

Review of the experimental studies on trombe walls hygrothermal performance: a special focus on the PIV application in such a system

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Abstract

Trombe walls have been recognized as a cost-effective solution for reducing energy consumption if designed properly. Most of the experimental studies available in the literature have been carried out to assess the thermal performance of various types of Trombe walls and to understand the impact of key parameters affecting their behavior. However, within the general framework of double-skin facade systems, some studies also consider the effect of moisture on the behavior of such a system and evaluate its hygrothermal performance. To date, there has been no comprehensive review of experimental studies on Trombe wall hygrothermal performance or the instrumentation needed to study this behavior. Therefore, this review has been designed to fill this gap by examining and classifying recent research papers from thermal, velocity, and hygrothermal perspectives. It also discusses the essential tools required to investigate the dynamic hygrothermal behavior of Trombe walls, with a particular focus on analyzing the potential of using particle image velocimetry (PIV) and relative humidity measurement devices. In detail, this review mainly classifies experimental studies according to the experimental environment (laboratory or in situ) and discusses the main experimental method, the challenges that may arise in each experimental protocol as well as possible solutions. In addition, this review concludes by highlighting current trends in experimental studies of Trombe walls and proposing a new experimental approach to adapt the existing protocols for investigating its thermal performance to include its hygrothermal behavior.

Keywords: Trombe wall, hygrothermal performance, PIV, thermal measurement techniques, relative humidity measurement sensors, laboratory and in situ experimental studies, double skin façade system.

1. Introduction

Trombe wall is a south-facing passive solar heating system consisting of an exterior glass, an air channel, and a massive wall. To improve heat transfer, vents are often installed at the top and bottom of the massive wall. Heat transfer within the system occurs mainly through a combination of conduction within the wall, radiation between the absorber and the glass, and convection within the air channel. This convection process is due to a buoyancy effect, leading to a reduction in the air density. As a result, the heated air rises and circulates to the adjacent area through the upper vent [1] (Figure 1).

Since its initial installation, Trombe wall has experienced improvement in both its operation and configuration, with a dual purpose of minimizing heating requirements in winter and reducing the cooling load in summer. However, to date, there is still a challenge in achieving optimal performance across varying environmental conditions due to the absence of demonstrating the real interconnected phenomena of heat, air, and moisture transfer that occur in such a system. Indeed, due to its interaction with the surrounding environment, Trombe wall operates as a dynamic system. Environmental factors vary inconstantly which introduces

unsteadiness in the heat transfer mechanism and fluid flow pattern. The material selection, geometric characteristics, and thermophysical properties of its components all have a considerable impact on its performance. In addition, moisture dynamics in building materials are intricate and influenced by the climate, which significantly affects the design of Trombe walls. Therefore, it becomes crucial to investigate the hygrothermal behavior of such a system to ensure the hygrothermal comfort, material durability, and energy performance of the building.

While numerical models are highly valuable for their ability to rapidly and cost-effectively investigate various aspects, experimental studies are still important for validating these models and ensuring their real-world application. Over the past decade, numerous experimental studies on Trombe walls have been conducted in various climates to evaluate their thermal performance. The experimental protocols are already well-established and need to be reviewed. As airflow condition is important for preserving the system's hygrothermal behavior, investigating accurately the natural convection phenomena becomes critical. Different velocity measurement techniques are available in the literature to examine the flow field in building facades. The direct measurement velocity technique is the most commonly employed for Trombe wall systems. Nevertheless, due to its limitations, many researchers have highlighted the potential of using Particle Image Velocimetry (PIV) for this purpose in Trombe wall systems [2]. According to our knowledge, there is no direct application of the PIV technique for this specific type of building façade or test bench connected to a room. Therefore, in order to provide a critical discussion of its potential, the case studies that are analyzed here can be divided into two main aspects. First, given that the Trombe wall thermal performance is influenced by the airflow condition within the air gap, we review PIV case studies applied to naturally ventilated cavities. Second, as it is also important to examine the response of ventilated spaces, including the analysis of fluid flow, thermal behavior as well as the presence of occupants, we sought case studies on the PIV application to indoor airflow monitoring to better understand the challenges associated with such technique. Furthermore, there are still significant research gaps regarding the effects of moisture accumulation on Trombe wall performance and occupant comfort. For this purpose, we review the experimental protocols that are commonly employed for investigating the hygrothermal performance of ventilated facade systems. These protocols can offer valuable insights for studying similar behavior in Trombe wall systems.

Consequently, this study systematically classifies existing literature with the aim of reviewing experimental protocols available for the Trombe wall and discussing the essential instrumentation required to analyze its hygrothermal behavior with a special focus dedicated to Particle Image Velocimetry and relative humidity measurement.

1.1. Research contributions

To date, there are many papers focusing mainly on reviewing the recent advancement experienced by Trombe wall design as well as the feasibility of applying different types of Trombe walls in several climates [1],[3],[4],[5],[6]. However, in all those papers, the experimental protocol is briefly discussed, and none of these reviews introduce the instrumentation required for studying the hygrothermal behavior of this system.

Although there are reviews on the use of the PIV technique in ventilated facades [7] and indoor environments [8], however, they usually address a variety of topics and do not concentrate specifically on the challenges associated with the implementation of this technique to a Trombe wall system.

To date, there is a significant research gap in studies addressing the hygrothermal behavior of Trombe walls, and no reviews of the experimental procedures required to analyze this behavior are found in the literature.

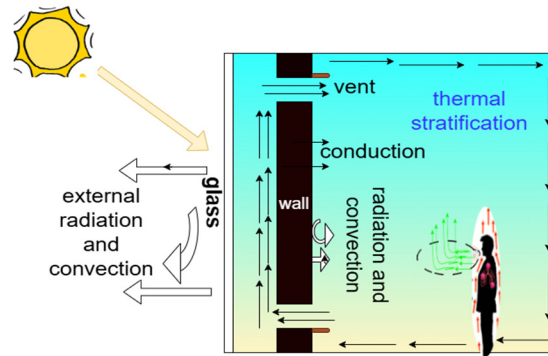


Figure 1: Trombe wall architecture

1.2. Review methodology and organization

This review focuses on English-language research articles published between 2010 and 2024 that address experimental studies of the hygrothermal performance of Trombe wall systems. The review process follows the PRISMA guidelines, which include processes for identifying, screening, and including relevant papers (Figure 2). The selected publications are categorized and analysed according to their classification, experimental procedures, and the instrumentation necessary for assessments.

This paper is organized as follows:

- The first section classifies experimental studies on the Trombe wall's thermal behavior. It also discusses the necessary instrumentation required for this type of study.
- The second section presents an overview of several velocity measurement techniques employed in a ventilated façade, with a special emphasis on the PIV method.
- The third section classifies experimental studies on the hygrothermal behavior of a ventilated façade. It also discusses the necessary instrumentation required for this type of study.
- This review ends with a discussion that suggests a new experimental protocol to investigate the Trombe wall hygrothermal behavior as well as a final conclusion.

