Real climate experimental study of two double window systems with preheating of ventilation air

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ABSTRACT

This paper aims to characterize the thermal performance of a window system that consists in doubling an existing window, converting it into a ventilated double window. The air coming from the outside circulates upwards through the channel between windows and enters the building through a vent on the top of the window’s case. A series of experimental measurements was conducted in a test cell exposed to real outdoor weather conditions located in a mountain region at Centre of Portugal, during heating season in order to determine how this window system can act as a heat exchanger. It was found that such window system act as an efficient heat exchanger using transmission heat losses and solar radiation to preheat ventilation air, thus reducing the building’s operational energy costs. An average of about 19 m³/h of air flow rate was found with an air temperature increment within the air gap of about 6 °C, during night-time, for an indoor/outdoor temperature difference of about 16 °C. Air temperature increment reached up to 12 °C using a plastic shutter. With solar radiation, the average of that increment was about 10 °C. This is a simple and cheap building technology which can be implemented both in new and existing buildings.

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1. Introduction

The need to ensure indoor air quality in all dwellings and other buildings requires air renovation through ventilation resulting in inevitable energy consumption for heating due to ventilation thermal losses, in winter. A variety of technical solutions have been studied and used in order to reduce those losses as, for instance, earth-to-air heat exchangers through buried pipes as used in DB Netz AG (Hamm), Fraunhofer ISE (Freiburg) or Lamparter (Weilheim) in Germany [1]. Fresh air is heated by heat transfer from the ground to buried pipes and then to air by convection. Another possibility is the construction of a conservatory, an enclosed glazed space attached to the main building with fresh air entering in it at a low level. The air is preheated within the space and enters the main building through top vents [2].

The use of unglazed transpired solar collectors [3], solar air collectors mounted on the sun-facing walls [4] or on the roof, the use of a window air collector that consists of two glazed windows with an intermediate device, usually a Venetian shutter [5] or a supply air window that consists of a window with two sashes separated by an air gap [6] or even a glazed ventilated double façade [7,8] are all similar systems in what concerns modus operandi. Solar gains and the heat coming from indoors warm the glass and thereby preheat the air stream which rises by stack effect and wind pressure. A fan can be associated to increase or maintain the air flow.

Measures to reduce energy consumption are needed if Kyoto Protocol commitments are to be met, i.e. the reduction of green house gas emissions reported in 1990 up to 5.2% in year 2012 [9]. With this in mind, the aim of the present study was to investigate the use of ventilated double windows to preheat ventilation air, which can contribute to reduce domestic energy consumption during heating season. Tests were conducted under outdoor weather conditions and considering exclusively natural ventilation.

Traditional Portuguese dwelling fenestrations are made of a single or double glazed window with a roller shutter case on its top. Windows and roller shutter cases are the thermally weakest components of a building envelope. Thermal comfort of the occupants and thermal losses are largely influenced by these two components. To reduce thermal loss and cold air infiltration in colder zones of Portugal, it is common to add a second single glazed window on the outside of the pre-existing window. The roller shutter operates then between the windows. Adding vents at the bottom of the outer window and at the top of the roller shutter case creates a path for incoming airflow through the gap between windows and through the upper case (Fig. 1).
The gap that is formed between the windows is supplied with fresh air from outside through vents at the base of the outer window. Air circulating through this gap is warmed by the heat coming from the inner window which transmits heat loss from indoors and also by solar gains. Preheated rising airflow, by stack effect and wind pressure, enters the room through a vent on the top of the roller case. Thereby the ventilated double window serves as a heat exchanger, recovering part of the heat losses through the inner window and providing solar gains. Besides this function, it is still a window offering a view to the outside and admitting daylight. The main advantages of this system are its simplicity, its inexpensive technology and the fact that there are no operation costs.

