Energy Saving through Material

Concrete and Concrete Masonry Trombe Wall Information Bulletin

Cement & Concrete Association of New Zealand

July 2017

Foreword

This information bulletin is for architects, designers and those interested in designing energy efficient homes. It covers the design and application of Trombe walls which are passive solar building elements that, designed correctly, provide an effective way of conserving energy in buildings.

Trombe walls are sun-facing, solid concrete or concrete masonry walls that are separated from the outside by glass and an air space. They make full use of the low rising sun's energy during winter months by collecting this heat during the day and releasing it into the room behind over an extended period of time and during the night.

Trombe walls are well suited to New Zealand conditions, where we often experience many sunny winter days followed by cold nights. They are gaining in popularity here as consumers become increasingly aware of the benefits of sustainability to their health and well-being and to the environment.

We hope you will find this information bulletin on Trombe walls of interest and that it provides inspiration for your next project.

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June 2017

Acknowledgements

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Information Bulletin: IB 96
ISSN: 0114-8826

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Contents

How Trombe walls work

A Trombe wall consists of a sun-facing, solid concrete or masonry wall behind a glazed space. When the sun shines, energy comes through the glass and is stored in the wall's thermal mass. When the sun sets or is blocked and the temperature drops, the wall releases its heat into the room behind.

Trombe walls are commonly used to absorb heat during winter sunlit hours and then slowly release that heat at night, when it is most needed. The concept was patented as long ago as 1881. However, it was not fully developed as an architectural element until the 1960s, by French engineer Félix Trombe and architect Jacques Michel.

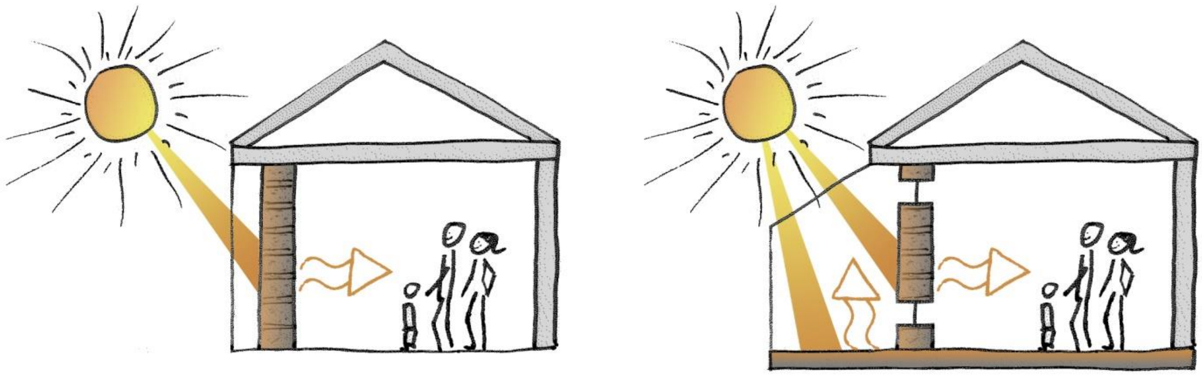


Figure 1: A simple Trombe wall, left, and one with an attached sunspace, right

Trombe walls work in a similar way to a greenhouse, by trapping solar radiation. The solar heat's higher-energy ultraviolet radiation has a short wavelength and this passes through glass almost unhindered. When this radiation strikes a wall or slab, the energy is absorbed and then re-emitted in the form of longer-wavelength infrared radiation. The infrared radiation does not pass through glass as easily, so the heat is trapped and builds up in the enclosed space.

For Trombe walls to work well they are best made from high heat capacity materials such as concrete or concrete masonry and positioned so the sun will strike them directly. They will also absorb radiant heat more effectively if they have a dark coloured, matte surface on their sun-facing side (there are no specific requirements for the room-facing side).

The most appropriate glazing to use in front of a Trombe wall depends on the location. Clearer glass allows more short-wavelength radiation to penetrate, which is beneficial for predominantly sunny locations to capture as much solar heat as possible. More reflective or non-transparent glass means that less re-emitted heat will escape from the building and suits less sunny locations, where better thermal insulation properties are desired.