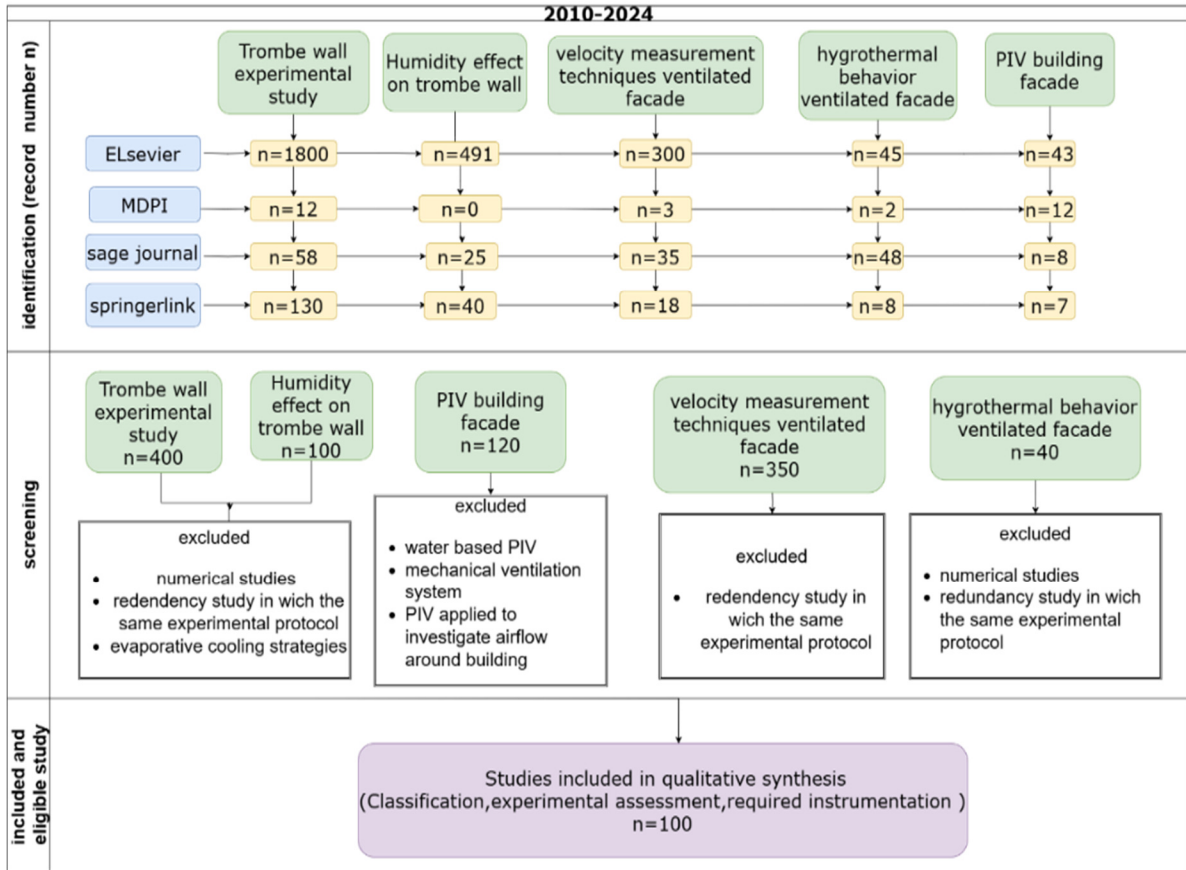


Figure 2: Review methodology

2. Review of the experimental studies of Trombe wall thermal behavior

Experimental studies of Trombe wall thermal performance can be classified according to the setup scale (full-scale or reduced-scale) and the conditions under which the experiments are carried out (real-world or laboratory-controlled). Each category has specific importance, degree of complexity, and limitations, impacting the choice of the instrumentation used and the overall contributions. Therefore, in this section, we will highlight the main characteristics of each category and the thermal measurement tools employed.

2.1. Stand-alone Trombe wall

This setup involves constructing a Trombe wall without a connected room (Figure 3). It is commonly used in studies investigating various materials and architectural designs of the Trombe wall [9]. Due to space-saving advantages, two prototypes are often built and exposed to the same ambient conditions for comparative purposes. However, from a practical application point of view, this type of setup is insufficient for accurately representing the real behavior of the Trombe wall system, as it cannot simulate the indoor environment and the behavior of the wall during its interaction with indoor and outdoor conditions.

2.2. Reduced scale Trombe wall

This setup consists of building a small-scale Trombe wall coupled with a room (Figure 4). Due to cost-saving considerations, it is commonly used to investigate the effectiveness of new technologies applied to the Trombe wall system such as in [10],[11] by simulating the thermal performance and heat transfer phenomena that occur in the system. Additionally, because of

its size, it can be placed in controlled environments or exposed to ambient conditions, depending on the study's objectives. However, one limitation of such a system is its inability to accurately represent the real behavior of an actual Trombe wall, necessitating a similarity analysis to preserve the physical phenomena that occur in both the actual and small-scale Trombe wall systems. Indeed, the simplified boundary conditions and potential scale effects may alter its thermal performance, affecting airflow patterns and heat distribution. Therefore, while small-scale Trombe walls offer flexibility in design and rapid prototyping of new configurations, they require careful consideration to ensure that findings can be reliably extrapolated to full-scale applications.

2.3. Full-scale Trombe wall

This setup involves constructing a real house equipped with a Trombe wall system (Figure 5). It is ideal for investigating the dynamic behavior of the system during its interaction with the surrounding environment, including both external conditions and occupant activity [12]. It provides a comprehensive assessment of the yearly system energy performance and savings. However, one limitation of such a setup is the cost burden, which can make such projects financially challenging. Furthermore, it may be difficult to assess various technologies and materials that could improve conceptual design.

Table 1 represents the main characteristics of each Trombe wall scale model.

Scale	Advantages	Limitations
Stand-alone Trombe wall	- Cost and space-saving - Enable the comparison between several design configurations	- No adjacent room, leading to insufficient representation of the real behavior of the system
Reduced scale model	- Enable the investigation of the Trombe wall heat transfer mechanism during its interaction with the connected room - Cost saving	- Problem in scaling and similarity law
Full-scale model	- Full assessment of the dynamic behavior of the system - Taking into account the human presence and behavior	- Cost challenging - Challenges in the application of findings in other geographical areas - Challenges in assessing the impact of different design configurations - No controlled conditions

Table 1: Characteristics of each scale model test bench



Figure 3: Stand-alone model [13]



Figure 4: Reduced scale model [10]



Figure 5: Full-scale model [14]

In the following, we will discuss the experimental procedures and thermal measurement tools commonly used in both controlled environments and in situ conditions.

2.4. Experimental procedures applied in controlled Laboratory-scale experiments

In laboratory-scale experiments, the impact of factors such as glazing properties [15], wall architecture and materials [9], [16], [17], enclosure properties [18], as well as internal structural parameters like channel width and height [19] on Trombe wall thermal performance, is evaluated under specific heat flux conditions. Most of these parametric studies are performed under steady-state conditions. These controlled environment experiments offer the advantage of focusing investigations on specified parameters through the manipulation of boundary conditions, facilitating systematic analyses of cause-and-effect relationships. Furthermore, the level of knowledge provided by these experiments can be used as a data source to validate numerical models. In the following sections, we will discuss two main experimental procedures used in the laboratory-scale experiments.

Table 2 summarizes the characteristics of laboratory-scale case studies.

2.4.1 Reduced scale Trombe Wall coupled to a room

In order to replicate the outdoor conditions, heating mats placed on the outer wall surface or solar simulators are typically used to replicate solar radiation. The decision between these two systems is primarily based on the technical specifications of the experimental test bench. For example, in the study of Wu et al. [19], due to the large size of the test bench, the authors prefer using a heating mat to ensure uniform distribution of the imposed heat flux on the wall surface. Nevertheless, the solar simulator allows the quantification of the radiative heat transfer mechanism and external heat loss from the glass surface under specific conditions. Also, some experiments use pyranometers to measure direct solar radiation emitted from the solar simulator.

To investigate the thermal performance of the system, different thermal measurement tools are frequently employed. Infrared cameras or temperature sensors such as thermometers or thermocouples of various types are commonly deployed across building facade experiments. Typically, to monitor the temperature stratification that occurs in the system, thermocouples are strategically positioned at different sections of each wall and glass side, alongside the air gap and vents. Radiative and convective sensors could also be positioned on each side of the glass and on the wall external side to monitor external loss. Similarly, conductive flux sensors are deployed on each side of the wall to estimate conductive heat transfer. However, to ensure measurement accuracy, it is imperative to shield these sensors from direct solar radiation [20], especially in the case of using a solar simulator as its placement at a small distance from the setup may impact the sensor's reading accuracy. Shielding all these sensors with reflective tapes is not a viable solution as it may obscure important physical phenomena occurring in the system. Therefore, a careful selection of the number of sensors and their placement as well as the assessment of the solar simulator's impact on sensors measurement is required. A transitional mechanical system is usually used to finely adjust the air channel width, allowing the investigation of the impact of different aspect ratios on the system performance [19]. A control system is used to adjust finely the height, and the slat angle of Venetian blinds employed in studies investigating the effect of shading devices on the cooling performance of a Trombe wall. Usually, Venetian blinds are made of a material of high thermal reflectivity (white aluminum cover) enabling the reflection of a high fraction of solar radiation [20].

It is also important to highlight that, there are very few laboratory-scale experiments reported in the literature where a Trombe wall is integrated into a room and the thermal and radiative environments are controlled simultaneously. Additionally, according to Jankovic [20], there have been no experiments conducted yet on such type of building facade where the surrounding temperature, incident solar radiation, and wind conditions were controlled simultaneously. To date, the laboratory test bench representing a double skin façade system developed by this researcher is considered the most adaptable mock-up, enabling control over various boundary conditions and facilitating the investigation of the thermophysical properties of such a system.

2.4.2 Climatic chamber

Another experimental setup used at the laboratory scale consists of building a controlled climatic chamber enabling the simulation of outdoor and indoor conditions. For example, Jerzy Szyszka et al. [21] conducted an experimental study to assess the influence of outdoor temperature, variable duration, and intensity of the solar flux on the performance of the ThermoDiode Trombe Wall (TDTW) under laboratory conditions. Their experimental setup as represented in Figure 6 involves placing the TDTW prototype inside a climatic chamber equipped with an HVAC unit. To replicate indoor set-point conditions, the inner surface of the Trombe wall is kept at a constant temperature, while the outer surface is exposed to a controlled outdoor air temperature. A heating cable is attached to the wall surface to simulate solar radiation absorption. This configuration allows precise control of the investigated parameters, enabling the authors to establish correlations between the TDTW thermal efficiency and selected boundary conditions.



Figure 6: Climatic chamber [21]

2.5. Experimental procedure applied to in situ experiments

Most studies available in the literature on evaluating Trombe Wall thermal efficiency predominantly rely on in-situ investigations. Full-scale experiments enable the investigation of Trombe wall performance under real weather conditions, providing valuable insights into the dynamic behavior of this system, and the feasibility of using Trombe walls in specific climatic zones [22], [23], [13]. Furthermore, it allows a deeper understanding of how operational modes affect the system's behavior [24], [25], [26]. This contributes significantly to the specification of practical implications of implementing Trombe walls in real-world building projects. While full-scale experiments offer numerous advantages, they also have some limitations. Indeed, full-scale studies might be more difficult to control since ambient factors may produce uncontrollable fluctuations. Consequently, results from a specific full-scale experiment may not be immediately applicable in other climates or geographical areas. Furthermore, the challenge of isolating individual effects and setting specific boundary conditions adds complexity to interpreting the results and arriving at definitive conclusions.