2. Test cell and studied system description

The experimental studies were carried out in the test cell shown in Fig. 2. The windows being tested were fitted into a south-facing 1.43 m x 1 m opening of the test cell. This test cell is a metallic insulated container and has a width of 2.2 m, a length of 2.0 m and a height of 2.5 m. This outdoors test cell was used to characterize the potential for preheating ventilation air of the ventilated double window under effective winter conditions. The cell was located at 40° 20'N, 7° 21'W and at an altitude above sea level of 464 m, in a mountain region at Centre of Portugal. The system under investigation is composed by two commercially available windows mounted on the south-facing wall of the test cell. Two air inlets with a total area of 50 cm² were installed at the bottom of the outer window. The objective was to reproduce the current situation of a double window without ventilation and to convert it into a ventilated one. Portuguese double window system has a single glazed pane at the outer window and a single or double glazed pane at the inner window. The analysis was carried out with this type of double window in two stages for the two different combinations of the glazing. The original thickness of the gap was of 9 cm, glass to glass and of 5 cm, casement to casement. Glazing surface is about 54% of the surface of the whole window.

A pyranometer was used to measure total solar radiation, and it was fixed rigidly to the south-facing wall of the test cell. In this way, the value provided by the pyranometer corresponds directly to the solar radiation reaching the south-facing vertical surface. The air flow rate was measured at the outlet vent using a transducer. This outlet vent was placed at the top of the roller shutter case to provide the room with fresh air. Several thermocouples were located within the cavity to measure air temperature along the gap and of the delivered airflow. Both outdoor and indoor air temperatures were also measured. In Fig. 3, a scheme with the location of the points of measurement is presented and in Table 1 the experiment instruments are presented.

Table 1

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyranometer</td>
<td>0–2000 W/m²</td>
<td>±0.15 %/°C</td>
</tr>
<tr>
<td>Thermocouples</td>
<td>–270°C to 400°C</td>
<td>±0.1 °C</td>
</tr>
<tr>
<td>Transducer</td>
<td>0.05–2 m/s</td>
<td>±0.05 m/s</td>
</tr>
</tbody>
</table>

Two programmable data acquisition systems.

Fig. 1. Ventilated double window (systems 1 and 2).

Fig. 2. View of the test cell.
The experiments were performed from November to December 2008, in the beginning of heating season, using two programmable data acquisition systems. Experimental data was collected based on preliminary acquisition tests and considering that incident solar radiation varies continuously during the day and for this reason the cavity air temperature changes continuously too. However since the air temperature varies slowly an average value for each minute was considered as a suitable measurement for the purpose of this research.

3. Experimental measurements

3.1. Aim

The main objective of the experimental campaign was to evaluate the impact of real climatic conditions on the performance of the system. The test cell described above was used to investigate that impact. Measurements of the temperature rise along the window air gap, the solar irradiance on the south-facing vertical surface, the air speed and the indoor and outdoor temperatures were recorded on several days and the correlations between them were plotted on scatter graphs. Indoor temperature was kept at an almost constant level (around 20°C) using an electric radiator controlled by an ambient thermostat. The experimental program, over a period of several days, was performed using both systems sequentially (Fig. 1, systems 1 and 2) with the window’s vents open to provide free ventilation. By measuring the air temperature and speed at the outlet of the system (air inlet for the room), it was possible to estimate the resulting heat gains through the air flow of the ventilated double window. Several different factors and systems solutions were evaluated. In this paper some results related with the impact of solar radiation and with the influence of the roller shutter will be presented and the performance of the two systems presented in Fig. 1 will be compared.

