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Assessing Thermal Comfort Due to a Ventilated Double Window

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Abstract. Building design and its components are the result of a complex process, which should provide pleasant conditions to its inhabitants. Therefore, indoor acceptable comfort is influenced by the architectural design. ISO and ASHRAE standards define thermal comfort as the condition of mind that expresses satisfaction with the thermal environment. The energy demand for heating, beside the building's physical properties, also depend on human behaviour, like opening or closing windows. Generally, windows are the weakest façade element concerning to thermal performance. A lower thermal resistance allows higher thermal conduction through it. When a window is very hot or cold, and the occupant is very close to it, it may result in thermal discomfort. The functionality of a ventilated double window introduces new physical considerations to a traditional window. In consequence, it is necessary to study the local effect on human comfort in function of the boundary conditions. Wind, solar availability, air temperature and therefore heating and indoor air quality conditions will affect the relationship between this passive system and the indoor environment. In the present paper, the influence of thermal performance and ventilation on human comfort resulting from the construction and geometry solutions is shown, helping to choose the best solution. The presented approach shows that in order to save energy it is possible to reduce the air changes of a room to the minimum, without compromising air quality, enhancing simultaneously local thermal performance and comfort. The results of the study on the effect of two parallel windows with a ventilated channel in the same fenestration on comfort conditions for several different room dimensions, are also presented. As the room dimensions' rate changes so does the window to floor rate; therefore, under the same climatic conditions and same construction solution, different results are obtained.

1. Introduction

The perception of indoor comfort may include several different factors with or without relation between each other. It is well known that different people have different perception of the comfort factors in a building. Among those factors, one may include olfactory, acoustical quality, lighting conditions, glare, air quality, draught, view to the outside, thermal conditions, etc. Thermal comfort conditions were defined by scientific work being established in standards, which relate air velocity, temperature and asymmetric thermal radiation. Thermal comfort models can be found in two different Standards, ISO 7730 [1] and ANSI/ASHRAE 55 [2], based on the "Predicted Mean Vote" (PMV). The

PMV index is related to the operative temperature where the mean radiant temperature is included. Therefore, the response of a dynamic system construction is very important when comfort is to be achieved. The ventilated double window has its surface temperature dependent on the temperature difference between both ambient, on incident solar radiation and also on air stream. Once its channel is naturally ventilated, the intensity of the air flow influences the overall temperature of its construction components. The "Predicted Percentage of Dissatisfied" (PPD) is calculated as a function of PMV. People usually avoid discomfort; what relates to windows these are opened and closed by the users as pleased [3]. An operated vent should also be taken into consideration if an increasing air flow causes discomfort. Therefore, any building component must also be assessed to what concerns human indoor comfort.

The comfort impact of windows is strongly influenced by several mechanisms. Apart from the local comfort above indicated, the absorption of solar radiation by the user may be unpleasant [4]. Incident solar radiation on this window system heats up its elements increasing the temperature of its surfaces. Part of the solar radiation is transmitted inside through the glasses, with incoming heat to the ambient. Architectural parameters can be evaluated as the percentage of glazed area, type of window, air supply, day lighting and solar effect. As for a window, the view to the outside depends strongly on the location of the building and its surroundings. The quality of the frame, the glazing and the shading device are the most important factors to take into account in the window design to fulfill the overall comfort requirements [5]. Thermal strategies are crucial for the architecture design decisions. They must take into account the building shape proportions, apertures and the required ventilation, as well as the selection of materials and products. This study will consist on the characterization of the local comfort conditions based on the local climate and the air change under natural ventilation.

The use of a ventilated double window to preheat the incoming air of a naturally ventilated building replaces traditional ventilation systems and changes the proprieties of a fenestration, which is supposed to be fitted with a common and very tight window. Some comparisons are now presented between this construction system, common windows and also traditional ventilation system. A conclusion that may be reached is that it is possible to save energy keeping the minimum required ventilation without disregarding the minimum comfort. In consequence, the study of local thermal comfort is of special interest in future energy saving researches. This paper also presents an approach to an ideal room geometry, to accomplish the need for comfort during the winter, when fitted with a ventilated double window. Knowing that comfort can also be dependent upon room and window's geometry, this analysis could be endless. Some limits were defined for this study.