For real-time monitoring of external weather parameters during in-situ experiments, weather stations, and pyranometers are installed to measure direct solar radiation, wind speed, and

ambient temperature. To measure the diffuse fraction, the pyranometer is shielded by a shade ring or disk. A pyrgeometer can also be used to measure the intensity of long-wave radiation [27]. Temperature sensors such as thermometers or thermocouples of various types are commonly deployed across in situ experiments. Analytical models utilizing heat balance equations are frequently employed to estimate heat gain and losses. However, heat flux sensors (conductive, radiative, and convective) can also be positioned at various sections to estimate the heat transfer mechanism. While heat flux sensors offer a direct measurement approach, some papers highlight various issues when employing them to characterize heat transfer and energy loss in the building context. For instance, as indicated by Francois et al [28], the main disadvantage of using flux meters on building walls is their inability to provide a global heat loss measurement due to their local measurement characteristics, which prevent them from measuring the thermal bridge and multidimensional heat transfer that occurs naturally in the system due to its interaction with its surrounding environment. Second, the usage of several flux meters is frequently problematic due to their contact qualities in which their placement can alter heat flux measurements. As highlighted by several researchers such as in [29], [30], the placement of these sensors may modify the way heat is exchanged from the surface due to their emissivity and their sensitivity to radiation leading to false measurements.

System	Scale	Objectives	Investigating parameters	Findings	Instrumentation
Wavy shape Trombe wall [9]	Stand-alone laboratory test bench	Comparing the heating performance of the novel design to the conventional Trombe wall	4 different materials for the absorber Different angles of intersection are tested under constant heat flux conditions	The temperature of the novel design is higher than the conventional TW due to surface-to-surface radiation between different absorber sections The convective heat exchange is improved due to the reduced distance between the absorber partitions	Solar simulator (steady-state conditions) Temperature sensors Anemometers
dual-channel Trombe wall [16]	Laboratory small-scale stand-alone Trombe wall of size $2.4 \times 1.0 \text{ m}^2$	Testing the impact of adding an insulation baffle in the air channel on the performance of the conventional Trombe wall in winter	Testing the impact of different insulation shapes (C shape or flat) and positions on the temperature and heat transfer phenomena	The placement of the insulation baffle layer(aluminum) improves the heat transfer phenomena	Halogen lamps (steady-state conditions) Thermocouples Anemometer
Trombe wall [19]	Laboratory small scale Stand-alone Trombe wall channel	Testing the impact of aspect ratio and wind speed on the performance of conventional TW	Effect of aspect ratio on the convective heat transfer coefficient under different ventilation strategies (natural or forced convection conditions)	Correlation was proposed to describe the convective heat transfer coefficient, and the finding revealed that an increase in aspect ratio and wind speed led to a decrease in the intensity of convective heat transfer phenomena	Electric heat mat Thermocouples Infrared images Fan
PCM TW [15]	Laboratory scale standalone unvented TW placed	Influence of glazing characteristics on the heating	Impact of glass U value and solar radiation transmittance	To obtain the phase change of the PCM TW it is necessary to use a glass of high transmittance value	Heat fluxmeters Thermocouples Heating panels to control the inner

	in a climatic chamber	performance of PCM TW	Thickness and type (double or single layer)		side of the climatic chamber
Dynamic Trombe wall incorporating a PCM layer on one face and an insulation layer on the opposite face[10]	Large scale laboratory scale PCM TW of dimensions 3.0 m × 1.99 m × 1.99 m	Investigate the heating performance of this novel design compared to static PCM and conventional TW	Evaluate the dynamic behavior of the system including the charging and discharging period of the PCM under fixed heat flux conditions	Higher temperature and better performance	SFL 4000W lamp (metal halide lamp) Pyranometer Temperature sensors
Conventional TW [11]	Small-scale laboratory scale experiment Square 500mm	Investigating the effect of partition on the natural convection phenomena	Measurement of the thermophysical properties of the material used Quantification of the convective heat transfer coefficient	Interposition of vertical partitions helps to enhance the natural convective heat transfer	Hot plate simulating the partitions Electric resistance to generate the imposed flux Temperature sensors
PCM TW [17]	Small laboratory scale model	Investigating the impact of adding PCM consisting of a mixture of 55% decanoic acid and 45% lauric acid in the TW system	Measuring The melting temperature and the latent heat of PCM	There exists an irregular-shaped liquid/solid interface. The PCM above the liquid/solid interface can melt completely while the PCM below the liquid/solid interface is always in the solid state	Electro-thermal film which provided a variable heat flux Temperature sensors
Thermo Diode Trombe Wall[21]	Laboratory -scale Climatic chamber	Investigating the thermal behavior of the system	Statistical analysis	Correlation made for the thermal efficiency in function power supplied to the heat absorber, outside air temperature	A heating cable Temperature sensors Climatic chamber simulating the indoor and outdoor conditions
DSF [20]	Large laboratory-scale test bench of size 3700 × 1500 × 3240 mm ³	Description of the test bench	Controlling the ambient temperature, Relative Humidity level, solar radiation, wind speed and rain	Some practical solutions are proposed Controlling the run intensity by using a system imposing droplets of size 15 to 30µm Venetian blinds are covered by a white aluminum painting of high reflectivity and equipped with a control system	Shading devices Solar simulator Anemometers Temperature sensors Pyranometer RH sensors Heat flux sensors

Table 2: Laboratory scale experiments

3. Experimental techniques for airflow velocity measurement

Several experimental techniques have been proposed in the literature for characterizing the flow field in building façades. They vary in terms of complexity, the amount of information they provide, and their application to in-situ measurement. Generally, it can be grouped into three categories: direct velocity measurement, non-intrusive velocity measurement, and bulk airflow measurement [31].

3.1 Direct velocity measurement

This method is widely used in the experimental studies of Trombe walls, especially for the validation of numerical models [23]. Additionally, a recent review [2] of 70 research papers focusing on experimental studies of building facades found that all of these studies use a thermal anemometer (Figure 7) to measure the velocity. Usually, the velocity is measured at a characteristic point by a thermal anemometer (hot wire or hot sphere) located at the top vent of the air gap. However, the accuracy of this measurement technique remains a challenge due to its limitation in representing the spatial structure and direction of the flow stream. Indeed, buoyancy-driven flows are complex and have non-uniform distribution, and radiation may interfere with the airflow field resulting in high uncertainty of the measurements [32], [33]. Moreover, the use of multiple anemometers at various levels of the cavity leads to high disturbance in the experimental domain.

3.2 Bulk airflow measurement

This category is composed of the pressure difference method and tracer gas technique. The first approach involves measuring the pressure difference across an opening to quantify the airflow rate, requiring calibration to accurately define a relationship between the measured pressure differential and airflow rate. However, this technique presents some drawbacks, and it's considered unreliable in the studies of naturally ventilated cavities because the driving forces are usually weak [2]. Furthermore, its application to real-scale experiments is still limited because it shows a high sensitivity to fluctuations in wind direction and speed [34] which brings additional uncertainties during the selection of external pressure sampling points.

The tracer gas technique is often employed to monitor the airflow in a large room. Its main advantage is that it measures the ACH (Air Changes per Hour) while taking into consideration the infiltration/exfiltration flows. It relies on monitoring the concentration of tracer gas, typically carbon dioxide (CO_2) or sulfur hexafluoride (SF_6), within the room as ventilation occurs (Figure 8). The rate of decrease in the tracer gas concentration is then utilized to calculate the airflow rate. Three ways for injecting the gas inside the room are found in the literature: decay method, constant concentration, and constant injection method. In the decay method, the gas is released before the measurement, and the mean ACH is obtained from the decrease of the gas concentration between the first and last measurement points. In the constant injection method, the gas is injected during the measurement at a constant flow rate. In the last technique, instead of injecting a fixed amount of the gas, a controller releases a variable amount of the gas in a way to keep its concentration at a constant level during the measurement. All of these techniques assume the homogeneity of the tracer gas distribution in an occupied zone and the steadiness of the flow during the measurement which leads to high uncertainty, as reported by Gabriel Remion et al. in their review [35]. Although there is a significant research gap in its application to a Trombe wall system, it is necessary to mention that the application of tracer gas methods in a ventilated façade contributes to additional uncertainties induced by the turbulence effect of the wind and the location of both the injection points and recording sensors. Indeed, Giancola et al. [7] explain that a wash-out effect can be obtained if the gas is injected close to the inlet because of the unsteady and dynamic nature of the flow near an opening where the gas may be recirculated back before it mixes with the cavity air, leading to an overestimation of the airflow rate. Deviation in the results due to this effect is found in different experimental studies such as in [36] and [31].

3.3 Particle image velocimetry (PIV)

PIV is a non-intrusive optical technique for measuring the instantaneous velocity field of the flow. It is considered a laboratory technique to investigate the flow field. This method provides

detailed information about the development of the flow, its spatial structure and pattern, and its turbulence characteristics. It is based on tracking the displacement of particles seeded into the flow. However, the accuracy and reliability of this method depend on several factors related to experimental conditions and system component characteristics. These factors include particle characteristics and illumination and image acquisition systems.