3.2. Solar radiation impact—daytime performance

The following measurements were performed only in daytime to observe how incident solar radiation influences the ventilated double window’s behavior. Fig. 4 shows measured incident solar irradiance at the window’s vertical surface as a function of time during the observed periods on sunny days. A comparison between the measured outdoor air temperature and the temperature of the air at the top of the window gap is shown in Fig. 5. As it was expected, all the measured temperatures increase when incident solar radiation increases and start to decrease following decreasing incident solar radiation. Fig. 5 also shows that the temperature at the top of the window gap is always above outdoor temperature and that the biggest difference between them is coincident with the highest incident solar radiation. Southall, Dickson and Park also analyzed the influence of the climatic determinants on the delivered air temperature in similar systems, being the latter always higher than outdoors, as found out in each respective research work. Southall results were obtained by “supply air window” for the PASSYS test cell at the Scottish laboratory of the Building Research Establishment in a controlled environment followed by simulations with East Kilbride and Milton Keynes, UK Meteonorm climate files. Dickson studies were based in a double-skin façade for simulations with UK default climate files by ESP-r and, in turn, Park considered a “smart façade system” for Atlanta and Chicago, USA climatic data. For the lowest incident solar radiation, the difference between outlet and outdoor air temperatures was about 7.9°C with system 1 and 6.1°C with system 2. For the highest incident solar radiation, that difference was about 13.2°C and 12.2°C, respectively. Besides this obvious increment of...
temperature due to the solar radiation, there are other factors that cannot be ignored, since they contribute also to the final temperature achieved. Fig. 6 reveals a reasonable correlation between the value of solar irradiance and the temperature increment at the ventilated double window. Baker [13], using the test cell at the Scottish laboratory of the Building Research Establishment, found out by climate simulations the existence of a limited correspondence between solar intensity and the temperature along the height of the window. Concluding it was due to inversed air flow on the sunniest day, which was not found in this research work.

However, solar irradiance did not show to have a significant influence (by itself in a direct way) on the amount of the air flow, as it can be seen in Fig. 7 where there is almost no correlation at all between the measured solar irradiance and the air flow rate. This last parameter is the joint result of the direction and speed of the wind and of the temperature difference along the gap which is obviously influenced by solar irradiance, as Fig. 6 shows. It is difficult however to identify the individual impact of each factor involved, since measurements were carried out in real climate change situation.

3.3. The performance without solar radiation—night-time

The behavior of the ventilated double window without the sun’s influence was observed during night period since even on an overcast day there is always some solar radiation, at least its diffuse component. For this purpose the periods that were chosen were the nights where temperature differences between indoors and outdoors were the lowest and the highest. The lowest indoors/outdoors temperatures difference was of 11.0 °C when testing system 1 and of 11.6 °C, when testing system 2, with minimum temperature increments at window’s top of 3.9 °C and 1.5 °C, respectively. At that time the minimum air flow rate reached by the two systems was of about 15 m³/h and 13 m³/h, for systems 1 and 2, respectively. For the highest indoors/outdoors temperatures difference (of 24.9 °C and 19.3 °C for systems 1 and 2, respectively) the temperature rise along the window gap was of about 10.6 °C and 7.2 °C, with a highest air flow rate of about 29 m³/h and 26 m³/h. Although Fig. 8 reveals a great dispersion of results and a very low correlation between the air temperature increment along the

![Fig. 5. Outdoor air temperature (out) and temperature of the air at the top of the window air gap (top) on sunny days.](image)

![Fig. 6. Air temperature increment within the window air gap vs. solar irradiance.](image)

![Fig. 7. Solar irradiance vs. air flow rate.](image)

![Fig. 8. Air temperature increment within the window air gap vs. air flow rate.](image)
window gap and the air flow rate, numerical simulation with fixed values of air flow rate can prove that air temperature increment decreases when air flow rate increases and it increases when air flow rate decreases. This is because the total heat collected by the air stream from the glazing surfaces depends on the time in which air remains in contact with the hotter surfaces. As the air flow rate increases through the air gap, which means as the air velocity increases, the time of contact between the air and the glass surface decreases and so the air temperature increment along the gap is lower. The same result was found by Southall [10]. In Fig. 9, the variation of the temperature rise along the window gap in function of the temperature difference between indoors and outdoors is presented. It can be observed that the air temperature increment within the window air gap follows the indoors/outdoors temperatures difference tendency.

