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The effect of airflow rate control on the performance of a fan-assisted solar air heating façade

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Abstract. Solar Air Heating Façades (SAHF) can exploit solar radiation to partially fulfil the building heating and ventilation demand. This study was developed starting from an experimental campaign on a full scale fan-assisted SAHF applied to an outdoor test cell (TWINS) located in Torino (Italy). The data gathered from the monitoring activity were used to validate a white box model, developed in EnergyPlus. An axial fan drives the airflow through the façade; therefore, the supplied air temperature can be controlled by changing the fan speed. For this purpose, a PID (Proportional Integrative Derivative) controller was developed. This study demonstrates that the application of different control strategies significantly affects the façade overall performance and behaviour. Results highlight that the system can reach an average seasonal solar efficiency of up to 30%. Furthermore, by operating the system in heating-mode only and controlling the supply air temperature at 25°C, the system operates for 30% of the heating season, while at 40°C the system can provide fresh pre-heated air with an higher exergy level for the 10% of the winter period. Fan-assisted SAHF represent a valuable retrofit strategy solution in all buildings that present space limitations for the installation of centralised ventilation systems, helping to address the nZEB target requirements.

1. Introduction

The new frontier of buildings energy efficiency, for both new constructions and energy retrofit of the existing ones, is represented by the nearly Zero Energy Buildings (nZEB). This target can be reached, to a large extent, by simultaneously adopting different strategies to minimise the energy needs and to cover them, in large part with renewable sources.

Since the performance of the building envelope (high insulation level, air tightness, and optimal thermal inertia) can only partially help to reach the nZEB target, a new tendency is to design multifunctional and adaptive building envelope components that can integrate different functionalities (even combined) such as: ventilation, shading, heat storageas well as exploitation of Renewable Energy Sources (RES).

Building-integrated passive solar façades represent a widely used technology in retrofit and energy saving actions, demonstrating their potential for the reduction of the heating load up to 40–50% [1]. These technologies usually combine the effects of the solar collector, the thermal storage wall, and the solar chimney. An example of passive solar façade is the Trombe Wall, which consists of an external glazed layer, an air gap and a massive inner wall that presents two vents at the top and the bottom [2]. The amount of the heat transferred from the cavity of the wall to the internal environment and the air flow rate are strongly related phenomena. The unvented Trombe wall is used as an insulation layer which reduces the thermal transmittance of the building envelope [3], but several studies state that the ventilation of the component can be an important control mechanism for the building heating [4], [5], [6], [7], [8] or cooling (compared to the unvented Trombe Wall) [9].

In this study, the winter performance of an opaque solar façade system embedding decentralised ventilation (fan-assisted solar air heating façade) was studied. The system consists in a Supply Air

Façade (SAF) which provides fresh pre-heated air to the indoor environment in the winter season, while it can improve the exploitation of passive cooling strategies in summer (night ventilation).

The system is composed by different functional elements, a glazed layer in the outer part, a massive wall component in the inner side and an air cavity in the middle activated by an axial-fan that supply a controlled air flow rate to the indoor environment.

The system behaviour was preliminary monitored during an experimental campaign in outdoor test cells in Torino (Italy). During the experimental activity, the axial fan provided a constant air flow rate of 26 m^3/h (0.5 1/h Air Changes per Hour in a typical residential room of ~19 m^2 of floor area). The experimental results were used to validate a white box model of the façade, developed in EnergyPlus that has been used to perform parametrical analyses to optimise the system design.

The aim of the study is to analyse the effect of different fan operating strategies, for this sake, the results of the always-on configuration was compared with a system operating in heating-mode (supplied air is warmer than 20°C) that was controlled with a PID control that operates between different heating stages (supplied air between 25 and 40°C).

2. Methodology

The measured experimental data, deeply described in a previous publication of the authors [10], were used to validate a numerical model. A set of simulations were carried out during the heating season to estimate the effect of different system configurations on the annual performance by varying both the transparent and opaque wall components. This assessment led to the identification of the best technological solutions for the two components.

