Optimizing the ventilated double window for solar collection

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A B S T R A C T
Windows have been under study for the last decade due to their improvements and for being the lowest thermal resistance component of the facades. Amongst this component, the building also loses heat as a result of airing needs. Thermal losses through windows and ventilation may represent a large percentage of the whole thermal losses of the building. The double ventilated window is one of several construction systems that preheat the incoming air. It also reduces thermal losses through windows, reducing the heating load of the building. Several studies have shown the performance of the ventilated double window under different climatic conditions as well as the influence of different inputs. This paper shows how this passive air heating system can be improved in order to collect more solar heat. Thermal balance was improved by 8.4% and 12.5% in Bragança and Évora, respectively, while the delivered air temperature increased from 9.8 °C to 11.9 °C and from 13.5 °C to 17.4 °C in Bragança and Évora, respectively.

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1. Introduction

Windows are commonly the façade element with the weakest thermal resistance. Besides being the thinnest constructive element, it has the highest thermal conductivity of the building’s construction elements as one may find in the literature. Boyano et al. (2013) have studied the improvement of window insulation and external walls to provide new data about the energy consumption and the energy demand profile of European office buildings. The lowest U-value of windows was 1.78 W/(m2 K) and the highest U-value of the envelope was 0.49 W/(m2 K) of the roof (Boyano et al., 2013). A new weather database compiled for Perugia was used to compare different scenarios in terms of energy demand, such as the substitution of the glazing (2.4 W/(m2 K)) and lower U-value of the opaque envelope (0.8 W/(m2 K)) (Buratti et al., 2014). In the energy consumption study of a large public building calculated for Leadership in Energy and Environmental Design (LEED), U-values of windows have become as low as 1.8 W/(m2 K) and external walls as high as 0.66 W/(m2 K) (Pan et al., 2011). One may find in several studies a higher U-value of windows against a lower U-value of the building envelope as suggested in Carlos (2016) with 2 W/(m2 K) and 0.3 W/(m2 K) for walls. Stazi et al. (2012) proposed one refurbishment, where optimal retrofit solutions were identified for the external envelopes with a U-value of 2.4 W/(m2 K) for windows and 0.35 W/(m2 K) for walls, or 3 W/(m2 K) for windows and 0.57 W/(m2 K) for walls in Carlos and Corvacho (2010). Although there are thermal losses in cold climates, in hot climates they allow incoming heat. They also allow excessive solar radiation during the cooling season. Thermal losses are also verified through airing. Combining a double window with an incoming air path to heat the ventilation air, thermal losses may be reduced due to windows and airing. Several solutions have been studied during the last two decades namely combining windows and passive heating of the ventilation air.

An air window collector is a double window system with a vertical blind installed between glass panes for absorbing solar energy (Onur et al., 1996). The blind works as a solar collector. The absorbed solar energy is partially transferred by convection to the passing air on both sides. It can be used as a recirculating air window collector or a ventilated one (Hastings and International Energy Agency, 2000). A supply air window is a modified double window with a ventilation path, operable between the outer and middle panes. This air path enables heated ventilation air in winter (Baker and McEvoy, 2000; McEvoy et al., 2003). Unshaded, the air supply window contributed more significantly to reducing the ventilation load than heat transmission, depending on the ventilation rate. A ventilated window composed of two glass sheets separated by a space through which air is forced to flow, was also studied by Ismail and Henríquez (Ismail and Henríquez, 2006). Part of the incident solar radiation is absorbed in the external glass sheet. Part of the solar radiation crosses the first glass sheet and is then absorbed by the internal glass sheet; finally, the air flowing in the channel exchange heat by convection increases its temperature before it is delivered to the indoor ambient. A double window system similar to the one presented in this paper was studied by Kim et al. (2011) with ventilation slits to solve the window surface
condensation problem in apartment units without balconies. Initially, ventilation slits were designed to introduce natural ventilation with improved thermal performance. The thermal performance of an airflow window with triple glazing and internal cavities of various thicknesses was studied by Diomidov et al. (2012). They found that the thermal resistance of the transparent window part increased when compared to a standard triple glazing. The heat loss through the inner pane of the window unit decreased. It has also shown that airflow windows with triple glazing and natural ventilation ensure a higher temperature of the inner pane when compared to the window without air flow. Some other works have been carried out on the response of such a system considering the incident solar radiation and also the heat loss from inside. The study of the heat source influence was carried out by using a prototype of a supply air window (McEvoy et al., 2003) and a ventilated double window (Carlos et al., 2012). It was found in both studies that the heat recovered from indoors surpassed the absorbed solar heat that was transferred to the air; thus, when solar radiation was present, thermal conduction through the windows was also verified. The objective of this research, which has never been done, is to take advantage of solar radiation and therefore improve the efficacy of the ventilated double window. Consequently, this study aims at the optimization of the ventilated double window for solar collection under Portuguese climatic conditions through:

- System design: searching for a good system design in order to obtain the best thermal performance, under incident solar radiation;
- Physical proprieties: study the physical proprieties of the components to get the overall higher solar gains without reducing its overall thermal performance.

2. Physical model and mathematical formulation

The influence of the solar incident radiation on the ventilated double window is presented. Fig. 1 shows a basic configuration of the ventilated double window section with daylight source from the sun, sky and reflected from the ground. The model contains the following assumptions: (i) the diffuse daylight from the sky is always downwards, therefore the upper part of the inner window does not receive any diffuse daylight; (ii) the reflected light from the ground is always upwards, therefore the lower part of the inner window does not receive any reflected light; (iii) the direct sunlight depends on the location of the sun, the geometry of both windows and the cast shadow on the inner window due to the outer frame.

The angle of the incidence solar beam (i, in degrees) is found by (da Piedade et al., 2000):

$$\cos(i) = \cos(\beta) \sin(h) + \sin(\beta) \cos(h) \cos(y)$$

(1)

where $\beta$ is the angle between a tilted surface and the horizontal plan (in degrees), $h$ is the angle of solar altitude (in degrees) and $y$ is the azimuth angle (in degrees), meaning the difference between the solar and the surface’s azimuth, being:

$$y = |\alpha_s - \alpha_p|$$

(2)
where $a_p$ is the surface azimuth (in degrees), $a_a$ is the solar azimuth (in degrees). The angle between the window and the horizontal plane ($\beta$) is in this investigation of 90 degrees. The solar azimuth is determined through the following equation:

$$\cos(a_k) = \left[ \sin(h) \sin(L) - \sin(\delta) \right] / \left[ \cos(h) \cos(L) \right]$$  \hspace{1cm} (3)

where $L$ is the Latitude of the place (in degrees) and $\delta$ is the solar declination angle (in degrees). The solar altitude is determined by:

$$\sin(h) = \left[ \sin(L) \cdot \sin(\delta) \right] + \cos(L) \cdot \cos(\delta) \cdot \cos(\omega)$$  \hspace{1cm} (4)

where $\omega$ is the hour angle (in degrees), which is found by:

$$\omega = 15(LST - 12)$$  \hspace{1cm} (5)

where LST is the local solar time (hour). The solar declination angle may be found by:

$$\delta = 23.45 \sin(360(284 + d)/365)$$  \hspace{1cm} (6)

where $d$ is the day of the year (1–365). Due to the outer window, the sunlit and shaded areas of the inner window product are variable during the day and can be calculated for each hour using the following equations (Fig. 2):

$$A_{s} = (W_s - s_{v})H_s - (H_s - s_{v})$$  \hspace{1cm} (7)

where $A_{s}$ is the area of the sunlit glazing (m²), $W_s$ is the width of the glazing (m), $s_{v}$ is the horizontal shading of the glazing (m), $H_s$ is the height of the glazing (m), $s_{v}$ is the vertical shading of the glazing (m). The width of the cast shadow by the outer frame is:

$$s_{wg} = \tan(h)l$$  \hspace{1cm} (8)

where $l$ is the depth from the outer frame to the inner glazing (m). The height of the cast shadow by the outer frame is:

$$s_{wg} = \tan(h)l$$  \hspace{1cm} (9)

