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Publication date
2020

Document Version
Final published version

Published in
Bouwfysica Blad

Citation (APA)
Tenpierik, M. J., Turrin, M., Wattez, Y. C. M., Cosmatu, T., Tsafou, S. E., Farrugia, E. G., & van Unen, J. A. (2020). Double Face 2.0: An adjustable, translucent, PCM-based Trombe wall. *Bouwfysica Blad*, *31*(2), 14-21.

DOUBLE FACE 2.0

AN ADJUSTABLE, TRANSLUCENT, PCM-BASED TROMBE WALL

This article presents some of the results from the Double Face 2.0 project which focussed on the development of an innovative, lightweight, translucent, rotatable Trombe wall based on phase change materials and 3D printing technologies. This research has shown that such a Trombe wall can lead to a significant reduction in the energy demand of both offices and houses. This article focusses on some of the simulations related to the building physics. Other parts of this research concerning the (robotic) FDM printing, the methodology development, the design development, the user testing, the daylight analyses and the experimental tests are not included here. For more information, please contact the (co-)authors of this article.

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INTRODUCTION

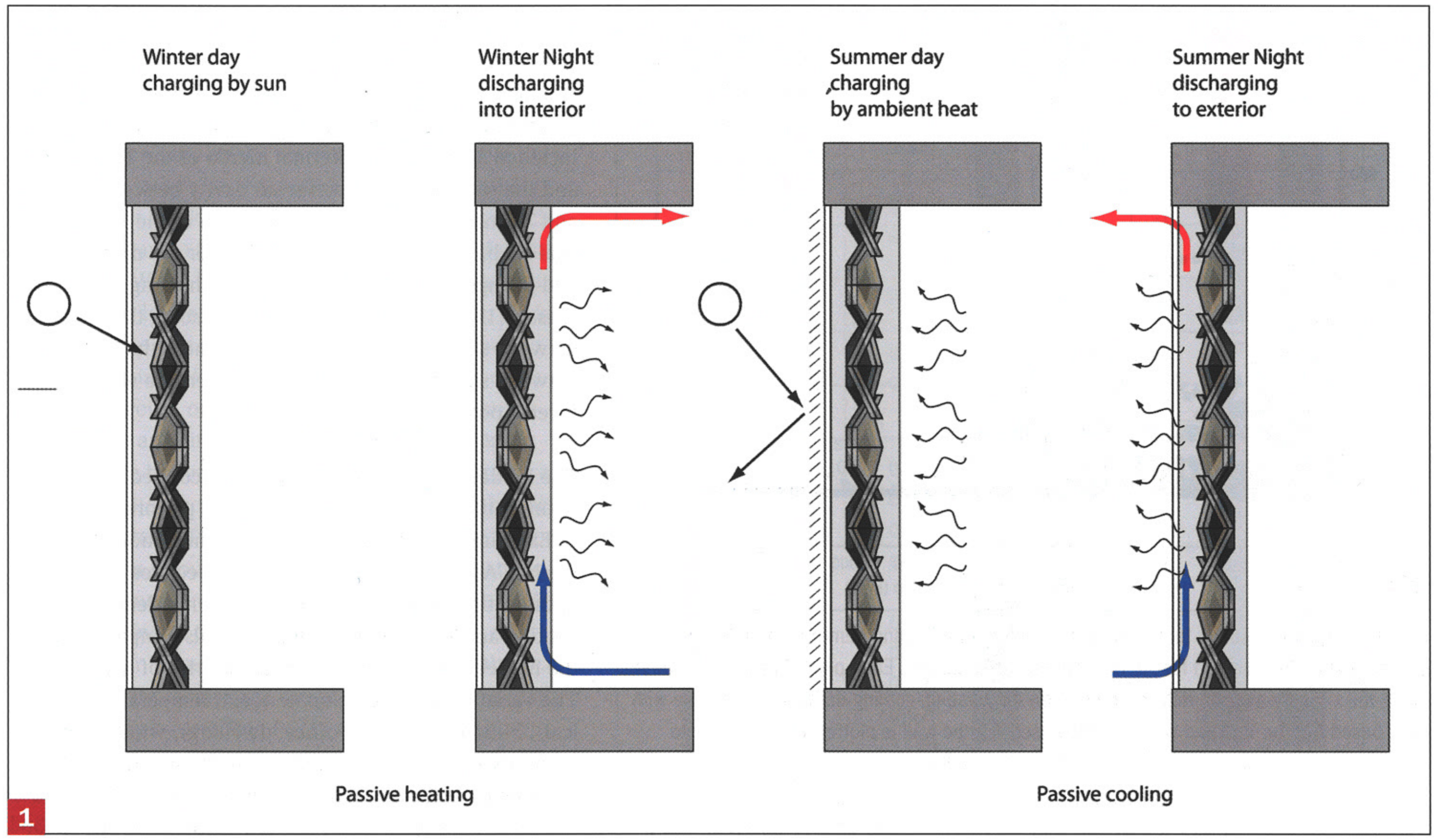
Over the past decades, significant progress has been made towards improving the energy efficiency of buildings by focussing on thermal insulation, airtightness and more efficient building services [1]. However, in 2018 the residential and services sector in the EU still accounted for about 40% of the final energy consumption in this area [2]. For the Netherlands especially heating and cooling have a large share in this energy consumption. Therefore, there still is a need for further reducing the (primary) energy use of buildings so that we can meet the targets set out by the Paris Climate Agreements and the national energy and climate accords.

Phase change materials (PCMs) have been identified by several researchers as a promising material that can contribute to reducing the final energy demand of buildings [3, 4]. Phase change materials are materials that can store large quantities of energy during a phase transition without significant change in temperature. Many of the PCMs useful for the built environment have a solid/liquid phase transition and thereby store energy when changing from solid to liquid and release that energy when changing from liquid to solid. Most applications of PCMs in buildings so far have been in the HVAC system or in interior wall or ceiling panels. Over the last decade, more and more research has focused on the application of PCMs in facades in form of sun shading and solar walls [5-9].