2. Methodology

2.1. The passive system under analysis

The ventilated double window is composed of two parallel windows in the same façade opening, forming a channel through which airflows, where a shutter may operate between them. The air that circulates through this channel is warmed by the heat extracted from the windowpane surfaces, which are warmed by the heat loss transmitted from indoors and by solar radiation. The ventilated double window serves as a heat exchanger, recovering part of the heat losses through the inner window and providing extra solar gains in winter conditions. Besides this function, it is still a window offering a view to the outside and admitting daylight. The double window configuration tested [7] (system 1) corresponds to an outer window with a standard white aluminium frame fitted with a 6 mm single transparent glass and a similar inner window. These represent a double casement of 1.43 m width by 1.00 m height, being the glazing 56.5% of the whole window area. A second system tested (system 2) provides the inner window with a double-glazed (4 + 12 + 4 mm) transparent unit. The material characteristics of the windows are shown in Table 1.

Table 1. Material characteristics

	Transmittance	Reflectance	Absorption
Single glass, 6 mm	0.79	0.07	0.14
Double glass, 4+12+4 mm	0.70	0.13	0.10
White aluminium frame	0	0.60	0.40

The shutter used in these systems was a commercially available plastic shutter, which works between the two windows, usually closed during the nighttime. When closed, the ventilated channel is divided into two, being the new ventilation path between the shutter and the inner window. With no sun, the air flow temperature depends only on the thermal losses from indoors. From the previous tests and for the purpose of this study one may assume a delivered air flow rate from 15 m^3/h to 45 m^3/h, with a mean value of 30 m^3/h. However, to maximize comfort in naturally ventilated buildings the designer should avoid problems with indoor air quality which provide motivations for excessive ventilation rates [3]. Due to the profile of air temperature in the air channel [8], for simplicity of this study a whole surface temperature of the window is assumed being equal to its mid height.

2.2. The studied room geometry

A work has been done by Ghisi and Tinker [9] to define an ideal window area for each room dimension ratio. Here, the integration of daylight and artificial light in relation to window and room size was studied. For the purpose of this study, the same room ratio of width and depth of 2:1, 1.5:1, 1:1, 1:1.5 and 1:2 are used. These room ratios were chosen in the referenced study to compare the amount of daylight reaching the working surface with wide-shallow rooms and narrow-deep rooms. In this study the influence of the ventilated double window on the thermal comfort of each room size is compared. The room area is of 17.86 m^2 with a height, from floor to ceiling of 2.80 m.
Table 2 presents the room dimensions for each of the room ratios and window ratio.

In order to demonstrate the impact of this window system configuration described above, with the same window area but different locations and room ratios, a comfort assessment is carried out for the geometry and dimensions above referred. The window is positioned either in the middle of the only outer facade or in one end. Consider a person sitting (1 met) in several locations, 1 m from the nearest wall and in middle positions of the room (1 to 9 in Fig. 1), wearing typical indoor clothing (0.75 clo). The thermal property of the exterior wall is 0.45 W/m^{2o}C as in Ghisi and Tinker [9]. The remaining walls, floor and ceiling are indoor partitions, heated up to the same temperature as indoors.

Table 2. Room dimensions for each room ratio

Room ratio	2:1		1.5:1		1:1		1:1.5		1:2	
Dimension (m)	W	D	W	D	W	D	W	D	W	D
	5.98	2.99	5.18	3.45	4.23	4.23	3.45	5.18	2.99	5.98
Window/Wall (%)	8.55		9.87		12.09		14.80		17.09	
Glass/Wall (%)	4.83		5.58		6.83		8.36		9.66	

The surface temperature depends on the physical properties and the temperature difference between both environments. In the case of this ventilated double window, the air stream passing between windows influences the overall surface temperature. When the air flow increases, more heat is removed from the surfaces causing a decrease in the surface temperature and vice versa.