Then, a second set of simulations, presented in this paper, were performed implementing different ventilation PID control strategies (supply temperature set-point from 25 to 45°C).

2.1. Numerical simulation

Building components implementing ventilated channels can be simulated by means of CFD models. However, several studies have demonstrated that, for annual simulations, the use of Building Energy Simulation (BES) software represent a good compromise between results accuracy and computational cost [11].

The examined element was modelled in DesignBuilder and simulated in EnergyPlus with a time step of 15 minutes.

The ventilated cavity was vertically divided into five thermal zones; two fictitious regions were modelled to simulate the air inlet and supply. Each zone was interconnected with the adjacent one by horizontal openings (holes) that allow the forced airflow to pass from one element to the above one, considering a perfect air mixing inside each zone (Figure 1).

Throughout the model calibration, the solar radiation, the air flow rate, and the external and internal temperatures measured values were set as input data, while the external surface and the supply air temperatures were compared to validate the simulation model.

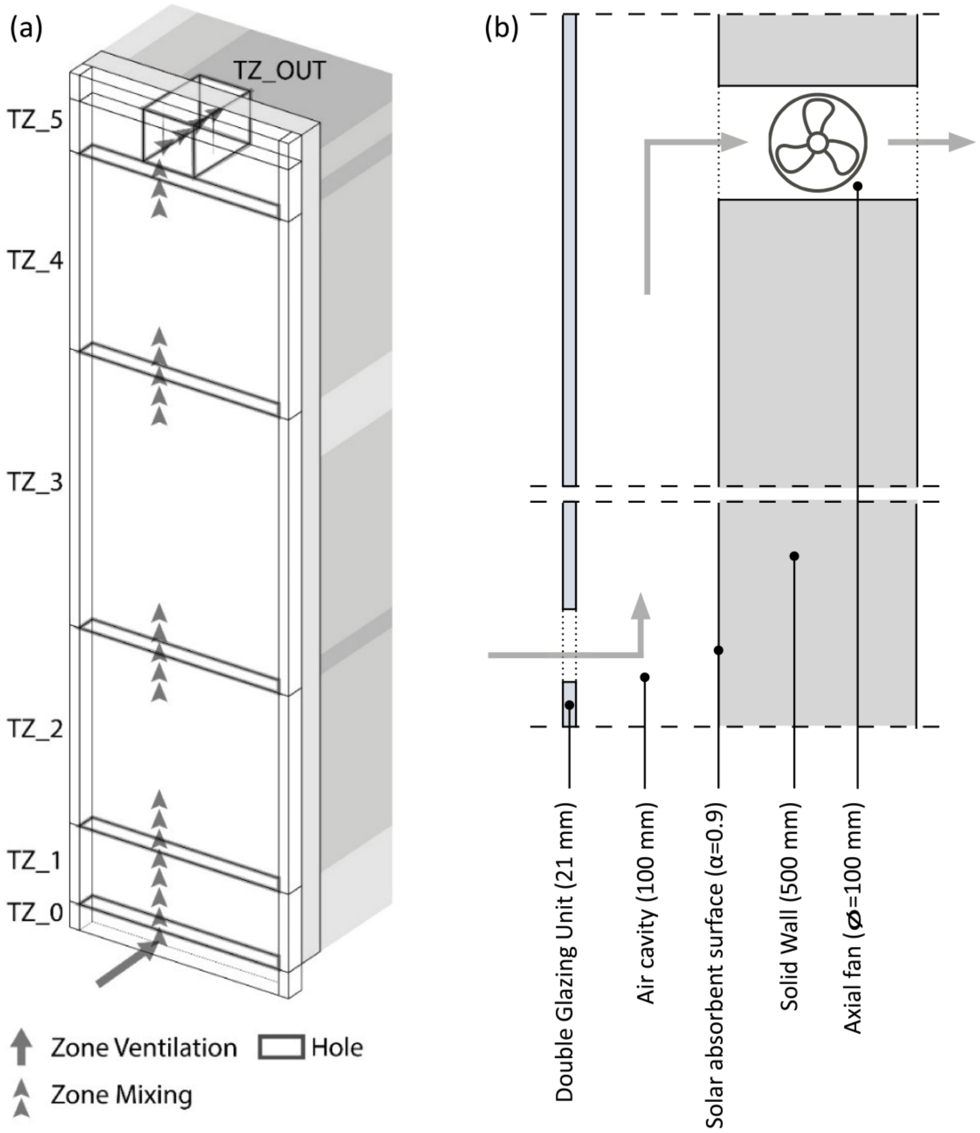

Figure 1. a) Scheme of the simulation model (TZ are the thermal zones); b) Layers and components of the SAHF

2.2. Optimisation of the functional layers

The façade element was optimised by changing its functional layers (namely, the transparent and opaque). To maximise free heat gains and to minimise the thermal losses, the transparent component needs to be chosen considering a balanced combination of solar transmission coefficient and thermal transmittance. The opaque component has mainly impact on the system heat storage capabilities, influencing the response of the façade (higher inertia means longer delays) and the attenuation of the peak temperatures.

Among different simulated scenarios that were not reported in the paper for the sake of brevity, it was found that the optimal configuration is the one that maximises the glazing insulation while increasing the wall heat capacity. For this reason, a Double Glazed Unit (DGU) with a low emissivity pane and argon-filled cavity (U-value 1.4 W/m^{2}K) was selected as the transparent layer, while a solid brick wall (50 cm thick) was selected as the opaque element (U-value 1.2 W/m^{2}K and Surface Mass Density 1040 kg/m^2).

