Analysis of the energy performance of a new ventilated brick wall: behaviour of real scale prototype under different ventilation configuration and weather conditions

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Abstract
The thermal behaviour of a high thermal inertia ventilated wall made of local bricks in Central Italy is investigated. According to laboratory results, a real scale ventilated façade 8.5 m high was built as a perimeter wall of a gym. The behaviour of the southern façade was monitored continuously for 26 months in different seasons, alternating different openings configurations. Non-ventilated, partially ventilated, and ventilated configuration were compared; the wall height influence on the temperatures within the ventilation gap, their phase displacement, and air velocity fields were investigated. Experimental results were used to implement and validate a 2D CFD transient model.

Key Innovations
- In-situ behaviour of a real scale prototype monitored continuously in winter and summer period for over a year
- Effect of number and position of the openings on the wall performance
- Correct assessment of the thermal transmittance of the ventilate façade given the inappropriateness of the available standards.
- Implementation and validation of a new 2D CFD model under dynamic conditions with experimental results.
- Use of traditional and local materials to guarantee thermal comfort maintaining the constructive tradition.

Practical Implications
Validation of the CFD model at real scale will allow to predict the behaviour of the wall under different climate conditions. The benefit of ventilation and the optimal openings configuration can be established at the design stage, allowing the construction of customized solutions and avoiding low energy performance during operation.

Introduction
GHG emissions reduction and energy saving are two of the main targets of international policy. In Europe the building sector is in charge of 40% of the energy consumption and the contribution of Italy amounts to 40% (IEA, 2012; EEA, 2020). Buildings contribute in a different way to the total energy consumptions and emissions, but a significant discrimination is given by their period of construction: the greatest responsibility lies with those built before adopting a common energy saving policy (about 75%) (EEA, 2012).

The most common way to improve the performance of buildings and encourage the recovery of existing ones is to act on the envelope. “Thermal coat” (Alonso et al., 2016; Gagliano et al., 2017; Kolaitis et al., 2013) shows an excellent behaviour during the heating period, whereas during the cooling season it contributes to the thermal loads increase and, if not properly designed, can cause wall transpiration problems, deterioration of the materials and reduction of its operating life (ENEA, 2015).

Ventilated façades are an alternative solution to the “thermal coat”, able to increase the winter thermal resistance and to provide a reduction of the summer heat load, due to the combined effect of the shading of the outside wall and of the air flow into the ventilation gap caused by natural convection. Their efficient design reduces thermal fluxes across the wall, as well as the overheating effect due to solar radiation (Arce et al. 2009). The heat transfer inside the ventilated cavity is due to the radiative heat exchange between the two walls of the channel, the convection heat exchange between cavity surfaces and the circulating air flow and the conduction through the walls (Figure 1).

Figure 1: Heat transfer mechanism of the ventilated brick wall.
The improvement of cooling potential could be achieved by integrating wall cavities with spray evaporative cooling systems or incorporating micro-encapsulated phase change materials (mPCM) in ventilated slabs (Alaidroos and Krarti, 2016; Faheem et al., 2016). Another way of ventilation regards hollow block ventilated walls (Yu et al., 2017; Yu et al., 2015; Xiong et al., 2015).

The performance of ventilated envelopes during the whole year are mainly devoted to envelope equipped with “active” systems for airflow control and/or energy recovery (Astorqui et al., 2017; Diallo et al., 2017), like Ventilated Active Thermoelectric Envelope (VATE) module (Zuazu-Rosa et al., 2018). Saadon et al. (2020) evaluated the integration of a semi-transparent PV system with natural ventilation (BISTPV/T), providing that the air flow that in summer cools the PV module.

For non-equipped walls, the influence of the outer skin in terms of climate-responsive materials (Patania et al., 2010; Stazi et al., 2018) as well as the distribution and dimensions of the openings (Buratti et al., 2018) is a remarkably important design issue. The optimization of bio-based or recycled materials from construction and demolition waste for the fabrication of ventilated façades adds enviro-economic benefits to thermal ones (Pujadas-Gispert et al., 2020; Bagaric et al., 2020).