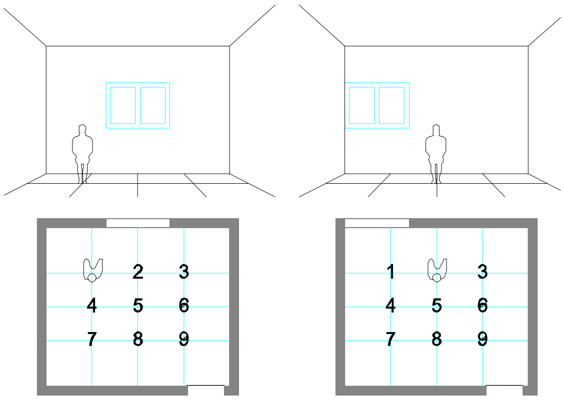

Figure 1 – Window and person's positions

3. Results and discussion

3.1. Radiant asymmetry from windows

During previous field tests, several thermocouples were used to measure the indoor and outdoor air temperature and also at mid height and at the top of the air channel (outlet), as reported by Carlos et al. [7]. A comparison between these measured air temperatures are shown in Figure 2 obtained with both systems. The Outdoor is the ambient air temperature, the outlet is the air inlet for the room and the channel is the space between windows. As it was expected, the air temperatures within the air channel and at the outlet were always above outdoor temperature, when indoor temperature was kept at 20ºC.

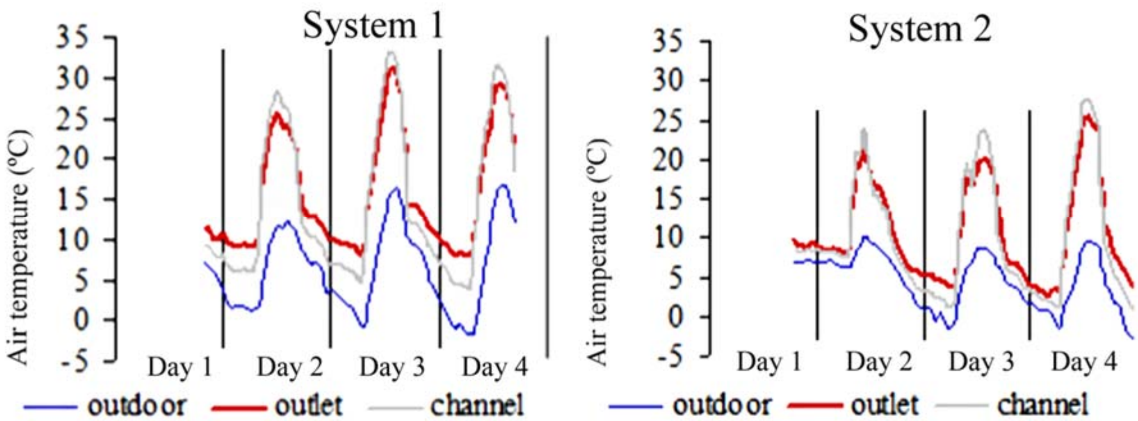

Figure 2. Air temperature (ºC) with systems 1 and 2

The inside surface temperature of the window may be found from:

$$\theta_s = \theta_{in} - \frac{Q_{loss}}{A_i h_i} \tag{1}$$

Where, θ_s and θ_{in}, represent the temperature of the inner surface of the window and the indoor air temperature (ºC), Q_{loss} represents the heat flux from indoors to the air channel between the windows (W), A_i is the inner window area (m^2) and h_i the inner surface thermal conductance ($W/m^{2o}C$), and,

$$Q_{loss} = A_i U_i \Delta\theta_{in-ch} \quad (2)$$

Where, U_i is the heat transfer coefficient of the inner window (W/m^{2}ºC) and $\Delta\theta_{in-ch}$ the temperature difference between indoors and the air channel of a ventilated double window (ºC). The composition of each system and the presence or not of the shutter also influence the temperature of the windows. Figure 3 shows the estimated inner surface temperature of both systems, with and without a shutter for different airflow patterns.

