EVALUATION OF VENTILATIVE COOLING IN A SINGLE FAMILY HOUSE

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ABSTRACT

A characterization and modeling process has been conducted in order to better account for ventilative cooling in the evaluation of energy performance of buildings. The proposed approach has been tested using a monitored zero energy Active House (Maison Air et lumière) located near Paris.
The air flow characteristics of a pivoted roof window have been evaluated using a test chamber installed in the CES laboratory. A CFD calculation has been used to model the air movements inside the chamber and derive the relevant location for the pressure sensors. The air flow rate has been measured as well as the pressure difference on both sides of the window. A flow coefficient and a flow exponent of a power law equation have been identified for different window opening angles.
Flow rates have been evaluated in “Maison Air et lumière” using an air flow model (CONTAM) with the characteristics evaluated previously. These results were compared with on site tracer gas measurements.
Indoor air temperatures in the house have been evaluated using dynamic thermal simulation complemented with air flow calculation (PLEIADES+COMFIE) in order to evaluate the potential of ventilative cooling.
Around 5K indoor temperature reduction has been obtained by the use of ventilative cooling, both by simulation and measurement: with similar outdoor conditions, the interior air temperature of the house was 5K lower using ventilative cooling than without any opening of windows.
The air exchange rates were between 10 and 22 air change per hour even with limited wind velocities (between 2 and 3 m/s) and low temperature difference between outside and inside (0-3 K). An acceptable correlation was found between calculations and measurements.
The overall consistency between calculation results and measurements shows that this process, including the evaluation of air flow characteristics and the use of combined thermal and air-flow simulation, is feasible. The aim is to progress towards assessing the effects of ventilative cooling. Such a process could be used in a regulatory calculation, provided that this calculation integrates an appropriate model.

KEYWORDS

Ventilative cooling, Thermal simulation, airflow simulation, measurements, characterization of air flow

1 INTRODUCTION

Low energy buildings, being highly insulated, are subject to important overheating risks if no proper cooling strategy is implemented. Thermal simulation as well as experimental studies has shown the large potential of ventilative cooling [Ghiaus, 2005]. One barrier against this approach is the difficulty of evaluating air flows. Appropriate calculation methods and characterization of openings are needed, so that these systems can be dealt with in design, regulation and certification tools.
The present work aims at studying a characterization and modelling process allowing natural ventilation to be accounted for in the evaluation of energy performance and thermal comfort of buildings. The approach is tested using the monitoring system of the zero energy Active House Maison Air et Lumière, located near Paris.

In summary, the following steps have been performed.

- A test bench has been used to characterize the air flow features of a roof window (such features of roof windows are not well described in literature)
- These air flow features have then been used for numerical simulations of the air flows and air temperatures in the building
- On site measurements of air flows and air temperatures have been performed in order to get realistic data about natural ventilation and its contribution to summer comfort
- Comparisons between simulations and on site measurements have been performed in order to validate the models used to evaluate air flow rates through windows. These comparisons are also used for checking the relevancy of numerical simulations in terms of summer comfort

2 LABORATORY MEASUREMENTS

2.1 Description of the method

Before performing on site tests, a test bench has been built in the laboratory in order to identify air flow characteristics of a roof window. A ventilator is used to create a pressure difference in a test cell divided in two compartments. A roof window has been installed between the two compartments. The pressure difference $\Delta P = (P1-P2)$ is measured, as well as the air flow rate Q. The air flow rate and pressure difference have been varied in order to get a curve and to derive characteristics C and n of the roof window corresponding to the following equation [Axley, 2002], [Walton, 2010]:

$$Q = C\,(P2 - P1)^n \qquad (1)$$

The flow coefficient C, depend on the size and opening angle of the window. In a first approximation, C can be considered proportional to the section S corresponding to the geometrical opening section, which is commonly assumed using a discharge coefficient C_d (i.e. $C = C_d*S*(2/\rho)^n$, ρ being the air density). ΔP is in the range from 0.05 to 10 Pa. In the real house, it may be lower, depending on wind conditions, but it is hoped that the values of C_d and n will not vary too much. The laboratory test therefore provides two parameters that can be used in the analysis of on-site measurements, and that can be refined using a calibration step.