The particles must follow the flow with minimum deviation, which implies a compromise between the size of the particles and their light-scattering capacity. To achieve better spatial resolution, a higher seeding concentration is recommended. However, it is essential to ensure homogenous particle dispersion during the experiment, and this is accomplished by setting a time interval between the end of the injection and the first PIV measurement.

A double-pulsed laser is typically used to generate a light sheet that illuminates a specific area and is synchronized with a digital camera. The synchronization system is used to trigger the camera such as the exposure occurs at each light pulse, preserving the temporal order of each illumination. Subsequently, an image processing technique is employed, involving the segmentation of the captured image into several interrogation areas, which are then analyzed through a cross-correlation algorithm to find the displacement vector. The working principle of this technique is represented in Figure 9.

With this setting, several parameters need to be adjusted:

- The exposure time (duration of each pulse) must be short enough to freeze particle motion during exposure.
- The time delay between two light pulses must be a compromise between the size of the Interrogation Area (IA) and the maximum particle velocity to prevent the particles from moving out of the interrogation zone. Usually, it is settled in a way to ensure that particles don't move more than $\frac{1}{4}$ of the interrogation area between 2 frames.
- The laser energy per pulse is an important parameter as it directly affects the light scattering behavior of particles. If the energy is too low, the particles may not scatter enough light to be detected by the camera, resulting in low image resolution and incorrect cross-correlation results. Conversely, if the energy is too high, it may cause excessive particle motion, leading to blurry images and reduced image quality due to the increase in signal-to-noise ratio.



Figure7:
Anemometers

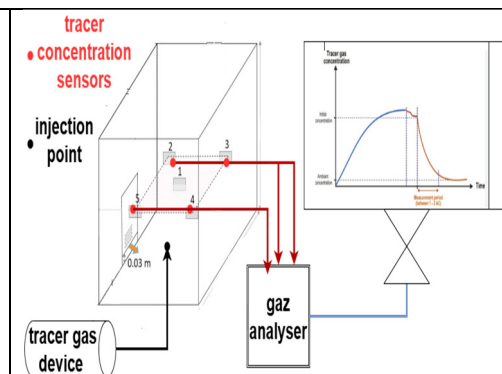


Figure 8: Tracer gas technique

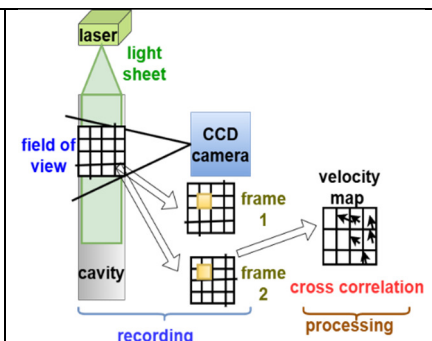


Figure 9: PIV technique

Table 3 provides a comparison between different velocity measurement techniques.

Velocity measurement techniques	Advantages	Limitations	Field application
Anemometers	- Cost-effective and simple	- Sensitive to radiation	- No limitation

	- Direct velocity measurement technique - Suitable for both steady and transient flows	- Localized measurement - The use of multiple anemometers leads to disturbing the buoyancy flow	
Tracer gas technique	- Effective for measuring the average velocity in a large room	- require steady flow and homogenous gas distribution - require precise types of sensors and equipment	- High uncertainty in its application to in-situ analysis of ventilated façade
PIV	- Provide full-field velocity measurement - suitable for steady and transient analysis - non-invasive method	- Very expensive - Sensitive to experimental conditions	- Laboratory scale experimental method

Table 3: Comparison between several velocity measurement techniques

As presented in the previous sections, the PIV technique has advantages over other velocity measurement methods, due to its capacity to present two-dimensional velocity fields, which is critical for characterizing buoyancy-driven natural flows. Therefore, the following sections will focus on reviewing the experimental protocols of the PIV technique applied to indoor environments, including its use in characterizing the human thermal plume, as well as its application in ventilated cavities.

3.3.1 PIV experimental setup applied to ventilated cavities.

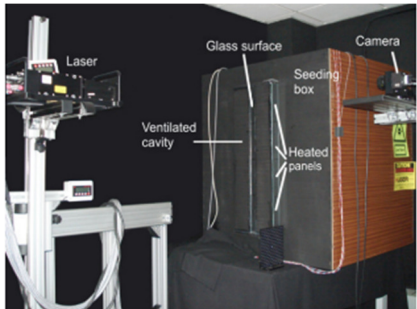
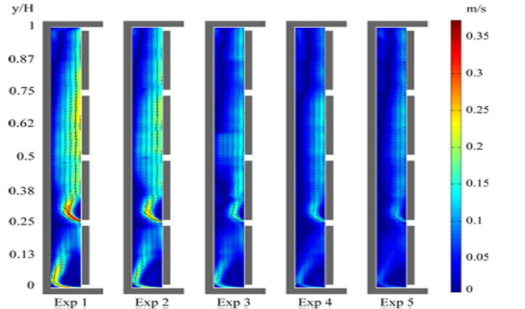
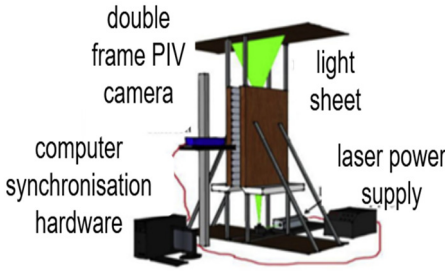
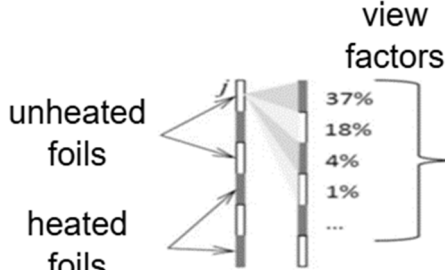
3.3.1.1 Review of PIV application in naturally ventilated cavities

It is worth highlighting that most laboratory-scale case studies involving the application of the PIV technique in building facades are restricted to characterizing only the natural convection phenomena and fluid flow regime within the channel for different ranges of Ra numbers. Usually, the Rayleigh number is controlled by changing the geometrical characteristics of the channel and the heat flux input conditions. Several papers such as [37], [38], [39], and [40] use PIV-based water channels to study the unsteady natural convection flows in cavities and their dynamic characteristics enabling the detection of important physical phenomena such as the appearance of the reversal flow. The water shows more stable properties compared to air and radiation heat transfer would be neglected. Nevertheless, the experimental requirement seems not to be relevant to our case study. Therefore, in this paper, we review only the PIV application to naturally ventilated cavities in which air is the working fluid, noting that there are fewer studies on ventilated air-filled cavities than those with water.

Several experimental studies were carried out using PIV to analyze the flow velocity field of different types of ventilated channels in building facades, including Open Joints Ventilated Facades (OJVF system) [41], [42] and Building Integrated Photovoltaic (BIPV) systems [43], [44]. These studies focused mainly on characterizing the flow regime and its kinematic behavior, allowing the quantification of the convective heat transfer mechanism under specific solar radiation flux and Rayleigh numbers. In such type of analysis, the mean velocity and instantaneous velocity fluctuations at different heights of the channel are measured (Figure 10,11) and turbulence is characterized by calculating turbulence derivatives, such as turbulence level (Tu), and turbulence intensity (It) using instantaneous velocity fields. Additionally, based on the PIV results, some indicators of transitional flow may also be determined and identified. For instance, in the studies of [44] and [43], the authors found that under the conditions

examined, the flow exhibited characteristics of both laminar and turbulent flows, suggesting a transitional regime. To analyze this behavior, Thebault et al.[44] identified three indicators of the transition: the height at which time-averaged temperature changes occurred at the wall and within the flow and the height at which time-averaged velocity changes occurred. The authors claimed that these first two indicators represent the late transition stage. They defined the third indicator as the changes in the slope of the maximum velocity near the wall, which is accompanied by drastic changes in the minimum temperature within the bulk. This indicator proves to be relevant for detecting changes in turbulent statistics of the flow, which represents the early stage of the transition. Moreover, very few studies combine PIV with non-uniform heat flux conditions[45], [46]. For instance, Tkachenko et al [46] used PIV to investigate the impact of non-uniform wall heat flux conditions on heat transfer and natural convection in a vertical channel representing a PV double-skin façade (Figure 12). To induce a non-uniform heat flux, they employed heating elements in the arrangement illustrated in Figure 13. Their findings revealed that non-uniform heating causes a periodic fluctuation in the temperature distribution of the wall in the vertical direction, with alternating heated and unheated zones. In addition, this configuration generates significant recirculation zones, enhancing mixing and improving heat transfer rates compared to a channel heated uniformly on one side.

Table 4 summarizes the case studies of PIV applied to naturally ventilated cavities.

 Figure 10: PIV setup [41]	 Figure 11: Velocity map for different Ra[41]
 Figure 12: Test bench[46]	 Figure 13: Configuration[46]

3.3.1.2 Standard experimental procedure

3.3.1.2.1 Solar radiation simulation

In such a setup, solar radiation is generally simulated using a heating mat adhered to the wall exterior layer. The definition of the thermal wall condition is challenging in this case as it affects the flow behavior in a ventilated cavity. Most studies investigating the natural convective phenomena in vertical channels impose either a uniform temperature profile on the wall[47], or a uniform heat flux [43]. The simulation of non-uniform heat flux conditions can be achieved by adjusting the arrangement of the heating elements, either in a staggered or discrete configuration [46]. Additionally, simultaneous PIV and thermal measurements (thermocouple, fluxmeter) have been successfully performed in asymmetrical channels with

one side uniformly heated [47], [44] as it has been shown that there is no effect of laser power on sensors' readings.