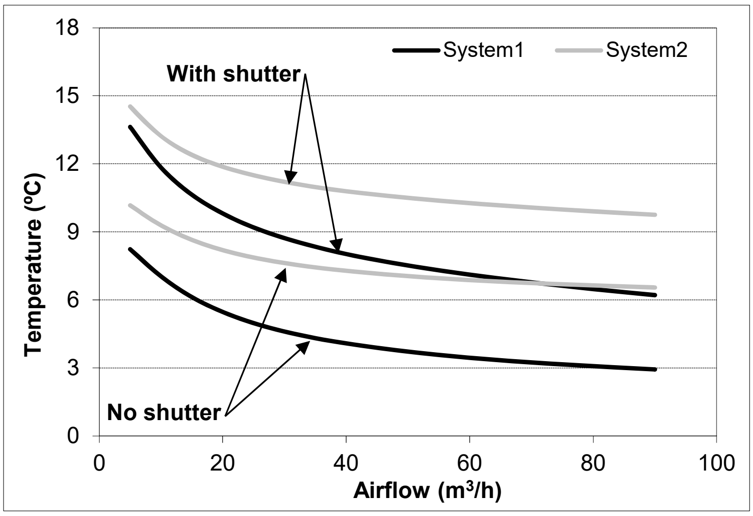

Figure 3. Window's inner surface temperature

When the airflow increases, the air temperature always decreases. This causes a higher heat transfer between the window and the passing air, allowing higher heat recovery from a window by the air stream, reducing the temperature of the inner window, which are critical for obtaining local thermal (dis) comfort. A system with a closed shutter with the air stream passing between the inner window and the shutter, the temperature of the window rises when compared to previous situations due to the reduction of heat transfer through the inner window.

3.2. Natural ventilation

The ventilated double window used for the current research has an air inlet and also an outlet, with an area of about 440 cm^2 installed at the top of the inner window (air inlet for the room). The mean air flow rate observed in the experiments was about 30 m^3/h [12]. For this air change rate, the tested ventilated double window is suitable for a 12 m^2 room. The obtained results from the experiments were done on a minute basis. During the whole observation period, the air velocity registered at the outlet has reached about 0.60 m/s. This represents an air velocity inside the room always below 0.01 m/s, according to the expression given by Liping and Hien [13] or Olgyay [14]:

$$V_i = \frac{VACH}{S3600} \approx \frac{C}{P} m \quad (3)$$

, where, V_i is the mean inside air speed (m/s), V is the volume of the room (m^3), ACH, is the air change per hour, S, is the section area of the room (m^2), C is the air flow rate (m^3/s), P is the air flow pattern (m^3) and m is the mean distance between inlet and outlet of the room (m). As the air velocity is far below the maximum value recommended of 0.15 m/s [1], this should be barely perceptive despite the resulted turbulence. Under this ventilation pattern, local discomfort due to draught is unlikely to occur, with a very low Draft Risk.

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Table 3. Minimum allowable outdoor temperature of different windows

Window type	Airflow m^3/h	U-value ($W/m^{2o}C$)	Minimum outdoor temperature (ºC)
From Huizenga et al. [11]			
Clear double glazing, wood frame		2.6	0
Clear double glazing, thermally-broken aluminium frame		3.3	5
Low-ε double glazing, wood frame		1.9	-8
Low-ε double glazing, vinyl frame		2.1	-6
Low-ε triple glazing, wood frame		1.2	-27
Low-ε triple glazing, vinyl frame		1.4	-20
From the present study			
System 1	15	*5.69	-4
	45		-1
System 2	15	*4.18	-9
	45		-6
System 1 with shutter	15	*5.69	-14
	45		-6
System 2 with shutter	15	*4.18	-23
	45		-14
*Inner Window and Outer window U-value = 5.69 W/(m2ºC)			