The aim of the present work is to validate CFD models for predicting the behaviour of ventilated walls. CFD simulation codes are widely used to implement and to develop both traditional and innovative ventilated walls (Buratti et al., 2017; Gagliano et al., 2016). Diarce et al. (2014) used Fluent CFD code in order to predict the thermal behaviour of a ventilated wall with PCM materials. Based on experimental data obtained from a real-scale test facility, a 2D model in transient conditions was validated, testing three different turbulent models (RNG k–ε, standard k–ω, and SST k–ω) and two radiation models (S2S and DO). Under complete turbulent model, CFD results were in very good agreement with the experimental data. A 2D CFD model in steady state was used by Santa Cruz and Porras (2017) in order to study a ventilated façade with double chamber, showing an increasing in efficiency by 38% and 333% in summer and winter respectively, when compared to a standard ventilated façade system with closed joints. By means of an experimental validated model, Liu et al. (2017) determined an energy saving of about 90% both in summer and winter for a façade ventilated by exhaust air.

In all the aforementioned papers, experimental and numerical analyses are related to openings for the ventilation as wide as the wall, with all the width completely opened.

The present work aims at extending at real scale the study on a ventilated brick wall developed in collaboration with an Umbrian brick producer (F.B.M.), as a solution able to preserve the constructive tradition of the Central Italy, thanks to the use of local materials. A preliminary scaled prototype was built at the laboratory of the Department of Engineering at University of Perugia in 2014 and experimental data, collected during the investigation of its thermal behaviour in controlled conditions, were useful for the validation of the mathematical equations to be solved in the CFD model. As reported in a previous paper (Buratti et al., 2018), a 3D CFD model was developed in order to design and optimize the openings’ size and to evaluate the opening area per unit width of the wall. According to these results, a prototype of the ventilated façade 8.5 m height was built in a new building, placing openings, 250x25 mm²/m of horizontal length, at the bottom and at the top of the wall. It is equipped with a system able to monitor air and surface temperatures, air velocity, and heat flux continuously in several winter and summer periods. The possibility of opening and closing the ventilation holes gave the possibility to compare non-ventilated, partially ventilated, and ventilated configurations. Experimental results at real scale enable to implement and validate a 2D CFD model in FLUENT that will allow to predict the behaviour of the wall in different periods of the year and climate conditions, in order to establish the real benefit of the ventilation. In future works, thanks to the validated models, results related to conventional and innovative brick ventilated wall will be compared in terms of energy demand both in different cities and climate conditions.
Materials and methods

Real scale ventilated wall prototype

In agreement with results obtained with the 3D CFD model validated at laboratory scale, a real prototype of the ventilated façade was built at the end of 2015 as a perimeter wall of a new gym in Central Italy (Foligno), with the aim of monitoring continuously its thermal behaviour and to gather experimental data for the validation of the mathematical equations to be solved in the new CFD model.

The building encloses a single space of 450 m². The roof is made with a load-bearing structure in laminated wood beams on which the slab in sandwich panels with mineral wool and aluminum sheet covering rests, separated from each other by an air gap of 100 mm. The supporting structure in elevation is made of a continuous perimeter wall in reinforced concrete insulated inside and outside with EPS panels, along which open four large glass surfaces of about 17 m² each, two on the North oriented façade and two on the South Oriented, and one of about 8 m² (entrance) on the eastern façade.

All the perimeter walls of the building are ventilated; the ventilation cavity is made of an anchoring system with uprights and transoms of the facing bricks as load-bearing structure. In addition, the steel substructure acts as a connection between the septum and the external masonry face, allowing to improve overall resistance against horizontal actions due to wind and earthquake. The 90 mm cavity thickness corresponds to the height of the “C” profile of the uprights, placed at a distance of 1 m. The counter wall was built with clay bricks (length = 250 mm, thickness = 120 mm, height = 55 mm) produced by the company FBM - Fornaci Briziarelli Marsciano, linked together with continuous horizontal and vertical joints of cement mortar. Openings, 250x25 mm² of horizontal length at the bottom and at the top of the wall were made by replacing standard bricks with similar bricks of reduced height (length = 250 mm, thickness = 120 cm, height = 25 mm), in order to simplify the management of the module and to remove less bricks as possible (Buratti et al., 2018).

The gym and the construction features of the ventilated wall are shown in Figure 2.