The correlation between ΔP and Q is derived from the measurements at different window opening areas. From equation (1) follows that

$$\ln Q = n*\ln\Delta P + \ln C \qquad (2)$$

2.2 Laboratory test results

An example of a fully opened window is shown in figure 1 in a double logarithmic presentation. n equals the slope of the curve, ie. n = 0.45 and lnC = -1.14 leading to C = 0.32
Similar analysis is performed for all six opening areas and shown in table 1.

100% opening refers to the maximum opening length of the actuator ~200 mm opening.

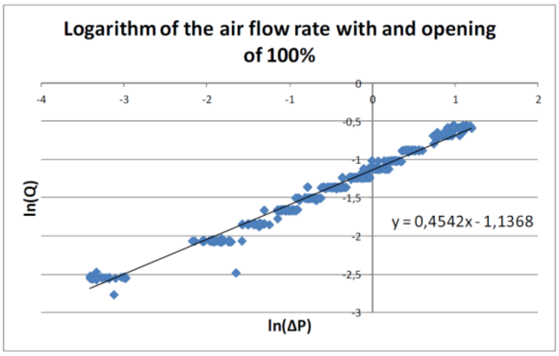

Figure 1. Air flow rate vs pressure difference for 100% opening length of the roof window.

With the assumption that the opening area *S* is around 0.07m² for 50% opening percent, we find a C_d value $C_d = C / S * (\rho/2)^{0,5}$ of around 0.75, which is near the standard values [Etheridge, 1996].

Table 1 Air flow characteristics of the roof window

Window opening percent [%]	n coefficient	C coefficient
50	0.49	0.074
60	0.46	0.12
70	0.45	0.17
80	0.48	0.22
90	0.45	0.27
100	0.45	0.32

3 ON SITE MEASUREMENTS

3.1 Description of the building

The 130 m² floor area extends over two storeys. The house is highly insulated and designed as a net zero energy Active House. Concrete slabs on the ground floor and first floor provide thermal mass. The window-floor ratio is nearly 1:3. All windows are equipped with dynamic solar protection and the operation of all systems in the building (heating, ventilation, shading window-opening, lighting etc) is fully automated.

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3.2 Measurements

Several tracer gas techniques can be found in the literature [Sherman, 1990]. CO2 concentration decay measurements have been performed in order to evaluate the air flow rate in the house and to compare it with values calculated using the laboratory characterization of the roof windows. Concentration decay is a widely used method to measure the air change rate in a building because it is the easiest to set up, it uses less tracer gas and it gives accurate results [Baptista, 1999].
In a second step, temperature measurements allow thermal simulation results to be compared in order to study the validation of the complete approach to evaluate ventilative cooling.

The house is equipped with a detailed monitoring and logging system providing event-driven data on indoor air temperatures and weather data. In addition the following sensors have been implemented:

- Anemometers and pressure difference (at different times for vertical and roof windows),
- Tracer gas concentration meters.

Tracer gas decay involves injecting a small amount of tracer gas, mixing it with the room air and then measuring the decay in gas concentration with time. The tracer gas was released inside the building and mixed with the inside air by use of a ventilator. The duration of each tracer gas measurement was 10 min including the release and decay. The experiments were carried out in both the living room on the ground floor and the south bedroom on the upper floor. For each room two scenarios have been adopted.

- Scenario n°1: Windows and doors are opened.
- Scenario n°2: Windows opened and doors closed.

3.3 On site air change measurements

For each room, the tracer gas tests have been executed during the morning noted (am) and the afternoon noted (pm). Therefore, four experiments have been conducted in each room.

Figure 2 shows as an example the relative CO_2 concentrations (CO2 concentration above outdoor level), measured in the living room for the two scenarios: internal doors being opened (blue curve) or closed (green curve). The continuous lines and the dashed lines correspond to respectively the measurements during the morning and the afternoon.

The air change rate is calculated from the tracer gas decay curve assuming the air-leakage rate remains constant throughout the measurement period and the incoming air mixes well with the indoor air.