The characterization of a ventilated double window was done through a series of experimental measurements exposed to real outdoor weather conditions (Carlos et al., 2010). During those experiments the global solar radiation on a horizontal surface was also registered. The values of solar irradiation based on the global solar radiation on a horizontal surface was estimated, as (Carlos and Corvacho, 2013a):

$$k_d = 1.0 \text{ for } k_t < 0.17$$

$$k_d = 0.90 + 1.1k_t - 4.5k_t^2 + 0.01k_t^3 + 3.14k_t^4 \text{ for } 0.17 < k_t < 0.75$$

$$k_d = 0.17 \text{ for } k_t > 0.75$$  \hspace{1cm} (10)

where $k_d$ is the percentage of diffuse radiation in the global solar radiation and $k_t$ is the clearness index that represents the percentage of solar radiation incident at the top of the atmosphere reaching the Earth’s surface. For a vertical surface, the hourly solar irradiation ($W h/m^2$), $I_g$, is quantified through the following expression:

$$I_g = I_b \cos(i) + 0.5I_d + I_r$$  \hspace{1cm} (11)

Being:

$$I_d = I_b k_d$$  \hspace{1cm} (12)

$$I_b = \frac{(I_b - I_d)}{\sin(h)}$$  \hspace{1cm} (13)

$$I_r = 0.5I_b k_r$$  \hspace{1cm} (14)

where $I_b$ is the hourly diffuse irradiation ($W h/m^2$), $I_h$ the hourly global solar irradiation on a horizontal surface ($W h/m^2$), $I_b$ the hourly beam irradiation ($W h/m^2$), $I_r$ the hourly irradiation being reflected ($W h/m^2$) and $K$ the surrounding reflectivity or albedo.

The overall thermal performance of the ventilated double window was carried out relating heat gain and heat loss, which result in thermal balance (B, in W) as (Carlos et al., 2011):

$$B = (Q_{tot} + Q_{care}) - (Q_{min} + Q_{air})$$  \hspace{1cm} (15)

where $Q_{tot}$ represents the solar heat gains that enters directly into the indoor environment (W), $Q_{care}$ represents the heat that is recovered by the passing air within the air channel and delivered into the indoor environment (W). $Q_{min}$ represents the heat loss that escapes through the window (W) and $Q_{air}$ represents the heat loss through ventilation (W).

3. Simulation and validation

A computational code was built and validated where different configurations of the ventilated double window were tested (Carlos et al., 2011). However, this simulation program used the registered total solar radiation. In order to validate the computational code with the formulas mentioned above, the thermal behaviour of the ventilated double window under solar radiation was simulated and the output temperatures were compared with the temperatures obtained under real weather conditions. A south-facing full-scale model of 1.43 m $\times$ 1 m was tested in real weather conditions. The model is composed of two windows with two air inlets and a total area of 50 cm² installed at the bottom of the outer window (Fig. 3). The thickness of the gap between the windows was about 9 cm, glass to glass and of 5 cm, casement to casement. The glazing surface was about 54% of the whole window surface. Different combinations of glazing were used. The whole window characteristics are shown in Table 1.
Thermocouples were used to measure the airflow temperature located at the top of the air gap and also the indoor and outdoor air temperatures. These were connected to a programmable data acquisition system to store the collected data based upon 1 min average data acquisition. The global solar radiation on a horizontal surface was collected from the local weather station. For all the inner glazing configurations, the outlet air temperature monitored was compared with the values generated by the simulation. The difference in the predictive capability of the simulation and the registered values for each glazing configuration can be observed in Fig. 4. It shows the results from the tests conducted within three different inner windows (Table 1) and the same outer window. These results present only the temperature when there was solar radiation, namely daily temperature.