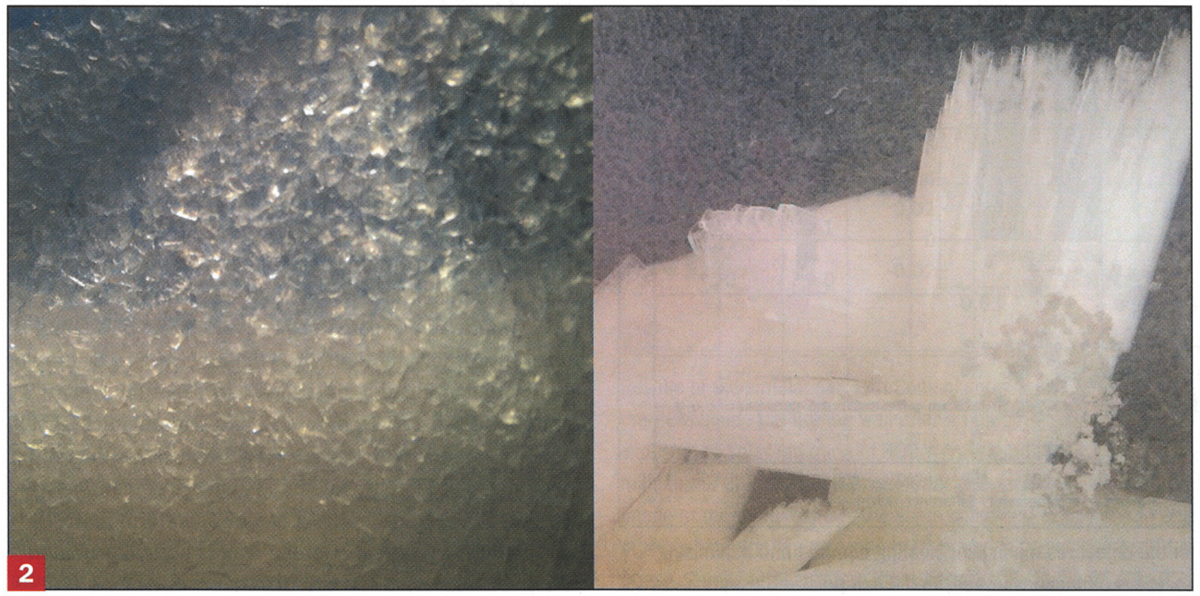
The Double Face 2.0 project looked into a way of harnessing the energy from the sun using an improved version of a Trombe wall. A Trombe wall, or solar wall, typically is a wall made out of thick and heavy stone-like material placed behind a layer of glass and air. During the day it captures the solar heat and stores that into its material. Slowly the heat conducts through the wall towards the other side where it is given off into the room in the evening and at night. Furthermore, sometimes valves can be opened enabling a flow of warm air from the air cavity to enter into the room. The Trombe wall thereby overcomes the temporal difference between when solar heat is available and when heat is needed (in dwellings). Disadvantages of the traditional version are that it is heavy, blocks daylight and cannot be adjusted to changing environmental conditions and seasonal differences.

BASIC PRINCIPLE

The Double Face 2.0 project therefore aimed to improve the traditional Trombe wall on a number of points. Especially worth mentioning in this respect are the application of a PCM, the integration of an insulation layer of aerogel, the ability of the system to rotate, the optimisation of the inner structure of the wall for controlling the behaviour of the PCM and the optimisation of the outer surface for enhanced heat transfer. Figure 1 shows the main principle of this Trombe wall in winter and summer mode. In winter during the day (PCM faces the window), solar energy is collected and stored inside the PCM; in the evening and at night the rotated wall (PCM faces the room) releases this heat into the room via convective and radiative heat transfer. In summer during the day (PCM faces the room), the wall collects heat from internal heat sources and stores that inside the PCM; in the evening and at night, the rotated wall (PCM faces the window) releases that heat mostly via convective heat transfer using cool(er) outdoor air and a little bit via IR radiation exchange with the inner surface of the glass. The wall is built up of two active layers: a layer of PCM which acts as the heat buffer and a thin layer of translucent aerogel grains that acts as thermal insulation to make sure the heat is not released too soon.



1 Main working principle of the Double Face 2.0 Trombe wall



2 Translucent aerogel grains (left) and salt-hydrate phase change material (right) used in this study

PHASE CHANGE MATERIAL

PCMs exist in different types. Especially for applications in buildings, salt hydrates, paraffins and bio-based PCMs are interesting. Paraffines generally have high latent heat of fusion, high chemical stability and relatively low cost; however, they are flammable. Salt hydrates generally also have high latent heat of fusion, have relatively low cost, are non-flammable and are highly transparent in liquid form; these however are corrosive to metals and are less chemically stable, meaning they can undergo phase segregation after a while. The bio-based PCMs are less flammable than the paraffins, can be transparent in liquid form, have good chemical stability, are non-corrosive but are relatively expensive and have low density, meaning that more volume is needed to achieve the same amount of latent heat capacity [10]. For this project, a salt hydrate with a phase change temperature between 23 and 25°C, latent heat of fusion of 180 kJ/kg and about 2°C hysteresis was selected, as can be seen in figure 2 (right).