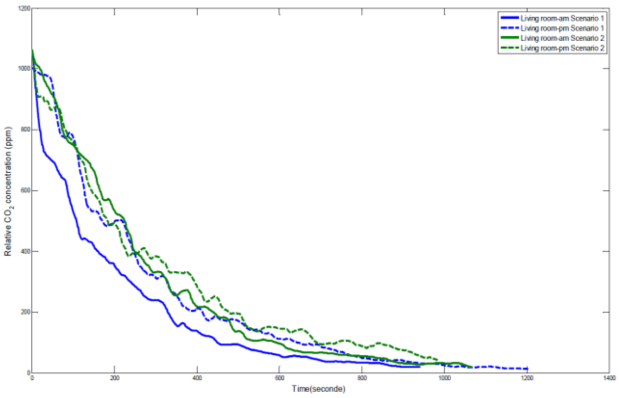

Figure 2. Relative CO_2 concentration in the living room during CO_2 decay test

The calculation of the air change rate is deduced from the general tracer gas mass balance equation [Cheong, 2001]:

$$V*dC_{int}(t) / dt = S(t) – Q(t) * (C_{int}(t) – C_{out}(t)) \quad (3)$$

where:

- $C_{int}(t)$ is the CO_2 concentration of indoor air (ppm)
- $C_{out}(t)$ is the CO_2 concentration of outdoor air (ppm)
- S(t) is the injection of tracer gas into the room (m^3*h^{-1})
- V is the indoor air volume (m^3)
- Q(t) the air flow rate (m^3*h^{-1})

Integration of (3) leads to an exponential function relating the concentration to the time, the air change rate being in the exponent: $(C_{int}(t) – C_{out}(t)) = C*e^{–Q*t/V}$ where C is a constant.

A linear regression is fitted : Log ($C_{int}(t) - C_{out}(t)$) = a t + b. The logarithm of the relative tracer-gas concentration is plotted against elapsed time. The slope of the line (a) is equal to the air change rate (Q/V, in ACH, i.e. Air Change rate per Hour) and b is a constant.
The relative CO_2 concentration profiles in the log-scale are presented for the living room in figure 3. Similar data have been derived for all scenarios and the results are shown in table 2 together with simulated values.

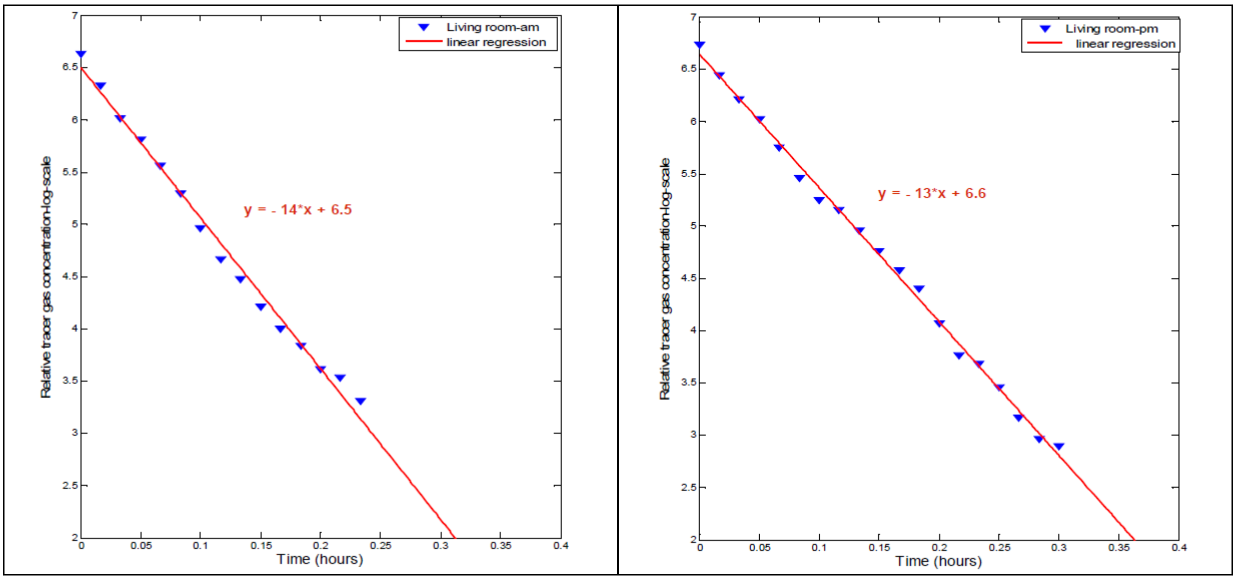

Figure 3 Relative CO_2 concentration profile in the living room. Morning (left) shows 14 ACH and afternoon (right) 13 ACH.

