Natural ventilation with a supply air window and motorized skylight: a field study

Diane Bastien1,*

1 University of Southern Denmark, Campusvej 55, Odense M, 5230, Denmark
*dib@iti.sdu.dk

Abstract. Fenestration systems that allow air to circulate between window panes, also called ventilated or airflow windows, can be a simple and efficient way to provide or remove air in a building. This contribution presents modelled and experimental results from a field study where a triple-glazed supply air window is installed in the bedroom of a small, airtight house. A motorized skylight in the living room completes this natural ventilation system. Simulations of the ventilated cavity following ISO 15099 reveal an effective U-value 12-26% lower and a heat recovery efficiency of 58-38% when under a natural ventilation regime and a constant airflow of 14.4 m³/s. The temperature and CO₂ levels in the bedroom and living room and window air outlet velocity were measured during 2 nights of single occupancy and 2 nights of double occupancy. Experimental data reveal a dynamic airflow through the ventilated window where local wind conditions have a large influence on the airflow. Effective average room ventilation flow rate between 27 and 42 m³/s were calculated with the transient mass method. This ventilation system is simple, silent and provided satisfactory indoor air quality in the building.

1. Introduction
Airflow windows are windows that are designed to introduce ventilated air in between window panes. They can operate in five different modes: 1) Supply air (outside air → inside air), 2) Exhaust air (inside air → outside air), 3) Indoor air curtain (inside air → inside air), 4) Outdoor air curtain (outside air → outside air) and 5) Airflow to return air (inside air → return air) [1].

Airflow windows have the capability to preheat fresh air and/or reduce solar gains. They are very flexible and can be designed as simple systems such as naturally ventilated buildings or as more complex systems coupled to HVAC equipment.

Early studies have shown that various configurations of airflow windows can generate significant benefits compared to non-ventilated windows. Wright [2] computed effective U-values with VISION that consider the energy gained by the supply air into an effective U-value. The resulting effective U-values where 31-58% lower for 11 different configurations of air supply ventilated windows made of 2-4 panes with low-emissivity coatings at various locations. He noted a proportionally higher effective U-value reduction with more insulating glazing configurations where the lowest effective U-value of 0.38 W/(m²°C) was reached with a four panes glazing with low emissivity coatings on surfaces #5 and #7.

Airflow windows are still generating significant interest in the scientific community and valuable studies have been more recently published about modelling methods for such systems. Glorian et al.[3] presented a comparison of Computational Fluid Dynamics (CFD) simulations and an analytical solution for isothermal panes. Their results show a satisfactory accuracy of the simplified model under lower flow rates (<15 m³/h). They expressed the need to validate their models with experimental data, as the difference between experimental and numerical results is often non-negligible.

Carlos and Corvacho [4] carried simulation of U-values of airflow windows. Two different airflow window configurations were installed on a test cell and tests were performed in real weather conditions under natural ventilation at night. The experimentally estimated U-values and flow rates were...
plotted. These experimental results show significant scatter, indicating a highly dynamic system influenced by changing local weather conditions.

The concept of airflow windows evolved over time where some authors proposed a new dual-airflow configuration, where in this case the window itself acts as a cross-counterflow heat exchange \[5\]. Conceptually very interesting, active ventilation within the frame is however required for driving the air flow as in this proposed design.

In this contribution, a field study is conducted in a small house equipped with a natural ventilation system that consists of a triple-glazed supply air window and a motorized skylight. This paper presents simulation results of the effective U-value of this system in natural and forced ventilation modes and experimental data. The \(\text{CO}_2\) levels, temperature and velocity at the air outlet of the window were recorded during 4 nights under single and double occupancy and effective room ventilation flow rates were calculated with the transient mass balance method.

2. Modelling of the airflow window

The geometrical parameters of the triple-glazed airflow window are provided in Table 1. The dashed line indicates the presence of a low emissivity coating on surface \#3.