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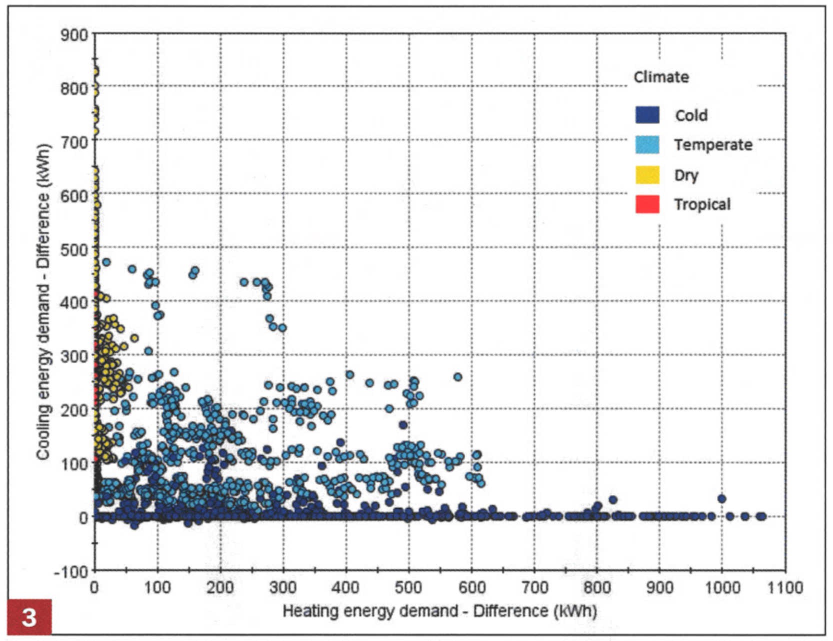

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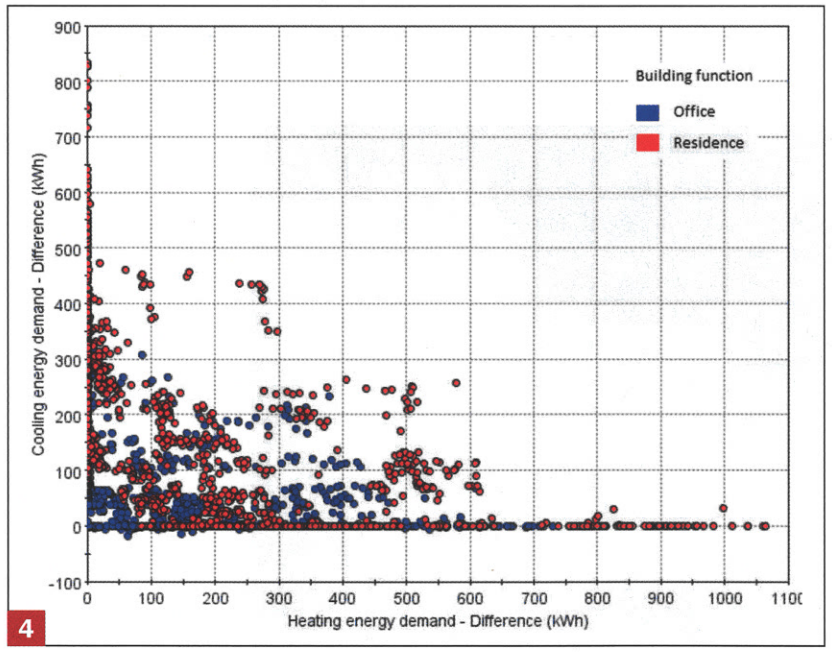
Results of the optimisation for the objectives minimising heating demand and minimising cooling demand, presented for the four climates investigated. Each point represents a variant. Along the x- and y-axis the difference between the heating/cooling demand of the case with PCM-based Trombe wall and without PCM-based Trombe wall is plotted. A positive value means energy demand reduction due to the Trombe wall [11]



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Results of the optimisation for the objectives minimising heating demand and minimising cooling demand, presented for the two functions investigated. Each point represents a variant. Along the x- and y-axis the difference between the heating/cooling demand of the case with PCM-based Trombe wall and without PCM-based Trombe wall is plotted. A positive value means energy demand reduction due to the Trombe wall [11]

FLAT PANEL AND ROTATION

In order to investigate the impact of a flat rotating Trombe wall with PCM on the energy demand of a room, a custom-made simulation model in the Matlab/Simulink environment was made by Willem van der Spoel and further developed by graduation student Jeroen van Unen [11]. This simulation model, benchmarked with the software Design Builder for a non-rotating Trombe wall, describes a room with a window on one side behind which the Trombe wall is placed. The model includes all relevant modes of heat transfer and thermal buffering, including transmission through the walls and glass, (night-time) ventilation, infiltration, solar radiation, internal heat gains, the thermal inertia of the walls and floor/ceiling and all heat exchanges to and from the PCM-based Trombe wall. Also, the enthalpy curve of the PCM is included as part of the thermal inertia of the Trombe wall and the stack effect inside the air cavity between glass and Trombe wall is modelled. Rotation of the Trombe wall was set based on sunrise and sunset for the diurnal cycle and changed in direction between the heating and cooling season [11]. So, in winter the PCM is facing the window between sunrise and sunset, while it faces the room between sunset and sunrise. In summer, the wall is in reverse position.

The Matlab/Simulink model was next connected to the optimisation platform modeFrontier to perform a Design of Experiments (DOE) and several optimisations based on the NSGA-II genetic algorithm. The objectives of these optimisations were minimising the energy demand for heating and for cooling. Cooling was also implemented in the model as an indicator of potential risk of overheating. The variables included climate (cold, temperate, dry, tropical), building function (office, dwelling), window orientation (North, East, South, West), room size (20, 100 m²), window-to-wall ratio, type of glazing (double clear, double coated, triple clear, triple coated), building age (relating to R_c-values and airtightness) and thermal mass (lightweight, medium weight, heavyweight). Altogether this led to 2304 different variants. In a next step, also heating and cooling thermostat set-points, sun-shading, and type of PCM (latent heat of fusion and phase transition temperature) were investigated with a sensitivity analysis.

Figures 3 and 4 present some results of the optimisation run in which the cooling energy demand reduction versus the heating energy demand reduction is plotted for each variant simulated and individually highlighted for the four climates investigated respectively the two different functions: office and housing. The difference in heating or cooling demand is the difference between a room with rotating PCM-based Trombe wall and without such a wall (solely a window). A positive value reflects a reduction in heating energy demand or cooling energy demand as a result of the Trombe wall. As can be seen from figure 3, the rotating PCM-based Trombe wall is particularly interesting for temperate climates like the Netherlands because in these climates it can both save energy for heating and for cooling. For this temperate climate the average reduction in heating demand was 36,1% and in cooling demand 49,9%, considering the average of all simulated variants [11]. But also in the other climates simulated the Trombe wall can lead to significant reductions in energy demand. Furthermore, there does not seem to be a very big difference between offices and housing.

