A Comprehensive Evaluation

Evolution of the Trombe Wall System and its Future Prospects

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In line with the sustainable development goals as defined by the UN, increasing emphasis is being laid by building professionals on passive energy systems so as to minimize our dependence on active energy systems. New innovations are being carried out on some of the vernacular solar passive strategies for achieving energy efficiency.

It would be worthwhile to mention here the recent 'One Sun, One World' initiative. Trombe wall is one such solar passive system which has stood the test of time. It is continuously evolving as a technology, having originated way back in the 18th Century. Though having originated as a means for indoor heating for cold climates, it has good potential for indoor cooling as well, a fact that is little known due to the lack of information dissemination.

As compared to many other solar passive techniques, there is a lack of sufficient data with respect to the part played by the various constituents in the effective functioning of the system and some misconceptions exist about the same. Besides, the Trombe wall technology has not been perfected to the extent that some other technologies such as the Earth Tunnel system have been, though there have been various innovations both in terms of design and materials.

In spite of having tremendous potential as a technology as well as the requirement for the same in various climatic zones worldwide, the implementation of Trombe wall has been on a very small scale. There is, therefore, a strong need to consolidate and disseminate the research done on all the above-mentioned points.

Concept and Origin of the Conventional Trombe Wall

Concept

A Trombe wall is essentially a thermal storage device whose primary objective is to absorb and store thermal energy from the Sun and release it to the indoor environment at an appropriate rate when required. It has proven its effectiveness in climatic regions with high solar irradiation and low diffuse radiation. Essentially, it takes advantage of the high quantum of solar energy present during the day, creates a thermal lag, and transfers the stored thermal energy to the indoor space when the external temperatures and solar radiation fall much below the comfort range.

The primary objective of a Trombe wall is indoor heating, though it has proved its effectiveness in indoor cooling as well, as covered in other sections of this paper. The major mode of heat transfer indoors, as established by research, is by means of radiation, followed by conduction and convection. The convective heat transfer process was introduced in the Trombe wall as an improvement over the original concept, and has its origin in the requirement of indoor air changes for ventilation purposes. However, there are varying opinions about the thermal effectiveness of the Trombe wall on account of air circulation, as covered in latter parts of the paper.

> "It has proven its effectiveness in climatic regions with high solar irradiation and low diffuse radiation."

Origin of Trombe Wall

As per one study, the origin of the Trombe wall can be traced to the vernacular architecture of the Persian Gulf and Mughal Architecture of the Indian sub-continent. (Hatamipour MS, Abedi A. 2008) A vestibule was placed between the external face of the buildings and the main walls of the living areas. The air gap in the vestibule performed the role of thermally insulating the living room from the external climate during the day while the openings in the vestibule wall permitted the ingress of solar radiation. The living room wall facing the vestibule, built of local masonry and thicker than contemporary walls possessed adequate thermal inertia to absorb solar heat energy during the day and release it indoors when the external temperatures fall. (Fig. 1)

Fig. 1: Vestibule as Trombe Wall

The Modern Trombe Wall

It should be noted here that the examples of vernacular architecture quoted above happen to be in predominantly hot and dry climatic regions, where the primary intent was to keep the building interiors cool during the hottest part of the day. However, the formal development of Trombe wall as a concept, in the 18th Century was mainly for providing indoor heating for buildings located in predominantly cold climatic regions.

An American named E. L. Morse was the first to describe the Trombe wall concept in 1881 and get it patented. The idea was ahead of its time. It was in 1972 that Felix Trombe and Jacque Michel, a French engineer and a French architect, respectively, popularised and re patented the design. It was popularly known as

