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Experimental analysis on a solar air heating façade system

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ABSTRACT
In this study, investigations on the thermal performance of a solar air heating façade system were carried out. The system consists of a double skin building envelope composed by an opaque internal face, with a novel solar absorbent layer and a glazed external face. This kind of system, particularly suitable to refurbish existing building envelopes, is designed to work as a fan-assisted air supply, which mitigates the heating and ventilation demand during the winter period.
An experimental campaign was set up using a full scale façade module in order to thoroughly characterize its thermal behavior and the air flow rate. This module was also compared with a similar one, having a conventional dark flat surface instead of the above mentioned solar absorbent layer. The system has proven great potential in both reducing the energy demand and maintaining proper the ventilation rates in the winter period. In facts, results show that the cavity air temperature reaches values close to 90°C (unventilated buffer mode) and that, in fan-assisted mode, the air temperature introduced in the indoor environment was up to 25°C higher than the external one. Moreover, the supplied air flow rate was of about 26 m^3/h, providing about 0.5 air changes per hour (ACH) in a typical residential room (16 - 22 m^2 of floor area).

KEYWORDS Solar air heating; Opaque Double Skin Façade; Fan-assisted; Solar collector; Supply air façade

INTRODUCTION
Providing feasible solutions to take action against building energy consumption while promoting on-site energy generation through renewable resources is of paramount importance nowadays. Particular effort needs to be put into the energy refurbishment of the existing building stock, since it is largely composed by old, energy-demanding constructions, characterized by high total energy demands, not evenly distributed over time.
According to the Building Performance Institute Europe (BPIE), a deep renovation of the existing buildings could cut the 36% of their energy consumption by 2030 (Building Performance Institute Europe, 2018). Solar air heating façade systems can provide an effective solution: not only they guarantee an improvement in terms of thermal insulation, but they also mitigate buildings heating and ventilation demand by exploiting solar energy. The analysed façade system presents similar technological features of a classic Trombe Wall (Trombe and Michel, 1974), which consists of an external transparent layer and an internal opaque one, separated by an air gap. Usually, the classic Trombe Wall presents two vents installed at the bottom and at the top of the opaque layer. In this way, indoor air flows through the bottom air gap, it heats up due to the greenhouse effect and enters back into the internal environmental through the top vent (Özbalta and Kartal, 2010).
Several studies have investigated different ventilation modes of the Trombe Wall. Considering a total of four vents, placed at the top and at the bottom of both the transparent (external) layer and the opaque (internal) layer, there are four main ventilation modes

(Tiantian, et al. 2014): not ventilated wall (Buffer mode); thermal insulation mode; natural ventilation mode (summer cross ventilation); space heating mode.

When the façade component is needed to function mainly as an insulation layer, the buffer or the thermal insulation mode are usually employed. The first mode is applied during the heating season, with all the vents closed, while the second one is used during the cooling season, with both the outer vents opened. It was demonstrated that by using these strategies the façade element was able to significantly reduce the thermal transmittance of the wall (in winter) and to improve solar heat removal (in summer) (Callegari, et al. 2015).

In the natural ventilation mode, the vents at the bottom of the opaque layer and at the top of the transparent part are opened. This ventilation mode results the most efficient during the cooling season (Krüger, et al. 2013; Gan, 1998).

The space heating mode is employed during the heating season in order to supply pre-heated air into the internal environment. In this ventilation mode the vent at the bottom of the transparent layer and at the top of the opaque layer are opened, and it was defined as the best mode during the heating season (Bajc, et al. 2015; Briga-Sá, et al. 2017).

This last ventilation mode is more efficient when the external layer of the opaque component is able to maximise the solar radiation-to-heat conversion, as a solar receiver (López-Herraiz, et al. 2017), and it was proved that the application of a high absorption coating on the exterior surface of the massive wall can improve the absorption and storage capacity of the Trombe Wall (Nwachukwu and Wilfred, 2008; Özbalta and Kartal, 2010). Usually, high absorption coefficient values correspond to dark colours. This might lead to have a limited choice of materials and coloured coatings to be used, slowing down the spread of this technology mainly for aesthetic reasons.