Survey of New Zealanders finds satisfaction with Trombe walls

Trombe walls were recommended by all New Zealand users surveyed by BRANZ in 2014. As one user commented:

"The quality of the heat is really enjoyed - not stuffy like artificial heating. The subtle radiative heat of the wall seems to be better than other forms of heating."

Recent studies suggest that the overall performance of Trombe walls can be improved by using more advanced materials in place of glass, such as lightweight polycarbonate panels filled with aerogel insulation. However, these systems are still being researched (refer to Appendix A) and are not yet commercially available in New Zealand.

The following table contains some common reasons for designing a Trombe wall.

Why design a Trombe wall?	
Suitable for New Zealand conditions	Trombe walls are well suited to conditions in New Zealand, which has sunny winter days and cooler nights.
North orientation	Trombe walls are ideally located on the northern side of rooms that have with a good view to the south, as the Trombe wall will provide a solid heat buffer. They are also well suited to north facing corridors that provide access to bedrooms, as they can provide heat for these nightly-occupied rooms.
Energy savings	A well designed Trombe wall can lower heating bills by a substantial amount if properly placed. For example, the case study of the Zion Visitor Centre (refer pages 14-15) demonstrated a 20% energy saving. Energy savings can be maximised by providing additional or temporary thermal insulation for less sunny and cold winter days to avoid heat loss from habitable spaces.
Healthy and pleasant heat, sustainable energy	Trombe walls provide radiant heat, which people perceive as more comfortable than convection heat. The walls provide a sustainable form of energy as they are passive solar collectors. They do not release volatile organic compounds (VOCs) and they are not prone to carrying dust mites or fungi.
Little to no running costs	Costs are mostly confined to design and construction. Trombe walls do not require mechanical ventilation so they use little or no energy. Similarly, they need little or no maintenance.

Design features for Trombe walls

The key design features for Trombe walls to function effectively are described below. A table of design options and some common modifications follow.

Solid concrete or concrete masonry wall with suitable finish

Trombe walls should be made of a conductive material with high heat capacity: solid concrete or concrete masonry is ideal for this.

The walls need to be on the sun-facing side of the building to gain and store solar heat. Note that a wall with traditional, non-translucent thermal insulation applied will not be able to store any solar heat energy, as the thermal mass wall has no access to this energy.

It is recommended that Trombe walls are made single storey height or less. This is because homeowners with two-storey Trombe walls have reported that controlling heat gain and loss is extremely difficult, as such walls involve very large panels of glass and often incur higher cooling and heating costs to offset the excessive temperature changes.

In terms of finish, a darker surface colour (on the Trombe wall's sun-facing side) is better for heat absorption. A bright surface will reflect the light and heat energy, where a dark surface absorbs both. A matte surface also provides superior results to a glossy one, which reflects more light and heat.

Guidelines for wall volume and area

There are no minimum or maximum requirements for the volume or area of Trombe walls as their performance depends on the particular climate, location and exact sun orientation as well as the specific concrete or concrete block properties. The best advice is to thermally simulate a proposed design with software such as IESVE® or WUFI® to gain an understanding of the thermal impact and options to improve the wall and make it more efficient.

However, the following dimensions can be used as a guideline:

- The volume of the wall should be at least 1.25% of the room's volume, with non-ventilated walls no thicker than 150 mm and ventilated walls no thicker than 400 mm.
- The wall's height and width, and that of the associated glazing, should each have an area at least 15% of the room's footprint.

Example:

A living room behind a Trombe wall has a footprint of 20 m^2. The ceiling height is 2.5 m, so the room's total volume is 50 m^3.

Therefore, the wall must have a volume of at least 0.63 m^3 (ie 1.25% of 50 m^3). Assuming this wall is full height, its minimum dimensions are 2.5 m x 2.5 m when 100 mm thick, and 1.66 m x 2.5 m when 150 mm thick. In the same room, the upright wall and associated glazing should each have an area of at least 3 m^2 (ie 15% of 20 m^2).

Walls at least 100 mm thick

Any concrete Trombe wall should be at least 100 mm thick, as thinner walls may not provide sufficient heat storage mass. Non-ventilated walls should be no thicker than 150 mm. Ventilated walls can range from 100 to 400 mm thickness (refer to Non-ventilated walls/ Ventilated walls below for reasons).