2.3. Ventilation control

During the previous simulations, the component was analysed considering the fan always on at its maximum speed. In this way, the supply air was introduced in the internal environment even when it reached temperature values below 20°C (indoor heating set-point temperature in winter period). To use the façade component as an auxiliary system for heating, supply temperatures below 20°C should be avoided. Therefore, a PID controller was developed to modulate the air flow rate, enabling the control of the supply set-point temperature. Different set-point temperatures were considered (25°C, 30°C, 35°C and 40°C). If the measured supply temperature reached values below 20°C, the controller would stop the air flow (air flow rate set to 0 m^3/s).

3. Results and discussion

The seasonal simulation of the base façade system demonstrates that for around 30% of the heating period the system keeps the supply temperature above 20 °C, positively contributing to the indoor space heating. Even if the façade system is not always able to contribute to the space heating, it can still provide fresh pre-heated air required for ventilation purposes, thus allowing a reduction of the energy consumption through the decrease of the ventilation heat losses. In particular, the component (of about 2.5 m^2) supplies 26 m^3/h, which corresponds to about 0.5 ACH considering a ~19 m^2 room of 2.7 m height.

3.1. Ventilation control results

When the PID controller is implemented in the numerical simulations, the air flow rate is evaluated at each time step so to keep the supply temperature at the desired set-point. The lower the fan speed, the higher the supply temperature, since at lower flow rates it takes longer for air to travel inside its cavity, where the heat transfer occurs. In Figure 2 it is possible to see how the PID controls the supply temperature so to maintain it in the desired set-point (only 25°C and 40°C are shown) by changing the air change rate.