3.4 On site indoor temperature measurements

Inside air temperature measurements have been performed from 23 July to 20 August 2012, according to four scenarios successively:

- No natural ventilation (all windows closed), from 23 to 26 July
- With natural ventilation (all roof windows and top vertical windows are constantly open), without movable shading and with internal doors open (to get the maximal effect of natural ventilation), from 27 July to 3 August,
- With natural ventilation, with movable shading and internal doors closed (to get the minimal effect of natural ventilation), from 4 to 7 August (tracer gas and pressure difference measurements have been performed from 8 to 10 August),
- With natural ventilation, with controlled movable shading and internal doors closed, from 13 to 20 August.

4 AIR FLOW SIMULATIONS

Complementing monitoring results, numerical simulation constitutes another way to better understand the behavior of a building. Studying natural ventilation is improved by using both thermal and air-flow models.
Air flow simulation requires information about pressures on the external sides of the windows. These pressures can be evaluated in terms of the wind velocity and direction using pressure coefficients, C_p. We use the software “Cp generator” [cpgen.bouw.tno.nl/cp/] to find the values of C_p for all the 14 windows in the building.
The input file of the C_p generator software needs information such as the orientation of the house, the roughness of the terrain for different direction of the wind, some obstacles near the studied building, the direction in degrees of the north arrow as well as a short description of

the house, the roof and where the C_p value are to be calculated. The main problem comes from the description of the roof of the house. Only one pitched roof description is available, and it is not possible to have three different roofs in a row like in the investigated house. That's why we chose a unique angle of the roof of 45°.

4.1 Air flow simulations using CONTAM

Knowing the geometry of the house, wind pressure coefficients and the characterization of the windows, it is possible to perform an air flow simulation of the house and to compare the results with the values obtained from the tracer gas experimentation.
The air flow simulation is done using CONTAM7 [Axley, 2002] and [Walton, 2010], a multizone indoor air quality and ventilation analysis software. It allows the simulation of infiltration, windows, and room-to room airflows in building systems driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by the indoor and outdoor air temperature difference.

The simulation model of the house is simplified and takes into account five thermal and air flow zones: The living room and the mezzanine, each of the bedrooms and the bathroom at the first floor.
14 windows are modeled, and the corresponding C_p values have been calculated with "Cp generator". There are also 4 doors between the living room-mezzanine and all the other rooms. Each of these openings is modeled by a power law corresponding to a leakage area. For each item, a leakage area is given by the cross section of the window or the opened area of the door. The power law is then standard as in equation (1) with $C = C_d*S*(2/\rho)^n$.

The C_d coefficient is 0.6 for a vertical window [Walton, 2010] and 0.75 for a roof window (obtained via the laboratory test), and the flow exponent n is 0.65 for a vertical window and 0.5 for a roof window. The closed door has a standard value for the C_d coefficient of 0.6, and a flow exponent of 0.65 [Walton, 2010] with a leakage area of 0.03 m^2. An open door has the same parameters but a flow area of 2 m^2.

For each tracer gas experiment, the same case is simulated with CONTAM. The following table shows the results of air flow for the tracer gas experiments and using the software CONTAM. The results are given in (ach) with a volume of the living room + mezzanine zone of 340 m3 and the volume of the south bedroom at the first floor of 35 m3.

The power law model used for the window is not valid for the experiment in the bed room with closed doors. The stack effect is less important due to the closed door - a very small air flow is going under the door. The power law being a one way flow model, the air flow in the bedroom calculated using CONTAM is very small (0.6 ach for the morning case, 2 ach for the afternoon case) compared to the measured (13.4 ach for the morning case, 13.2 ach for the afternoon case). The stack effect being small, the opening model is different in these two cases: a two way flow model is used with two openings. One opening is the upper part of the open roof window, the other corresponds to the lower part. No laboratory test was done for this model, so the C_d coefficient used is a standard value given by CONTAM: 0.7, the flow exponent n being automatically 0.5. The results for two way flow are shown with * in table 2.