While overheating can be a problem during hot summer months, this can be mitigated as long as the thermal mass wall is of a suitable thickness to absorb the excess heat. Shading is also important (refer page 8).

Ventilation is optional

When they were first designed, all Trombe walls had vents to provide air flow between the glazing and the room on the other side. However, recent studies show that, in many cases, non-ventilated walls can achieve at least the same performance. The features of each are described below.

Non-ventilated walls have the advantage of a more predictable and stable performance than ventilated walls (these can have a volatile output as their performance changes quickly depending whether or not there is direct sun). Non-ventilated walls rely on conduction through the wall to heat the room behind. For this reason they should be no thicker than 150 mm or the system will become inefficient: that is, the heat may not be able to travel to the side intended to receive this for many hours. For example, heat absorbed by a 150 mm thick Trombe wall takes about 12 hours to reach the interior of the building. (A simple rule of thumb often used when designing Trombe walls is that heat will be absorbed and lost at around two hours per 25 mm.)

Ventilated walls provide more options for circulating warm air when it is needed and shedding it when it isn't, so may be more suitable in hotter areas. The combined area of ventilation openings at the top and at the bottom is typically about 2% of the wall area, as larger openings risk reducing the wall's heat storage capacity. These vents allow building occupants to actively or passively circulate room air past the heated side of the wall for more immediate warmth.

Unlike non-ventilated walls, ventilated walls can be thicker than 150 mm and are often as thick as 400 mm. This is because the collected heat on the cavity side of the wall can be circulated by airflow through the wall's ventilation openings rather than having to travel through the wall itself.

Vents in Trombe walls may be closable to stop the flow of warm air when it's not required or may have flaps to prevent convection in the wrong direction; ie when the wall heats on summer days or cools on winter nights. In some cases, insulated vent covers are used to improve performance.

In climates with higher summer temperatures Trombe walls may also be designed with external vents to improve heat shedding at night-time.

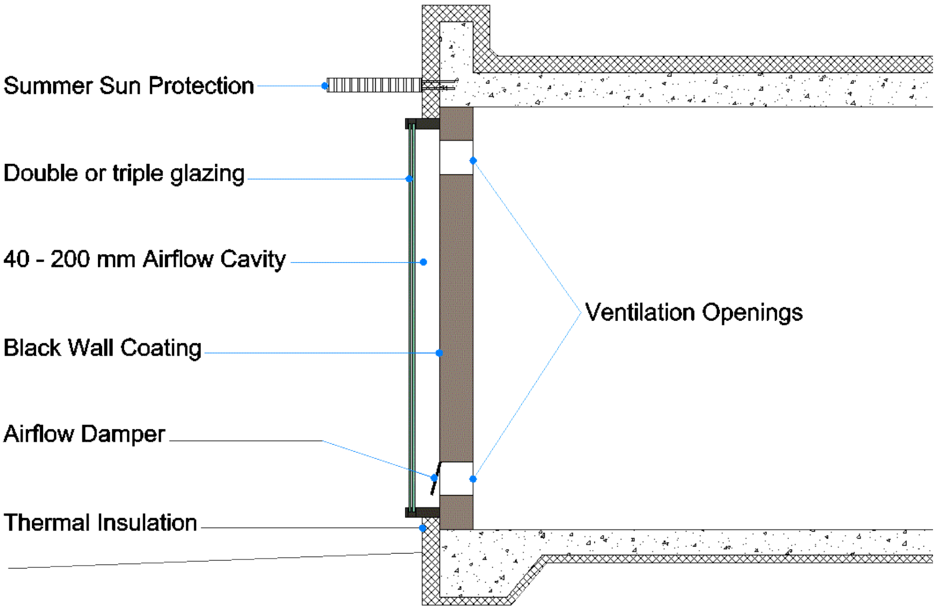


Figure 2 : Ventilated Trombe wall option with airflow damper

Glazing and air space

The gap between the external glazing and a Trombe wall is typically between 40 mm and 200 mm. However, this gap can be increased to create a useful space. A good option for combining a Trombe wall with a functional use is to make it a corridor wall; in which case the gap between the glazing and the wall would be at least 800 mm. Another option is to combine the Trombe wall with a sun space or winter garden in which the sun could also be captured through a glazed roof.