According to the ISO 7730 [1], the empirical termed "Draft Risk" (DR), i.e. the percentage of people dissatisfied due to draught can be predicted using an expression that takes into consideration the local air temperature (θ_a, in ºC), the local mean air velocity (v_a, in m/s) and the local turbulence intensity (Tu, in %), as:

$$DR = (34 - \theta_a)(v_a - 0.05)^{0.62}(0.37 v_a Tu + 3.14) \tag{4}$$

The temperature of the incoming air, during winter time, is mostly lower than the inside temperature. In these circumstances the air flow that comes out from the ventilated window tends to drop down. The flow drops quickly to the floor for lower air temperatures. It comes furthest into the room for higher air flow rate due to increased stream velocity leaving the window, as was found by Southall [15] on similar system. This is substantially different from traditional ventilation systems, when the incoming air, on crossed ventilation is usually near the floor. As Ayata and Yildiz [16] stated, from the geometric optimization point of view, both size and position of windows in buildings are important parameters to obtain a uniform indoor air velocity distribution. A person near the window may feel discomfort due to a vertical air temperature difference above the floor which should be less than 3ºC [1]. This discomfort penetrates far into the room when the stream velocity at the outlet is higher. In a previous study [7], it has been shown that the temperature of the incoming air of the ventilated double window was always higher than outside. When comparing this ventilation to the traditional one, the air flow delivered by the ventilated window is relatively warmer, being, at the outlet, about 8ºC higher than outdoor air temperature for a temperature difference between indoor and outdoor of 20ºC. When the stream reaches the floor due to convection exchange and flow mixing, the air temperature will be higher than at the outlet. Moreover, Toftum [17] has shown that the mean air velocity under 0.1 m/s has 0% of the percentage of dissatisfied due to draught. As Rabah [18] stated, the air movement can produce different thermal effects at different air temperatures as it increases convective heat loss, as long as the temperature of the moving air is less than the skin temperature. Moreover, as the air motion increases, the thermal losses from the body also increases, which can lead to unpleasant feelings. However, according to thermal comfort standards [1] [2], 80% of all adults dressed for winter indoor conditions find temperatures acceptable between 20 and 23.5 ºC, a relative humidity of 30–60% and the air velocity at 0.15–0.25 m/s. Despite the thermal comfort, it is also possible to save energy if the number of air changes is reduced to the minimum required.

3.3. Room comfort

The relative position of a person in a room determines the view factor and hence the radiation heat exchange (long-wave) between the person and the surfaces. The view factors were estimated according to the method proposed by Fanger [6]. The mean radiant temperature for a person is calculated after accounting for all view factors between the person, the surrounding surfaces and surface temperatures, as:

$$t_{mr\_p} = F_{p-1}t_1 + F_{p-2}t_2 + \ldots + F_{p-n}t_n \tag{5}$$

Where t_{mr_p} is the mean radiant temperature for a person (ºC), $F_{p\text{-}n}$ is the angular factor between a person and a surface and t_n is the temperature of surface (ºC). The operative temperature is calculated as:

$$t_o = At_a + (1 - A)t_{mr} \tag{6}$$

Where, t_o is the operative temperature (ºc), t_a is the air temperature (ºC), t_{mr} is the mean radiant temperature (ºC) and A is related to air velocity (V, in m/s), being 0.5 if V < 0.2 m/s, 0.6 if 0.2 ≤ V < 0.6 m/s or 0.7 if 0.6 ≤ V ≤ 1 m/s. PMV and PPD indexes were calculated based on ISO's thermal comfort, which is a condition in which 80% of people do not express dissatisfaction. Figure 4 shows the operative temperature for the nine-person's location in the room and for the fifth room ratio. A lower operative temperature was found when a person sat near the window, as it was expected, however there is little difference on the operative temperature across the room. A higher operative temperature is found for a position far from the window.

