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# Numerical Comparison of Ventilation Strategies Performance in a Single-family Dwelling

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## SUMMARY

A single-family house and its ventilation systems are simulated using SIMBAD Toolbox, a combined mass and heat transfer model implemented in MATLAB/Simulink environment. Numerical investigations are then performed with four ventilation systems for a heating period. This paper deals with the simulation results with regard to indoor air quality and energy demand. These results show that the best performances are obtained by using mechanical balanced ventilation: the total energy savings that can be expected, compared to the reference system, is about 22 to 31% depending on the efficiency of the heat exchanger. Balanced ventilation also appears to be an accurate strategy for assuring better IAQ, while the humidity-controlled ventilation systems, although allowing a great reduction in energy demand (18 to 22%), fail at times to ensure a good IAQ. Besides, natural ventilation system, though seems to be oversized, yields a worse IAQ performance and obviously a great energy losses (+18.5%).

## INTRODUCTION

Ventilation systems aim at maintaining a good indoor air quality (IAQ) within buildings. However, as envelope insulation is improving, the energy consumption due to ventilation has become important; this part is about 30-50% of the building total energy according to Liddament [1]. Therefore new ventilation strategies such as intermittent ventilation tend to reduce air change rates for achieving buildings energy requirements. It has also been shown that the choice of ventilation strategy can have a significant effect on energy consumption [2]. Thus, the evaluation of building global and long-term performance has become a subject of matter and several studies are carried out for this purpose. Afshari [3] has experimentally compared two ventilation strategies in a four-room house; the results show that, using demanded-controlled ventilation based on relative humidity, the ventilation rate would be reduced by 20-30% while maintaining an indoor climate according to the requirements, and consequently reduces the building energy consumption too. Besides, Jreijiry [4] simulated with SIMBAD models, for four European cities, two hybrid ventilation strategies and standard mechanical exhaust system in a two-storey dwelling. The author showed that low pressure ventilation systems can improve the IAQ and reduce the fan energy while maintaining the same heating energy as the reference system. Pavlovas [5] also compared numerically four ventilation strategies in a Swedish apartment. The yearly energy savings is more than 50 % for CO<sub>2</sub> and humidity DCVs and around 20 % for presence detection strategies compared to the permanent mechanical systems. Hekmat [2] studied the impacts of five ventilation strategies in three climates of the Northwestern United States. The simulations show that the overall energy consumption (including domestic hot water) can be reduced by 9 to 21% by using mechanical ventilation systems with heat recovery, and by 18 to 21%

achieved by superinsulating the same houses; results also show that houses with mechanical ventilation exhaust fans have better IAQ.

Generally, a few studies deal with simultaneous energy and IAQ assessment. This study presents some results of simulations carried out for a heating season in a single-family dwelling. The study involves three mechanical systems which are exhaust-only ventilation, balanced ventilation with heat recovery and humidity-controlled ventilation, and Natural ventilation. The impacts of these ventilation strategies on energy consumptions and IAQ are compared for an occupancy and pollution schedules.

## METHODS AND SIMULATIONS

The experimental house MARIA [6] is a typical single-family dwelling built near Paris by French building research center CSTB. It has four bedrooms, a bathroom with toilets and a shower room at first level; the living-room, the kitchen and the toilets are located at the garden level (Figure 1). The house is equipped with different ventilation and heating systems.

