 7a – Difference in heating demand (absolute and relative) between room without and with Trombe wall for offices versus houses [13]. Positive absolute values / negative percentages denote that the Trombe wall leads to an energy saving.

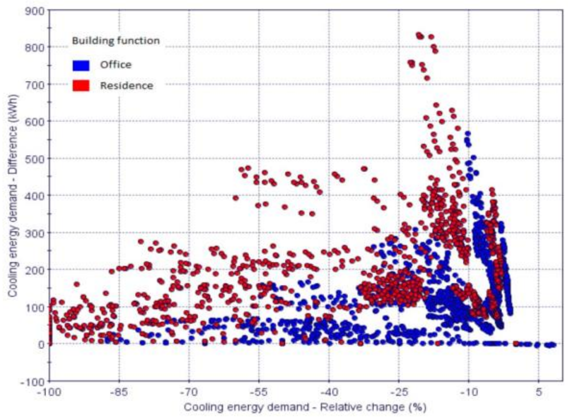

Fig. 7b – Difference in cooling demand (absolute and relative) between room without and with Trombe wall for offices versus houses [13]. Positive absolute values / negative percentages denote that the Trombe wall leads to an energy saving.

3.3 Orientation of Trombe wall

Also the impact of the orientation of the Trombe wall was investigated: North, West, South or East. Looking at Figures 8a/b a first conclusion is that the PCM based Trombe wall leads to heating and cooling demand reductions for all façade orientations. A closer look at Figure 8a shows that in general the South orientation appears more often towards the left upper corner (yellow data points) meaning that a South oriented Trombe wall in general leads to higher energy savings for heating. To get a better understanding of the impact of orientation three rooms were investigated more closely and the green arrows in Figure 8a show how these cases move in the chart when their orientation changes from North/East/West to South. The performance of the Trombe wall is similar for North, East and West orientations but is better for South orientations (in relative terms).

Also for the cooling demand reduction three data clusters were further investigated (green circles in Figure 8b). Concerning cooling demand reduction, the performance of the Trombe wall is similar for all orientations. This can also be explained by the fact that in that case the wall is cooled at night using outdoor air and is taking up heat from internal heat sources throughout the day. Such performance is hardly impacted by orientation.

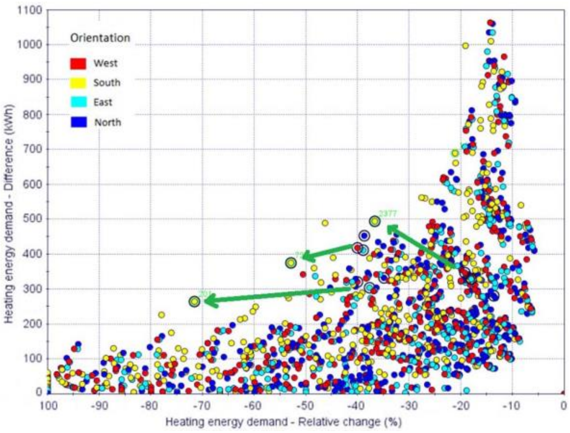

Fig. 8a – Difference in heating demand (absolute and relative) between room without and with Trombe wall for different orientations [13]. Positive absolute values / negative percentages denote that the Trombe wall leads to an energy saving. The green arrows denote how certain cases change if their orientation changes.

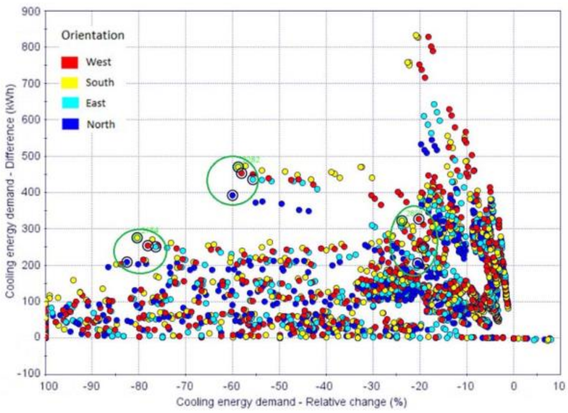

Fig. 8b – Difference in cooling demand (absolute and relative) between room without and with Trombe wall for different orientations [13]. Positive absolute values / negative percentages denote that the Trombe wall leads to an energy saving. The green circles denote how certain cases change if their orientation changes.

3.4 PCM thickness: offices in the Netherlands

The results of the simulations show that on a mild summer day the indoor air temperature is hardly affected by the thickness of the PCM layer in the Trombe wall [11]. On warm and sunny summer days, however, thicker layers of the PCM are better able to stabilise the room air temperature. If no proper sun-shading is used, the temperature of the PCM can easily overheat to temperatures above its maximum operating temperature as stated by the manufacturer. Thicker layers are better able to reduce this overheating. The same applies to sunny winter days on which the sun-shading is not used. In that case a minimum thickness of around 30 mm is needed.