The simulation has proven to be sensitive to the main air flow driving forces and heat transfer confirmed by the values of $R^2$ given from 0.878 to 0.942, which are acceptable showing low dispersion. The comparison of results shows that simulation agrees quite well with experimental measurements. In fact, the model tends to underpredict the air preheating temperature. The obtained mean air temperature was 17.3 °C, 14.7 °C and 15.2 °C against the simulated mean air temperature of 15.6 °C, 13.3 °C and 14.8 °C for configuration 1, 2 and 3, respectively. Therefore, the simulated mean values were 90.1%, 90.9% and 97.3% of those registered. It clearly shows that the simulation provides temperatures slightly below the measured values with a fairly good adjustment.

### 4. Results and discussion

A passive heating system, named ventilated double window, consists of two parallel windows within the same fenestration and a ventilated channel between them. Heat escaping through the inner window and incident solar radiation pre-heats the ventilation air that rises through the ventilated double window before entering the building. Both heat sources were already discussed by Carlos et al. (2012) where, it was found that heat recovery is the most important function of the ventilated double window when pre-heating the incoming air. Thus, the problem to be treated here is to improve this passive system for solar heat gain due to solar radiation.

This study was carried out by comparing several modifications of the ventilated double window system to achieve the best performance under solar radiation. These modified systems are to be compared to a common configuration being the outer and inner window characteristics shown in Table 1 with the same glazing/window ratio (0.63). All systems are of 1.50 m width and 1.10 high with a 6 mm single glaze. In order to compare some systems, their frames were enlarged or shortened, which resulted in a different glazing/window rate. Different solar absorptance and reflectance was also introduced. These modifications have resulted in 14 different configurations, as identified in Table 2, where a thermal characteristic for each configuration is identified in Table 3. Dynamic simulations took into account a typical winter day for every hour of the day under incident solar radiation.

The performance of each configuration of this passive system was analysed under the weather of Bragança and Évora. The first is located in a colder zone of Portugal while the second is in a hotter zone. Bragança is located at Latitude 41.8° North and Longitude 6.7° West at Altitude of 692 m. Évora is located at Latitude 38.6° North and Longitude 7.9° West at Altitude of 321 m. Clear...
intermediate and overcast sky conditions were chosen, corresponding to a clearness index ($k_t$) of 0.75, 0.46 and 0.17 respectively. A sinusoidal variation of the outside air temperature during a 24-h period was taken into account throughout this study. This assumption is very closely linked to the meteorological data, and consequently to ambient-air temperature ($T_{oa}$ in °C) defined by (Kontoleon and Bikas, 2007) (Kontoleon and Eumorfopoulou, 2008):

$$T_o(t) = T_{o,ave} + \frac{|T_{o,max} - T_{o,min}|}{2} \sin \left( \omega t - \frac{\pi}{2} \right)$$

(16)

where $T_{o,ave}$, $T_{o,max}$ and $T_{o,min}$ correspond to the average, maximum and minimum outdoor temperatures (°C) of a day period (24-h). The rotational velocity is $\omega = 2\pi f$, with a radial frequency $f = 1/86,400$ s. The air temperature of the coldest day of each city was chosen. Airflow can significantly affect predictions of energy performance (O’Brien et al., 2011), however average air change per hour of flow can significantly affect predictions of energy performance. The air-temperature of the coldest day of each city was chosen. Airflow can significantly affect predictions of energy performance. The air-temperature of the coldest day of each city was chosen. Airflow can significantly affect predictions of energy performance.

Table 2
Different configurations of the ventilated double window under study.

<table>
<thead>
<tr>
<th>Glazing/window</th>
<th>Configuration</th>
<th>Inner glazing</th>
<th>Inner frame</th>
<th>Outer glazing</th>
<th>Outer frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner - 0.63</td>
<td>1</td>
<td>A</td>
<td>D</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>B</td>
<td>D</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Outer - 0.63</td>
<td>4</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>D</td>
</tr>
<tr>
<td>Inner - 0.50</td>
<td>7</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>A</td>
<td>D</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Outer - 0.78</td>
<td>9</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>B</td>
<td>D</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Inner - 0.78</td>
<td>11</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Outer - 0.50</td>
<td>13</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 3
Thermal characteristics of the studied windows.