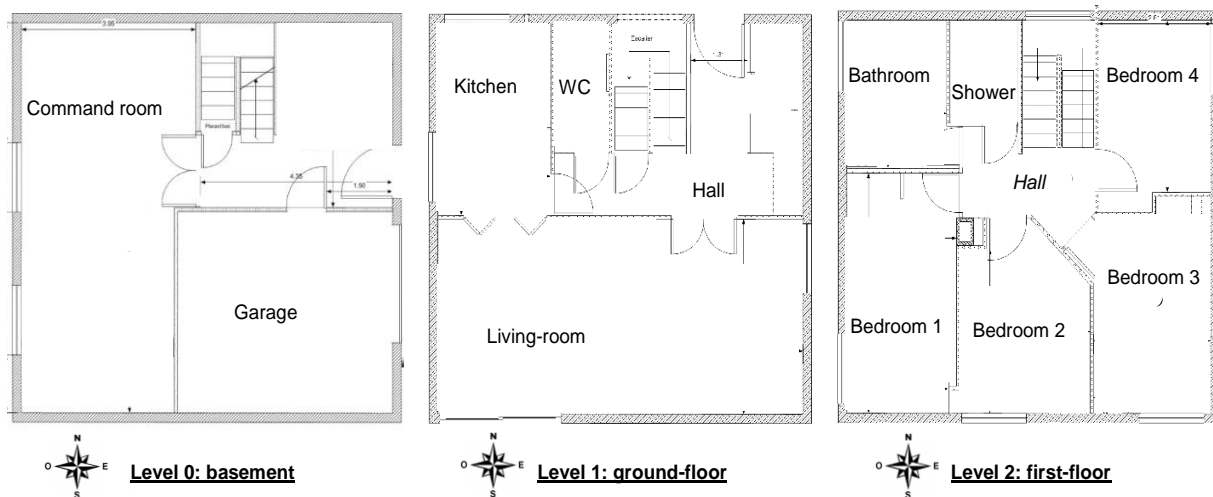


Figure 1. Configuration of the dwelling.

A multi-zone model of MARIA is implemented in MATLAB/Simulink environment using, on the one hand, existing thermal models of SIMBAD, a Building and HVAC Toolbox developed by CSTB. On the other hand, new airflow models are developed in order to assess the performances of ventilation systems. The latter models include a balanced ventilation system with heat recovery and free-cooling mode, humidity and presence controlled ventilation systems, natural ventilation, and the corresponding ductworks. The thermal and airflow models are coupled through the de-coupled (or "*ping-pong*") approach described by Hensen, in which each model uses the results of the other in the previous time step [7]. The model is a true representative of MARIA: the location, sizes and thermal properties of rooms, windows, walls as well as the ductworks, fans, heat exchanger, airflow paths and heating system correspond to the real systems. The airflow model is described in [8].

Four ventilation systems are simulated. The first one is mechanical exhaust ventilation (MEV), which is the reference system in French regulation. The service rooms are equipped with air-outlets for extracting  $45 \text{ m}^3/\text{h}$  in the kitchen,  $30 \text{ m}^3/\text{h}$  in the bathroom and the shower and  $15 \text{ m}^3/\text{h}$  in the toilets. Outdoor air enters the main rooms by self-regulated air-inlets: one inlet in each bedroom and two in the living-room. The same inlets are used for natural ventilation (NVent) which is also achieved with vertical individual ducts and a  $100\text{-cm}^2$  air-grille in service rooms.

Two strategies of mechanical humidity-controlled ventilation are simulated. “Hygro A” is made of the self-regulated air-inlets used for the reference system and humidity-controlled air-outlets in service rooms. For “Hygro B”, both air-inlets and air-outlets are relative humidity dependant; the inlets should provide 6 to 45 m<sup>3</sup>/h airflow rate along with RH ratio. In both cases A and B, the exhaust airflow rates are controlled by humidity ratio in the shower (5 to 45 m<sup>3</sup>/h) and the kitchen (20 to 60 m<sup>3</sup>/h), occupant detection in toilets (6 to 30 m<sup>3</sup>/h) and both occupant detection and humidity ratio in the bathroom (5 to 45 m<sup>3</sup>/h). The last system, mechanical balanced ventilation (MBV), is achieved with both air supply and exhaust systems. The exhaust airflow rates are those of the reference system. In addition, the fresh air is pre-heated, simulating different heat recovery efficiencies for assessing the energy impact, and distributed at 20 m<sup>3</sup>/h flow rate in the bedrooms and 40 m<sup>3</sup>/h in the living-room. Finally, all mechanical systems allow boosting airflow rate in the kitchen (135 m<sup>3</sup>/h) during cooking; in the case of balanced ventilation, each supply rate is raised to 35 m<sup>3</sup>/h.

The dwelling is occupied by a couple and three children: the occupancy schedule is described in IAE ECBCS Annex 27 [9]. Each occupant produces in the occupied room some amounts of water vapor, carbon dioxide and sensible heat depending on his/her age and metabolism activity. In addition, domestic activities generating water vapor are simulated:

- shower: 300 g is released per person for 10 minutes in the shower and the bathroom;
- daily emission is 200 g for clothes washing and 1000 g for drying in the bathroom;
- individual productions for food cooking are 50 g for breakfast, 150 g for lunch and 300 g for dinner. Simultaneously, a generic pollutant is also released in the kitchen at half flow rate compared to water vapor in order to check out whether the water vapor produced in the kitchen can affect the humidity level within the whole building.