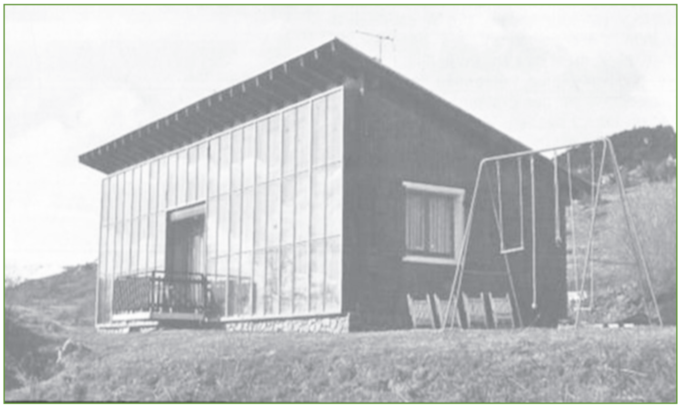

Fig. 2: Trombe Wall in Odeillo, France, by Jacque Michel

the Trombe – Michel wall. In 1960, both of them developed a passive mechanism used to heat a room at day and at night, utilizing solar energy. (Shen, J., Lassue, S., Zalewski, L., Huang, D. 2007) This was designed only for heating purpose initially.

Some years later, in 1967, the first house with Trombe wall was built by Jacque Michel in Odeillo, France to collect the solar heat and provide the interior space heating using the classic or standard Trombe wall. (Hordeski, M.F., 2004) (Fig. 2) It used a single layer of glass on the external face, an air cavity and a structural concrete wall with its external surface coated black. Air vents were provided on the North face as well as the South face so as to induce air circulation as well as convective cooling.

However, Trombe wall suffered from the following significant drawbacks:

- It lacked means of controlling the indoor temperature
- It faced difficulties in heating of rooms not directly exposed to sun or adjacent to the Trombe wall

“An American named E. L. Morse was the first to describe the Trombe wall concept in 1881 and get it patented.”

- Excessive wall thickness

(While this was acceptable in the initial stages of the development of Trombe wall, it could not meet the increasing requirements of indoor space savings.)

- Inefficient performance with increase in cloud cover

(It is notable to observe here that within the ambit of cold climatic regions, Trombe wall was found to be more suitable for cold and sunny climatic regions than for cold and cloudy climatic regions, for the simple reason that the quantum of direct solar irradiation was significantly lesser in cold and cloudy regions, though there are proven instances of effective functioning of Trombe wall in cold and cloudy regions.)

As an innovation over the Odeillo house, Architects Marc Vaye and Frédéric Nicolas designed the Maison à Argenteuil, in Val d'Oise, where the air cavity was converted into a usable space in the form of a greenhouse, which is integrated with the main entrance of the house. Vents on the top and bottom of the wall provided air circulation. The second innovation over the Odeillo house was orienting the two main facades towards South East and South West, in contrast to the Odeillo house where the main façade was oriented towards South. These innovations paved the way for further research. All the above mentioned examples have used Trombe wall for indoor heating. Nevertheless, it has proven itself for indoor cooling as well.

Cooling based Trombe Walls

A much lesser-known fact is the effectiveness of Trombe walls for cooling purpose. The concept of utilising the Trombe wall for cooling purpose has originated on account of its low thermal resistance. The process of cooling through Trombe wall consists of reduction of solar heat gain by using materials such as external blinds over the external glazing and utilising the air cavity for evaporative cooling by drawing the indoor hot air into the cavity and bringing it into contact with moisture. Various studies are available to establish the effectiveness ofTrombe wall for cooling. Trombe Wall has proven to be effective for indoor cooling in the Mediterranean climates and has led to lesser energy requirements.

Research carried out in the Mid-Mediterranean region has established the energy savings for indoor cooling by using Trombe wall. (KJ Kontoleon and E a. Eumorfopoulou (2008) In a study that focused on the analysis of the performance of the building with passive systems and the annual energy requirements for heating and cooling, the results of the simulation show that with the use of heavy massive structures for analysed climatic conditions in Belgrade, there is potential for reducing energy needs both for heating and cooling of space. (B. Andjelkovic, B. Stojakovic, M. Stojiljkovic, JJanevski and M. Stojanovic , 2012)