<table>
<thead>
<tr>
<th>Layer</th>
<th>s [m]</th>
<th>ρ [Kg/m³]</th>
<th>λ [W/mK]</th>
<th>γ [W/m²K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster</td>
<td>0.02</td>
<td>1800</td>
<td>0.90</td>
<td>1000</td>
</tr>
<tr>
<td>EPS</td>
<td>0.10</td>
<td>20</td>
<td>0.04</td>
<td>1200</td>
</tr>
<tr>
<td>Reinforc. concrete</td>
<td>0.25</td>
<td>2300</td>
<td>2.30</td>
<td>1000</td>
</tr>
<tr>
<td>EPS</td>
<td>0.10</td>
<td>20</td>
<td>0.04</td>
<td>1200</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.09</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Brick</td>
<td>0.12</td>
<td>1700</td>
<td>0.78</td>
<td>940</td>
</tr>
</tbody>
</table>

Table 1: Dimensions and thermophysics characteristics of the ventilated façade.

The theoretical thermal transmittance of the unventilated and ventilated wall was estimated in compliance with ISO 6946 starting from the thermos-physical properties of the materials provided by the Company. 0.162 and 0.168 W/m²K were found for unventilated and ventilated wall (Buratti et al., 2018).

The southern façade is equipped to monitor air and surface temperature, air velocity, heat flux. The measurement equipment into the air gap was predisposed during the building construction. 14 probes, 10 of which for the surface temperature on the EPS and bricks layers facing the cavity and 4 for the air temperature, were positioned at a height of 1.50 m from each other between 1.55 m and 7.50 m inside the cavity (Figure 3). A BSV 105 hot wire anemometric probe for air velocity was placed in the center of the cavity at half height of the wall. The surface temperatures of the internal layer and the heat fluxes were monitored in two symmetrical points with respect to the center of the wall by means of 2 resistance temperature detectors (PT100) at 4.25m and of 2 heat flux probes at 5.25m, respectively. Air temperature inside the gym and outside was monitored by means of Tiny Tag (5 indoor and 1 outdoor). The characteristics of the measurement equipment are described in Table 2.

Figure 2: Real scale prototype.

Figure 3: Ventilated wall. Particular of the stratigraphy and probes positioning.
Table 2: Characteristics of the measurement equipment used for the in field experimental campaign.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Measuring range (°C)</th>
<th>Measuring range (%)</th>
<th>Accuracy (°C)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiny tag Ultra 2 TGU-4500</td>
<td>T: −25 – +85; UR: 0 – 95%</td>
<td>T: ±0.4; UR: ±3.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tiny tag Plus 2 TGP-4500</td>
<td>T: −25 – +85; UR: 0 – 100%</td>
<td>T: ±0.4; UR: ±3.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat flux probes</td>
<td>−20000 → +2000 W/m²</td>
<td>±5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance temperature detectors – PT100</td>
<td>−50 – +200 °C</td>
<td>±0.05%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot wire anemometer 1</td>
<td>0.01 - 20 m/s</td>
<td>0.5 – 1.5 m/s; ±0.2 m/s</td>
<td>&gt; 1.5 m/s: ±0.3 m/s</td>
<td></td>
</tr>
<tr>
<td>Hot wire anemometer 2</td>
<td>0 - 5 m/s</td>
<td>v ≤1 m/s; ±0.2 m/s</td>
<td>v &gt; 1 m/s: ±0.3 m/s</td>
<td></td>
</tr>
</tbody>
</table>

The experimental campaigns were carried out with different ventilation holes configurations:
1. un-ventilated wall (configuration 1): all the ventilation holes are closed, therefore the air gap is not ventilated;
2. half-ventilated wall (configuration 2): only half of the ventilation holes are open (only left side of the façade);
3. ventilated wall (configuration 3): all the ventilation holes are open.

Half-ventilated and ventilated wall configurations are investigated in order to compare the behaviour under the same weather conditions.

The monitoring campaign discussed in this paper started in January 2017 and was stopped in March 2019.

CFD 2D model

Data collected during the experimental campaigns were used to implement and validate a 2D CFD model. The ANSYS Fluent Software (ANSYS Fluent User’s Guide) was used for assessing the dynamic thermal behaviour and the energy performance for ventilated configuration in both winter and summer conditions. Aiming to simulate a full-scale model, was first implemented in 2-dimensions a wall 4.25m high, relying on the symmetry of the façade. A 2D model was chosen instead of 3D one, able to take into account the real influence of the opening size on the ventilation of the air gap, since its advantage of allowing a better discretization of the domain with a reduced size mesh (hence minimizing the simulation error). The following CFD parameters were set in the model implementation:
- Energy model: for the heat exchange simulation;
- Turbulent model k–ε standard;
- Radiation P1 model, by setting the emissivity value of different materials in the 0.8 - 0.9 range;
- Solar load or Fictitious Temperature;
- Boussinesq approximation for the simulation of the air.