Table 2 Measured and simulated air change per hour (ACH)

		South bedroom temp	**North bedroom temp**	**Bath room temp**	**Wind speed m/s**	**Tracer Gas ACH**	**Simulated CONTAM ACH**
Morning	Closed door	23.7	21.3	22.5	3.6	13.4	13.9*
	Open door	23.7	21.3	22.5	2.8	22.5	20.6
Afternoon	Closed door	27.1	26.5	26.2	2.3	13.2	16.6*
	Open door	27.1	26.5	26.2	2.3	19.8	19.5
Morning	Closed door	24.2	22.5	23.3	3.6	13.4	14
	Open door	24.2	22.5	23.3	3.6	14.6	17.4
Afternoon	Closed door	26.5	25.2	25	2.9	10.6	13.2
	Open door	27	26.1	25.6	2.8	13.1	17

4.2 Thermal simulation of the house

A dynamic thermal simulation tool is used to evaluate temperature profiles in the house [Peuportier, 1990], which has been modeled using five thermal zones (identical to the air flow simulation). In this highly insulated building the effects of the ventilation flow rate is clearly visible in the calculated indoor temperatures.
The air change rate has a large influence on the temperature profiles. It can therefore be calibrated by minimizing the discrepancy between measured temperature profiles and simulation results [Mejri, 2011] using the climatic data corresponding to on site measurements (external temperature and solar radiation). This constitutes a third way to evaluate the global air exchange rate, and may be helpful to refine the characteristics evaluated in the laboratory benchmark, by taking into account the actual conditions in the real house. However such calibration step has not been conducted in the present study.
Another added value of numerical simulation is that once the model has been calibrated, temperature profiles with and without ventilative cooling can be compared under the same climatic conditions, in order to evaluate the effects of ventilative cooling.

Three simulations are conducted:

- Interior doors opened with the opening of the windows on July 26th
- Interior doors closed with the opening of the windows on July 26th
- Interior doors opened without any opening of the windows (in order to see the effect of absent natural ventilation)

Figure 4 presents the results of the first simulation for the ground floor bed room. The windows are opened during the 26th of July, at midnight for the simulation and during the morning in the measurements, therefore the results are different: this is a transition day.

During the first three days corresponding to the closed windows period, the temperature profile from the simulation follows the same tendency as the measured temperature inside the house but 0.5°C to 2°C higher or lower depending on the thermal zone. As the opening of the windows in the simulated case happens earlier during the night on the 26th day, the simulated temperature decreases more than the temperature inside the house, this is the transition day.