Improvements in the Modern Trombe Wall

Internal Insulation

The problem of the excessive wall thickness of Trombe wall and its poor performance in cold and cloudy climatic regions has been overcome to some extent by the introduction of insulation on the internal surface of the wall. Besides helping in reducing the thickness of the masonry wall, the insulation reduces the thermal energy required for heating the indoor space as it is able to control the loss of the internal energy to outside to some extent. It therefore helps in reducing dependence on solar irradiance which reduces drastically when the cloud cover increases, which makes it suitable for use incold and cloudy climatic zone, as mentioned earlier in the paper. (Fig. 3) Besides, provision of insulation maximises the ventilation rate as brought out in a study. (Guohui G., 1998)

Research undertaken to study the efficiency of an insulated Trombe wall has established that the insulated Trombe wall performs much better than the conventional Trombe wall in cold and cloudy weather. (Zrikem Z, Bilgen E., 1987)

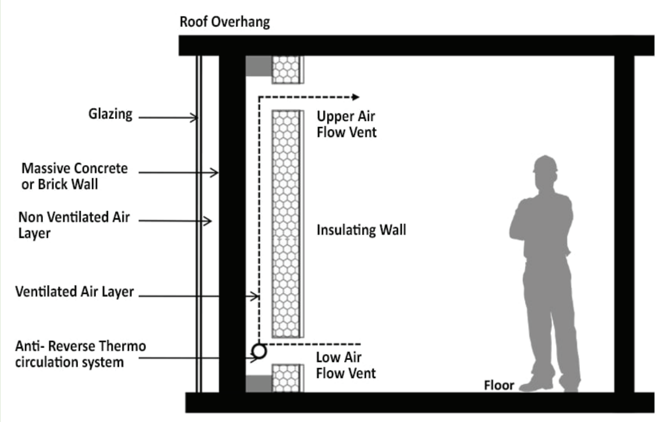

Fig. 3: Addition of Insulation to the Trombe Wall

Use of Double Glazing in Place of Single Glazing

Glass has proven to be an excellent material for the effective functioning of the Trombe wall, by virtue of its property of permitting the shortwave radiation and blocking the long wave radiation. It helps in trapping the thermal energy in the air gap and performs the dual function of a) minimising thermal loss and b) maximising thermal gain, both essential for the effective functioning of the Trombe wall. An important consideration in the selection of glass for Trombe wall is high solar transmissivity, so as to enhance the air flow in the cavity by stack effect.

However, there are some drawbacks with the use of glass, namely:

a) excessive heating of the air cavity, especially in cold climatic zones with predominantly clear skies, a problem that can be overcome by means of creating an air movement cycle through stack effect, which necessitates the provision of vents, b) thermal loss from the interface between glass and masonry/concrete when the external temperatures are below the indoor temperatures. It has been proven that the use of double glazing instead of a single glazing not only helps in the reducing the thermal loss during winters but also improves the passive cooling in summer. (Lee, K.H., Strand Richard, K., 2009)

> "The concept of utilising the Trombe wall for cooling purpose has originated on account of its low thermal resistance."

A comparison between the energy gain between single and double glazing was carried out and calculations were performed for usual heating season in a cold climatic region. The total energy gains by the glazing, including thermal energy and solar energy were computed. (Tomas Matuska 2008) Thereafter, the solar energy transmittance for these was set to zero and only the thermal properties of the glazing were considered for the energy gain. Results were obtained w.r.t the net thermal energy gains by the glazing on account of the insulation properties of the glazing. The results indicate a distinct edge that double glazing systems have over the single glazing system both in respect of the total energy gain as well as the net energy gain in respect of heating. (Table 1)

Table 1: Annual Energy Gains of Investigated Transparent Insulation Glazing

Material	Total Energy Gain in Kwh/ Metre square year	Net Energy Gain in Kwh/ Metre square year
Double Low- E glazing	93	43
Single Glazing	59	11

Use of Fans and Dampers in the Vents

In order to enhance the efficiency of the air circulation system, attempts have made to introduce fans in the vents. However, there have been mixed results and their contribution towards achieving the desired results has not been proved conclusively. (Zhongting, H., Wei, H., Jie, J., Shengyao, Z., 2017) The impact of fans on the overall performance of the Trombe wall is dependent on other parameters such as wall's thickness and climate zone. (Balcomb, J.D., McFarland, R.D., 1978) (Fig. 4)