In the present study, the fan-assisted solar air heating façade operates in space heating mode. The analysed façade is provided of an outdoor vent, placed at the bottom of the external layer, which enables external air to flow through the entire height of the air cavity. This flow is generated by an axial fan placed at the top part of the opaque layer, connecting the air cavity with the indoor environment. In this way, a controlled rate of air can be introduced in the indoor environment. Moreover, while dark coloured surfaces are used in Trombe walls to enhance the greenhouse effect happening in the air cavity, a novel lightweight and light coloured layer was here used.

METHODS

During a previous experimental campaign carried out on a façade system called Naturwall© (Callegari, et al. 2015), two types of façade component were installed on the south side of the test apparatus, an outdoor test cell called TWINS (Testing Window INnovative System), in order to evaluate the behaviour of a solar air heating component.

Both components are characterized by a first external transparent layer (6 mm), an air gap and an inner opaque component. The opaque component consists of (from the inside to the outside) an OSB (Oriented Strand Board) layer (1.8 cm), a honeycomb cardboard insulation layer (8 cm) and another OSB panel (1.25 cm).

Module D (Figure 2) is 0.82 m high and 0.82 m wide and it is characterized by having the external OSB layer painted in black, a non-ventilated air gap and a clear glass as the external transparent layer. The original Module A (Figure 3), 3.07 m high and 0.82 m wide was modified by the Authors adding an additional 1.5 cm cellular polycarbonate layer with a particular geometry against the OSB panel face toward the air gap and installing an axial fan at the top of the opaque component in order to guarantee about 26 m^3/h of air flow rate. Moreover, as external transparent layer a compact polycarbonate panel was chosen.

The main measured entities were the incident solar radiation, the temperatures (both air and surface ones) and the heat fluxes (between the cavity and the internal environment).

Measurements were performed through pyranometers, type T thermocouples and heat flux meter sensors (Figure 2, Figure 3) recorded every 15 minutes through a Datataker.
A first set of measurement was aimed at evaluating the effects of the cellular polycarbonate so to assess in the other analyses its influence on the global performance. A comparison between Module A and Module D was thus carried out, making the two modules operating in the same conditions: Module A fan was turned off and the vent was air-tight closed.

Figure 1 – Module A and module D installed on the outdoor test cell (TWINS)