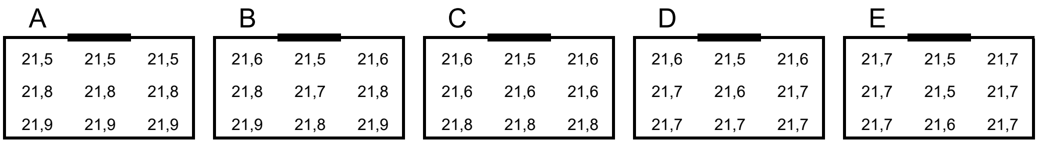

Figure 4. Operative temperature (ºC) for nine locations in five room ratios as in Table 2

PPD was found to be of 8.1% 1 m from the window. This is also true at any of the three locations ~~the~~ nearest to the exterior wall, for the narrowest room, being the window to wall ratio (WWR) of 0.22. As higher the WWR the higher is the view factor between the window and the person. For the lowest WWR, PPD is of 7.4% for the locations 1 and 3, while in front of the window it is still 8.1%. At the back of the room, when the view factor (window-person) is lower, the operative temperature is higher, being the highest for the longest room with PPD of 6.7%. Mean value of PPD shows that 5% to 10% of the people seem to be satisfied, however always slightly cold with PMV from -0.3 to -0.4. Highest thermal comfort is achieved in the middle of the room for the narrowest/longest room. Table 4 shows PMV and PPD indexes for the mean airflow rate (30m^3/h) at the middle of the room and the window at the centre of the façade.

Table 4. PMV and PPD at the middle of the room and the window at the centre of the wall.

	A	B	C	D	E
PMV	-0.31	-0.31	-0.34	-0.36	-0.39
PPD	7.00	7.00	7.35	7.73	8.14

Moving the window to the corner of the room (Fig. 1) the operative temperature on each place also changes. Table 5 shows PMV and PPD indexes for the mean airflow rate (30m^3/h) at the middle of the room and the window in the corner of the room. Comparing both tables (4 and 5) thermal comfort has improved on room ratio D and E.

Table 5. PMV and PPD at the middle of the room and a window at the corner

	A	B	C	D	E
PMV	-0.31	-0.31	-0.34	-0.34	-0.34
PPD	7.00	7.00	7.35	7.35	7.35

Figure 5 shows PPD for three different values of airflow rates (15, 30 and 45 m^3/h) for the three locations in front of the ventilated double window for the room ratio 1:1. A decreasing trend of PPD was observed when one gets away from the window. However, the shortest room has obtained a PPD from 7.4 to 7.7 when the window was at the centre of the façade.

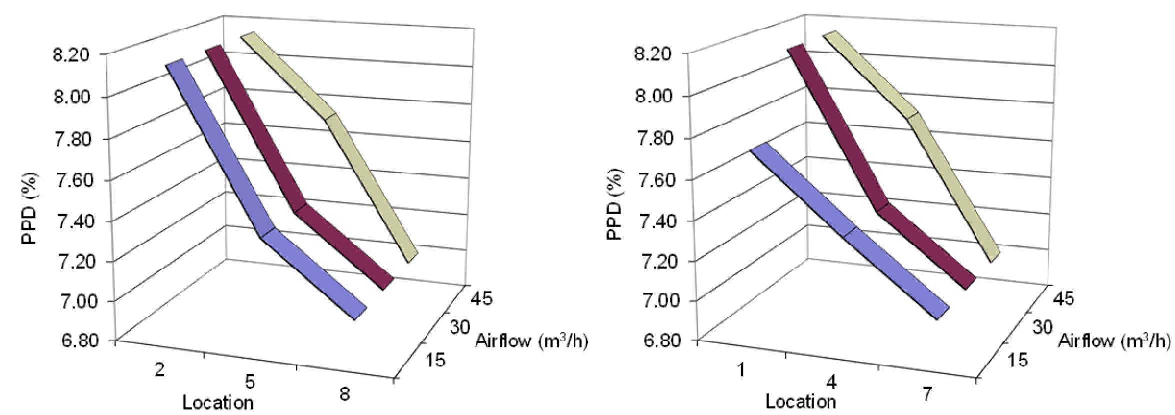

Figure 5. PPD of the room ratio 1:1 in front of the window for different positions and air flow rates

