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Renewed Trombe wall passively reduces energy consumption

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Abstract: In order to reduce the energy demand of households, a new type of Trombe wall is being designed during a 'research through design project' called 'Double Face 2.0'. A Trombe wall is a passive system that reduces the energy demand of a building. In winter, it captures the heat from the sun during the day and releases this heat into the building at night. In summer, it captures the heat from internal sources during the day and releases that heat at night towards outdoors. First simulations showed that our prototype of a lightweight, translucent, adjustable Trombe wall reduces the energy demand for heating of a typical Dutch household by 25-30%. Instead of stone-like materials, the new type of Trombe wall will consist of translucent materials: phase change material (pcm) and insulating aerogel. The insulation gives the opportunity to direct the thermal mass of the pcm. In this way, the system is adjustable for cooling and heating purposes. A selection of the design concepts is described in this paper, explaining the design choices and method of validation. Depending on the level of detail, different simulation software has been used. This paper describes the comparison and the experiences of using it.

Keywords: Trombe wall, passive, heating, cooling, pcm

Introduction

Although there has been a lot of progress towards energy efficiency of households since 2000 (Gerdes, 2015), we still need to strongly reduce the energy demand of buildings in order to reach the European 20-20-20 targets (European Union, 2017). In the Netherlands, the majority of the energy consumed in households is used for heating. Nevertheless, the share of energy demand for cooling to prevent overheating increases.

During the two 'research through design' projects 'Double Face 1.0 and 2.0', a new type of Trombe wall is being designed in order to reduce the energy demand for both heating in winter and cooling in summer. A traditional Trombe wall is a passive system consisting of a massive stone-like wall placed behind a glazed façade. In between the glass and the wall a thin layer of air exists (Saadatian et al, 2012). Furthermore, it is common practice to install controllable vents at the top and bottom of the wall enabling air exchange between the inhabited space behind the wall and the thin layer of air whenever required. In winter, the Trombe wall captures the heat from the sun during the day and releases this heat slowly into the building in the evening and at night. Whereas the traditional Trombe wall was designed to be only used in winter, with adjustments it could also be used in summer. In summer, it then captures the heat from internal sources during the day and releases that heat at night towards outdoors by a combination of ventilation cooling and nocturnal radiation towards a clear sky. A new development in modern variations of the

Trombe wall is the inclusion of phase change materials in order to decrease the weight of the wall (Saadatian et al, 2012; Castellon et al, 2009; Fiorito, 2012; Kienzl, 1995; Manz et al, 1997; Weinläder et al, 2005). All of these Trombe walls, however, are fixed in place and can hardly be adjusted to the dynamics of the environmental conditions.

The Trombe wall presented in this paper consists of translucent materials: phase change material (pcm) and insulating aerogel. The insulating layer gives the opportunity to direct the thermal mass of the pcm towards either the room or the window. Furthermore, the system's configuration can be adjusted so that it can be used for both cooling and heating purposes. This novel Trombe wall can be used in existing and new buildings.

This paper presents two of the design concepts, explaining the design choices and the methods of validation. Depending on the level of detail, different simulation software has been used.

Double Face 1.0

During the project 'Double Face 1.0', a first adjustable, translucent Trombe wall has been developed (Figure 1). Instead of concrete, the elements are filled with 4 cm pcm type RT25E2. This pcm has a transition temperature for melting and freezing around 25^{o}C and a latent heat storage capacity of 180 kJ/kg (Rubitherm, 2015). According to a numerical study by Bourdeau, a 15 cm concrete wall can be replaced by a 3.5 cm wall of phase change material and perform similarly (Bourdeau, 1980). By using pcm, a more lightweight system was developed with a thermal storage capacity similar to a traditional Trombe wall. Apart from the pcm, the Double Face Trombe wall consists of 1 cm of translucent Lumira aerogel insulation with a thermal conductivity of 0.018 W/(m·K) (Cabot, 2017). Both the pcm and aerogel are encased in transparent containers with a shape as can be seen from figure 1 (right). All together these modules form a 3D undulated Cairo pentagonal tiling pattern.