### Table 1. Technical characteristics of the airflow window.

| Parameter                  | Symbol        | Value    | Schematic   |
|----------------------------|---------------|----------|-------------|
| Glazing height             | \(H_g\)       | 0.785 m  |             |
| Glazing width              | \(l_g\)       | 0.785 m  |             |
| IGU thickness              | \(\text{IGU}_{\text{gap}}\) | 16 mm   |             |
| Thickness ext. IGU pane    | \(t_{12}\)    | 4 mm     |             |
| Thickness int. IGU pane    | \(t_{34}\)    | 4 mm     |             |
| Thickness int. pane        | \(t_{56}\)    | 6 mm     |             |
| IGU filling gas            | \(\text{IGU}_{\text{gas}}\) | argon   |             |
| Ventilated cavity thickness| \(\text{cavity}_{\text{gap}}\) | 102 mm  |             |
| Emissivity of surface \#3  | \(e_3\)       | 0.039    |             |
| Emissivity of surfaces \#1,2,4,5,6 | \(e\)      | 0.84     |             |

An analytical model characterizing the heat transfer in the glazing system presented in Table 1 was developed in Matlab. Only heat transfer through the glazing is modelled here, the frame is not modelled at this early stage.

The imposed environmental conditions where defined as in ISO 10077 where values for boundary temperatures and surface coefficients as given in Table 2. The convective heat transfer of a closed cavity was calculated from the Nusselt number for vertical cavities as given in equations 48-52 from ISO 15099. The convective coefficient for a naturally ventilated cavity was calculated using equations 94-102 and 104-111 provided in ISO 15099 where

\[
h_{c,\text{vent}} = 2h_c + 4\nu \tag{1}
\]

The temperature profile in the cavity is assumed to follow an exponential rise. The mean air velocity in the gap \(\nu\) is estimated by performing a pressure balance; relevant equations and explanations can be found in the EnergyPlus documentation \[1\]. Linearized radiative heat transfer coefficients between surfaces in a cavity are calculated with

\[
h_r = \frac{\sigma(T_1^2+T_2^2)(T_1+T_2)}{1/e_1+1/e_2-1} \tag{2}
\]

The heat transfer coefficients and temperatures of the 6 glazed surfaces were calculated iteratively until convergence was reached (criteria: iterative difference below 0.05°C for all surface temperatures). Under the defined boundary conditions, 14 iterations were necessary.

The U-value of the double Insulated Glazed Unit (IGU) was calculated with the current model as well as with LBNL WINDOW 7.6. They are presented in Table 2 along with the U-value of the triple...
glazing as presented in Figure 1 assuming a closed cavity. The small differences between the U-values calculated by LBNL WINDOW 7.6 and the current model are likely explained by alternative calculation methods for radiative heat exchange (based on radiosities in ISO 15099).

The current model was then employed to calculate the U-value of this glazing system now under natural ventilation. Inducing air circulation in the ventilated cavity increases the convective heat transfer coefficient, thus resulting in a higher U-value.

It is of particular interest to estimate an effective U-value that takes into account the heat transfer through the glazed component and the heat recovered by the air flow. This would allow the modelling of airflow windows in conventional building simulation software. However, such an effective U-value is highly dependant on the dynamic of the system and especially the air flow rate.

Following a similar approach as Carlos and Corvacho [4], an effective U-value was computed as

\[
U_{\text{eff}} = \frac{Q_{\text{loss}} - Q_{\text{vent}}}{A_g(T_i - T_o)} \tag{3}
\]

\(Q_{\text{loss}}\) is defined as the heat loss between inside and the ventilated cavity, \(Q_{\text{vent}}\) is the heat recovered by the air stream where \(M\) is the mass flow rate in m\(^3\)/s.

\[
Q_{\text{loss}} = A_g U_w (T_i - T_{\text{cavity}}) \tag{4}
\]

\[
Q_{\text{vent}} = \rho_{\text{air}} c_{\text{p,air}} M (T_{\text{outlet}} - T_o) \tag{5}
\]

Another variable of interest is to evaluate the equivalent heat recovery of the supplied air, \(\eta_{\text{ventilation}}\), which can be defined as

\[
\eta_{\text{ventilation}} = \frac{(T_{\text{outlet}} - T_o)}{(T_i - T_o)} \tag{6}
\]

Under the imposed boundary conditions, the airflow rate circulating in the naturally ventilated window was computed as 7.7 m\(^3\)/h (2.1 L/s). This corresponds to an average air speed of 0.03 m/s in the ventilated cavity. At last, simulations under a forced fl ow rate of 14.4 m\(^3\)/h (4 L/s) were also performed. This flow rate corresponds to an average air speed of 0.05 m/s in the cavity. Results from these calculations are presented in Table 2.