It would be worthwhile to mention here that there are conflicting arguments for and against the contribution of air movement towards the overall thermal efficiency of the Trombe wall. One school of thought suggests that the stack effect produced in the air cavity induces the air movement which contributes to the indoor ventilation as well as convective cooling. However, research showed that the unvented Trombe wall performs better than the vented Trombe wall. (Balcomb, J.D., McFarland, R.D., 1978)

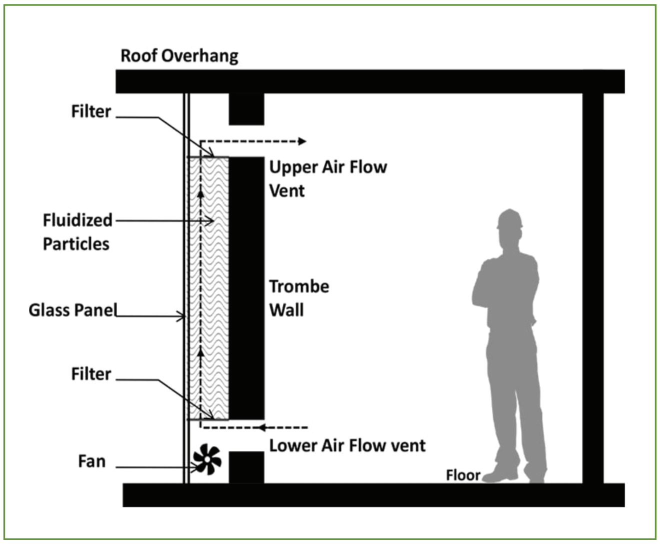

Fig. 4: Use of fans to improve the performance of Trombe Wall

Ventilation tends to negate the storage effect of the wall and eliminates the effectiveness of the air gap as insulation. Studies in nine different climates of USA have established that vents reduce the efficiency of the Trombe wall substantially under certain circumstances. (Balcomb, J.D., McFarland, R.D., 1978)

As an improvement over conventional vents, controllable vents were created in the external glazing to address the problems of reverse air flow, observed when the indoor space gets overheated and its temperature becomes more than the temperature of the external assembly. The vents release the internal heat to the outside. (Fig. 5) Dampers were also introduced to regulate the flow of air.

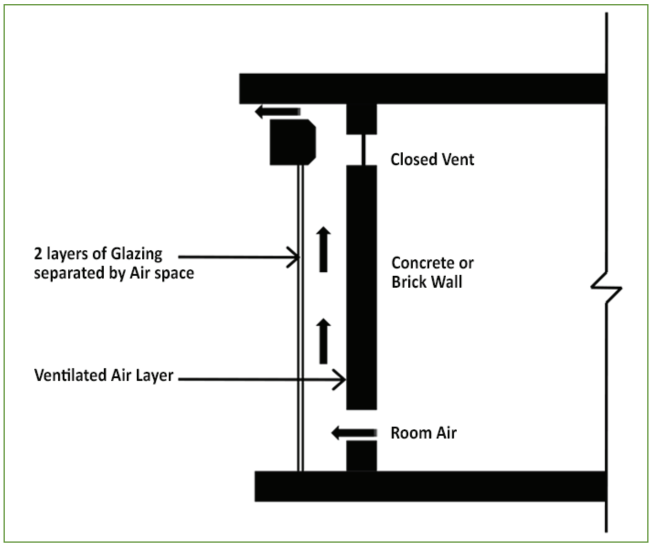

Fig. 5: Vents to control the reverse Air flow

Improved Surface Coating on the Inner Wall Surface

In the conventional Trombe wall, the surface of the wall facing the glass was painted black. However, in later developments, surface coatings of high thermal absorptivity are being used, mainly to absorb the infrared energy transmitted through the glass and reduce the infrared energy radiated back to the glass. However, it also has a disadvantage, since it is known to contribute towards overheating of indoors. (Nwachukwu NP, Okonkwo WI., 2008)

Major Innovations in Trombe Walls

While the above-mentioned improvements are known to have brought about significant and tangible enhancement in the performance of the Trombe wall, these have been, by and large, restricted to augmenting the effectiveness of the system, retaining the same basic construction materials and technologies. Over and above these, there have been some important innovations in respect of using non-conventional materials and technologies which have proven their efficiency. Some major ones are listed below:

Use of Water as a Replacement of the Wall

As a substitute to the conventional masonry/concrete wall which has low specific heat, water has been explored for constructing Trombe wall as it has higher specific heat. In this case, water fills the air gap behind the glass. The glass panel is placed on the front of the water storage medium which absorbs the radiated heat from the glass which is distributed to the internal space by convection. (Fig. 6)

The surface temperature of water does not rise to the extent to which the surface temperature of masonry rises. Excess heat is reflected back through the glazing. The water Trombe wall is effective both for heating as well as cooling. In order to enhance heat absorption, the barrels containing water should have a dark colour. They have proven to be more thermally efficient than masonry walls. However, a greater degree of design consideration is required for these walls compared to the conventional Trombe wall. This type of Trombe wall is particularly useful in regions where it is difficult to transport materials like stone or brick or concrete and the skilled labour for construction is not available.

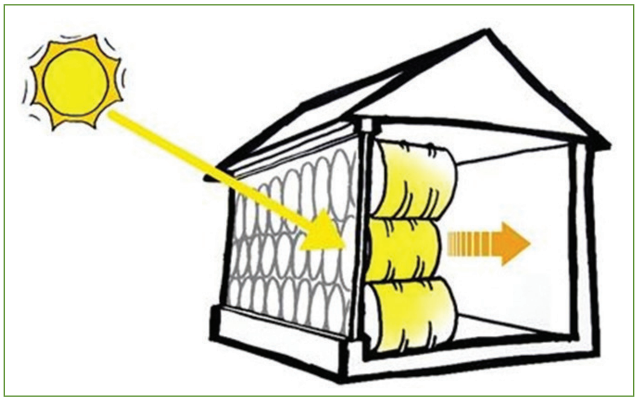

Fig. 6: Water as a substitute to Masonry

Fluidized Trombe Wall

As another innovation, low density particles having high capacity for thermal absorption fill the air cavity. (Fig. 7) The particles acquire high temperatures and transfer the same to the air, thereby setting in motion the air cycle.

Research has established that the fluidized Trombe wall can achieve better thermal efficiency than the conventional Trombe wall. (Tunç, M., Uysal, M., 1991)

Filters are used at the top and bottom of the air cavity to prevent the particles from entering the indoor space. However, this type of wall has a major drawback in terms of not having any circulation of outside air in the indoor space, thereby affecting the indoor air quality. (Tunç, M., Uysal, M., 1991) There are few practical applications of this wall and the concept has largely remained on paper.

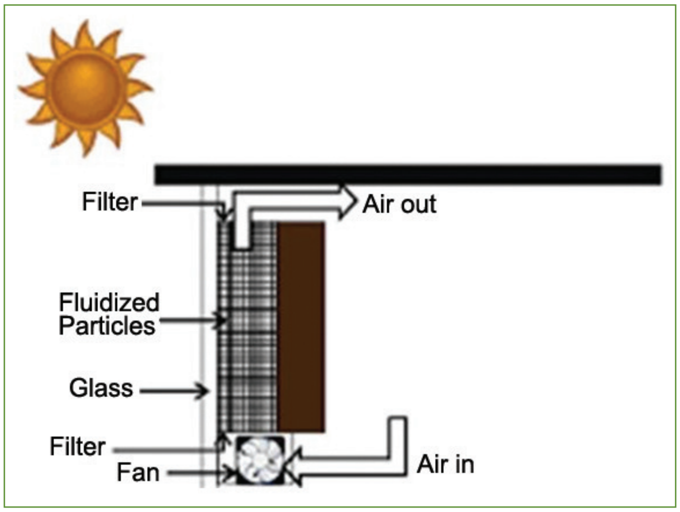

Fig. 7: Fluidized particles as a replacement for Masonry

Trans Wall

Trans wall essentially consists of a metal frame with a water container which is contained between two glass panels, with a semi-transparent glass panel in the middle. (Fig. 8) Most of the solar energy is absorbed by the semi-transparent glass panel, some of it by water, while the rest of it is transmitted inside. In this manner, Trans wall makes use of both direct and indirect thermal gain. However, one of the disadvantages of this system is that it requires high daytime temperatures for effective functioning, the other one being the prevention of renewed air from entering inside, thereby diluting the quality of ventilation in the indoor space. Trans wall is, therefore unsuitable for climatic regions with moderate to high