The wall's associated glazing should have an area of at least 15% of the room's footprint. Less reflective glass provides a larger olar gain.

Double or even triple glazing is best for thermal insulation purposes and to address condensation.

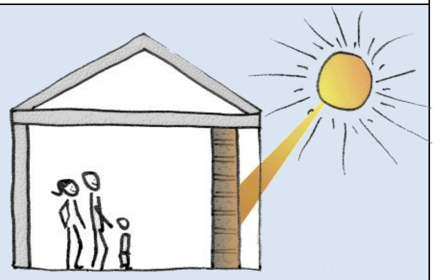
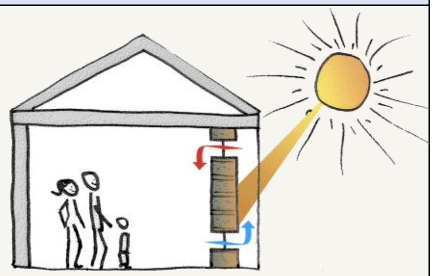
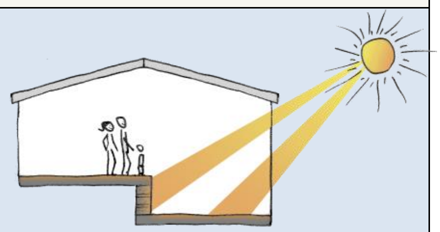
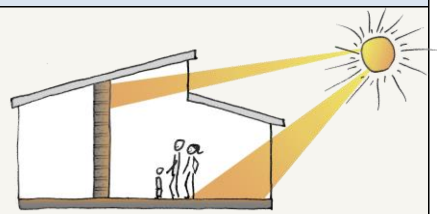
Also refer to Appendix A: Aerogel use in Trombe walls for research into alternatives to traditional glazing.

Shading and insulation

Shading is a key requirement for appropriate climate control of Trombe walls. This is ideally achieved by a roof overhang. The overhang should be of a suitable depth so that it shades the top of the glass panel while still allowing the rays of the higher summer sun to penetrate the lower area of the glass. This ensures that just enough heat is absorbed to be comfortable without overdoing it.

External sun blinds are also an option but may not suit all New Zealand locations because of the high wind loads. Only external blinds are suitable to address overheating (internal blinds or curtains do not help with this, as the heat is inside once it is through the glass). Careful planting of deciduous trees near the Trombe wall can also mitigate potential summer overheating.

Trombe wall and thermal mass wall design options

Description	Characteristics	Example
Full height – fully closed	These types of walls are located near north glazed panels, say at 1 m or 1.2 m distances. They serve ideally as a corridor to rooms in a larger home (for example, where bedrooms are lined up along a long corridor). The sun's heat balances the temperature within the corridor, prevents overheating on sunny days, and releases the heat back when the sun has gone. Heat will transfer through the wall to the room on the other side.	
Full height – openings to adjacent room	These walls are typically located next to living spaces. They absorb heat when it is sunny and release this heat back into the room during less sunny hours. For this design option, the heat is released and transferred into the adjacent living space via openings at the top and bottom of the wall. If the openings can be adjusted, this will let building occupants stop the flow of air through the Trombe wall during warmer months when it is not required.	
Semi height	Semi height thermal mass walls are ideal for split level living spaces. The low rising winter sun coming through the north glazing at the lower end of the room will be absorbed and released into both the lower and elevated spaces. Thermal insulation shall be applied to the back side of the wall to prevent heat loss into the soil.	
Full height – in room depth, roof windows	These walls can be located on the south side of a space. Roof windows enable the sun's energy to reach the wall. These walls perform slightly less well than the three design types described above because the windows are narrower.	

NOTES:

1. Trombe walls should have a thickness of at least 100 mm. Any less and the storage mass is insufficient to provide substantial energy gain.
2. Non-ventilated walls should not exceed 100 mm or the heat will take too long to move into the habitable space.

Harnessing the sun's energy: Trombe walls help residents of Ladakh

The Ladakh village in India hosts one of the few remaining mountain societies where a traditional Tibetan Buddhist way of life is practiced. The only connecting road is impassable for seven to eight months due to heavy snow coverings. The local education campus comprises of buildings built from local materials and labor, photovoltaics for electricity, waterless-composting toilets, passive solar design and other sustainable features.