3.4. The influence of the roller shutter

The shutter used in the system under analysis was a commercially available plastic roller shutter which works between the two windows. Usually the roller shutter is closed at night-time. When closed, the ventilated gap is divided into two gaps with three options of ventilation pattern: only through the exterior gap, only through the interior gap or through both gaps (Fig. 10). The adding of a plastic shutter between the windows leads also to an increase of the global thermal resistance of the system. Since this shutter is usually closed only at night-time, during the winter season, and air flow's temperature depends on the thermal losses from indoors to outdoors, the analysis was performed for the case of a ventilation path only through the interior gap and for the night period. For this new air flow path, meaning that air flows between the roller shutter and the inner window, the temperature gradient along the window air gap obtained with the two systems is shown in Fig. 11, revealing a very good correlation to the air temperature difference between indoors and outdoors.

4. Results and discussion

When a ventilated double window is integrated in the building façade, depending on the design of the construction system, ventilation can be either natural or mechanical. The design of this new building component affects its thermal behavior and thus the heating needs of the building, especially due to air renovation. If part of the solar heat gains absorbed by the inner window is removed by ventilation air and part of the heat losses from indoors to outdoors is also captured by the same ventilation air, it will enter the building warmer than directly from the outside. The effective heating of the ventilation air depends on the climatic conditions, the thermal characteristics of the system and the indoor conditions. From direct measurements of some parameters under

![Fig. 9. Air temperature increment within the window air gap vs. temperature difference between indoors and outdoors.](image)

![Fig. 10. Three different possible air flow paths when there is a shutter between windows.](image)

![Fig. 11. Air temperature increment within the window air gap (when there is a roller shutter) vs. air temperature difference between indoors and outdoors.](image)
real conditions, some others can be estimated. Thermal losses due to air renovation \((Q_{\text{air}}, \text{in W})\) can be determined by:

\[
Q_{\text{air}} = C \rho V (\theta_{\text{in}} - \theta_{\text{out}}) \tag{1}
\]

where \(C\) is the specific heat capacity of air (J/kg °C), \(\rho\) is the density of air (kg/m³), \(V\) is the volumetric air flow rate (m³/s), \(\theta_{\text{in}}\) and \(\theta_{\text{out}}\) are the indoor and the outdoor air temperatures (°C). Expression (1) presupposes that air is drawn directly from outside. With ventilation air being supplied through the ventilated gap of the double window the heat gained by preheating the air \((Q_{\text{util}}, \text{in W})\) is:

\[
Q_{\text{util}} = C \rho V (\theta_{\text{top}} - \theta_{\text{out}}) \tag{2}
\]

where \(\theta_{\text{top}}\) is the air temperature at the window’s outlet (°C) (inlet for the room). Thus, the new ventilation heat loss \((Q_{\text{vent}}, \text{in W})\), as used by Baker [13], will be:

\[
Q_{\text{vent}} = C \rho V (\theta_{\text{in}} - \theta_{\text{top}}) \tag{3}
\]

The reduction in ventilation heat loss as a result of preheating the ventilation air is therefore:

\[
Q_{\text{vent}} - Q_{\text{air}} = C \rho V (\theta_{\text{top}} - \theta_{\text{out}}) \tag{4}
\]

Figs. 12 and 13 present the heat transfer due to ventilation over the measured period. These graphs show a clear daily variation due to the pattern of solar radiation and to the outdoor air temperature variation. The percentage of heat loss reduction after preheating the ventilation air can be estimated as:

\[
\frac{Q_{\text{air}} - Q_{\text{vent}}}{Q_{\text{air}}} \times 100\% \tag{5}
\]