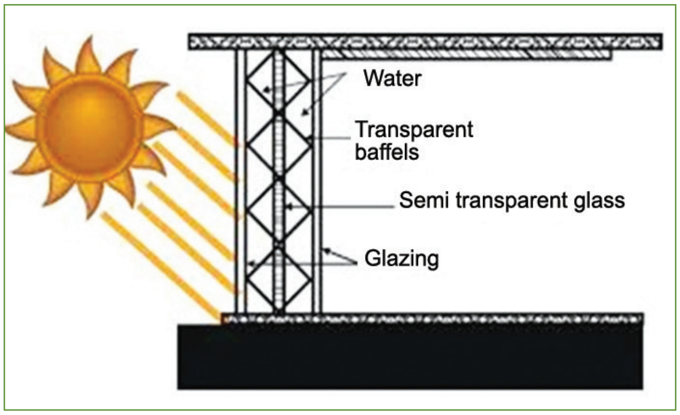

Fig. 8: Trans Wall

cloud cover and appropriate for cold and sunny climatic zones only. Besides, a separate system is required to control the air flow.

Ceramic Evaporative Cooling Trombe Wall

Spanish scholars came up with this Trombe wall which utilises solar heat gain for evaporative cooling. Blinds are placed on the external wall surface so as to reduce the intensity of heat gain. A ceramic porous material which can absorb water is placed in the air gap. The air entering the air cavity from the bottom vent becomes warm and rises in the air cavity, gets cooled by the ceramic material and enters the indoor space. (Fig. 9)

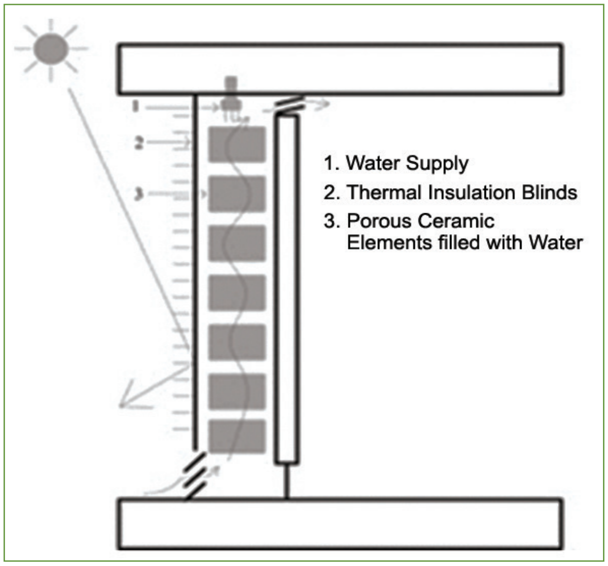

Fig. 9: Trombe Wall using Ceramic for cooling

Trombe Wall with Double Air Cavity

This type of Trombe wall consists of two air cavities. Outdoor air heated by the external solar radiation enters the outer cavity from below, rises, comes in contact with the moist plate and lowers the plate temperature. The plate cools the outdoor air rising in the inner cavity which finally enters the living space. Research has shown that the cooling effect was found to be the same as the Ceramic evaporative cooling Trombe wall. A major drawback of both the ceramic and double air cavity Trombe wall is the lack of a mechanism for controlling the indoor humidity.

Trombe Wall with BIPV on Façade

The use of BIPV on the external face of the Trombe wall has been found to be most suitable for areas having poor quantum of electrical power supply, since it has the potential to store solar energy and convert it into electrical energy when it is most required - during late evenings and nights.

BIPV also provides a superior aesthetic appearance than the conventional Trombe wall, on account of the variety of colours available.