This research also showed that around 85% of the energy saving results from the presence of the Trombe wall and its construction (including its insulating effect in winter) while around 15% is due to the performance benefit of the PCM [11].

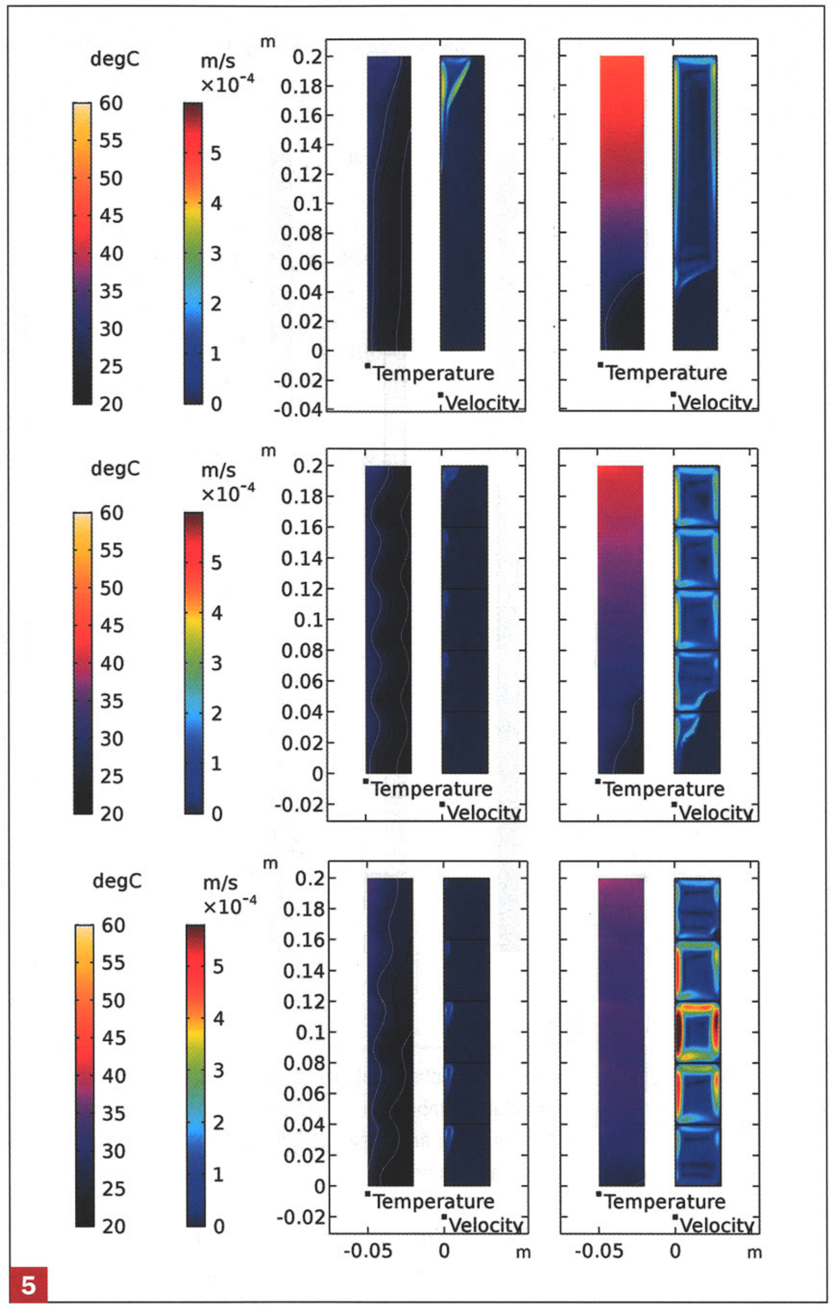
SEGMENTING THE INNER STRUCTURE

Furthermore, the software Comsol was used to get a clearer picture of how the temperature distribution inside the PCM-based Trombe wall would be under different environmental conditions and for different shapes of the wall. From the simulations we clearly observed that the Trombe wall had to be segmented in height. Figure 5 (top) shows a block of PCM inside the wall with a thickness of 3 cm and a height of 20 cm exposed to solar radiation of 300 W/m² from the left side after 4 hours (first column) or 8 hours (second column) of exposure. During the first one to two hours the PCM is still solid and the heat transfer is uniform and perpendicular to the outer surface. However, once some PCM has melted, convection starts to arise inside the molten PCM transporting heat from the bottom of the block towards the top. As a result, more heat collects at the top speeding up the melting process there. This process can induce a large temperature gradient throughout the block, high temperatures at the top, and non-uniform, less-effective heat storage. An important thing to consider in this respect is that most PCMs have an upper temperature limit to which they can be exposed. By segmenting the block in height (figure 5 (middle)) and by selecting PCMs with different phase change temperature for the different segments (figure 5 (bottom), with lower phase change temperature at the bottom and higher at the top, this melting process can be controlled. More details on the modelling and more results can be found in [12].

SHAPING THE SURFACE GEOMETRY

Other aspects investigated were the wall's surface geometry, the thickness of the air cavity, the percentage of openings in the walls and the amount of PCM needed. For these studies a 2D room model was developed in Comsol using the heat transfer and CFD modules and including all relevant heat transfer modes and air flow representing conditions of a typical house or office in the Netherlands. NEN 5060 [13] weather data was connected to the model and selected winter and summer weeks were simulated. An example of such a model with three rotating PCM Trombe panels is shown in figure 6.