Considering the temperatures gathered during the in field experimental campaign, the validation of the model was performed in transient conditions; the implementation in the simulation of the hourly variation of the weather conditions requires to develop specific User Defined Functions (UDF). The outputs were monitored on control points corresponding to some thermocouples positions in the field: T2-m and T5-m on the brick, T1-i and T4-i on the EPS, and T3-a and T6-a in air (Figure 3).

Results

In field experimental campaign

Non-ventilated, partially-ventilated and ventilated wall in winter case inside the cavity have surface temperatures and air temperature curves overlapping (Figure 4). For partially-ventilated configuration cavity temperatures never reach the external lower peaks, departing from them of about 3°C, allowing heat losses reduction during the heating hours. Ventilation configurations affect air temperature profiles in the cavity, with an almost linear trend as the height increases, according to stack-effect.

For the ventilated configuration in the coldest hours, the temperature is higher in the upper part of the wall, in the warmest at 3.55m and 6.5m. At the bottom (2.55 m) the lowest temperatures are generally recorded.

The phase displacement between exterior and interior in ventilated conditions can be seen from Figure 5: while the maximum temperature outside is at 12.00, inside the maximum is reached after 3 hours. The deviation of the air temperature inside the cavity from the surface ones of about 5°C allows to reduce the heating demand. Not reliable data of thermal flux are available in winter campaign.
In the summer period (Figure 5), the internal surface temperature fluctuations (31.5°C-23.5°C) are much more contained than those detected both in the cavity and for the external air (44.5°C-13°C). In August, considered as a typical summer month (Figure 6), the temperature inside the cavity oscillates in the 17.5 - 43 °C and the temperature of the brick is more influenced by external conditions. Maximum and minimum peaks are observed, whereas the temperatures on the insulation and in the air cavity are equivalent. It means that the air flow in the cavity has a good effect on the inner layer by reducing its temperature. The thermal peaks of the indoor air, especially the minimums, are mitigated and staggered with respect to the external ones. Moreover, even when the day is not sunny, the internal, surface and air temperatures maintain a trend in line with the other days. In Figure 5 three significant days are highlighted: one with maximum outdoor air temperature and radiation (typical summer day) (03/08/2017), one with maximum outdoor air temperature and minimum radiation (cloudy day) (12/08/2017), and one with minimum outdoor air temperature and maximum radiation (07/08/2017). In the first case (Figure 7), despite the significant difference between the external and internal temperature peaks, (42°C and 32.5°C respectively), the phase shift is about 1.5 hours. Inside the cavity the daytime and night time shifts are about 5 and 3.5 hours, showing a trend similar to the one of the outside air, with peak values higher by about 3°C, due to the significant contribution of solar radiation. For this reason, between the interior cavity and the internal surface, there is a temperature gap of about 8°C. The temperatures in the cavity settle on higher values even during the night period, with a gap of 7.5°C. The internal surface temperature always remains below the internal air, with a greater difference between 8:00 and 15:00. In the situation with maximum external air temperature and minimum radiation (Figure 8), the daytime shifts are the same as in the first case, with lower oscillations in the cavity temperatures (32-18 C). Night temperatures are even lower than indoor temperatures due to the absence of solar radiation.

The heat flux has a variable trend throughout the period, with maximum values of incoming and outgoing flow, during day and night hours, of about 15 and 5 W/m² respectively (Figure 9). The trend recorded by the heat flux probe 2 in July shows very small fluctuations (Figure 10, Figure 11), because it is placed on the left side of the façade (looking from the outside), where during this month the openings were closed.

Figure 6: Profiles of average temperature in the ventilated cavity, internal surface temperature and indoor and outdoor air temperatures in July.

Figure 7: Temperature profiles with maximum outdoor air temperature and maximum solar radiation.

Figure 8: Temperature profiles with maximum outdoor air temperature and minimum solar radiation.

Figure 9: Heat fluxes trend during the month of July (partially ventilated configuration).
2D CFD model implementation and validation

First of all, a numerical validation in steady state was carried out, in order to verify the geometric model, the mathematical models of the heat exchange through the building envelope, as well as the attribution of the boundary conditions valid for both the winter and summer models. The values of the outside air were obtained from the UNI/TR 10349 standard (monthly average value for the city of Foligno in the months of January and July, equal to 9 °C and 34 °C respectively), whereas for the indoor a standard temperature value of 20 and 26°C were set for winter and summer respectively.