The results for the two different systems are presented in Figs. 14 and 15. Fig. 14 shows the percentage of heat loss reduction without solar radiation influence. As it can be seen, system 1 presents values greater than 40% for the majority of the measured values of temperatures difference (the average value of the percentage of heat loss reduction is of 43%), whilst system 2, in spite of a little increase in its percentage with the increase of temperatures difference, presents values mainly lower than 40% (with an average value of 26%). This reflects the capacity of each system to recover part of the heat lost from the indoors through the inner window. System 1 shows a better response since its inner window has a lower thermal resistance than the inner window of system 2. This causes more heat transfer from inside to the gap and so more heat can be recovered by the air stream. Fig. 15 shows the increase of the percentage of heat loss reduction in function of the solar irradiance, for both systems. Also for the supply air window [10,13], considerable savings were obtained at moderate levels of solar radiation. The experimental results by Southall [10] showed an approximately linear response of the increase of preheating to the increase of solar radiation, for a constant flow rate. This percentage has an average value of 82%, for system 1 and of 68%, for system 2. In this case, the results express the joint effect of solar gains and heat recovery. Fig. 16 shows the percentage of heat loss reduction when the vertical shutter is closed and there is no solar radiation. With this new construction component an extra thermal resistance is added. Since the air flow path is found between the inner window and the vertical shutter, meaning that for the same conditions thermal losses from inside to the air gap is unchange-

Fig. 12. Heat transfer by ventilation air, with system 1.

Fig. 13. Heat transfer by ventilation air, with system 2.

Fig. 14. Percentage of heat loss reduction vs. temperature differences between indoors and outdoors, without solar radiation.

Fig. 15. Percentage of heat loss reduction vs. solar irradiance.
above the outdoor air temperature. With solar radiation, air at least 3.9°C to a rise in the delivered air temperature, without solar radiation, of at least 1.5°C. In these conditions, the experiments carried out using this modified window system lead to a rise in the delivered air temperature, without solar radiation, of at least 3.9°C with system 1 and at least 1.5°C with system 2, above the outdoor air temperature. With solar radiation, air temperature minimum rise has doubled. The maximum values of the percentage of heat loss reduction (Figs. 14–16) obtained with these systems were the following: without solar radiation and with the solar shutter opened, 59% and 46%, with systems 1 and 2, respectively; without solar radiation and with the solar shutter closed, 63% and 58%; in the presence of solar radiation, 131% and 134%.

This window system, that is applicable to both new and old buildings, has proved to be able to provide preheated ventilation air in winter time, by recovering part of the heat losses from indoors and by transferring solar radiation heat gains. This kind of system helps to reduce the global heating energy needs of a building, in winter, since it can lead to a significant reduction of the heat loss through ventilation. Furthermore, with the highly insulated envelopes of modern buildings and the correspondent low transmission losses, the heat losses through ventilation became an important part (sometimes the most important) of the total heat losses of the buildings. Therefore, the cost of the initial investment on heating devices could also be reduced as a consequence of preheating the ventilation air. Finally, it must be noticed that ventilated double windows are quite inexpensive and easy to install and offer a wide diversity of design. Its optimization however, due to the large number of design and operating related parameters and because of the time needed for testing, demands the use of a simulation code. The obtained results are encouraging for the adoption of this kind of window system.

5. Conclusions

This paper presents some results of a wide experimental study performed on a two ventilated double window systems exposed to real outdoor weather conditions. This study aimed to characterize the use of this double window as a passive system for the preheating of ventilation air. Air temperatures, solar radiation and air speed were measured to get information about the way the temperature of the delivered air at the outlet of the system varies with the influent factors. In this paper, the relationship between the solar irradiance, the air flow rate and the temperature of the air entering the room was described. The results indicate that there is a good correlation between solar irradiance and the air temperature increment within the air channel but a very low direct correlation was found between solar irradiance and the air flow rate. A good correlation was shown between indoors/outdoors temperatures difference and the air temperature increment within the air channel.

During the periods of experimental measurements outdoor temperatures varied between –6.6°C and 16.6°C and the indoor air temperature was kept at around 20°C. In these conditions, the experiments carried out using this modified window system lead to a rise in the delivered air temperature, without solar radiation, of at least 3.9°C with system 1 and at least 1.5°C with system 2, above the outdoor air temperature. With solar radiation, air

![Graph](image)

Fig. 16. Percentage of heat loss reduction vs. temperature differences between indoors and outdoors, with the shutter closed and without solar radiation.

References