| Environmental conditions | ISO 10077 (\(h_o=25\text{ W/(m}^2\text{K)}, h_i=7.7\text{ W/(m}^2\text{K)}, T_o=0, T_i=20^\circ\text{C}) | LBNL WINDOW 7.6 | Current model |
|--------------------------|--------------------------------------------------|----------------|--------------|
| Double IGU U-value       | 1.191 W/(m\(^2\))                               | 1.144 W/(m\(^2\)) |
| Triple glazing – closed cavity U-value | 0.926 W/(m\(^2\))                               | 0.931 W/(m\(^2\)) |
| Triple glazing – nat. vent. cavity U-value | 0.967 W/(m\(^2\))                               | 0.824 W/(m\(^2\)) |
| Triple glazing – nat. vent. effective U-value | 0.693 W/(m\(^2\))                               | 0.693 W/(m\(^2\)) |
| Triple glazing – 4 L/s effective U-value | 0.693 W/(m\(^2\)) | 0.693 W/(m\(^2\)) | 0.693 W/(m\(^2\)) |
| \(\eta_{\text{natural ventilation}}\) | 54.8%                                             |                |              |
| \(\eta_{4 \text{ L per s}}\) | 37.8%                                             |                |              |

The effective U-value under a natural ventilation regime is 12% lower than the closed cavity U-value, while a reduction of 26% is observed under a forced airflow of 14.4 m\(^3\)/h. The efficiency is however reduced with increased airflow rate as the outlet air temperature is reduced. This could also pose a threat to thermal comfort, but not necessarily considering the very low air speeds involved. Additional research in this area would be desirable.

3. Experimental results

An experimental airflow window was installed in the bedroom of a small recreative house. Other fenestration elements are comprised of additional conventional windows and a motorized skylight. A
schematic and a picture of the house are depicted in Figure 2. The airtightness of the house was measured in compliance with EN 13829 as 1.4 ACH (1.0 L/s/m²).

Measurements were taken during four nights in late March/Early April 2019 every 3 minutes except the anemometer which recorded data every 5 second. The bedroom sliding door had a 11 cm opening during the measurement period. The window was covered with a shutter at night. An effective ventilation flow rate \( Q \) was calculated from the monitored CO\(_2\) level in the bedroom by solving [6]

\[
C_{t+1} = \frac{60000 \, \alpha_p}{Q} \left(1 - \exp\left(-\frac{Q}{V} \, dT\right)\right) + (C_t - C_0) \exp\left(-\frac{Q}{V} \, dT\right) + C_0
\]

assuming that \( C_0 \) is at a level of 400 ppm and where \( \alpha_p \) is the CO\(_2\) production rate and \( V \) the volume.

Technical characteristics of the monitoring equipment are provided in Table 3.

**Figure 1.** Picture and schematic of the test house with location of monitoring equipment

**Table 3.** Technical characteristics of the monitoring equipment

| Parameter(s)        | Manufacturer | Type/Model | Accuracy                                      | Location                  |
|---------------------|--------------|------------|-----------------------------------------------|---------------------------|
| Air speed           | Testo 0635   | 1570       | ±(0.03 m/s + 4%) [0 to 20 m/s]                | Window outlet             |
| Temperature         | Graywolf     | Advanced   | ±0.3°C [0 to 70°C]                            | Living room/bathroom     |
| Relative humidity   |              | Sense Pro with ±2% [<80%] | ±3% ± 50 ppm | Living room/bathroom     |
| CO\(_2\)            | Green Eye    | TIM12 AZ-0003 | ±0.6°C                                      | 1 in bedroom and 1 in living room/electric panel |
| Temperature         |              |            | ±5% [10 - 90%]                                |                           |
| Relative humidity   |              |            | ± 40 ppm ± 3% m. v.                          |                           |
| CO\(_2\)            | PCE          | PCE-313A   | ±0.8°C                                       | Outdoor air               |
| Temperature         |              |            | ±3% [<70%], ±3% ± 1% m. v.                   |                           |
| Relative humidity   |              |            |                                              |                           |

Monitored CO\(_2\) levels in the bedroom and at two sites in the living room, effective ventilation flow rate, the temperature of outside air, indoor air and window outlet air and velocity are presented in Figures 2 and 3. During single occupancy, the skylight opening was 20% on March 30 and 10% on Apr 9th while the occupant went to bed at around 21.30 and got up at 6.00. A similar slow CO\(_2\) rise can be observed during both days in the bedroom with a maximum CO\(_2\) level around 1000 ppm at the end of the night.