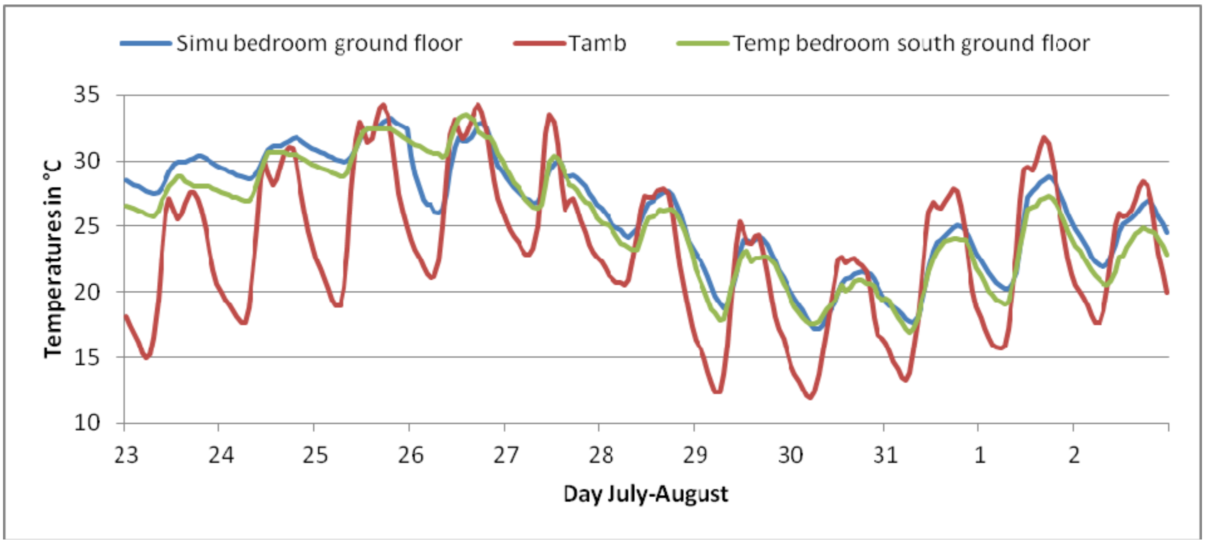

Figure 4 Example of simulated and measured indoor temperature in the ground floor bed room. Simulated indoor temperature in blue, measured in green and external temperature in red. Windows all closed until 26th – all open after, internal doors open.

After that it is possible to see the effect of the natural ventilation with the decrease of the temperature in a similar way for the simulation and the measurements.
The closed doors simulation results are presented in figure 5. The results are in line with the previous: Good correspondence between measured and simulated indoor sir temperatures.

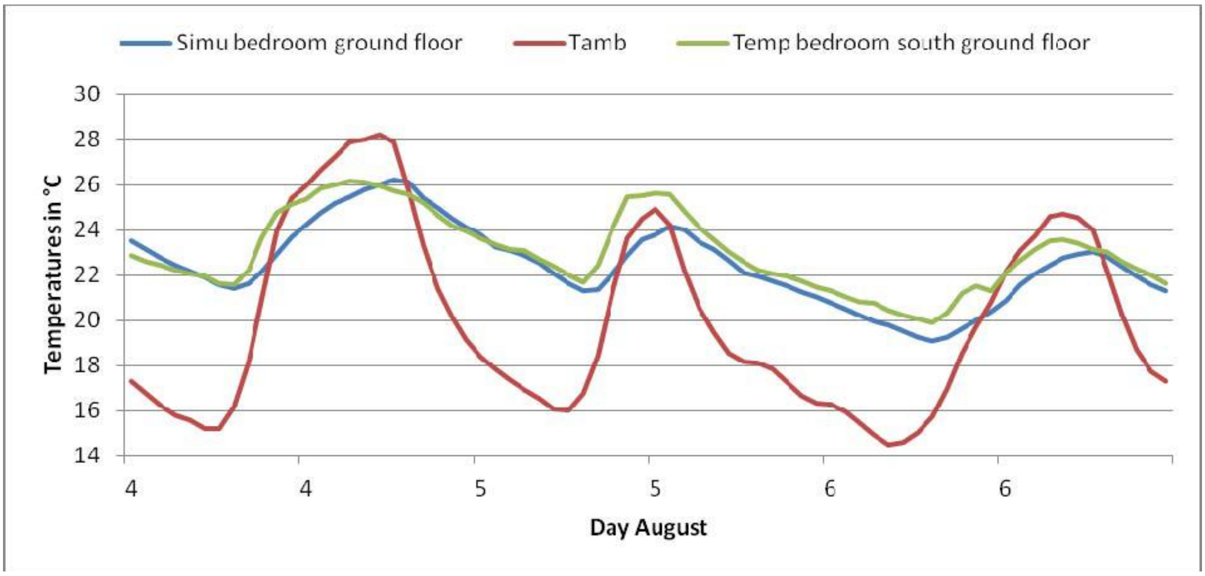

Figure 5 Example of simulated and measured indoor temperature in the ground floor bed room. All windows are open and all internal doors closed.

A third simulation has been conducted with the windows closed during all the period from July the 23rd to August the 2nd. It allows the comparison of the temperature with and without natural ventilative cooling. The results are shown in figure 6 for two thermal zones, the ground floor bedroom and the living room + mezzanine zone. The effect of natural ventilation is very important; there is around 5°C in difference between the indoor temperatures with and without the windows opening. We can see that the temperature when the windows are opened follows the ambient temperature but with smaller variations.