3.3.1.2.2 Lighting system and data acquisition system

The standard experimental procedure consists of using a laser as a lighting system in addition to a camera placed perpendicular to the light sheet plane. Mirrors and articulated arms are commonly used to direct the laser light sheet parallel to a specific plane. However, it is found from these works, that it is not feasible to capture the entire cross-section area in a single image using a CCD camera. Consequently, multiple runs are carried out for each condition to acquire data for the entire flow field, which can be performed using a transversal system to move the camera without the perturbation of its calibration process. However, this approach is very sensitive to the conditions under which measurements are conducted. Factors such as slight equipment misalignment during measurements and uncontrolled environmental conditions can potentially lead to image overlap and data discontinuities. To address these issues, interpolation techniques may be employed to merge the velocity fields obtained from adjacent images, thereby enhancing data continuity [48]. Additionally, to ensure the accuracy and reliability of measurements throughout numerous runs, tests must be repeated with the same boundary conditions which require that ambient conditions be continuously monitored and controlled [43]. Moreover, to track the particle's motion over time, most studies used a double-pulsed laser mode. The continuous mode may also be used such as in the study of Sanchez and al. [41]. However, it should be noted that this operation mode may cause an elevation in fluid or surface temperature, disrupting the buoyancy flow and leading to errors in velocity measurement. The level of disturbance caused by laser usage is dependent on multiple factors, including laser power, sheet thickness, operation mode, and acquisition duration which implies a careful selection of laser parameters during experiments. This heating effect was observed in an experimental investigation of natural convection in a tilted enclosure [49], [50]. To mitigate this issue, the researchers employed a strategy of firing the laser for 8 seconds every 5 minutes, capturing 50 images without any prior preview.

3.3.1.2.3 Seeding procedure

Most of the research papers on the PIV application to naturally ventilated cavities use **Di-Ethyl-Hexyl-Sebacic** (DEHS) as tracer particles generated by aerosol generators. This device operates by forcing compressed air into a DEHS container through an inlet. The air then becomes loaded with small DEHS droplets, resulting in the formation of an aerosol that is directed into the flow for seeding purposes. However, introducing the tracer particles in a closed channel is quite challenging due to the entrainment velocity produced by this seeding device. Various seeding approaches have been adopted in the literature. For instance, Yanyu Lu [51] and Han [52] preloaded the VZ09-0751 atomization system to the lower part of the apparatus to eliminate the effect of initial particle velocity and ensure particle homogeneity distribution in air. Similarly, Zhang [48] injected particles from the intersection points between the ceiling and side walls. Sanjuan [53] resolved this issue by using a wood box of size 1 m^3 opened from the top to generate the seeding and ensure the homogeneity of the particles before entering the cavity. However, Jiayu Li [54] highlights difficulties in achieving the ideal homogeneous distribution of particles required for PIV measurements using these methods, as ambient air without particles is entrained. Therefore, the author prefers pre-seeding the tracer particles generated by a Laskin atomizer inside the cavity. Thermal equilibrium was disturbed but after 15 minutes, the initial momentum of the pre-seeding airflow became negligible, and homogeneously mixed particles reached thermal equilibrium with the airflow.

Authors	System	Dimension	Instrumentation
Yassine [47]	Open channel's With constant wall temperature	Height=1m Air channel width=4cm	YAG laser with an energy of 30 MJ equipped with a divergent Lens Double pulse duration = 0.01 μ s paraffin microparticles of about 2.5 μ m diameter generated by a smoke generator Flow sense 2M camera
Sanchez [41]	OJVF	Cavity 0.825 m high and 0.3 m wide	YAG pulsed laser, a CCD camera Seeding particles of olive oil of diameter 1 μ m 2D Positioning structures allow the displacement of the camera in a vertical position Heating mats
Sanchez [42]	OJVF	0.825 m $\times$ 1.225 m with a ventilated cavity of 0.045 m	Heating mats stereo PIV Seeding Box Same equipment of [40]
Sanvicente [43] Thebault[44] Tkachenko [46]	PV double skin façade (open Channel)	1.5 m height, 0.70 m depth, cavity width 5-30cm	YAG laser of 120 MJ pulse energy Heating mats converging and diverging cylindrical lenses laser sheet thickness 1-2mm CCD camera Positioning system DEHS of diameter 1 μ m injected from the lower part of the channel
Sanjuan [53]	OJVF Channel	H=825 mm high, A=300 mm depth and W =40 mm wide	YAG pulsed laser of energy 120 MJ/pulse CCD camera Heating mat Seeding particles of 200 g of salt in 1.5 l of water of diameter 1 μ m
F. Corvaro[49]	Tilted enclosures filled with air and with opposite active walls	L = 0.05 m and a depth of 0.42 m	Isothermal temperature conditions Sunflower oil of diameter 1 μ m generated by compressed air device oil sprinkled inside the cavity by three holes positioned in the rear part of the top wall of the cavity Nd: YAG laser lens 50mm interrogation area IA 32 $\times$ 32 pixels 50% overlap
Leporini[50]	Tilt square cavity	L = 0.05 m and a depth of 0.41 m.	Laser CCD camera. oil nebulizer device

Table 4: PIV applied to naturally ventilated cavities

3.3.2 PIV setup adaptation for indoor airflow monitoring

3.3.2.1 Review of PIV applications in an indoor environment

Precise monitoring of indoor airflow in Trombe walls is crucial to evaluate the energy performance of these systems, to regularize indoor air quality parameters, and to achieve human hygrothermal comfort. Therefore, it becomes essential to review the application of PIV for indoor airflow monitoring. While the research subjects in this area are extensive, however, in this paper, we focus mainly on case studies investigating the natural convection phenomena in closed indoor spaces and thermal plumes generated by humans in indoor environments.

Some studies have evaluated the indoor natural convection phenomena. Those studies vary in terms of the setup size and the replication of indoor conditions. Among them, Mortensen et al. [55] employed PIV to study airflow patterns between a constant temperature wall and furniture in a room. Yanyu Lu et al. [51] and Xiwen Zhang et al. [48] used PIV to investigate the stack effect in a small prototype designed to represent large-scale thermal stratification environments, with heating elements positioned at the top and bottom to simulate various

environmental conditions such as solar radiation and heat generation from occupants. Other studies used PIV to examine natural convection in square cavities with actively heated walls, focusing on the positioning of heated walls (either horizontally or vertically) [56], [57], [58] and their impact on convection.

Table 5 summarizes the case studies of PIV applied for indoor airflow monitoring

3.3.2.2 PIV Experimental protocol

The experimental protocol for applying PIV to indoor environments is largely similar to that used in ventilated cavities in which the use of laser and CCD cameras as illumination and acquisition systems is common in studies involving indoor airflow monitoring. However, indoor environments present additional challenges, such as the need to effectively remove background noise, optimize the seeding procedure for adequate particle tracking, and ensure the preservation of boundary conditions throughout the experiment.

3.3.2.2.1 Seeding particles

In naturally ventilated indoor spaces, different types of particles, such as water glycerin, DEHS, and smoke generators using water-glycol or oil droplet solutions, are commonly used for flow visualization. However, as previously discussed, seeding these particles can be challenging due to the entrainment velocity of seeding devices, which may disrupt natural buoyancy effects. To mitigate this, pre-seeding the room and allowing time for particles to settle before measurements are recommended to ensure uniform distribution. Additionally, the size of the prototype significantly influences the choice of seeding particles and methods. Larger volumes may require either a high number of small particles or larger ones, depending on the experimental conditions. Special techniques like seeding from multiple points can help achieve consistent particle distribution across the flow field in a large room. For instance, several studies have used PIV for full-scale airflow analysis, employing different types of particles such as fluorescent dye [59], DEHS [60], [54] water-glycol [61], Helium bubble [62], [63]. However, the PIV setup and results of each study are subject to the limitations imposed by the specific experimental conditions used, including the particles' suspension time, their scattering capacity, the particles' size, and the type of illumination system used.

3.3.2.2.2 Removing background noise

In indoor environments, there is often a higher tendency for background noise due to reflections from several surfaces and the lighting system, which can interfere with camera images. To mitigate this issue, a 532 nm bandpass filter with a specific bandwidth is recommended for the camera [43], [64]. Moreover, Xiwen Zhang et al. [48] propose a methodology to eliminate background noise by averaging multiple images, thereby isolating and subtracting background information from individual frames, ultimately highlighting features of tracer movement (Figure 14). This methodology enables the authors to precisely visualize the flow field and analyze the fluid flow dynamics.