Table 2 provides the reduction of the heating and cooling demand for an office in the climate of the Netherlands with a PCM with melting temperature of 25 °C and latent enthalpy of 180 kJ·kg^{-1}. These results show that generally thicker layers of PCM in the Trombe wall lead to higher performance. However, increasing the thickness from 10 to 20 mm has more effect than from 50 to 60 mm; a thickness beyond 30 mm hardly adds to additional energy savings in the Netherlands. Also from a cost perspective, considering a bulk (>10,000 kg) price range of between 2-4 €·kg^{-1} for inorganic and 4-10 €·kg^{-1} for organic PCMs [11], it would be advisable to limit the thickness.

Tab. 2 – Difference in heating and cooling demand (absolute and relative) between an office space without and with Trombe wall for different thickness of the PCM layer using NEN5060 weather data [11]. PCM melting range between 23-26 °C (latent heat peak at 25 °C). Positive absolute and percentile values denote that the Trombe wall leads to an energy saving.

PCM thick-ness (mm)	Cooling demand reducti on (%)	Heating demand reducti on (%)	Cooling demand reduction (kWh/m^2)	Heating demand reduction (kWh/m^2)
10	49	51	9.2	2.8
15	53	60	10.0	3.3
20	58	64	10.9	3.5
25	59	72	11.1	3.9
30	60	72	11.3	3.9
40	62	77	11.6	4.2
50	62	**80**	11.6	**4.4**
60	**63**	**80**	**11.8**	**4.4**

An important consideration, however, is that for thicker layers of PCM the melting process becomes uneven. Some of the authors have performed CFD simulations to investigate this phenomenon [15]. A 30 mm thick, 200 mm high block of PCM with a melting temperature of 25 °C exposed to solar radiation for 8 hours was simulated. The results showed that after several hours a free-convective fluid flow develops inside the melted PCM which transports heat from the bottom to the top, speeding up the melting at the top. By segmenting the block of PCM in height the melting process can be made more even. Figure 9 shows some of these results. Also segmenting the block with one or two vertical barriers would be beneficial.

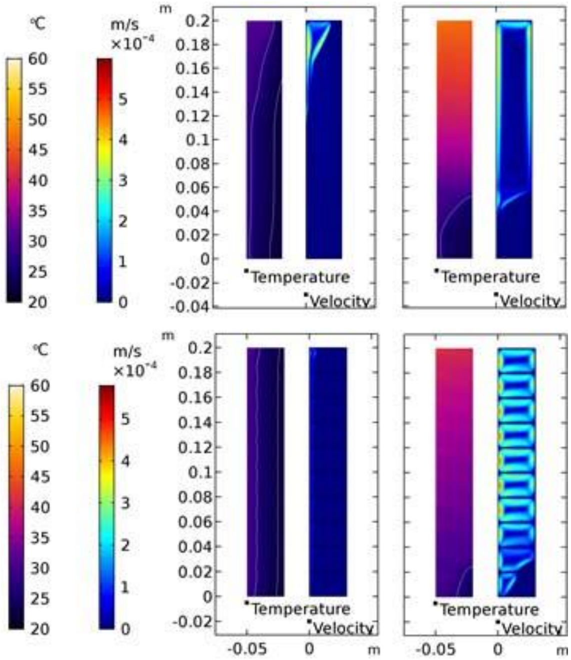

Fig. 9 – Temperature and fluid flow inside a block of PCM with a melting temperature of 25 °C and a thickness of 30 mm exposed to a radiation source of 300 W·m^{-2}, after exposure of 4 (left) and 8 hours (right). The top image shows an unsegmented block of PCM; the bottom image shows a segmented block of PCM (2 cm). [15]

3.5 Melting temp.: offices in the Netherlands

Figure 10a and 10b show the temperature development of the PCM and the room air when the PCM based Trombe wall is used, for different melting temperatures of the PCM (20 °C up to 26 °C; mid-point of melting range). The figures show that in general PCM with a high melting temperature has the best performance under both summer and winter conditions. In summer the room air temperature remain coolest for the PCMs with higher melting temperatures; in winter the daily average room air temperature is higher and more stable for higher PCM melting temperatures. The higher PCM temperatures in winter as compared to summer are a result of the activation of the sun-shades in summer.