A model outlined by Fanger [6] is used to estimate the mean radiant temperature. This is done disregarding the location of the person, as:

$$t_{mr} = \frac{A_1 t_1 + A_2 t_2 + \ldots + A_n t_n}{A_1 + A_2 + \ldots + A_n} \tag{7}$$

Where t_{mr} is the mean radiant temperature (ºC), A_n is the area of the surface (m^2). For the defined peak 45 m^3/h of airflow through the window's air channel, the asymmetry temperature of the overall exterior wall comes within the ISO Standard's recommended maximum limit of 10ºC. The mean radiant temperature of the room was from 17.5ºC for the narrowest room to 18.8ºC for the widest room. Although, being the window's inner surface temperature of about 8ºC, who sits close to a window may feel discomfort, representing about 9.2ºC sensation when sitting 1 m in front of the

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window or 9.3ºC if the window is in the corner. Besides, as was seen above, PPD is always under 10%.

4. Conclusions

Nowadays, building construction incorporates new system construction where energy efficiency has become one of the most important principles in building design. Windows are important sources of natural light and views in buildings, and in many cases of fresh air. Opening or closing windows or opening or closing vents are actions that can be subject to various constraints, as thermal discomfort or energy waste related to excessive ventilation. The relationships between window properties, glazing-to-floor ratio, orientation, etc. affect energy consumption, thermal indoor environment and therefore thermal comfort.

The use of a ventilated double window to preheat the incoming air of a naturally ventilated building replaces traditional ventilation systems and changes the proprieties of a fenestration which is supposed to be fitted with a common and very tight window. Due to wind pressure and stack effect, the air coming from outside rises through the channel and enters the building through a vent on the top of the inner window providing the required ventilation air. The air that circulates through this channel is warmed by the heat extracted from the window pane surfaces which are warmed by the heat loss transmitted from indoors and by solar radiation. Besides this attribute, it is still a window offering a view to the outside and admitting daylight.

In this research, the analysis of thermal comfort in accordance with international standards based on the geometry and position of the opening, as well as the obtained air flow rate, has reached several conclusions applicable to this passive window design, regarding thermal comfort. The study was based on two similar systems that were previously tested and then fitted into a different shape room with different window and glazing to wall ratio, for the same natural ventilation strategy. The rooms have the same floor area and the same window area. The methodology cannot cover all possible hypotheses, but it does aim to show the most relevant relationships between window and enclosed space. The study points out the following main findings:

- Comparing both natural ventilation strategies, one directly from outside and the other through the ventilated window, the latter have significantly increased local thermal comfort with a very low value of Draft Risk;
- The use of a pre-warmed ventilation is feasible for any room geometry and a very harsh outdoor environment;
- The use of a protection shutter increases the window temperature and improves thermal comfort;
- The overall analysis lead to a PPD less than 10%, no matter where the person was sitting in the room, near or far from the window.
- In deep or narrow rooms, thermal comfort is not compromised with the use of a ventilated double window.
- The study also finds that minimum outdoor temperature without compromising indoor thermal comfort may drop down to about -23ºC.

This paper demonstrates that it is possible to use ventilated double windows to ventilate the enclosed space in winter without thermal discomfort. The factors that affect the performance of this system are the air change rate and the thermal losses through the windows. In all cases, comfort is improved when compared to common windows and direct ventilation which exhibits the best performance. An improved system would need to incorporate much more realistic geometry that defines the building occupants. Different parameters can alter the general thermal comfort in localized zones of the indoor environment such as the air velocity and vertical temperature difference, amongst others. The outcome would be a powerful tool to allow prediction of the comfort implications of this kind of ventilation system. It is believed that this kind of warming ventilator should be appropriate to any type of building in a ‘free-running’ ventilation mode.

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