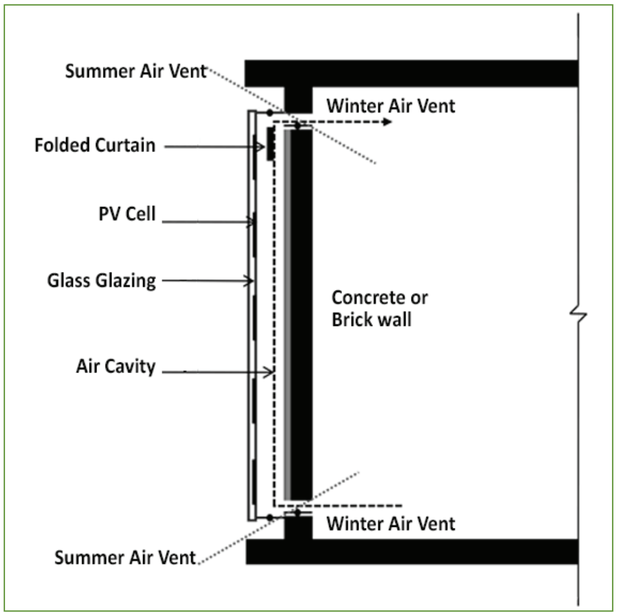

Fig. 10: BIPV on Trombe wall for heating as well as cooling

In terms of application, BIPV is most suitable for cold and sunny climatic zones due to the reasons explained above. BIPV has also proven its effectiveness for cooling. Since BIPV restricts the ingress of solar radiation into the air cavity, it enhances the Trombe wall's capacity for cooling. (Fig. 10)

However, the biggest disadvantage of this system is that PV cells block the entry of solar energy into the cavity, thereby reducing the thermal efficiency of the Trombe wall. In order to quantify the loss of thermal efficiency, an experiment and a computer simulation was carried out. The building was equipped with south-facing windows and a PV panel installed on a Trombe wall.

The study revealed that installing PV panels over the glazing reduces the thermal performance of the Trombe wall up to 17%. (Chow TT, Hand JW, Strachan PA. 2003) In another research, it was observed that PV window reduced the room heat gain by 200% compared to double-glazed clear glass and low-e glass windows. (Sun W, Ji J, Luo C, He W., 2011)

> "Since BIPV restricts the ingress of solar radiation into the air cavity, it enhances the Trombe wall's capacity for cooling."

Another significant disadvantage of BIPV that has been observed is that the glazing inner temperatures have been found to be higher than the indoor room temperatures during summers, thus causing discomfort to the persons sitting near the windows.

In addition, PV cells possess low thermal inertia and their temperature is more sensitive to variations in solar insolation as compared to indoor temperature variations. When there is an increase in the external cloud cover and reduction in solar irradiance, the efficiency of the PV panels reduces, thus making the efficiency of BIPV highly dependent on external weather conditions (Agrawal, B., Tiwari, G.N., 2011)

Conclusions and Way Forward

To conclude, the conventional Trombe wall, though well-conceived as a concept, suffers from some important drawbacks, namely a) low thermal resistance, b) over- heating of interiors, reverse air flow, c) inferior external aesthetics, and d) dissatisfactory indoor illumination levels. Improvements in the design and materials over the years have resolved some of these problems. New innovations such as the use of BIPV, Water Trombe Wall, Trans Wall, Zig Zag Trombe Wall, Trombe wall with phase change materials etc., have shown promising results at the experimentation stage and have the capability to overcome most of these drawbacks.

However, all these innovations have been confined to the research stage by and large and their superior efficiency needs to be demonstrated by actually building structures on a larger scale and observing their performance over longer time periods. Similarly, though the potential of Trombe wall for cooling has been proven experimentally, the public perception among the building professionals continues to associate Trombe wall with heating. This myth needs to be broken by proving the effectiveness of Trombe wall in cooling as well by executing structures in hot climates and documenting their performance. The way forward lies in synthesising the original concept with more innovative designs and materials that are structurally and thermally more efficient than the conventional materials and technologies.

> "The potential of Trombe wall for cooling has been proven experimentally, yet the public perception continues to associate it with heating."

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