Winter temperatures in the Ladakh region can drop as low as -30°C, making home heating essential. The Ladakh project has installed over 75 solar retrofitted houses, replacing some traditional heating methods (stoves fuelled with dung, wood and kerosene) with the use of Trombe walls that complement this region's traditional masonry style architecture.
Other buildings in the area have also incorporated Trombe walls, as Ladakh receives about 320 days of sun annually and is ideally suited to their use.

The Ladakh project has found a Trombe wall house can reduce reliance on heating fuels by about two thirds, as well as reducing indoor air pollution and health hazards.

(*Image: Dormitories at the Druk White Lotus School, Ladakh, heated by Trombe walls.*
Courtesy of the Druk White Lotus School, Ladakh.

Common modifications

Some common modifications to Trombe walls include the following:

- **modified finish - selective surface:** Trombe walls can have a selective surface (also called a selective absorber) applied to their sun-facing side. This can improve the wall's performance by reducing the amount of infrared energy radiated back through the glass. A selective surface is a coating or metal foil that is absorbent in the solar/ visible spectrum and reflective in the infrared range. (This distinction, which can be made according to wavelength, is known as the selective effect.) High absorbency turns the light into heat at the wall's surface, while low emittance prevents the heat from radiating back towards the glass.

- **exhaust vents within the top of the wall's glazing** that can be opened to the outside during the summer. These make the Trombe wall act as a solar chimney, pumping fresh air through the house during the day even if there is no breeze.

- **windows,** which lower the wall's efficiency but may be included for natural lighting or aesthetic reasons. If the outer glazing has high ultraviolet transmittance and the window in the Trombe wall is made of normal glass this allows efficient use of the ultraviolet light for heating and, at the same time, protects people and furnishings from the damaging effects of ultraviolet radiation.

- **patterned glazing:** the glazing can be patterned so that the dark wall behind is less obvious (which could be desirable from an aesthetic point of view) without sacrificing transmissivity.

- **half-height walls:** these improve views while still providing energy benefits

- **electric blowers** controlled by thermostats, which may be installed to improve air and heat flow

- **fixed or movable shades,** including trellises, which can reduce night-time heat loss and summer overheating

- **temporary insulation** to help avoid heat loss at night-time or on cloudy and cold winter days. Examples include coverings used at night on the glazing surface, temporary insulation filling the space between the glazing and the wall, or insulated internal or external sliders, and

- **tubes or water tanks** that form part of a solar hot water system.

Half-height Trombe walls still provide valuable energy benefits

Trombe walls do not necessarily have to reach the full height of the space behind but can be built to whatever suits the homeowner's needs. Any reduction in height simply reduces the solar absorption area while increasing the direct light and heat gain area.

For example, half-height Trombe walls are a relatively simple solution that still greatly enhance the solar storage capacity of a passive solar home while allowing for views to the sun's winter direction.

Half-height Trombe walls function in the same way as full height walls. They are commonly constructed with a gap of about 100 mm to 150 mm from the inner window surface, which is large enough for curtains or blinds to reduce heat loss on winter nights and for heat gain on sunny days. Even if these walls are set back further into the room, as long as they get direct sunlight the stored heat they release will still make a substantial contribution to balancing the interior climate.

Complying with the New Zealand Building Code

Trombe walls, like every other part of the residential building envelope, must comply with New Zealand Building Code Clause H1 Energy efficiency and cited standard NZS 4218 Thermal Insulation - Housing and Small Buildings.

The designer can choose one of three compliance approaches: the schedule method, the calculation method or the modelling method.

Of these, the modelling method will deliver the most accurate result. This is the only method to take account of the wall's thermal mass benefits. It is also the only method that can be used if the total glazing area is more than 40% of the total wall area.

The calculation method can be used if the total glazing area does not exceed 40% of the total wall area and the combined glazing area of the eastern, western and northern walls does not exceed 30% of the respective wall areas.

The scheduling method can only be used if the total glazing area does not exceed 30%.

For the schedule method, NZS 4218 provides defined construction R-values for building envelope elements. The designated R-value for thermal mass walls (NZS 4218, Table 4) is set at 0.8 K·m²/W for climate zone 1, 0.9 for climate zone 2 and 1.0 for climate zone 3. However, these values can only be achieved by applying thermal insulation either internally or externally to the wall. As this would eliminate the desired effect of a Trombe wall, glazing performance must be considered. Glazing has to provide at least 0.26 K·m²/W, so double glazing at the least will be required.