Figure 1. Artist impression and photo of the first adjustable translucent Trombe wall prototype.

Besides the use of new materials, the adjustability of the system plays an important role. If the pcm is facing the window during a winter day, it stores the energy of the sun. After rotation at night, the pcm faces the inhabited room in order to release the heat into the room. In summer, the cycle reverses: during the night, the pcm faces the window and releases the heat by night ventilation and nocturnal radiation towards the sky. During the day, the pcm faces the inhabited room and stores heat from internal sources. If the room temperature rises above 22^{o}C, the pcm slowly starts melting. The higher the room temperature, the quicker the melting process, with an optimum at 25^{o}C. During this process the temperature of the pcm stays stable; it only rises again after the pcm has fully molten.

To prevent the Trombe wall from taking away the view to outside, openings were realized in the design. Simulations in Design Builder v3.4 showed that the best trade-off between unobstructed views and heat storage capacity would lead to a ratio of approximatively 10% of openings in the system's overall surface. When increasing the percentage of openings, the heat transfer via convection between the cavity and the room increases which reduces the advantageous time lag of the Trombe wall.

One of the strengths of this new Trombe wall system is the ability to rotate the elements in order to orient the pcm either towards the room or to the window. Because Design Builder is not able to move or rotate elements during a simulation, a Matlab/Simulink model was set-up to simulate a 2D flat Trombe wall that rotates twice per day. The model is a full energy performance model for a small room with a window facing South including solar gains, internal gains, ventilation and infiltration losses, transmission losses through the façades, heat storage in walls, sun-blinds, temperature set-points, schedules, etc. The ceiling and floor were assumed to be adiabatic surfaces. Relevant settings are presented in Table 1.

Table 1. Settings used for the simulations in Matlab/Simulink.

calculated time (one winter)	1 Oct. - 30 Apr.	% of holes in Trombe wall element	10%
orientation Trombe wall	South	thickness of PCM	varies
size of room w*d*h	3.6*5.4*2.7 [m3]	thickness of insulation layer of Trombe wall	0.01 m
window to wall ratio South	80%	PCM: specific heat	2000 J/(kg·K)
window to wall ratio North	40%	PCM: density	1450 kg/m3
U-value of glass	1.65 W/m2·K (double glazing)	PCM: thermal conductivity	0.6 W/(m·K)
Rc-value of opaque walls	3.0 m2·K/W	PCM: latent heat of fusion	1.8·105 J/kg
solar heat gain coefficient - no sunblind	0.6	Insulation material: specific heat	1440 J/(kg·K
occupancy	18.00-8.00 h / 7 days a week	Insulation material: density	75 kg/m3
Internal heat gains	1.8 W/m2 according to NEN 7120 for dwellings	Insulation material: thermal conductivity	0.012 W/(m·K)
Ventilation rate of the room	1.2 when occupied	weather data	Dutch NEN5060 B2 reference weather data
PCM in solid phase	< 23 Celsius	set-point temperature of heating system	20oC
PCM in liquid phase	> 26 Celsius		

The results of the simulations are shown in Figure 2. It gives an overview of the amount of energy needed to heat the room. During one winter period, the energy use of this room without a Trombe wall would be 4.78 GJ. If a Trombe wall of 4 cm concrete is added, the heating demand is reduced to 3.71 GJ. When the concrete is replaced by an insulated and adjustable Trombe wall (rotates 180^{o} twice per day) of 4 cm pcm and 1 cm aerogel, the required energy drops to 3.18 GJ; a reduction of 33%. The optimal thickness, though, lies at 1-2 cm of pcm with a decrease of 30-32%. With these insights, new design concepts are being developed during the Double Face 2.0 project.