We also simulate emission in main rooms of alpha-pine, a volatile organic compound released from pine carpet, at 55 µg/h/m<sup>2</sup> flow rate determined in MARIA by Akoua [10].

Finally, simulations are carried out during the heating period in the weather area of Trappes (near Paris, France); the indoor set temperature is 19°C.

## RESULTS

### Airflow analysis

Figure 2 and Figure 3 present respectively the exhaust airflow and infiltration rates in the building; Table 1 presents the resulting mean air change rates. The airflow rates resulting from exhaust and balanced ventilation systems are identical as well as the design. In the latter case, as the supply and exhaust fans are equal in capacity to maintain indoor pressure balance by providing the same volume of air, infiltrations are less influenced by the system: all the volume of air infiltrating the house is returned outside through the envelope air leakage. This result underlines the importance of a tight building envelope for achieving efficient balanced ventilation. Conversely, the combined impact of a relatively high air leakage (0.9 m<sup>3</sup>/h/m<sup>2</sup>) and the depressurization engendered indoors by systems with exhaust fans and natural ventilation increases infiltration. As direct consequent, the flow rates through air-inlets are reduced; this is likely to produce undesirable effects on energy consumptions and air quality.

For humidity-controlled systems, the airflow rates are fundamentally the lowest but system “Hygro A” provides greater fresh air than “Hygro B”. The deviation arises from the control of fresh air by humidity in strategy B. Besides, the airflow rates extracted by natural ventilation are similar at each level of the building whatever is the service room. The total mean airflow rate is the highest one as consequent of elevated indoor-outdoor temperature differences.

Locally for each system, the air change rate is quite uniform in bedrooms excepted bedroom 2 which is located downwind. Values are significantly higher in the living-room because of double air supply and high infiltrations through the facades. Finally the global air renewal, calculated as average of total ventilation flow rate and infiltration, is obviously lower for humidity-controlled systems A and B, respectively 0.26 and 0.22 vol/h, against 0.39 vol/h for the reference system. However, the maximum values are reached with natural ventilation (0.50 vol/h) and balanced ventilation (0.45 vol/h). These values are consistent with usually required air change rate in dwellings, i.e. between 0.3 and 0.5 vol/h.

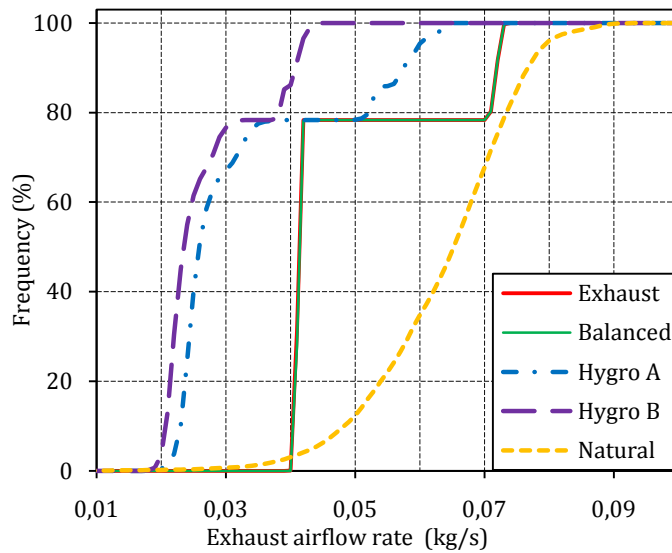


Figure 2. Frequencies of exhaust airflow rates.

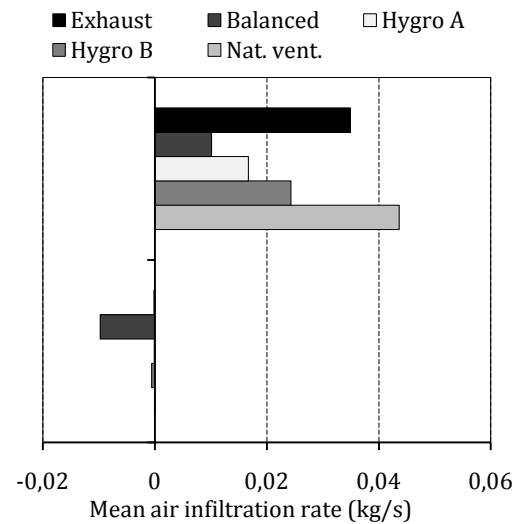


Figure 3. Mean air infiltration rates.

Table 1. Global and local mean air change rate according to ventilation strategies.