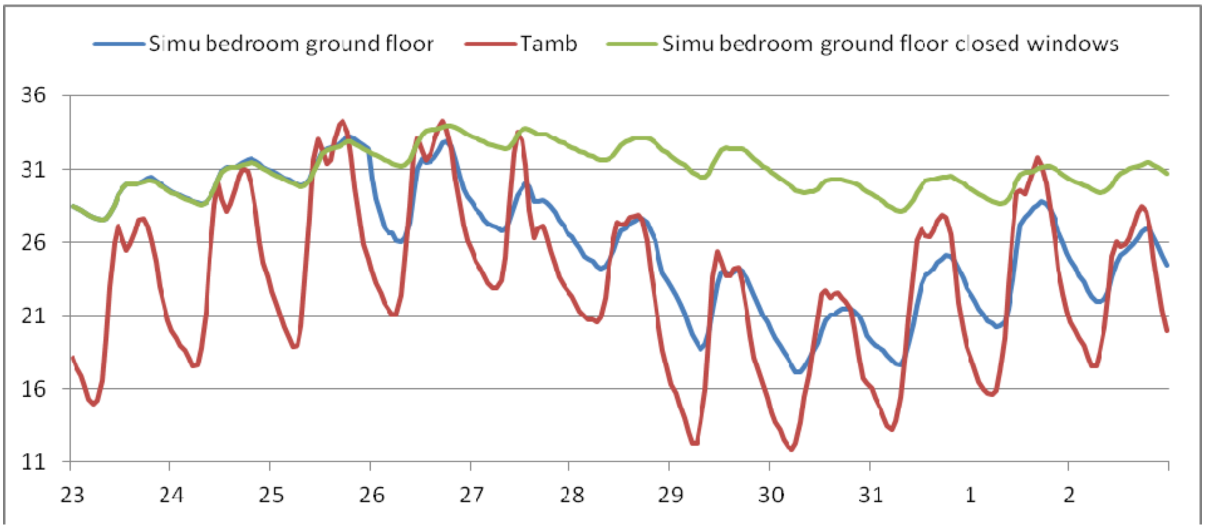

Figure 6 Simulated indoor air temperatures of the ground floor bedroom. Green: All windows closed. Blue: all windows opened from 26th of July. Red: Ambient temperature.

The work done on the thermal simulation of the house with a natural ventilation module could be improved by a calibration of the ventilative part of the thermal model, especially the C_p coefficients which are very difficult to measure or calculate. However, we are able to characterize the effect of the natural ventilation on the « Air et lumière » house, showing a large difference with and without the opening of the windows. This improved thermal comfort will be even better if the windows are opened only during the night, to take advantage of the night free cooling and avoiding venting with warm outdoor air.

5 CONCLUSIONS

The measurements performed in Maison Air et Lumière have shown that during the period without ventilation (end of July 2012), the temperature has reached 35°C. Ventilative cooling allowed a rapid reduction of this overheating, and temperatures stayed within the comfort interval (less than 27°C in the occupied rooms) during the rest of the measurements period. This shows that during summer, ventilative cooling is efficient.
10-22 ACH was measured even with times of low temperature differences and relatively low wind speed (between 2 and 3 m/s). In addition air flow rates were simulated in CONTAM for similar boundary conditions. Simulated and measured air flow rates correspond rather well with an average difference of 10% and local differences up to 30%.
In complement of measurements, dynamic thermal simulations have shown to reproduce the resulting indoor air temperature well with average difference between measured and calculated overheating of around 1K (average difference between indoor and outdoor temperatures). Thermal simulation has been used to evaluate the effects of ventilative cooling by comparing temperature profiles with and without ventilation during the same period, i.e. in the same climatic conditions. According to these results, indoor temperatures were decreased by about 5°C thanks to ventilative cooling. A further decrease will occur if the ventilation is controlled to avoid venting during warm periods.
The comparison between simulations and measurements gives confidence in the reliability of the model regarding both the evaluation of temperatures and flow rates even without detailed model calibration.
The consistency between calculations and measurements show that this process, including the evaluation of air flow characteristics using a laboratory test bench and the use of combined thermal and air flow simulation, is feasible and allows the effects of ventilative cooling to be assessed in a project. Such a process could be used in a regulatory calculation, provided that this calculation integrates an appropriate thermal and air-flow model.

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