Construction R-values from NZS 4218 Table 2 –buildings with any wall type (K·m²/W)			
Building element	**Climate zone 1**	**Climate zone 2**	**Climate zone 3**
Roof	2.9	2.9	3.3
Wall	1.9	1.9	2.0
Floor	1.3	1.3	1.3
Glazing	0.26	0.26	0.26
Skylights	0.26	0.26	0.31

When using the calculation or modelling methods, a reference building has to be created using the R-values from NZS 4218, Table 2 (reproduced above) and pretending that the glazing will not exceed 30% of the wall area. The total of the calculated or modelled annual heating and cooling load of the proposed building shall not exceed that of the reference building.

CASE STUDIES: Performance of Trombe walls

The performance of Trombe walls at the modern Visitor Center at Zion National Park, Utah and the National Renewable Energy Laboratory's wind site in Colorado, USA have both been monitored over a two-year period. These walls and their performance are described below.

Visitor Center at Zion National Park, Utah

The designers of the Zion Visitor Center chose a Trombe wall design as shown in Figure 3 and Figure 4. The 1.8 m high Trombe wall runs along the full length of the building's south side under a row of windows. It has a total area of 68.7 m^2, which is 44% of the total south facing wall.

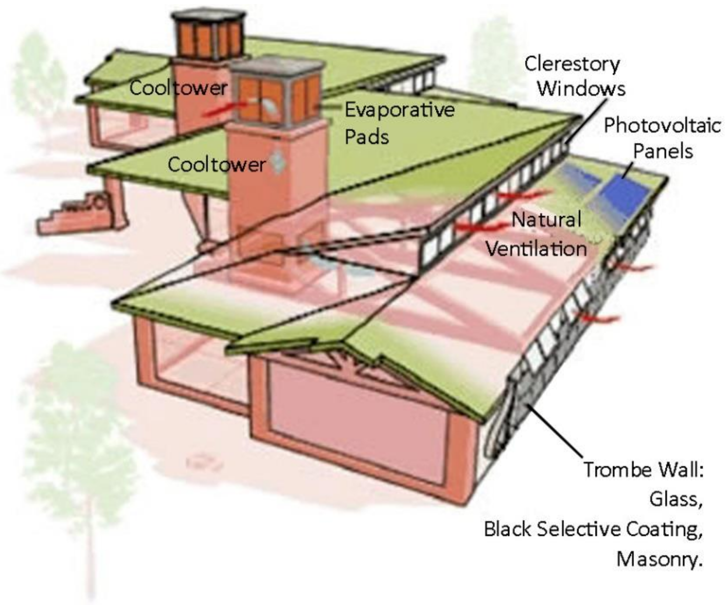


Figure 3: Zion Visitor Center showing location of Trombe wall
Image Courtesy of the US National Renewable Energy Laboratory

The Trombe wall is 200 mm thick and made from grout-filled concrete masonry units (CMU). The other walls in this building are 150 mm framed and thermally insulated walls with an R-value of 2.8 $K{\cdot}m^2/W$. The Trombe wall has a single piece of high transmittance patterned glass in front of it that has been installed on a thermally broken storefront system. Patterned glass reduces visibility of the dark wall without sacrificing transmissivity. This is rather a design requirement than performance

A selective surface was also applied to the sun-facing side of the wall (refer page 6).