From all these investigations we concluded that a PCM layer thickness of around 2,5 cm would be ideal for both summer and winter mode, that the inner structure of the entire wall should be segmented in height into blocks of around 2 cm, that a layer of 1 cm aerogel would be suffi- ▶



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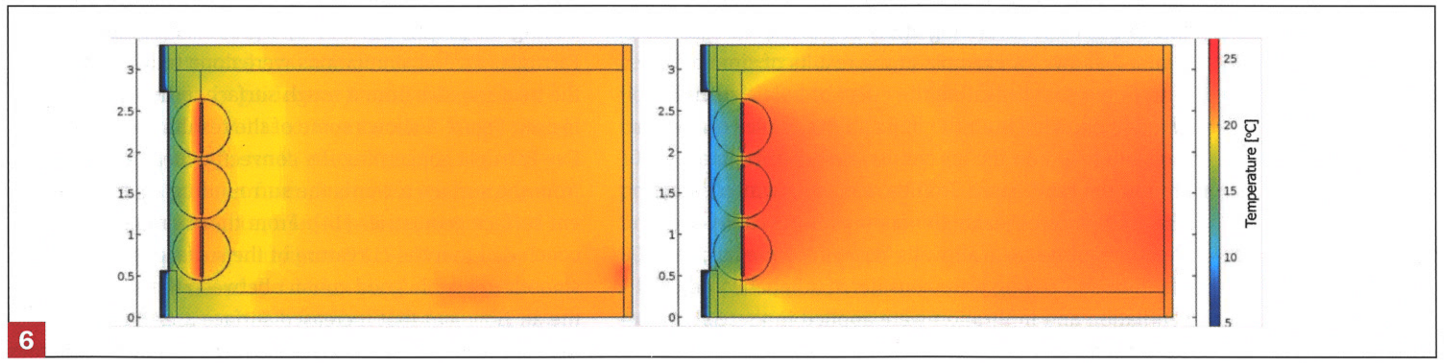
Results of the simulations with Comsol showing the temperature and velocity distribution of the PCM inside the Trombe wall after 4 hours (left column) and 8 hours (right column) of exposure to solar radiation of 300 W/m² from the left side. The image at the top presents a full column of PCM with a phase transition around 25°C of 3 cm thick and 20 cm high; the image at the middle shows the same column of PCM but now segmented into smaller pieces of 4 cm high; the image at the bottom shows the segmented PCM column with different PCM phase change temperatures (from bottom to top: 23, 24, 25, 27, 29°C) [12]



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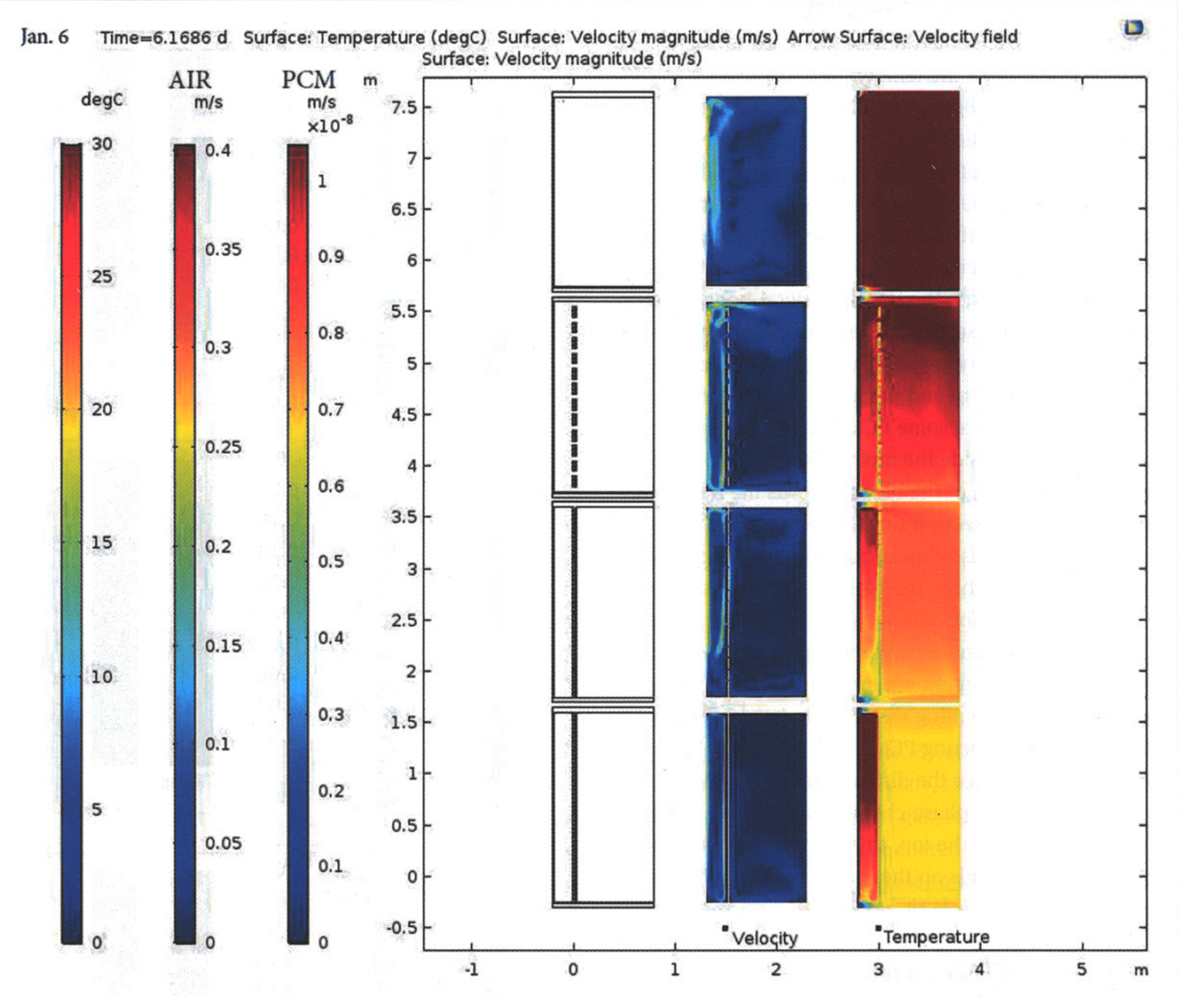
Results of heat transfer simulations in Comsol showing a cross section through a room with a South-facing façade and three rotating PCM Trombe panels (PCM faces the window between 8:00 and 18:00 h). The left image shows the temperature distribution throughout the room during charging of the PCM Trombe wall by solar radiation (January 9, 12:00 h). The right image shows the temperature distribution during discharging of the PCM wall (January 10, 00:00 h)