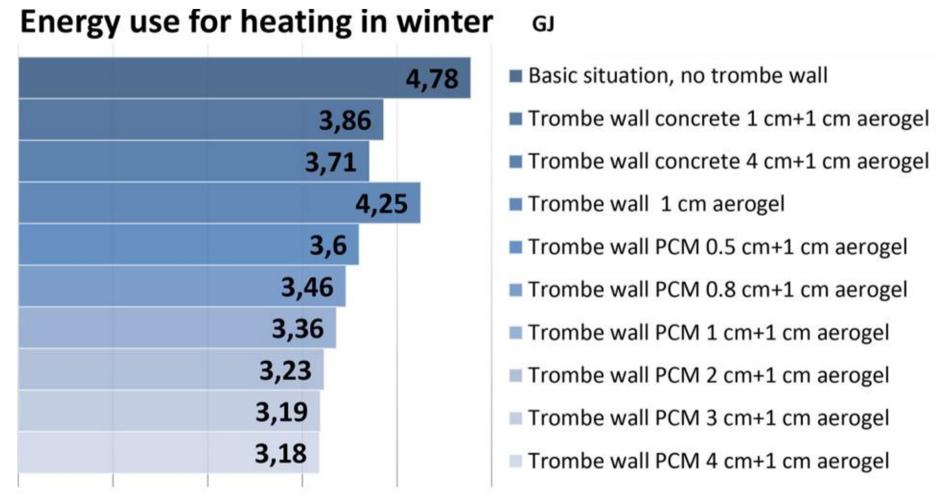


Figure 2. Results regarding the energy use.

Double face 2.0: a selection of developed designs

With the goal of a lightweight, adjustable, translucent Trombe wall, eleven different design concepts have been developed during the 2.0 project so far. Two of these concepts are explained in this paper: the ‘Trombe panel’ and the ‘Jacobs ladder’.

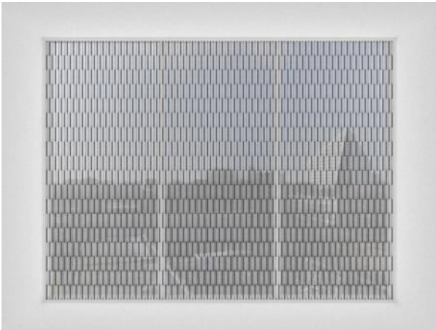
Trombe panel

This design integrates thermal, structural and optical properties in one aesthetically designed panel. The panel stands behind a window and needs to be vertically rotated by hand or by an electro-motor, in the morning and afternoon. The design is based on a brain coral pattern which is filled with pcm with a melting temperature of around 25^{o}C. Due to this pattern some parts are filled with pcm and some parts remain open for view. The thickness of the pcm in the panels varies to optimize the translucency for daylight at certain positions. The total volume stays the same as for a flat panel with a thickness of 2 cm pcm.

The yearly energy savings resulting from the use of this Trombe wall are similar to the ones calculated with the Matlab/Simulink script in a previous section (Figure 2).

Figure 3. Design impression of Trombe panel concept

Jacob's ladder
The design concept 'Jacob's ladder' is based on a movement principle. The elements of the Trombe wall need to flip sides twice per day to orient the pcm in the required direction. The movement in this design comes from a toy (figure 5). If the ladder is held at one end, blocks appear to cascade down the strings. This effect is a visual illusion which is the result of one block after another flipping over. An arrangement of interlaced ribbons allows each block to act as if hinged to the next one at either of its two ends. An impression of the design is shown in figure 4 where the black, vertical lines show the strings of the ladder.



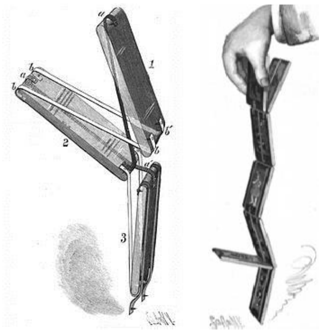


Figure 4 (left). Design impression of Jacobs ladder concept.
Figure 5 (right). Principe of Jacob's ladder movement (Scientific American, 1889).

Double face 2.0: selection of simulation results

Jacob's ladder
More detailed simulations are used to compare different design variations of the 'Jacobs ladder concept'. Therefore, a 2D simulation model in the program COMSOL v.5.2 was made. This program allows to simulate 2D and 3D models over longer time periods; import geometries; simulate with moving elements; simulate with real weather data; and use the same model for more detailed CFD-simulations (Computational Fluid Dynamics).