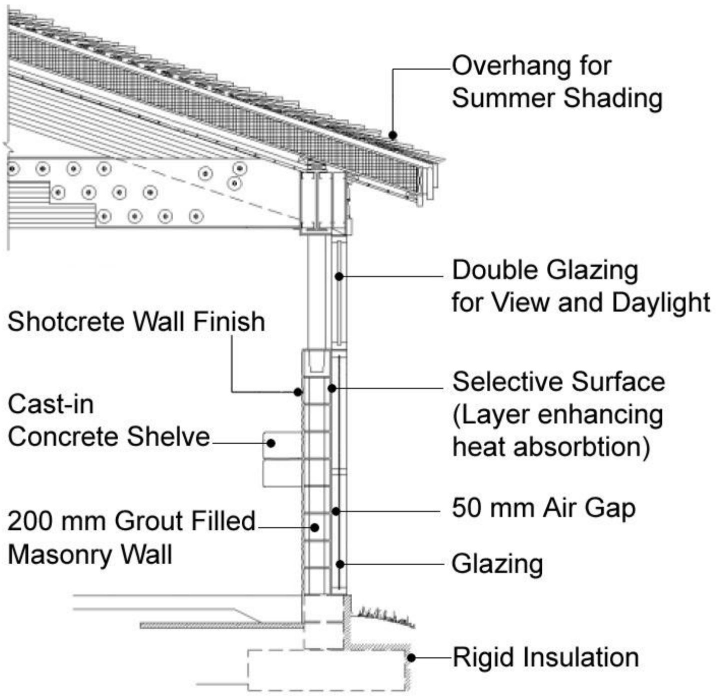


Figure 4: Zion Visitor Center - Trombe wall cross-section
Image Courtesy of the US National Renewable Energy Laboratory

The temperature gradient in the wall was measured during the 2001-2002 heating season. With internal temperature measurements, the Trombe wall energy supplied to the building was calculated based on published heat flux calculation methods (Balcomb and Hedstrom, 1980).

The electric radiant heating system used 22,680 kWh over the year, with the Trombe wall contributing 20% of the total heating for the building. The Trombe wall imposed a heating load on the building for only two of the 151 days of the 2001-2002 heating season. For the other 149 heating days the wall was a net positive; ie provided heat at no additional cost. The peak heat flux through the wall was 89 W/m^2 over the entire Trombe wall area. The average efficiency of the wall (defined as the heat delivered to the building divided by the total solar radiation incident on the exterior of the wall) was 13%.

National Renewable Energy Laboratory, Colorado

At the NREL's wind site building (Figure 5) a Trombe wall is used as an integral part of the heating system. The wall is 100 mm thick and made of concrete with a dark painted surface. In front of this is a single piece of high transmittance patterned glass installed on a thermally broken storefront system. The other walls are solid 100 mm tilt-up concrete walls with EIFS (exterior insulating finishing systems). The 130 mm exterior foam has an R-value of 4.4 m^{2}K/W.

Figure 5: National Renewable Energy Laboratory: Trombe wall
Image Courtesy of the US National Renewable Energy Laboratory

The total area of the NREL's Trombe wall is 4.1 m^2 or about 34% of the total south-facing wall. As for the Zion Visitor Center, a roof overhang provides shade for most of the summer.

The surface temperature of the Trombe wall's sun oriented side typically peaks at 49-54°C at 3:30 pm to 4:00 pm during winter. The interior temperatures of this wall are generally higher than for the Trombe wall at the Zion Visitor Center, but this occurs earlier in the day as the NREL wall is thinner (100 mm compared with 200 mm) and releases its heat more quickly.

During good solar days in the heating season, the NREL Trombe wall typically provides all of the necessary heating for the building throughout the afternoon and evening.

Dealing with heat when you don't need it

A potential design issue to consider in any passive solar building is overheating in the summer and swing seasons. The roof overhangs at both the Zion and NREL buildings were designed to shade the Trombe walls during this period. However, these walls still impose an additional cooling load on the buildings. This is because early morning and late afternoon radiation is not shaded, and diffuse and reflected radiation is not negligible. In addition, the insulation values of these walls are low.

At Zion, any additional cooling loads are not a significant issue as the passive direct evaporative cooling system, a cooling tower at the centre of the building, provides an abundance of cheap cooling. At the NREL a summer shading blind was recommended for the Trombe wall, which otherwise reached an average 38°C in the afternoon in mid-summer.

Case study conclusions

Trombe walls can enable a building envelope to go from net loss to net gain in terms of heat energy. At the Zion Visitor Center, the Trombe wall supplies 20% of the annual heating. At the NREL building it typically meets the afternoon and evening heating loads. However, the annual net effect has to be considered when designing a Trombe wall, as the additional cooling loads can affect the cooling system performance.

Trombe walls also provide passive solar heating without introducing light and glare into these commercial spaces. Roof overhangs were used in both cases to minimise summer overheating, but additional means such as stable external sliders or deciduous trees planted nearby would also be helpful. In both walls, thermal bridging effects were minimised with appropriate ground insulation.