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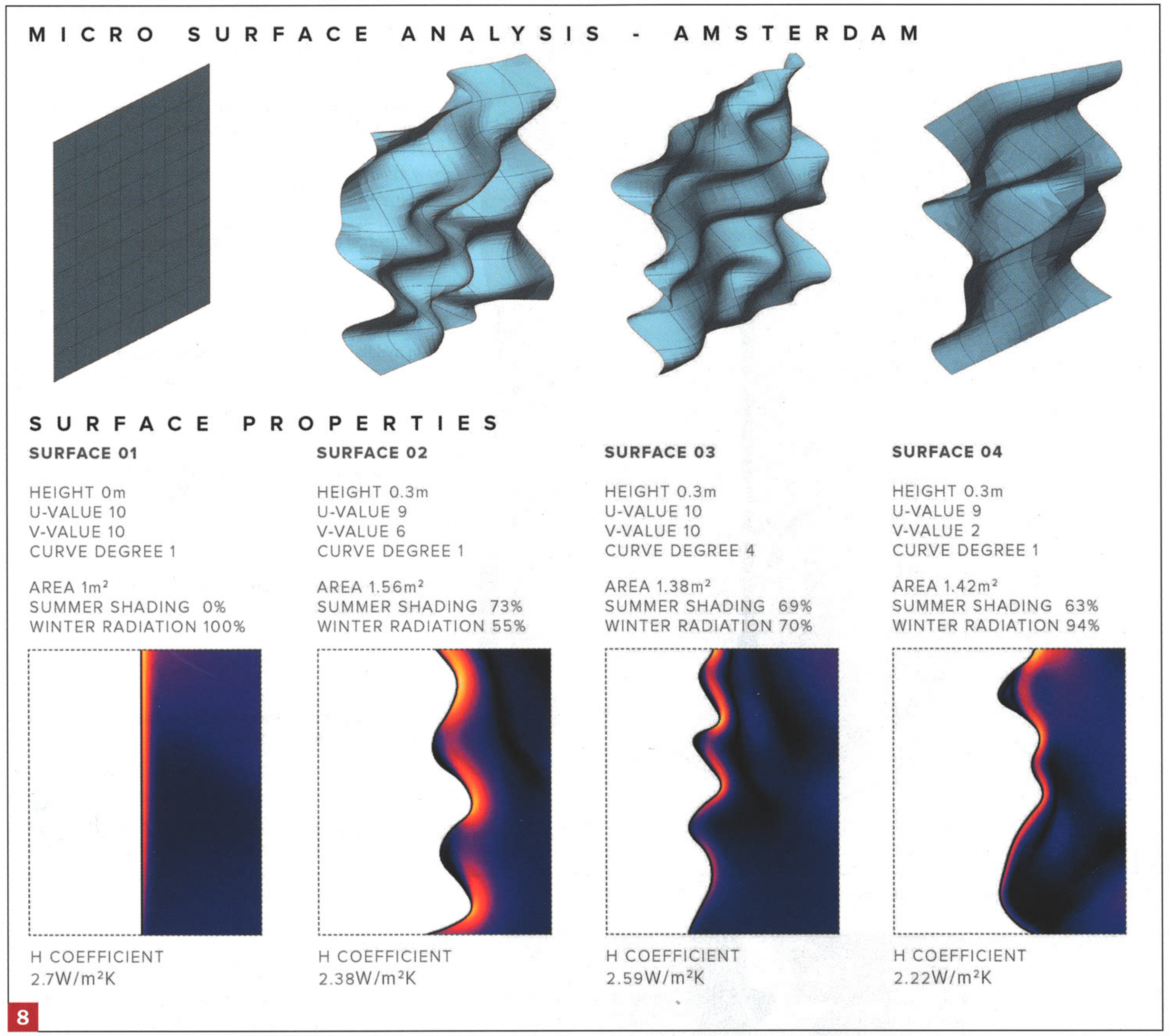
Results of Comsol simulations for January 6, 04:00 h, showing the simulated geometry (left column), air flow (middle column) and temperature distribution (right column) for part of the simulated room and for four different opening sizes and amounts in the Trombe wall. The number and size of openings decrease from top to bottom (top: no Trombe wall; bottom: fully closed Trombe wall; middle two: Trombe wall with holes)

cient, and that the air cavity between the window and the wall should ideally be around 5 cm thick.

Furthermore, we found that openings in the wall allowing for daylight to more easily enter into the room are acceptable up to around 20% of the area of the wall with a maximum height of each opening of around 5 cm. Such openings, however, do lead to a (small) reduction in energy saving performance, partially due to uncontrolled air exchange between the cavity and the room, partially due to a reduced amount of PCM and partially due to a smaller insulating effect of the wall in winter. Figure 7 shows an example of the results of simulations with Comsol investigating the effect of hole size and amount, showing both the impact of the holes on the air movement and on the air temperature distribution around the PCM-based Trombe wall for a winter's day. The temperatures inside this room and the cavity are slightly high because all walls (except for the façade), the floor and ceiling were considered adiabatic and no ventilation and infiltration were applied in these shown simulations.

Another important aspect we observed during all these simulations was that the charging of the PCM on a sunny winter's day is relatively fast because it is solar radiation driven, while the discharging process is slow because it is driven by a temperature difference (convective heat exchange between the wall and the surrounding air and IR radiation exchange between the wall and other walls, the floor and the ceiling). As a result, it is important to create on the one hand some self-shading to make sure the PCM will not get overheated and on the other hand to increase the convective heat transfer by enlarging the surface area and while doing that ensuring no pockets of still air along the surface arise. During the project but also by a graduation student, Eve Farrugia, several simulations were done to investigate the heat transfer from a rough surface to the surrounding air. Figure 8 shows some of the results obtained by Eve Farrugia concerning the convective heat transfer from the surface towards the surrounding air for different surface geometries [14]. From these simulations, we concluded that the curvature of the surface should be smooth to enable good contact between the surface and the air flow and that increased surface area ensured increased total convective heat transfer defined by the product of the boundary heat transfer coefficient (*h*) and the surface area (*A*). From the four surface geometries displayed in figure 8 the second surface would have the highest convective heat transfer but at the same time also have the highest self-shading for solar radiation in winter.