A simplified version of the Jacob's ladder design is shown in Figure 6, with 2 cm of pcm and 1 cm of aerogel, the properties of which are shown in Table 1. The floor, ceiling and walls are made of concrete and contain an adiabatic boundary along the outside. Heat transfer only takes place through the South façade with the Trombe wall via conduction and radiation from the sun. The opaque walls of this façade have a U-value of 0.34 $W/(m^2{\cdot}K)$; the double glass has a U-value of 1.65 $W/(m^2{\cdot}K)$. Moreover, no heating system is active, no sun-shades are used and no people are present inside the room. The panels rotate around their centre at fixed times: at 8:00h and 18:00h. The weather data used is shown in Table 1.

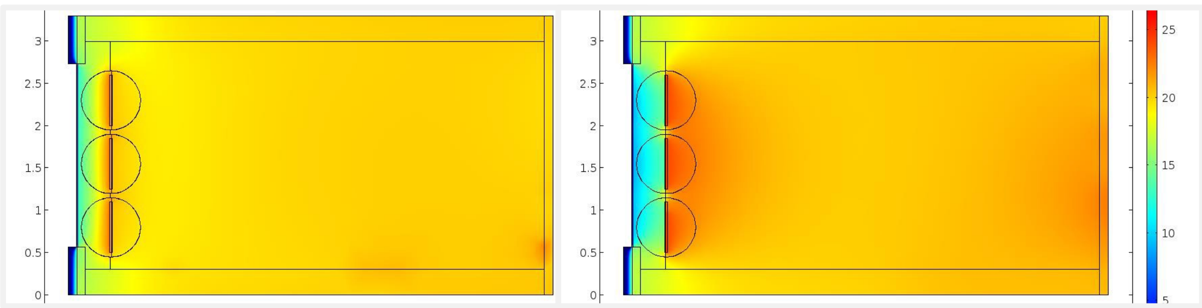


Figure 6. Simulation result of Jacob's ladder design concept; vertical cross-section of a room.
Left: January 9, 12.00h - pcm faces window. Right: January 10, 00.00h; pcm faces room

Figure 6 (left) shows the temperatures on day 9.5 (January 9, 12.00h) so the pcm faces the window and the aerogel faces the room whereas figure 6 (right) shows the temperatures on day 10.0 (January 10, 00.00h) when the position of the pcm and aerogel are reversed. Solar radiation clearly heats up the cavity during the day, visualized by the red colours on the left side of the panels. Some sunlight passes through the openings in between the panels, indicated by the orange dots in the bottom right corner. In the evening, the pcm, which now faces the room, clearly radiates heat into the room. The circles in the model are necessary to simulate a rotating mesh and are not part of the design.

The effect of the use of different materials

In order to understand the effect of material types and thicknesses in the Jacob's ladder concept, different configurations of this basic model were simulated in Comsol (Table 2). Figures 7 and 8 show the simulation results for Jan. 1 till Jan. 21, giving the average room temperature per configuration and the average temperature of the thermal mass component (pcm or concrete). The effect of the solar radiation is clearly visible in both graphs. The pcm heats up quickly in the configurations with 2 cm pcm. The release of the heat takes a long time. A thicker layer of pcm (7 cm) gives a more stable room temperature and a lower temperature of the pcm itself, see the purple line in Figures 7 and 8.

The positive effect of rotating the pcm panels on room temperature is visible in the results of day 0-10 where the red line, the rotating Jacob's ladder, shows a higher and more stable room temperature than both the configurations without a Trombe wall and with non-rotating panels. The rotating pcm Trombe wall is able to maintain a comfortable room temperature in winter for many days after a day of moderate sunshine (2.8 kWh/m^2 of global normal radiation on day 2) without the need for an additional heating system.