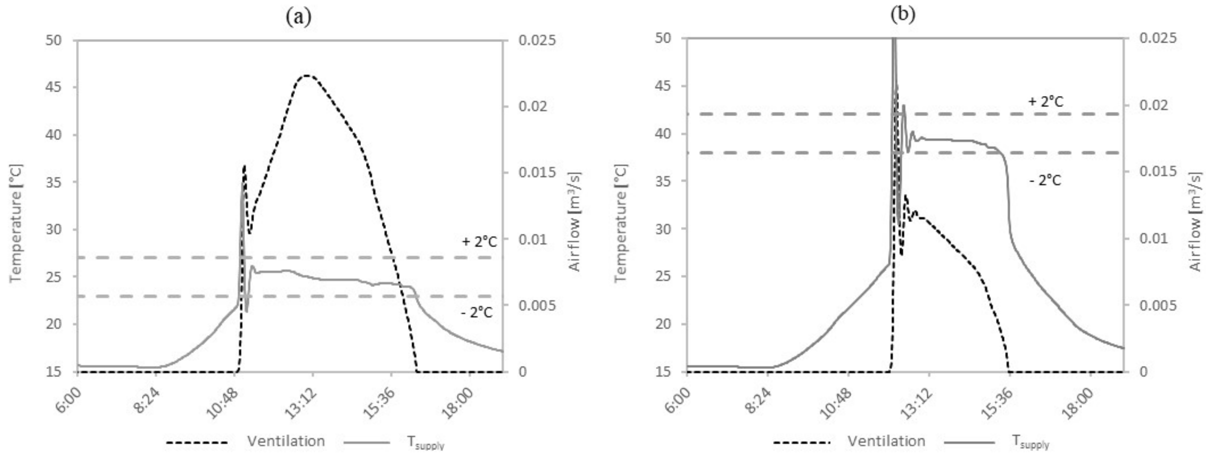

Figure 2. Supply air temperature (T_{supply}) and inlet air flow (*Ventilation*) values obtained by applying the PID control with set-point temperature of (a) 25°C and (b) 40°C in a typical winter day.

From Figure 3 (a) it is possible to notice several peculiarities of the system. First of all, in all the PID systems, the fan is off for the 70% of the heating season because the supply temperature would have been lower than the indoor air temperature (20°C). Considering all the different set-point cases, from $T_{sp,25}$ to $T_{sp,40}$, the set-point supply temperatures were maintained within ±2°C for, respectively, the 17%, 15%, 12% and 9% of the simulated period.

The obtained results demonstrate that during the simulation period there are entire days in which the ventilation is absent.

In Figure 3 (b) the average seasonal solar efficiency (η_{sol}) are summarised. This performance indicator is defined as the ratio between the heat energy provided by the supplied pre-heated air and the incident global solar energy radiation (Eq. 1):

$$\eta_{sol} = \frac{\sum_n^m Q_{supply}}{\sum_n^m Q_{sol}} \cdot 100 \quad (1)$$

where *n* and *m* refer to the beginning and the end of the heating period (15th October – 15th April) [10]. It can be observed that compared to the not-controlled component (C_i), the average seasonal efficiency values increase in the case of T_{sp25} and T_{sp30} while achieving similar or slightly lower performances in the T_{sp35} and T_{sp40} configurations. It is worth to be noted that to maintain lower set-point temperatures, higher air flows are needed (Figure 2). This also implies fans of bigger size, with the drawback of higher energy consumption and noise emission. In the present study, the fan energy consumption was neglected in the calculation of the performance indicator η_{sol}. In the experimental case study (not-controlled component, C_i), two monthly energy efficiencies were assessed in the winter period: the total efficiency (η_{tot}) and the net efficiency (η_{net}):

$$\eta_{tot} = \frac{\sum_n^m Q_{supply} + \sum_n^m Q_{cond}}{\sum_n^m Q_{sol}} \cdot 100 \quad (2)$$

$$\eta_{net} = \frac{\sum_n^m Q_{supply} + \sum_n^m Q_{cond} - \sum_n^m Q_{fan}}{\sum_n^m Q_{sol}} \cdot 100 \quad (3)$$

Where Q_{cond} is the heat exchanged between the cavity and the internal environment and Q_{fan} the electrical power required by the fan.