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Results of simulations with Comsol showing how the air flows along a vertical surface in case of free convection for different surface geometries, and the resulting boundary heat transfer coefficient (h) and surface area (A). h*A is a measure for the total convective heat transfer. White represents the material of the wall, colours represent the velocity of the air from low speed (purple) towards higher speed (yellow) [14]

DESIGN AND PROTOTYPE

The previously discussed heat transfer and fluid flow simulations resulted in guidelines for the design and engineering of the PCM-based Trombe wall. These guidelines together with structural, manufacturing and daylight concerns and input from potential users were used to develop a design concept for this Trombe wall. This design concept is shown in figure 9 [15]. Due to the geometric complexity of the design regular production techniques were not suitable for the manufacturing of a prototype. Because we had already anticipated such geometric complexity from the onset of the project proposal, the exploration of FDM (Fused Deposition Modelling)-based 3D printing with a robotic arm was explicitly included in the studies. The choice for this rapid prototyping technique had an important impact on the development of the final design concept. The design had to be optimised for printability. Besides print quality, print speed and limited deformation during the cooling process, also water tightness was an important consideration because the used salt hydrate PCM is corrosive to metals and may damage the top layer of concrete. Figure 10 shows a picture of the printing process of part of the prototype with the material PET-G. After many days of printing this resulted in the final prototype measuring 80 cm wide and 240 cm tall, which was installed in the OfficeLab of the Green Village on the campus of TU Delft, as shown in figure 11. Last January, we started a measuring campaign monitoring outdoor weather conditions, solar radiation, temperatures, air flow and heat fluxes. Hopefully we will soon be able to collect all the data and see if the wall performs as intended.

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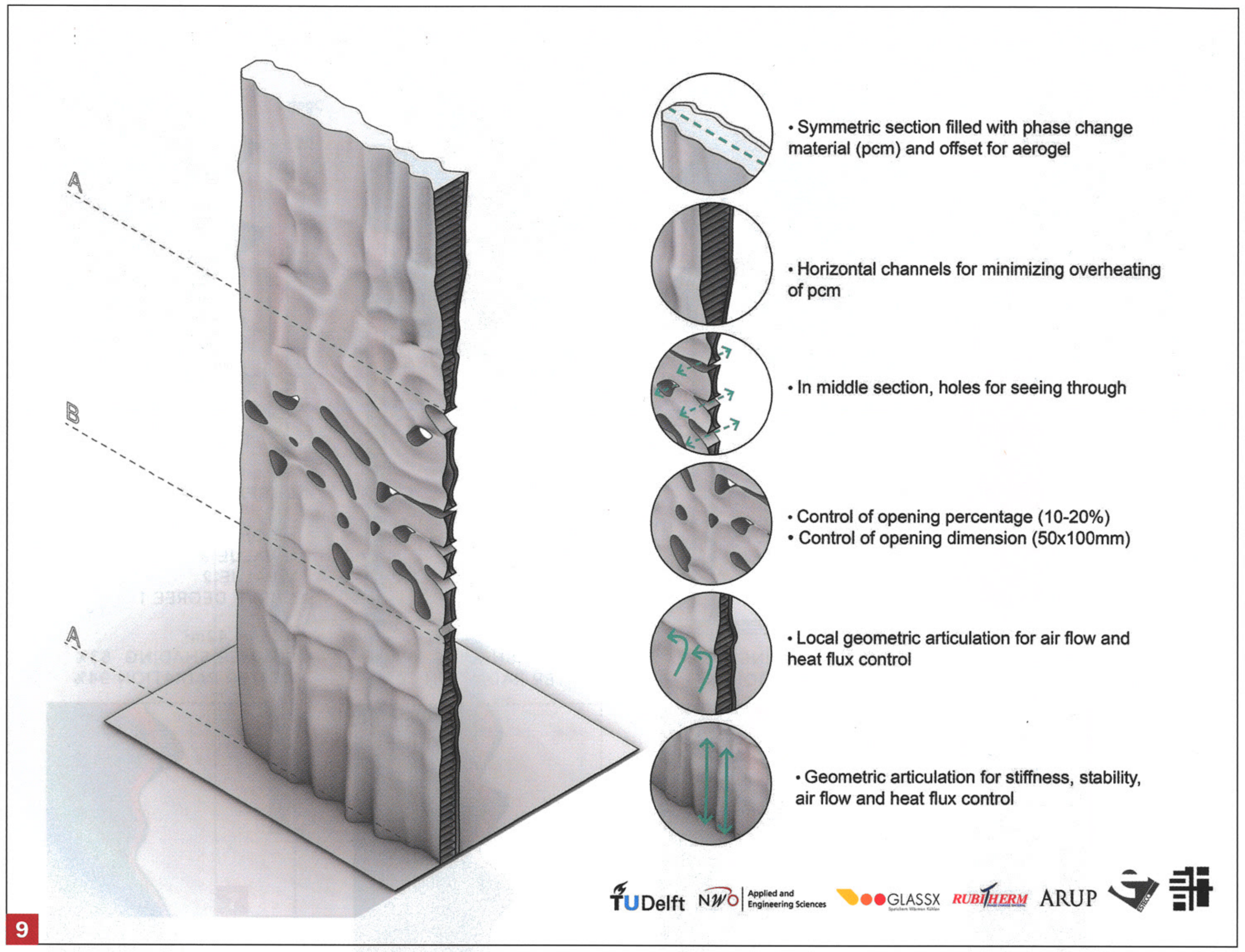