It was significantly colder on April 9th, about 8°C lower on average with below zero temperatures. A consistent window outlet air velocity profile is observed on March 30th, with dynamic variations between 0 and 0.3 m/s. A changing profile is observed for April 9th, with high variations early in the night, where some negative wind speeds were recorded, indicating reverse flow, and more stable air velocities close to 0.1 m/s during the rest of the night. An increased inter zone air exchange can be observed in early morning on March 30th, before the occupant get up and open the door, likely due to increased movements and thus air mixing.

During double occupancy, a notable CO\(_2\) rise is observed on April 5, accompanied with highly dynamic air velocities, sometimes negative. The peak is reached around 1am, which coincides with the end of occasionally negative air velocities. During April 6th, the CO\(_2\) levels monitored at the three locations are practically identical, indicating high inter zone air mixing.
Figure 2. CO₂ level, effective ventilation rate, temperature and air velocity during single occupancy

Figure 3. CO₂ level, effective ventilation rate, temperature and air velocity during double occupancy
Figure 4. Picture of the airflow window showing the anemometer location (left)

Table 4. Comparison of the effective ventilation rate with skylight opening and average air speed

| Date       | Average Q (m³/h) | Skylight opening | Average air speed (m/s) |
|------------|------------------|------------------|-------------------------|
| March 30   | 28.8             | 20%              | 0.123                   |
| April 5    | 37.8             | 35%              | 0.018                   |
| April 6    | 41.8             | 25%              | 0.079                   |
| April 9    | 26.8             | 25%              | 0.075                   |

The window outlet air temperature is generally following very closely the room air temperature, indicating that at the low air speeds involved here, the sensor’s response is dominated by the bedroom temperature. Locating the sensor in the ventilated cavity would be necessary to capture the air temperature rise, which would then necessarily alter the airflow to some extent.

The effective ventilation rates calculated by performing a CO₂ mass balance at every time step exhibit significant variations but are generally around 20 to 40 m³/h. This parameter captures not only the fresh air supply through the window but also infiltration and inter zone air exchange. Infiltration is expected to be minimal, but the recorded data show significant inter zone air exchange during some periods. The effective U-values in section 2 were calculated under natural ventilation at 7.7 m³/h and a constant air flow at 14.4 m³/h. The experimental data presented here allow to infer that these values are reasonable and likely representative of typical average airflows in this window, but also indicate that wind seems the most influential parameter defining the actual airflow transferred to the room.

4. Conclusion
This contribution presents simulation and experimental results characterizing the behaviour of a naturally ventilated triple-glazed air supply window. Simulations of the ventilated cavity following ISO 15099 yield an effective U-value 12-26% lower and a heat recovery efficiency of 58-38% when under a natural ventilation regime and a constant airflow of 14.4 m³/s.

Experimental data reveal a fairly dynamic airflow through the ventilated window. Local wind conditions might have a larger influence on the airflow rate than the skylight opening; additional investigation of the thermal performance under different weather conditions would be desirable. Effective average room ventilation rates ranged between 27-42 m³/h during the four monitored nights. This ventilation system is simple, silent and provided satisfactory indoor air quality in the building.

References
[1] U.S. Department of Energy. EnergyPlus Engineering Reference.
[2] Wright JL. Effective U-values and shading coefficients of preheat/supply air glazing systems. Sol energy Soc Canada 1986; 219–224.
[3] Gloriant F, Tittelein P, Joulin A, et al. Modeling a triple-glazed supply-air window. Build Environ 2015; 84: 1–9.
[4] Carlos JS, Corvacho H. Evaluation of the thermal performance indices of a ventilated double window through experimental and analytical procedures : U w -values. 2014; 63: 747–754.
[5] Gosselin JR, Chen Q (Yan). A computational method for calculating heat transfer and airflow through a dual-airflow window. Energy Build 2008; 40: 452–458.
[6] Batterman S. Review and extension of CO2-based methods to determine ventilation rates with application to school classrooms. Int J Environ Res Public Health 2017; 14: 1–22.