In order to carry out a CFD simulation in dynamic regime, it was necessary to write profiles that would allow to set a variation of a specific physical quantity as a boundary condition. The geometric model developed for the winter case consisted only of the stratigraphy of the ventilated wall, starting from the internal plaster layer, up to the solid bricks of the counter wall. The external and internal air temperature values with the corresponding convective coefficients K = 25 and K = 7.7 were attributed to the extreme layers. As a boundary condition in the inlet section of the fluid domain, a speed of 0.29 m/s was set, equal to the average value measured near the opening during the 2017 winter campaign, whereas in correspondence with the air outlet, a pressure of 980 hPa was assumed, as detected in measurement campaigns carried out in years prior to those treated in this paper.

Calculations revealed that the regime condition is reached within the first hours of simulation; for this reason it was decided to streamline the calculation times by carrying out the simulation over 24 hours, identifying February 20th 2017 as a representative day of winter weather conditions. On the basis of the data collected on that day, the temperature profiles of the external and internal air used as inputs of the CFD model were wrote. The two-dimensional computational domain employed for summer period validation includes a portion of the indoor and the outdoor environment adjacent to the wall, 4.25m high and 0.25m thick. It allowed to have two surfaces that identified the air in the wall proximity to which attribute the temperature profiles of the external and internal air, whereas a fictitious temperature profile was associated with the external brick surface. Unlike the winter situation, in the summer case the solar radiation is not negligible. In order to reduce the computational time required for the CFD simulation, the effect of the solar radiation to the external surface was calculated by using the fictitious temperature method (air-sun temperature) (Buratti et al., 2018).

These simulations highlighted the necessity of carrying them out for several days, in order to stabilize the thermal response. They were therefore carried out for 72 hours, identifying as significant days for the writing of the profiles those from 20 to 22 July, and taking into account that 21 July is the theoretical day of maximum solar radiation. In both cases the radiation model P1 used initially was deactivated, obtaining more reliable results. From the winter simulations (Figure 12), in accordance with the experimental results, the fluctuation of temperatures in the cavity (of about 20°C) is more contained than that of the outside air; in particular the negative peaks are not reached. The differences with the measured data are attributable to the set speed value. It has been noted that velocity affects the phase shift: Figure 13 highlights that for v = 0.013, the lowest velocity measured in the reference day, the phase shift is strongly reduced.

![Figure 10: Heat fluxes trend during a typical day of July.](image1)

![Figure 11: Heat fluxes variations with temperature.](image2)

![Figure 12: Winter results (simulated), v=0.29m/s.](image3)
Due to its both winter and summer efficiency, ventilated wall represents an innovative solution to the "thermal coat”. Its behaviour involves benefits, especially in southern Europe regions where the highest levels of solar radiation are encountered. Measurement campaigns over more than 2 years, allowed to evaluate the behavior of a ventilated brick wall 8.5 m high and facing south for different seasons and weather conditions. Non-ventilated, partially-ventilated and ventilated configurations in winter showed surface temperatures and air temperature curves overlapping. When partially ventilated, cavity temperatures never reach the external peaks, allowing heat losses reduction during the heating hours. Ventilation configuration affects air temperature profiles in the cavity, with an almost linear trend as the height increases, according to stack-effect. During the daytime the counter-wall maintain low surface temperatures on the inner wall of the cavity: up to 4.5°C lower than the external. Summer difference between average flow values for ventilated and partially-ventilated wall is 8 W/m². The behaviour of the naturally ventilated façade is an improvement in terms of passive cooling of the building compared to the non-ventilated façade, since it allows the peak load to be shifted.

Implementation and validation of a 2D CFD model with experimental results at real scale allow to predict the behaviour of the wall in different periods of the year and in different climate conditions, in order to establish the real benefit of the ventilation. After a settling period of a few days, the simulated trends are consistent with the measured data. Elaborations and results of the present work will be used for implementing a new 3D CFD model at real scale, in order to consider the depth of the openings and their real influence on the ventilation of an air gap highly developed in height. The further validation of the 3D model will also allow to estimate the correct value of the ventilated wall thermal resistance, useful in dynamic simulation of buildings with tools such as TRNSYS, Energy+, IDA-ICE and so on.

**References**