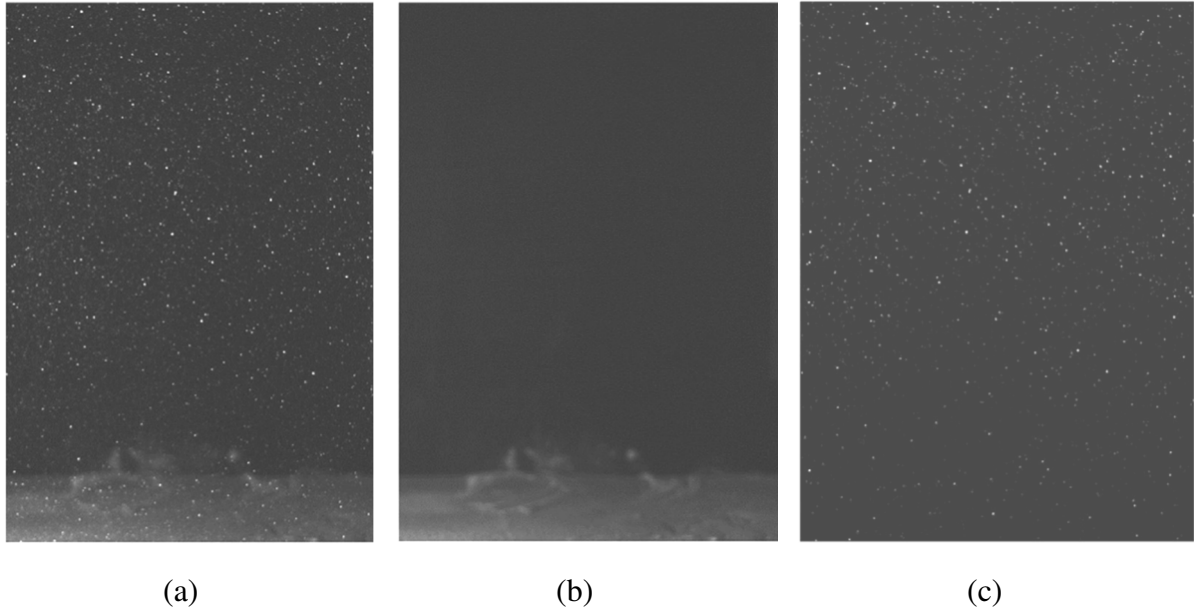


Figure14: Background-elimination technique proposed in [48]: (a) the original image; (b) the background extracted from the original image; (c) the image with background extracted

3.3.2.2.3 Preserving the boundary conditions

Another challenge is maintaining the thermal boundary condition of room walls, often replaced with glass for optical access necessary for PIV measurements. M. A. H. Mamun [57] proposes a methodology involving machining small parts of the side wall away and replacing them with acrylic strips for laser light admission, without significantly altering the temperature distribution in the side walls. Additionally, small holes are drilled through the side walls for image acquisition, running parallel to the lines of heat flow. Tanathep Leungtonkum [58] suggests employing triple-glazed windows to maintain consistent boundary conditions between the two boxes (Figure 15). These windows consist of three layers of glass, each 4 mm thick, separated by two 10-mm argon gaps. As a result, the overall heat transfer coefficient of the box made of glass walls closely aligns with that of the original insulating box.

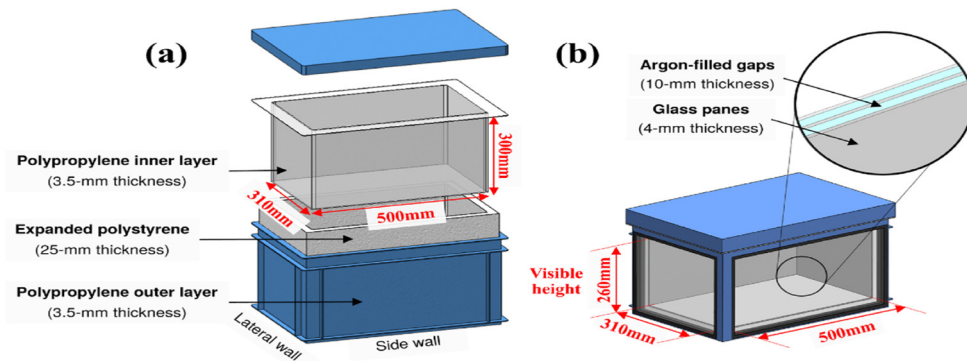


Figure15: Test bench : (a) Original insulated box (b) Walls replaced by triple glass windows [58]

Authors	System	Objective	Instrumentation
Mortensen [55]	Room of size $3.6 \times 4.5 \times 2.5$ m ³ in which the external wall is omitted by using a chilled wall with a temperature	Effect of aspect ratio and furniture position on the velocity field	Tracer gas: A smoke of small oil droplets (glycol 0.1–1.0 mm) CCD camera YAG laser system (100 MJ/pulse) light sheet thickness=3mm
Yanyu Lu [51]	Prototype of size 500 mm $\times$ 700 mm $\times$ 1000 mm Representing large space	Investigate the stack effect	Laser 135-mJ/pulse with sheet thickness 1-2mm CCD camera equipped with 50mm lens Tracer particles DEHS 1 μ m generated by a VZ09-0751 atomizer connected to the bottom of the prototype
Xiwen Zhang [48]	Cavity of size 1960 $\times$ 980 $\times$ 800 mm ³ representing an indoor environment	investigate the natural convection in an enclosed cavity with a small horizontal heated plate	YAG double pulse laser 200 MJ/pulse CCD camera with 35mm lens Time between pulses =15 ms Particle hollow glass micro balloon of diameter 10 μ m
Carvaro [56]	Square cavity 0.05m	Investigate natural convection for 3 architectures (position of hot and cold plate)	Laser and a CCD camera. Seeding sunflower oil 1 μ m The holographic interferometer And thermal circuit
Mamun [57]	Square cavity with active walls of size 1.27m ³	Investigate the airflow velocity in response to temperature change	YAG laser of 120-mJ equipped with a lens Seeding particles were generated by burning solid insect repellent in a separate container and introducing them into the cavity
Tanathep Leungtongkum [58]	Insulated box equipped with PCM	Investigate the natural convection and the effect of PCM position on convection	YLF laser 10 MJ /pulse with sheet thickness 1mm CMOS camera equipped with lens 4 nozzle Laskin-type seeders were placed in the center of the experimental chamber. Oil particle diameter of 0.3 μ m

Table 5: PIV applied to indoor airflow monitoring

3.3.3 PIV for human airflow characteristics

Furthermore, numerous studies have investigated airflow characteristics around thermal manikins. These studies vary in their focus, examining different regions around the manikin and measuring various airflow values associated with the thermal plume generated by the manikin. The differences in airflow values obtained from various studies result mainly from factors such as the size and shape of the manikin, the surrounding environment, and the experimental conditions. Typically, in such type of analysis, it is necessary to reduce reflections during measurements which can be achieved by coating the thermal manikin's body and the wall behind it in black. Furthermore, the correct alignment and location of both the laser light sheet and the camera are critical since they have a major impact on the quality of the data obtained. Moreover, the number of cameras used highly determines the ability to track the evolution of thermal plumes over time. In Rehan Yousaf's study [65], for example, the researcher positioned the laser in front of the manikin, about 1 mm behind the centerline of its head, to eliminate reflections. Furthermore, two cameras were strategically placed—one focused on the center of the head and the other on the area above the head (Figure 16) allowing for simultaneous measurement of the thermal plume around the manikin's head and a detailed characterization of its temporal development. In contrast, setups using a single camera frequently necessitate sequential measurements across different zones in both cross-sectional and longitudinal directions [65], [66]. One disadvantage of this approach is the potential loss

of temporal information about the flow development which may restrict the analysis to statistical evaluations. The choice of statistical indicators may vary depending on the specific objectives of each study. For example, in Jiayu Li's study [66], the swirl strength criterion defined in Equation 1 is used to detect vortex structures around the manikin, along with the standard deviation of instantaneous velocities(u , v) in the vertical and transverse directions to map the main airflow paths. The velocity contour map obtained is shown in Figure 17.

$$\lambda = \sqrt{\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)^2} - 4\left(\frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial v}{\partial x} \frac{\partial u}{\partial y}\right) \quad (1)$$

On the other hand, Mengtao Han and al [67] use metrics including peak velocity (PV), peak velocity time (PVT), and cough duration time (CDT) to characterize exhaled airflow from human coughs (Figure 18).

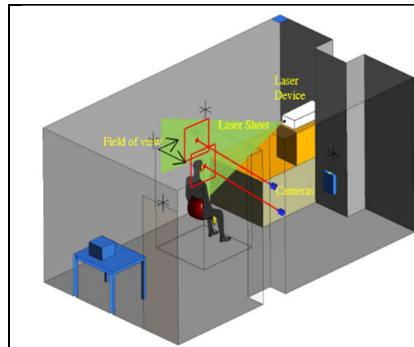


Figure16: Test bench [65]

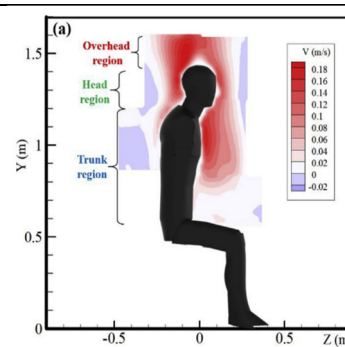


Figure17: Velocity contour[66]

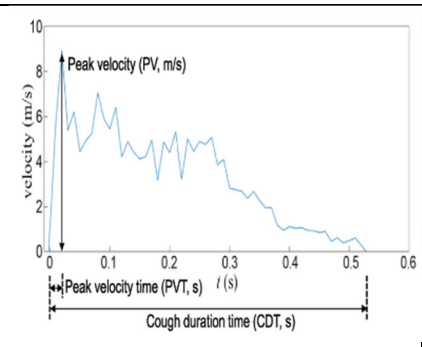


Figure 18: Statistical indicators used in [67]

4. Review of the hygrothermal analysis of the façade system

Maintaining the hygrothermal performance of building facades is critical for ensuring the building's energy efficiency and occupant comfort. The literature on this subject is extensive and can be divided into two categories: experimental studies, which determine the thermo-hygric properties of small samples of a specific material type in a laboratory-installed climate chamber and provide data input for numerical models [68], and case studies, which investigate the hygrothermal behavior of wall assemblies in a largely controlled laboratory [69] or real-environmental conditions [70].