Table 3 shows the effect of the PCM melting temperature on heating and cooling demand reduction. These results confirm that for summer a relatively high melting temperature is beneficial but also that the improvement per unit change of the melting temperature becomes smaller. In winter, a melting temperature of around 23 °C performs best for offices. The annual best performance is found for a melting temperature of about 25 °C. A remarkable finding is that the optimal melting temperature for PCM applied in a Trombe wall is higher than what would generally be advisable for indoor PCM use as a passive stabiliser of room air temperature.

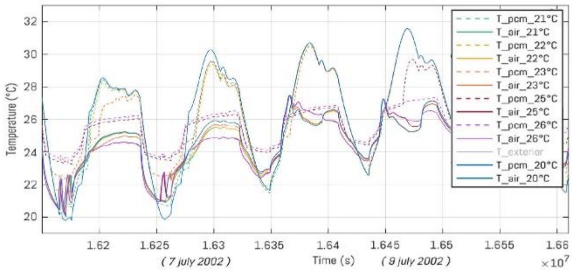

Fig. 10a – Temperature of the PCM and room air of an office space of 60 m^2 for different PCM melting temperature (mid-point of range at 20 to 26 °C with ΔT of 3 °C) under warm summer conditions using NEN5060 weather data [11].

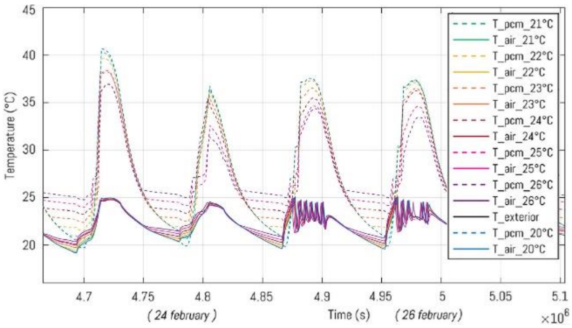

Fig. 10b – Temperature of the PCM and room air of an office space of 60 m^2 for different PCM melting temperature (mid-point of range at 20 to 26 °C with ΔT of 3 °C) under sunny winter conditions using NEN5060 weather data [11].

Tab. 3 – Difference in heating and cooling demand (absolute and relative) between an office space without and with Trombe wall for different PCM melting temperature using NEN5060 weather data [11]. PCM layer thickness is 25 mm and has a ΔT of 3 °C. Positive absolute and percentile values denote that the Trombe wall leads to an energy saving.

PCM T_{melt} (°C)	Cooling demand reduction (%)	Heating demand reduction (%)	Cooling demand reduction (kWh/m^2)	Heating demand reduction (kWh/m^2)
20	42	59	7.9	3.2
21	44	67	8.2	3.7
22	47	72	8.8	3.9
23	50	**73**	9.4	**4.0**
24	54	72	10.2	3.9
25	59	72	11.1	3.9
26	**61**	64	**11.5**	3.5

4. Prototype development

4.1 Impact of shape, position and holes

The results presented in the previous section dealt with a flat wall PCM-based rotatable Trombe wall. Additional research was performed by the research team working on the Double Face 2.0 project [16] and MSc student Eve Farrugia [17] using the heat transfer and fluid flow modules of the software

Comsol, to investigate the melting and solidification process of the PCM and the impact of the overall shape of the Trombe wall. More specifically, these simulations investigated how surface geometry, variation in thickness, holes inside the wall and position in relation to the glass impacted the capture of solar heat on a winter day, the release of heat via convection and infrared radiation towards the room on a winter evening, the capture of internal heat via convection and infrared radiation on a summer day and the release of heat via convection on a summer night. Figure 11 shows an example of CFD simulations along several surface geometries.

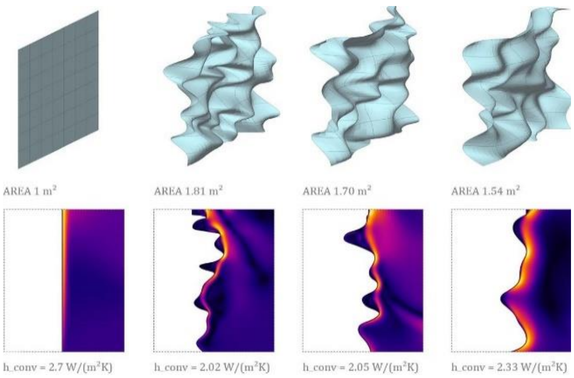

Fig. 11 – Effect of surface geometry on convective heat transfer coefficient [17].

Main conclusion from these simulations was that the melting of the PCM due to exposure to solar radiation, even in winter, is fast but that the cooling down by convection and infrared radiation exchange is slow. This means that, to reduce the risk of overheating the PCM to beyond its service limits, sun-shades are needed in front of the wall for conditions with high solar radiation. The PCM volume also needs to be subdivided into smaller pockets to have good control over the melting and solidification process. A small percentage of holes in the Trombe wall of less than 10% of the surface area does not largely impact the thermal performance of the wall. And a PCM of higher melting temperature could be used in the upper one-third of the wall.