Case study conclusions in New Zealand context

To put these results into the New Zealand context, a detached modern house uses about 75 KWh/m^2 of heat energy per annum, according to the Energy Efficiency and Conservation Authority (EECA). A Trombe wall has the potential to reduce this figure by 20%, to 60 KWh/m^2 per annum.

Considering a 160 m^2 home with an average electricity cost of (say) 30 cent/KWh, a Trombe wall could reduce the annual heating bill from $3,600 a year (160 x 75 x 30 cents) to $2,880 (160 x 60 x 30 cents) ie saving the occupants $720 per year.

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Appendix A: Aerogel use in Trombe walls

British-based research into the efficiency of Trombe walls (Dowson et al., 2014) has concluded that their efficiency could be greatly improved by replacing conventional glass covers with lightweight polycarbonate panels filled with nanoporous aerogel insulation. This is because aerogels allow solar gain but also function as thermal insulation. This aerogel insulation is translucent and enables the sun's heat energy waves to strike the wall. At the same time, it provides outstanding thermal insulation properties as the many closed cells contain trapped and non-moving air.

What is aerogel?

Aerogel is the world's lowest density solid and most effective thermal insulator. It is non-combustible and withstands heat up to 1400°C.

Aerogel is a synthetic, porous, ultralight material derived from a gel, in which the liquid component of the gel has been replaced with a gas. Silica aerogel, which is nanoporous, has the best insulation properties of any solid. It can retain up to four times as much heat as conventional insulation, while being highly translucent to light and solar radiation.

Aerogels were first developed in the 1920s but have only been studied successfully in recent years for their thermal insulation properties.

As aerogel is very fragile, it should be contained within protective glass panes or translucent polycarbonate panels (flute boards) when used for building insulation.

The study by Dowson et al. examined the thermal performance, energy savings and financial payback period of passive aerogel Trombe walls when applied to the existing UK housing stock. It noted that there was no design guidance for sizing Trombe walls containing aerogel insulation and aimed to fill this knowledge gap through a parametric, steady state modelling exercise. It provided initial design guidance on the likely energy savings depending on system size and house type, and also on the potential overheating risk (which it noted the designer must then mitigate through static or movable shading grills to cut high summer sun, eventually combined with passive vents at the top and bottom of the wall).

Testing four different dwelling types across the UK, the researchers calculated an energy savings ranging from 62 kWh/m^2/year for a 32 m^2 system retrofitted to a super insulated apartment to 183 kWh/m^2/year for an 8 m^2 system retrofitted to a solid walled detached house.

"Predicted energy savings from aerogel Trombe walls up to 24 m^2 are found to possibly exceed the energy savings from external insulation across all house types and constructions. Small areas of Trombe wall can provide a useful energy contribution without creating a significant overheating risk. If larger areas are to be installed, then detailed calculations would be recommended to assess and mitigate potential overheating issues."

(Dowson et al., 2014)

Influences on wall size

The greater energy saving for the much smaller system in the results described above reflects the difference in building type. The super insulated apartment was already energy efficient but the 32 m^2 Trombe wall was still able to provide some benefits. Significantly more gains accrued from retrofitting a Trombe wall a quarter the size at a detached house, as such structures usually need more planning to control weather and temperature changes.

The researchers measured the in-situ performance of a flat plate solar air heater connected to a dwelling's active mechanical ventilation system with heat recovery. Instead of glass, the cover was a lightweight multiwall polycarbonatb e panel filled with granular aerogel. During a seven day in-situ test, peak outlet temperatures of up to 45°C were observed inside the collector. This preheated the dwelling's fresh air supply by up to 30°C, facilitating internal temperatures of 21–22°C without auxiliary heating. Monitoring results were validated to within 5% of predictions.

The researchers also carried out efficiency calculations for a range of thicknesses compared to single and double glazing. Their findings demonstrated that a 10 mm granular aerogel cover provided the optimum balance between light transmission and heat retention.

This saved up to 166 $kWh/m^2/year$ compared with annual savings of 110 $kWh/m^2/year$ for a single glazed collector and 140 $kWh/m^2/year$ for a double glazed collector.