Moisture can originate from various sources both internal and external. Continuous exposure of building facades to such moisture sources has an impact on their thermal resistance, material properties, and degradation over time. Indeed, experimental research conducted by Vololonirina [71] has demonstrated that an increase in the moisture content of construction materials results in an increase in their thermal conductivity, especially for hygroscopic materials. Ultimately, the presence of moisture can elevate the material heat capacity. This, in turn, affects the overall energy performance of the building. This study along with others [72] and [73] highlight the importance of incorporating moisture-dependent properties into building energy simulation software for accurate estimation of heat losses, thermal insulation capabilities of building envelopes, and the annual cooling and heating load. To date, there is a well-defined experimental protocol to determine the thermo-hygric properties of materials. However, this review mainly focuses on the case studies aiming to assess the hygrothermal performance of facade assemblies, specifically ventilated wall assemblies as these structures are related to Trombe walls.

4.1 Experimental protocol for in-situ hygrothermal analysis of ventilated façade system

Some experimental studies such as in [74] have been performed to investigate the hygrothermal performance of different types of façade systems under several climatic conditions. Furthermore, several research papers demonstrate that ventilation contributes to preserving the hygric behavior of the walls by effectively facilitating the removal of water vapor by convection and functioning as a capillary break for liquid transport between the external cladding and the interior layer [75], [76], [77]. The hygrothermal behavior of different types of ventilated façade was assessed in the literature including ventilated timber walls [78], buildings renovated with prefabricated ventilated façade elements [79], and opaque ventilated façade made of recycled materials [70].

The experimental procedure for this type of analysis is similar to that employed in the in situ thermal analysis of the Trombe wall system, discussed previously (Figure 19). However, thermo-hygrometric sensors as well as weather stations are required to monitor RH levels at different sections. Most of these studies employed RH capacitive sensors at the internal and external surfaces of the wall or at the interface between different layers in multilayer wall assembly as well as in the cavity and external cladding section (Figure 20). Other types of moisture content sensors can be installed in the middle of the wall [76]. These sensors must be positioned diagonally in the wall for many reasons, including avoiding edge contact between multiple sensors and capturing multidirectional moisture and heat flux. Measured factors such as temperature and relative humidity at various locations permit the prediction of other variables such as vapor pressure, moisture content, and in-situ thermal resistance. The experimental dataset obtained from field investigations is essential to define some moisture damage functions or indexes such as Time Of Wetness (TOW) or mold growth index [80] required for a complete assessment of the hygrothermal behavior of a façade system in specific climate conditions.

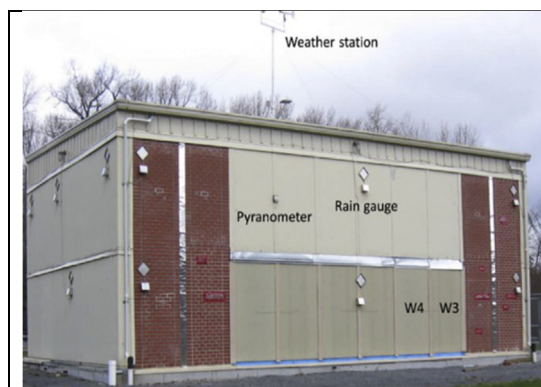


Figure19: Ventilated facade test bench[76]

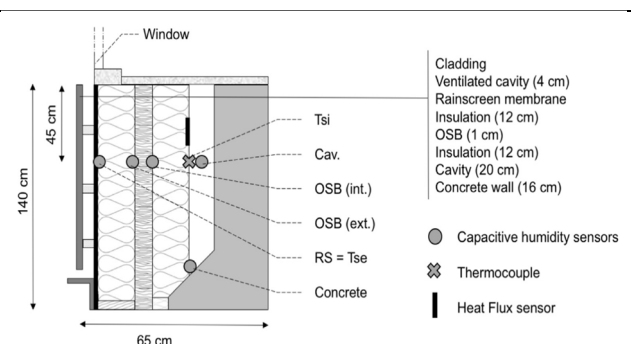


Figure20: Thermo hygric sensors position[79]

4.2 Experimental protocol for Laboratory scale hygrothermal analysis of ventilated façade system

On the other hand, few experiments are conducted under large-scale controlled laboratory conditions. At the laboratory scale, an additional device for moisture generation is required for such an analysis. For instance, different types of humidifiers are adopted in the literature such as ultrasonic humidifiers [69], steam humidifiers [81], and vaporizing systems [82]. For

example, M.I. Nizovtsev [69] conducted laboratory and field-scale experiments to evaluate the hygrothermal behavior of an open joint-facade system (OJVF) and the impact of the air gap ventilation rate on its drying capability. The laboratory test bench as represented in Figure 21 includes an ultrasonic humidifier for moisture generation as well as thermo-hygrometric sensors.

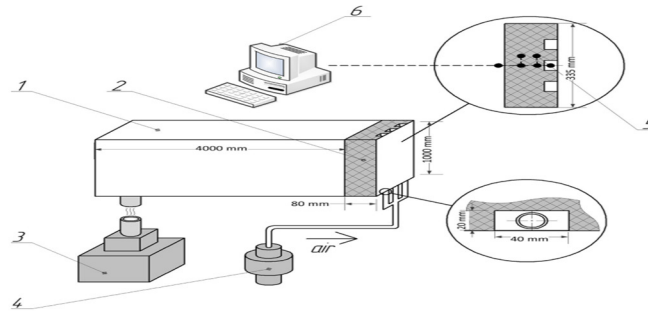


Figure 21: Laboratory test bench [69]: 1 – humidity chamber, 2 – cavity with a panel, 3 – ultrasonic humidifier, 4 – air pump, 5 – sensors (Temperature and RH), 6 – computer

Teodosiu ,Steeman and Van Belleghem [83], [81], [84] conducted laboratory experiments to validate their numerical model and experimentally assess the condensation risk in enclosures. Their experimental setup comprises a closed-loop air handling unit (AHU) containing cooling, heating, and humidification systems that are used to control the temperature and relative humidity levels. For example, in the Van Belleghem study [84] as represented in Figure 22, the air handling unit uses a recirculation fan to extract humid air from the inner room. A cooling coil continuously cools the air. When the air reaches its dew point, condensation occurs, and the humidity ratio of the air decreases. The cooled air circulates through a heat exchanger, where a resistive heater raises the temperature to the desired level. Heating the air lowers its relative humidity. Steam is then added to humidify the dry air to the desired relative humidity level.

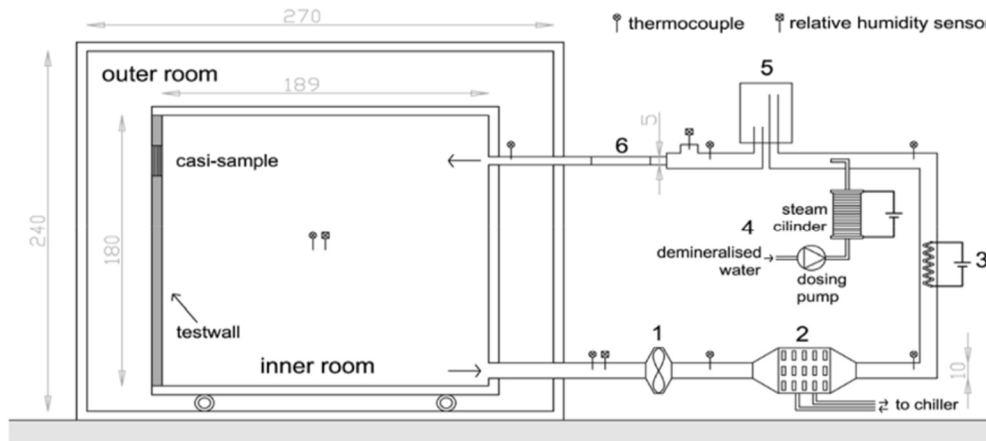


Figure 22: Laboratory test bench [84]: 1- recirculation fan, 2- cooling coil, 3- resistive heater, 4- steam humidifier, 5- buffer vessel, 6- flow straightener

5. Discussion

As represented in this review, since its initial installation, numerous experimental studies have been carried out to investigate the thermal behavior of Trombe walls. Field investigations are essential to evaluate the performance of these systems in specific climatic conditions. However,

the results of such an analysis can't be generalized and lack the possibility of defining a clear framework for investigating the hygrothermal performance of such a system or determining its optimal geometrical characteristics. For this purpose, the need for laboratory-scale experimental investigations remains essential to determine the effect of the geometrical characteristics of a Trombe wall system on its performance. This review analyses existing experimental protocols available in the literature to study various aspects related to the hygrothermal behavior of Trombe walls. In this section, we will discuss the main suggestions for a reliable design of future experimental procedures that can be applied to these systems.