Ventilation system	Mean local air change rate (vol/h)					Mean global air change rate in MARIA (vol/h)
Exhaust (ref.)	Bedr.1	Bedr.2	Bedr.3	Bedr.4	Living	0.39
Balanced	0.43	0.34	0.40	0.39	0.62	0.39
Hygro A	0.73	0.89	0.79	0.92	0.66	0.45
Hygro B	0.32	0.27	0.30	0.30	0.46	0.26
Hygro B	0.25	0.16	0.20	0.22	0.33	0.22
Natural	0.62	0.53	0.60	0.61	0.72	0.50

Note: 1 vol/h means a volume of air equivalent to the room volume is renewed in one hour

## Energy demand

Figure 4 presents the energy impact of the ventilation strategies compared to the consumption of the reference system.

The fan consumption is 224 kWh for the exhaust ventilation system and 310 kWh for both exhaust and supply plants of the balanced system, that is 38% extra-consumption. Besides, humidity-controlled systems use low-pressure fans and lead more than 77% energy savings. The Energy consumption for heating with exhaust ventilation is 7417 kWh over the considered period. About 46.7% of this amount, i.e. 3467 kWh, is due to losses through ventilation and infiltration. Globally, the energy demand for air renewal represents from 21.1% (MBV E90%) to 55.2% (NVent) of the total energy demand. These high differences indicate a significant effect of the choice of ventilation strategies on energy consumption.

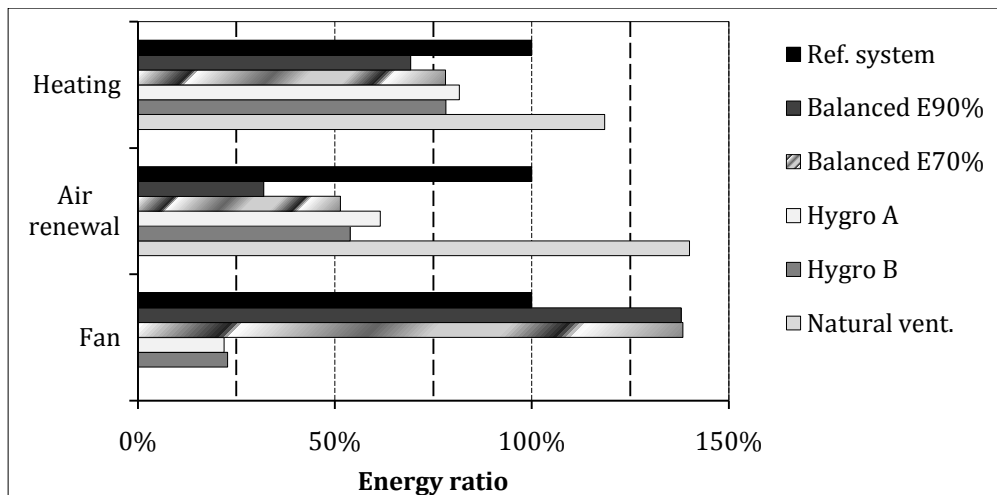


Figure 4. Energy consumptions due to heating, air change and fan.