Figure 2- Scheme of the functional layers and the sensors used in Module D

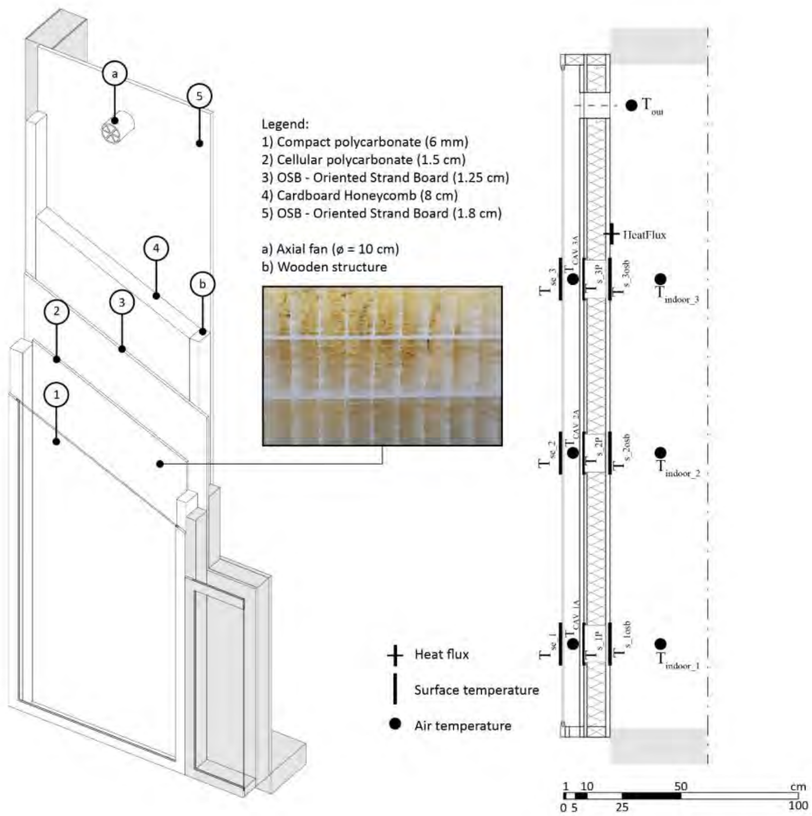


Figure 3 - Scheme of the functional layers and the sensors used in Module A.

In order to provide a quantitative indicator to assess the capability of the ventilated module to mitigate the heating and ventilation loads, solar efficiency (η_{sol}) was defined considering the heat supplied into internal environmental (Q_{supply}) and the incident solar radiation measured on the vertical plane (Q_{sol}) according to Equation 1:

$$n_{sol} = \frac{\sum_{n}^{m} Q_{supply}}{\sum_{n}^{m} Q_{sol}} \cdot 100 = \frac{\sum_{n}^{m} \dot{V} \cdot C_p \cdot \rho \cdot (T_{out} - T_{ext})}{\sum_{n}^{m} I_{sol} \cdot A} \qquad (1)$$

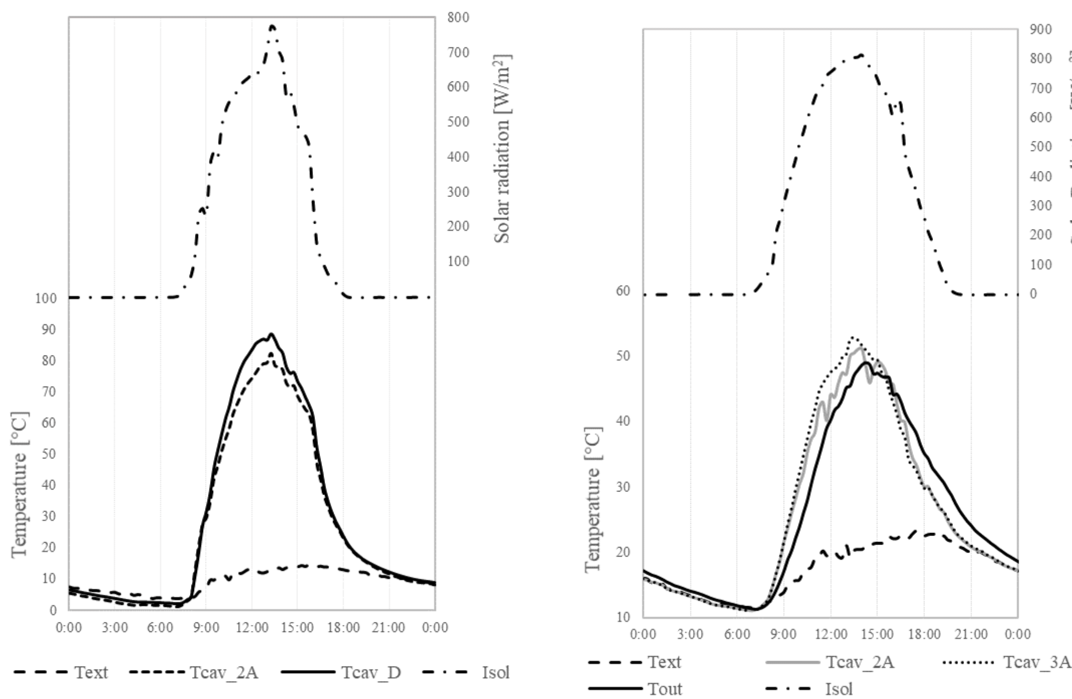
where n and m are respectively the beginning and the ending time of the examined day; $\dot{V}$ is the air flow rate (m^3/s); C_p is the air specific heat (J/kgK); ρ is the air density (kg/m^3); T_{out} and T_{ext} are respectively the supply and the external air temperatures (K); I_{sol} is the incident solar radiation (W/m^2) and A is the surface area (m^2).