<table>
<thead>
<tr>
<th>Components</th>
<th>Absorptance</th>
<th>Reflectance</th>
<th>Transmissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.14</td>
<td>0.07</td>
<td>0.79</td>
</tr>
<tr>
<td>B</td>
<td>0.62</td>
<td>0.12</td>
<td>0.26</td>
</tr>
<tr>
<td>C</td>
<td>0.4</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
</tr>
</tbody>
</table>

As the ambient temperature is higher in Évora, less heat is lost through the windows. In spite of this, the systems with higher solar absorptance of the inner window deliver air at a lower temperature. Comparing the delivered air temperature at noon with the common configuration, configuration 6 and 14 supplied air ventilation 0.5 °C and 4.5 °C higher in Bragança and 6.5 °C and 6.2 °C in Évora, respectively. When these configurations were under overcast sky, they supplied air ventilation 0.2 °C and 0.6 °C was higher than the referred common configuration. Low incident solar radiation has little effect on the system since the heat recovery has the highest impact on the delivered air temperature (Carlos et al., 2012). Under intermediate sky conditions the results are similar. For instance, configuration 6 and 14 delivers air 0.5 °C and 0.9 °C higher in Bragança.

The configuration delivering lower air temperature is configuration 8 in Bragança and 7 in Évora. These represent −0.9 °C and −0.1 °C in Bragança and Évora, respectively. Despite their difference on solar absorptance, there is a common characteristic between these two configurations. Both have greater frame of the inner window compared to the outer window, allowing higher solar absorptance of the inner window. As this inner window heats up due to solar radiation, the heat loss from inside through this window is reduced. Therefore, less heat is recovered by this.
ventilated passive system. As found in a previous study (Carlos et al., 2012) heat recovered from heat loss has a higher contribution to the air temperature than the one coming from the solar radiation. Therefore, these configurations present the lowest delivered air temperature under incident solar radiation.

The ventilated double window not only infers in delivering warmed air inside, it is also involved in the thermal performance of buildings, just as any other regular window. During winter time heat is lost to the outdoor environment but it also gains heat due to incident solar radiation directly through the glazing. Therefore, it was necessary to understand the overall thermal performance of the passive air heating system. This was done by analysing the thermal balance between heat gain and heat loss as in (Carlos et al., 2011), which compared the new configurations (1–14) with the common system.

Figs. 8 and 9 show the investigation of the thermal balance as defined by Eq. (15). The results represent the comparison between each configuration system (1 to 14 – Table 2) and a common system. The negative values indicate that the new configuration performs worse than the common one, and the positive values indicate a better thermal performance.

As one may observe from Figs. 8 and 9 all configurations of this passive heating system representing inner and outer frames different in size, had worse thermal balance results when compared to the common system. When the new passive system had the same glazing/window ratio of both windows (inner and outer),...
configuration 4 is the only one performing better both in Bragança and Évora. Configuration 1 has a similar response while the remaining performs worse than the common passive system. Comparison between all configurations for both climate data of Bragança and Évora is shown in Fig. 10. The total thermal balance difference between each configuration and the common one shows the same tendency in both climate zones. At the end of the day configuration 1 is similar to the common configuration. Configuration 4 has performed better, with a positive value of 70 W and 242 W in Bragança and Évora, respectively. All the
remaining configurations performed worse than the common configuration, where configuration 11–14 have a negative value of nearly −3.000 W.

Configuration 4 corresponds to a system with higher solar absorptance of the outer frame and transparent glazing. Therefore, it allows more solar heat to be absorbed by the frame which increases thermal transfer to the ventilation air. It also allows indoor solar radiation through transparent glazing whilst heating the interior space. Comparing the thermal balance at noon between configuration 4 and a common one, it is seen from Fig. 8 that the new system had a better overall performance with a result of 24 W in Bragança. The thermal balance in Évora was 43 W (Fig. 9). When this configuration was under overcast sky the thermal balance was 2 W, both in Bragança and Évora. This new system delivered warmed air 2.1 °C and 0.2 °C higher in Bragança, under clear and overcast sky. Under the same sky conditions, the delivered air in Évora was 4 °C and 0.2 °C higher than the common system.