5.1 In situ experimental procedure

The experimental procedure for investigating the thermal behavior of the Trombe wall is discussed in this review, along with the challenges of employing various thermal measurement tools such as flux meters and thermocouples. To overcome these challenges and reliably analyze the hygrothermal performance of the system, additional thermocouples, and hygrometers must be installed diagonally within the wall along its thickness, allowing for the estimation of multi-dimensional heat and moisture transfer. However, it is still crucial to shield the thermocouples placed on the external wall and glass surfaces to ensure accurate measurement. The simplest way to measure the flow velocity is by using anemometers as the other velocity measurement techniques still face several challenges during their implementation to in situ investigations of building façade systems. When assessing the impact of occupants on the system behavior, experiments can be conducted with human presence. Parameters such as temperature, velocity, CO₂ levels, and relative humidity (RH) should be measured in the room to provide a comprehensive evaluation of both the system's hygrothermal performance and occupant comfort.

5.2 Laboratory scale experimental procedure

This review highlights the significant variations and differences in experimental procedures used in controlled laboratory-scale experiments, particularly in assessing the thermal performance of Trombe walls and the hygrothermal behavior of a building wall assembly. However, two experimental procedures can be proposed to extend the experimental approach of Trombe wall thermal analysis to include its hygrothermal performance.

5.2.1 Reduced scale Trombe wall coupled to a room

The recent trend of the experimental protocol for investigating the thermal performance of such a system consists of building a test bench representing the Trombe wall coupled to a room along with a solar simulator which allows to replicate the daily solar radiation. As previously discussed, the thermal sensors must be shielded from direct solar radiation, and the edge contact effect needs to be prevented. To investigate the hygrothermal behavior of the wall, thermo-hygrometric sensors must be placed within the wall diagonally to avoid measurement perturbation. Furthermore, to reflect the real behavior of such a system, it is necessary to predict the human behavior's impact on the system's performance. While it is common to use a manikin at the laboratory scale, to assess thermal plumes in an interior environment. However, this does not replicate human breathing and moisture generation rate which requires a more accurate experimental approach to mimic the real human behavior. One alternative method consists of using an ultrasonic humidifier for this purpose due to its entrainment velocity, which is equivalent to an occupant thermal plume, in addition to the moisture generated by this device that represents the human breath. Furthermore, this humidifier can be used to control the conditions required to investigate the hygrothermal behavior of the Trombe wall. As airflow condition is important for preserving the wall hygrothermal behavior, investigating accurately the natural convection becomes critical. PIV is considered a promising method due to its

capacity to represent the 2D velocity field. Nonetheless, given that to date, very few studies have utilized a solar simulator with PIV measurement, the prerequisites for such an experimental setup are not yet defined and several challenges may arise when applying it to a test bench consisting of a Trombe wall coupled to a room. One significant challenge is the scattering effect caused by tracer particles from the solar simulator, which can create background noise resulting in difficulties in distinguishing tracer particles from the background or optical distortions in the PIV images, such as changes in the apparent size and location of tracer particles leading to inaccurate velocity measurements. To overcome those problems, Cristiana V. Croitoru et al [85] opted to conduct two separate experiments to evaluate the thermal performance of a solar collector equipped with perforations. A standalone PIV measurement was carried out to investigate the flow characteristics of various cladding perforation shapes. The second experiment was conducted using a solar simulator along with a thermal anemometer to compare the heat transfer between two different designs. An alternative solution consists of employing a new processing technique to remove the background noise from the acquired images such as that used in [48]. However, it is important to highlight that the level of background noise on the PIV images depends on the solar simulator type and power. Adding specific 532 nm band filters to the camera helps reduce these effects. However, it may not always be sufficient. For example, Mirzaei et al [64] found that, even with the use of a 532 nm filter, the solar simulator still negatively impacted the velocity measurements. However, they chose to neglect this effect since the overall deviations of all velocities did not exceed 18%.

5.2.2 Climatic chamber adapted to assess the hygrothermal behavior of Trombe wall

Combining the experimental procedures of Jerzy Szyszka [21] and Van Belleghem [84] could result in a new and reliable method for investigating the dynamic hygrothermal behavior of Trombe walls. The proposed setup involves constructing a climatic chamber that simulates both indoor and outdoor environments, with a Trombe wall exposed between them. The control of ambient conditions can be achieved using the air handling unit proposed in Van Belleghem's study [84], which utilizes a recirculation fan to extract humid air, cool it to induce condensation, and then reheat and humidify it to the desired conditions. This ensures accurate control of ambient temperature and relative humidity. The key difference between the proposed method and Van Belleghem's procedure lies in the positioning of the air handling unit's inlet and outlet. Directly connecting it to the internal chamber could disrupt fluid flow patterns and interfere with velocity measurement techniques, such as PIV or tracer gas methods. Therefore, the air handling unit would be connected to the external chamber simulating ambient conditions. Solar radiation can be mimicked by applying a heating mat to the external wall surface. Multiple thermo-hygrometric sensors would be installed for accurate monitoring. Additionally, to simulate the human presence and behavior, thermal manikins or humidifiers, as previously discussed, would be necessary. All the velocity measurement techniques presented in this review can be applied to this setup to analyze the flow field. However, PIV remains the most accurate technique enabling a precise analysis of the flow regime and convective heat transfer mechanism. It is crucial, though, to follow the specific experimental procedure discussed in this review based on the zone being investigated.

5.2.3 Combining a solar simulator with an air handling unit equipped with a humidifier

Integrating a solar simulator into a climatic chamber equipped with an HVAC system allows for precise control of outdoor temperature, solar radiation, and radiation temperature, making this setup ideal for simulating the daily performance of a Trombe wall. To date, there is no defined protocol for integrating a solar simulator into a climatic chamber equipped with the type of air handling unit (AHU) proposed by Van Belleghem [84], in Trombe wall systems,

and several aspects must be considered for a flexible experimental approach. First, it's important to design the outside chamber in a way that allows flexibility in adjusting the distance between the solar simulator and the Trombe wall to ensure uniform radiation distribution across the wall surface. Generally, the outside chamber's side walls should have minimal radiation reflection. However, to achieve this in a flexible manner, low-reflective coatings or baffles may be utilized to absorb reflected radiation. Furthermore, the primary challenges in such a setup lie in controlling ambient temperature, radiation temperature from the solar simulator, and relative humidity levels due to the interaction between this AHU system and the heat emitted from the solar simulator. This interaction has the potential to disrupt the normal operation of both systems, as well as complicating the overall control of environmental conditions in the chamber. Therefore, the AHU system must be carefully designed and strategically positioned to account for the solar simulator's effects, and further control of its operation mode is needed. The previously discussed considerations regarding the application of PIV with the solar simulator also need to be addressed.

Addressing all these issues enables the feasibility of this setup, providing a reliable method for studying the dynamic hygrothermal behavior of Trombe walls.

6. Conclusion

Despite the Trombe wall being a subject of study over many years, there has been significant variability and dissimilarity in terms of experimental setups and research objectives. For this purpose, this paper was systematically designed to classify and review the existing literature covering various aspects related to the hygrothermal behavior of Trombe walls. It addresses the main challenges and proposes possible solutions for designing a reliable experimental protocol to investigate the dynamic hygrothermal behavior of such a system. Additionally, this review highlights current trends in experimental studies of Trombe walls by examining recent research papers from thermal, velocity, and hygrothermal perspectives.

The main conclusions derived from this review are as follows:

- The experimental studies of the Trombe wall system can be categorized based on the scale of the model or the experimental environment (laboratory or real-world experiment). Each category has its advantages and limitations. This review highlights the characteristics of each category and the appropriate experimental procedures for investigating the thermal performance of Trombe wall systems.
- Since heat transfer and fluid flow are interrelated in Trombe wall systems, this review presents various velocity measurement techniques applied to building façades, with a particular focus on the potential use of PIV to investigate several aspects related to Trombe wall systems. It was found that this method is promising and effective for conducting laboratory-scale experiments related to these systems. It enables the precise visualization and identification of critical physical phenomena such as flow direction (including reverse flow) and convective heat transfer mechanism, that may occur naturally in these systems due to their interaction with the surrounding environment. However, to date, there is still a significant research gap in the PIV application to a test bench consisting of a Trombe wall coupled to a room. Several challenges such as the effect of solar radiation on the velocity measurement, seeding procedure, and preservation of boundary conditions that may occur are discussed in addition to their possible solutions.
- This review classifies the hygrothermal analysis of building facades into in situ analysis and laboratory scale experiments highlighting the instrumentation used in each. It is found that

ventilation is necessary for maintaining the facade hygrothermal behavior. Additionally, thermo-hygrometric sensors placed within the wall are essential for monitoring heat and moisture transfer. For laboratory-scale experiments, two setups using either a stand-alone humidifier or an air-handling unit equipped with a humidifier are commonly employed. While it is common to use this type of AHU unit to control the conditions necessary to analyze the hygrothermal behavior of a wall assembly at a large-scale laboratory experiment, however, there is still a significant research gap in its application to Trombe walls coupled with rooms, and careful selection of this system is required.

- This paper ends by suggesting an experimental procedure that extends existing protocols for analyzing Trombe wall thermal behavior to include its hygrothermal performance. However, these protocols need to be further tested and evaluated to ensure their applicability to Trombe wall systems.

7. References

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