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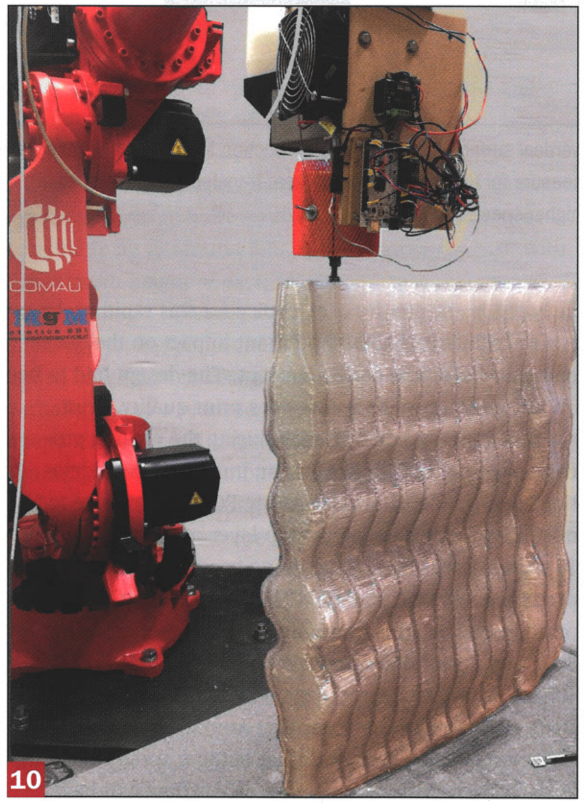
Integrated design concept of the prototype



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3D printing of part of the prototype using a robotic arm with a custom-made FDM extruder and print head

CONCLUSION

To conclude, the Double Face 2.0 project has provided us with interesting new insights into the behaviour of Trombe walls, into the behaviour of PCM and into (robotic) FDM 3D printing. This research has shown that such solar walls can contribute to a reduction of the energy demand for heating and for cooling. The exact amounts of energy saving for a whole building/house still need to be proven with monitoring in practice, though. Furthermore, the current version of the wall probably is still too complex to be used in practice. Developments into simplifying the geometry and making the wall even more lightweight will be interesting next steps.

Acknowledgement

The Double Face 2.0 project was part of the research program Research through Design with project number 14574, which is financed by the Netherlands Organisation for Scientific Research (NWO) and Taskforce for Applied Research SIA. We are also grateful for the help and knowledge provided by the project's partners from industry: Shau Architecture and Urbanism, GlassX AG, Esteco SpA, Rubitherm GmbH and Arup. The researchers would also like to thank MgM Robotics for the technical support and advice when using a Comau robot which was used for the construction of the prototype.

The Double Face 2.0 project was conducted by staff members from TU Delft: Martin Tenpierik, Michela Turrin, Yvonne Wattez, Tudor Cosmatu and Stavroula Tsafou, supported by Willem van der Spoel on Matlab/Simulink, Paul de Ruiter on additive manufacturing, and Arno Freeke and Arend-Jan Krooneman on virtual reality. Furthermore, two students' graduation projects were also closely connected to this project: that of Jeroen van Unen and of Eve Farrugia. ■

REFERENCES

▶ **[1]** van den Brom, P.I., Energy in Dwellings: A Comparison between Theory and Practice, PhD thesis, TU Delft, Delft, 2020

▶ **[2]** Eurostat, Final Energy Consumption by Sector, Eurostat, Luxemburg, [online], available: <https://ec.europa.eu/eurostat/databrowser/view/ten00124/default/table?lang=en>, [April 22, 2020]

▶ **[3]** Baetens, R., Jelle, B.P., Gustavsen, A, Phase change materials for building applications: A state-of-the-art review, Energy and Buildings 2010, 42, 1361-1368

▶ **[4]** Kalnaes, S.E., Jelle, B.P., Phase change materials and products for building applications: A state-of-the-art review and future research opportunities, Energy and Buildings 2015, 94, 150-176

▶ **[5]** Weinläder, H., Beck, A., Fricke, J., PCM-façade-panel for daylighting and room heating, Solar Energy 2005, 78, 177-186

▶ **[6]** Soares, N., Samagaio, A., Vicente, R., Costa, J., Numerical simulation of a PCM shutter for buildings space heating during the winter, Proceedings of the World Renewable Energy Congress, Linköping, Sweden, May 8-13, 2011, 1797-1804

▶ **[7]** Fiorito, F., Trombe walls for lightweight buildings in temperate and hot climates, Exploring the use of pcms for performance improvement. Energy Proceedia 2012, 30, 1110-1119

▶ **[8]** Goia, F., Perino, M., Serra, V., Improving thermal comfort conditions by means of PCM glazing systems, Energy and Buildings 2013, 60, 442-452

▶ **[9]** Komerska, A., Bianco, L., Serra, V., Fantucci, S., Rosinski, M., Experimental analysis of an external dynamic solar shading integrating PCMs: first results, Energy Proceedia 2015, 78, 3452-3457

▶ **[10]** Su-Gwang J. et al., Improvement of the thermal properties of Bio-based PCM using exfoliated graphite nanoplatelets, Solar Energy Materials & Solar Cells 2013, 117: 87-92

▶ **[11]** Unen, J. van, The energy and comfort performance of a lightweight translucent adaptable Trombe wall in different buildings and climates, MSc thesis, TUDelft, Delft, 2019

▶ **[12]** Tenpierik, M., Wattez, Y., Turrin, M., Cosmatu, T. and Tsafou, S., Temperature Control in (Translucent) Phase Change Materials Applied in Facades: A Numerical Study, Energies, 2019, 12(17), 3286, 1-16, <doi:10.3390/en12173286>

▶ **[13]** NEN 5060:2018, Hygrothermische eigenschappen van gebouwen – Referentieklimaatgegevens, NEN, Delft

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Final prototype hanging in the OfficeLab of the Green Village on the TU Delft campus

▶ **[14]** Farrugia, E.G., Thermal morphology. A geometrically optimized Trombe wall, MSc thesis, TUDelft, Delft, 2018

▶ **[15]** Tenpierik, M., Turrin, M., Wattez, Y., Cosmatu, T. and Tsafou, S., Double Face 2.0: A lightweight translucent adaptable Trombe wall", Spool, 2018, 5(2: Expo #1), <doi.org/10.7480/spool.2018.2.2090>