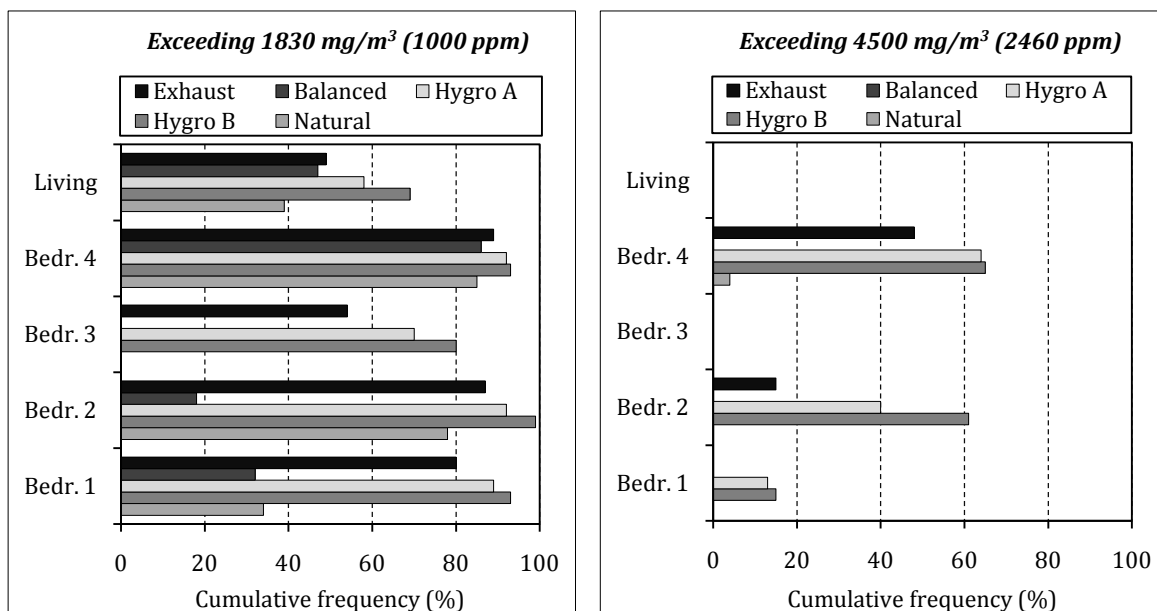


Figure 5. Cumulative frequencies of CO<sub>2</sub> concentrations higher than 1830 mg/m<sup>3</sup> (1000 ppm) and to 4500 mg/m<sup>3</sup> (2460 ppm) in main rooms during occupancy periods.

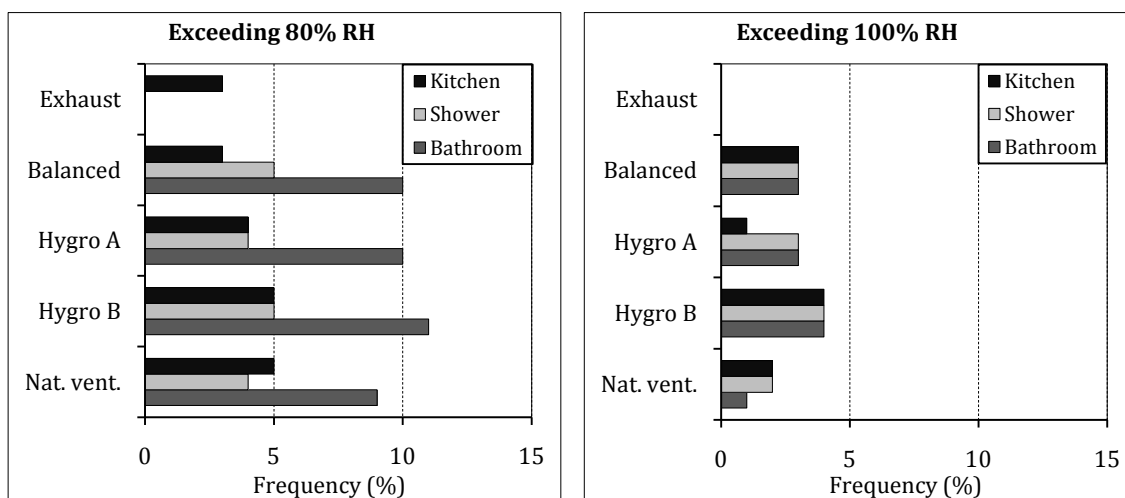


Figure 6. Cumulative frequencies for exceeding 80% and 100%RH in services rooms.

In comparison with the reference system, balanced ventilation systems, with almost the same effective ventilation rate and temperature distribution, lead to energy savings from 21.9 to 30.8% on heating, and between 48.5 and 68.1% on air renewal. These systems show essential difference on energy loss through air change. In fact, the savings when switching the recovery efficiency from 70% to 90% is about 19.6% for sensible heat; one can so save 8.9% of the total energy demand. Nevertheless, “Hygro B” clearly appears to be more efficient than “Hygro A” because of airflow differences: the energy savings one can expect to achieve using these strategies are respectively 46.1 and 38.4% for the studied configuration.

The energy-efficiency also depends on the recovery efficiency and the delivered airflow rates according to indoor humidity ratio. Here, it appears that 70% is roughly the lowest value of the heat recovery efficiency for which balanced ventilation remains more efficient than “Hygro A”: the total consumption (heating + fan) of both strategies is then about 6100 kWh. However, balanced ventilation “E70%” remains better than both Hygro A and B in terms of ventilation energy losses only, even if the heating demands are quite similar with “Hygro B”.