A simple and intuitive assessment of building systems, namely fenestration and natural ventilation, provides useful data that can help architects, building industry and decision makers to obtain the solution with less thermal disadvantages for each case. This investigation can be beneficial when designing windows that ventilate the building in winter providing warmer air than outside. With the combination of the intuitive assessment of building systems and simulation methodology, it is possible to extrapolate this study for all existing climate data, being helpful to the overall designer’s community, according to the study presented by Carlos and Corvacho (2013b).

5. Conclusions

A ventilated double window is a passive system that pre-heats the incoming ventilation air before it is delivered inside. This system is composed by two parallel windows within the same fenestration. The channel between both is a pathway for the incoming air. In that channel the passing air is pre-heated through removal of heat from windows by convection. It is simultaneously a recovering and collecting device. On the one hand it recovers part of the heat lost from inside to outside through the windows, on the other it is capable of gathering part of the solar heat absorbed by the windows.

This passive system has been under study, focusing on different aspects. This paper investigated how this system could be optimized for better performance under solar radiation. Several configurations of this system were analysed, being the results compared to the results of a called and defined common system. A better performance system may obtain an air flow temperature about 6° higher than the worse system under the clear sky conditions of Bragança. The first is able to deliver the air at 14.8 °C while the second only around 9 °C. In Évora, the air flow temperature may increase up to about 8° between two opposite performance systems, corresponding to a delivered air at 20 °C and about 12.4 °C.

Fig. 9. Thermal balance difference obtained in Évora environment under clear sky conditions.

Fig. 10. Comparisons of the total thermal balance difference between all configurations in Bragança and Évora climate.
respectively. This higher difference in Évora is related to a higher available solar radiation. Under intermediate and overcast sky conditions, the differences of the air flow temperature between configurations may reach about ± 1°C, both in Bragança and Évora. This low difference is not relevant to determine which configuration responds better to the solar radiation. The results have shown that this system may be improved for solar collection without disregard of the recovery function.

A thermal balance was introduced to evaluate the overall performance of each system to be compared with the common one. The heat balance, which accounts for the thermal gains and losses of this passive system, has always been worse when direct but reduced solar radiation reached the inner ambient. When the glazing ratio is the same of both inner and outdoor windows of the system with higher glazing transmissivity, the thermal balance has become positive, of about 312 W in Bragança and 388 W in Évora. The common configuration has obtained 288 W and 345 W in Bragança and Évora, respectively. A worse configuration represents a thermal balance of about −207 W and −150 W in Bragança and Évora, respectively. This shows how the outcome results may be highly influenced by the design of the system and the choice of its components.

From the present study, several conclusions may be withdrawn:

- Both windows should have the same geometry relationship, meaning the same glazing/window ratio. A lower glazing/window ratio (0.50 in this study – Table 2) of one of the windows, blocks the direct solar radiation inside;

- Provides a high glazing/window ratio of both windows (0.63 – Table 2). The higher the ratio, the higher the solar heat entering directly through the glazing;

- The transmissivity of the glazing should be as high as possible to allow the incoming solar radiation. This component of solar heat is more advantageous to the thermal balance of the air stream;

- The frame of the outer window should be capable of absorbing solar radiation as much as possible, being in the present study an absorbance of 0.8. By increasing the solar absorbance of the frame, more heat is available to be transferred to the passing air through the channel between windows;

- The frame and glazing of the inner window, contrary to the outer window, should absorb solar radiation as minimum as possible, with low absorbance values. As the recovery function is the dominant factor to heat the air stream, if the inner frame is heated by the effect of solar radiation, less heat is transferred from the inside and therefore to the ventilation air.

A potential future of this research relies on the overall design of this passive system. How can it be improved to increase the level of insulation and at the same time increase the capacity of a passive heating system? This could be done through monitoring multiple outdoor and laboratory tests, thus not only the design should be considered, but also the materials that constitute this system. The influence of the inlet, its location and air admission is also the next step to be analysed.

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