The advantage of pcm above concrete is also visible in the graphs. Where the concrete Trombe wall extracts heat from the room during day 10-20, the pcm stabilizes the room temperature and uses the radiation of the sun to heat. If the pcm temperature is always within the transition range on freezing and melting (shown by 'PCM_trans' in Fig. 8), the room temperature is stable. This is for instance the case for a Trombe wall of 2 cm of pcm facing the room and 1 cm of aerogel facing the window (1P_ins_room). The pcm is barely heated up by the direct sunlight because of the insulating layer, so its temperature stays within the transition range. Nevertheless, this configuration does not use the incoming solar radiation for heating the room optimally; for that the pcm needs to face the window.

Table 2. Different configurations simulated in COMSOL.

name	***description***	***material 1***	***material 2***	***rotate***
No_Trombe	no trombe			
Concrete_30	classical 30 cm	concrete 30 cm		no
Concrete_15	classical 15cm	concrete 15 cm		no
1P_7cm	pcm 7cm	pcm 7 cm		no
1P_2cm	pcm 2 cm	pcm 2 cm		no
1P_ins_window	pcm to window, 2 cm, insulated	pcm 2 cm	aerogel 1 cm	no
1P_ins_room	pcm to room, 2 cm, insulated	pcm 2 cm	aerogel 1 cm	no
3P_rotate	3panels pcm rotate	pcm 2 cm	aerogel 1 cm	yes
3P_room	3panels no rotate pcm to room	pcm 2 cm	aerogel 1 cm	no
3P_window	3panels no rotate pcm to window	pcm 2 cm	aerogel 1 cm	no

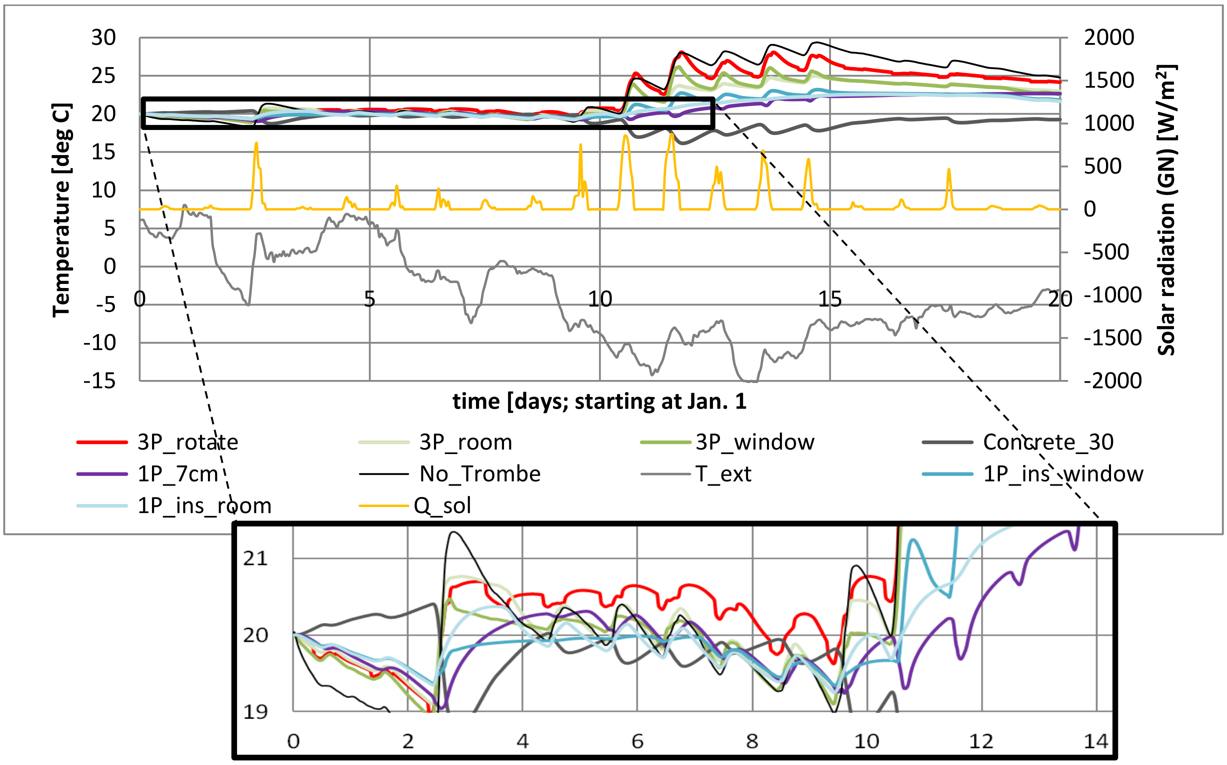


Figure 7. Room temperature due to Jacob's ladder concept from Jan. 1 - 21; no heating / room unoccupied.