Observing the difference between the above described winter monthly average efficiencies, it is possible to have an idea of the fan energy consumption impact on the overall efficiency. On average, fan energy consumption led to a reduction of the total efficiency (η_{tot}) of around 6%. However, this efficiency reduction cannot be extended to the controlled case studies, since the system operates with variable air flow rates. Further investigations will be carried out.

(a) (b)

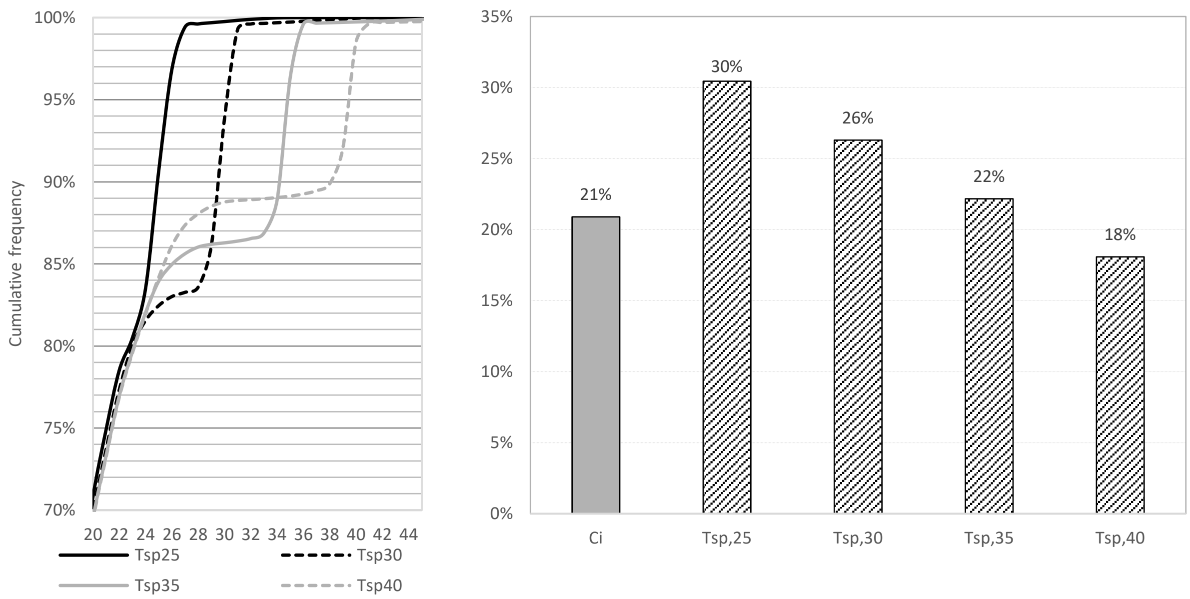

Figure 3. (a) Cumulative frequency distribution of the supply temperature obtained by the façade system during the PID control actions; (b) Comparison of seasonal average solar efficiency (η_{sol}) values obtained during the PID control simulation.

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4. Conclusions

In this study, the effect of different ventilation setting on the performances of a fan-assisted Solar Air Heating Façade (SAHF) was investigated. The experimental results carried out on a full-scale façade module where used to validate a dynamic simulation model, which was then used to assess the performance of the system under different PID control actions.

The façade system is able to supply fresh air that can be used for heating or ventilation purposes. By controlling the ventilation system through PID control actions, it is possible to use the system in heating-mode only, with the result of keeping a desired set-point temperature for a significant portion of the heating period.

Simulation results highlight that operating the SAHF system in heating-mode only and controlling the supply air temperature with a PID control at 25±2°C the system can provide pre-heated air for about the 17% of the heating season, while increasing the supplied temperature to 40±2°C, the system can supply air with an higher exergy level for the 9% of the winter period. Fan-assisted SAHF represent a responsive building element that can operate as a decentralised ventilation unit while exploiting solar radiation as a renewable energy source. This feature makes the system a valuable solution if applied as a retrofit strategy in all buildings that present space limitations for the installation of centralized ventilation systems, helping to address the requirements to reach the nZEB target.

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