4.2 Developed prototype

Some previous plus aesthetical considerations resulted in geometrical complexity in the design. For this and to facilitate options for product customisation, it was decided to use Additive Manufacturing (Fused Deposition Modelling) with an extruder connected to a robotic arm for producing the prototype. This decision, in addition to the thermal considerations, involved that the design process from the onset integrated considerations deriving from the possibilities and limitations of the 3D printing technique. The research and design process developed by the researchers Tudor Cosmatu, Yvonne Wattez and Stravroula Tsafou led to the design of a prototype as shown in Figures 12, 13 and 14. The thermal response of this wall was monitored for several months after installing it in a meeting room; the data will soon become available.

Fig. 12 – Robotically 3D printing of the prototype of the developed PCM based Trombe wall.

Fig. 13 – Installed full panel of the prototype of the developed PCM based Trombe wall in a meeting room.

5. Conclusion

The research into the use of PCMs in facades of buildings for solar heating and passive cooling has shown that a PCM-based rotatable Trombe wall with a thickness of around 35-40 mm (25-30 mm PCM and 10 mm aerogel) can lead to an important reduction of the heating and/or the cooling demand of both offices and houses, in different climates. The exact reduction depends on the use and characteristics of the room and the façade, and the type and amount of PCM. This reduction is not only because of the presence of the PCM but also because the Trombe wall creates an additional insulating layer behind the glass in winter and a solar shading layer in summer.

It is important to mention that a solution like this would only be cost-effective for thin layers of PCM. In the case of a 25 mm thick Trombe wall, in a 100 m^2 modern apartment with approx. 25 m^2 of facade with a WWR of 0.75, the heating and cooling demand can be reduced by 326-369 and 369-458 kWh/yr respectively in a temperate climate. Assuming a SCOP/SEER of 3 and a cost of 4 €·kg^{-1} for the PCM and 0.3 €·kWh^{-1} for electricity, the payback time would be 30-35 yrs. A similar analysis for a 10 mm thick Trombe wall leads to a payback time of 15-18 yrs. Interesting next steps, therefore, would be to explore thinner curtain-like layers having higher user-friendliness and shorter payback time.

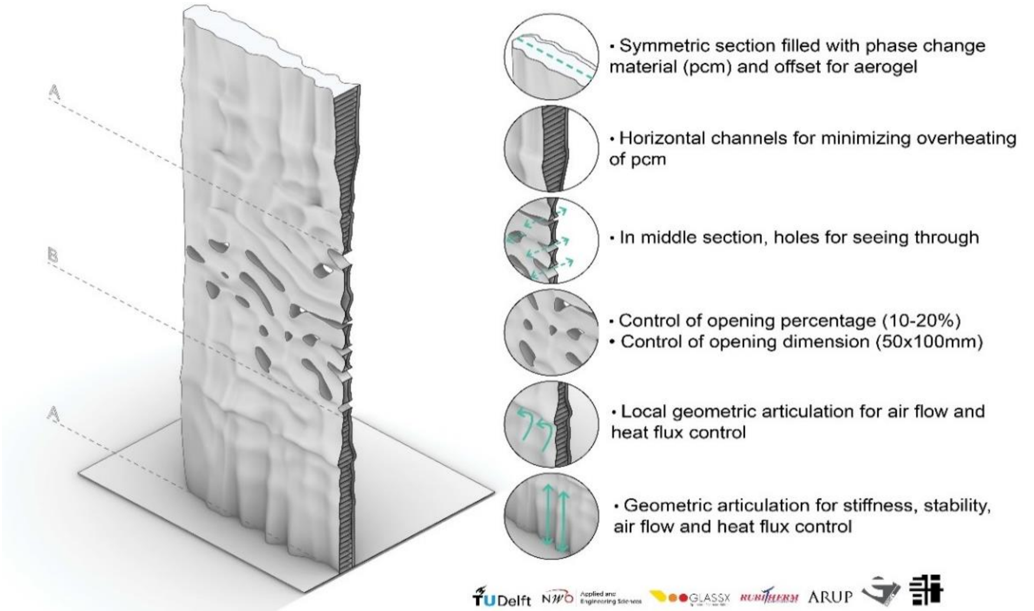

Fig. 14 – Final design of the prototype of the Double Face 2.0 PCM-based rotatable Trombe wall.

6. Acknowledgement

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7. Data statement

The datasets generated during and/or analysed during the current study are available in the MSc theses and project report, which can be obtained from the TU Delft repository, https://repository.tudelft.nl/.

8. References

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