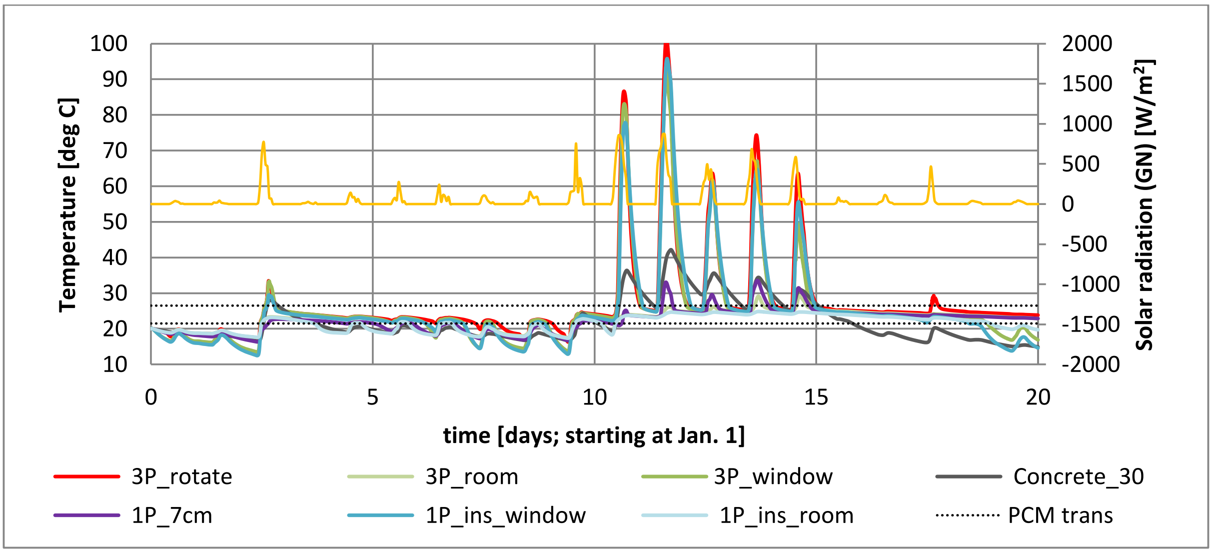


Figure 8. Pcm temperature due to Jacob's ladder concept: average temperature of thermal mass component.

Conclusions

This paper describes a novel, adjustable, lightweight, translucent Trombe wall containing pcm and an insulation layer of translucent aerogel. One of the strengths of this wall is its adjustability allowing the pcm to face either the window or the inhabited room. As a result, the system can both be used in winter in heating mode and in summer in cooling mode.

Several design concepts have been developed, two of which were described in this paper. Simulations with a model developed in Matlab/Simulink, that includes the adjustability of the system, have shown that a layer of 2 cm pcm together with an insulation layer of 1 cm aerogel can reduce the heating demand of a room in the climate of the Netherlands by around 30%. More advanced simulations with a 2D model in Comsol have shown that in case of a well-insulated room, this 2 cm of pcm heats up very fast due to the solar radiation. To prevent it from overheating and to optimize the heating capabilities, the design should be equipped with a thicker layer of pcm in winter. However, since the release of the heat takes longer than the absorption of it, the extra pcm might be unwanted during summer where the transition works in reverse.

The simulation results showed the advantages of the rotation of the elements during a sunny winter day. However, on a cloudy winter day, the pcm slightly cools the room. During the next phase of the project, smart rotation algorithms will be investigated in order to optimize the thermal effect of the system. As such, innovative Trombe walls may be an important means of passively reducing the energy demand of buildings.

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