RESULTS AND DISCUSSIONS

Figure 4a shows a sunny winter day characterized by high solar radiation, which reaches values of 800 W/m^2. It is possible to notice that, during the hours of maximum solar radiation, external air temperature ranges between 10°C and 14°C, while the air temperatures in the two cavities are of 83°C and of 89°C respectively for Module A (T_{cav_2A}) and Module D (T_{cav_D}).

Figure 4b shows experimental data from Module A when ventilated by the above described axial fan. Solar radiation was stable throughout the day, with peak values of 800W/m^2 and external air temperature of about 20-23°C between 12:00 and 18:00. At around 14:00 it is

possible to notice that the air cavity temperature at middle height (T_{cav_2A}) is of about 51°C, at the highest measurement point (T_{cav_3A}) is 53°C and enters the indoor environment (T_{out}) at 49°C[1]. In these conditions, the solar efficiency for the analysed day (April 8th) is of about 20%.
Results shown in Figure 4 show that the cellular polycarbonate layer, although being characterized by a much lower absorption coefficient (α), is able to heat up the cavity air roughly as much as the black-painted surface. This is due to its particular geometry, which provides more exposed surface to the solar radiation.



(a) (b)

Figure 4 – (a) Experimental data measured of the cavities air temperatures. (b) Module A: experimental data measured of the cavity air temperatures at the different heights and of the outlet temperatures.

When working as a solar air heating façade module (ventilation turned on), it was observed that a significant increase in temperature between the intake and the supply air occurred. Figure 4b shows an increase of about 25°C between external air temperature and the outlet one, meaning that the system was providing 26 m^3/h of air useful for both ventilation and heating purposes. Moreover, the solar efficiency (of about 20%) is in line with that of existing air heating collectors (VijayaVenkataRamana, et al. 2012).

CONCLUSIONS
In this study the behaviour of an adaptive façade system was investigated through an experimental campaign. As a first step, a comparison between a novel solar absorption layer (the cellular polycarbonate) and a traditional dark surface (typical of Trombe walls) was carried out, demonstrating how both have almost identical effects on the air cavity

[1] It is worthy to mention that the thermocouple used to measure the outlet temperature is placed on the internal side of the opaque component, therefore a little drop in temperature occurs between the air cavity and the outlet temperature.

temperature. Then, assessment in terms of performance and efficiency of the façade system were performed trough additional experimental measurements of Module A working in space heating mode (ventilation turned on).

From the obtained results it is possible to state that more aesthetically pleasant solutions for solar air heating façades are possible. Indeed, the use of a lighter material colour with an adequate geometry has demonstrated to be comparable to a flat, black surface in terms of capability of heating the cavity. This outcome could enable similar solutions to arise, resulting in an easier integration of solar air heating façade systems in buildings.

When operating in space heating mode, the façade showed interesting capabilities in rising the air temperature, since a 25°C difference in temperature was observed between external and outlet air. Moreover, the system solar efficiency of about 20% is absolutely comparable with that of existing solar air heating technologies.

Given the great potential of the system to lower building energy need for heating and ventilation, further studies need to be carried out to assess the façade behaviour over a longer period (the entire heating season), also evaluating different technological solutions for both the transparent and the opaque components. Moreover, different control strategies can be explored to best modulate ventilation over time, with potentially great impact on the overall façade efficiency.

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