As it could be predicted through airflow rates, natural ventilation is the worst strategy among the studied systems in terms of energy consumption. The loss through ventilation and infiltration is increased by 40% compared to exhaust ventilation and leads 18.5% increase in heating energy demand. Finally, the global energy savings over the heating period, including fan and heating demand, compared to exhaust ventilation are as follows:

- balanced ventilation: -28.7% (E90%) and -20.1% (E70%);
- humidity-controlled ventilation: -20.2% for Hygro A and -23.5% for Hygro B;
- natural ventilation: +15%.

Such an analysis is done over a whole year and leads to practically similar conclusions, as only fan energy during hot periods is added to the global energy consumption.

### **Exposure to carbon dioxide**

The impact of ventilation strategies on indoor air quality is analyzed through carbon dioxide and water vapor levels. Figure 5 presents the exposure to CO<sub>2</sub>, evaluated by the cumulative frequencies of concentrations exceeding guideline values of 1000 ppm (1830 mg/m<sup>3</sup>) and 2460 ppm (4500 mg/m<sup>3</sup>), French *Limited Risk Value*, VRL, for 1-24h exposure).

With the reference system, bedroom 3 and the living-room are the lowest polluted rooms. In spite of occupancy density, the high air change in the living-room maintains a better air quality: CO<sub>2</sub> concentration exceeds 1000 ppm for only 50% of the occupancy duration against more than 80% elsewhere. Besides, concentrations in these rooms do not exceed 1600 ppm. On the contrary, bedroom 4 occupied by the man and the woman presents the highest CO<sub>2</sub> levels for each of the simulated systems. However, there is a slight difference among these systems resulting from air change differences in this room: the 1000-ppm frequencies vary from 85 to 93% of occupancy duration.

Balanced ventilation brings a better air quality: concentrations do not exceed 1300 ppm excepted in bedroom 4 and somewhat in the living-room where the pollution level even remains under 1750 ppm. This performance is basically due to supply airflow control and lower infiltration. Natural ventilation brings also better IAQ than the reference system, but less good than with balanced ventilation. Moreover, the pollution level appears to be more important with “Hygro B” compared to “Hygro A”; these systems reduce a lot the airflow rates for energy purpose, then the resulting air quality decreases in the whole building and particularly in bedrooms 2 and 4.

The VRL threshold 2460 ppm is only exceeded using exhaust and humidity-controlled systems, during respectively 48% and 65% of bedroom 4 occupancy. A comparable pollution is observable in bedroom 2 with “Hygro B” against 40% for “Hygro A”; concentrations are quite similar in bedroom 1, but never this pollution is detected with the other systems.

Globally, results show that the humidity-controlled ventilation strategies bring the worst IAQ due to the low airflow rates depending on humidity ratio; however, as it is shown below, this parameter seems to be insufficient to ensuring proper air renewal in main rooms. On the contrary, using a balanced ventilation system for supplying the required airflow rates yields a very good IAQ. Finally, the studied ventilation strategies seem to be efficient in removing pollutants; in fact, CO<sub>2</sub> concentration levels do not present any particular danger.

### **Humidity and risk of condensation**

The relative humidity ratio in main rooms, ranging between 30 and 60%, is similar to those often encountered in residential buildings; the maximum level is again obtained in bedroom 4 due to higher occupancy. It therefore appears that condensation cannot occur in these rooms: this result indicates a good operating of the systems in terms of IAQ. During domestic activities, water vapor production leads to increasing the risk of condensation on the walls of the bathrooms and the kitchen. This is illustrated by Figure 6 presenting the cumulative frequencies for which relative humidity reaches or exceeds of 80% and 100%. For all systems, the highest risk is found in the bathroom used as laundry in addition to body washing. The reference system seems nevertheless to provide better air quality as humidity ratio exceeds 80% only in the kitchen for 3% of time. This result can be interpreted as a consequence of infiltration since the air change is equal to that of balanced ventilation.

### **CONCLUSION**

We simulate a combined thermal and airflow model of the experimental house MARIA in order to compare the energy and IAQ performances of four ventilation systems used in single-family dwellings. The house was placed in the French RT2005 weather area H1a and the results show differences among the ventilation strategies.

At equal air change rate as mechanical exhaust ventilation, balanced ventilation brings from 20.1 to 29% energy savings, depending on the heat recovery efficiency. Systems Hygro A and B provide respectively 20.2% and 23.5% energy savings by reducing air change rates. But one should keep in mind that the properties of humidity-controlled devices are parameters of matter, as well as heat recovery efficiency, for choosing the suitable strategy for reducing energy demand. Besides, natural ventilation provides the highest airflow rates: this system seems to be oversized for the building. But such results are a good illustration of both envelope air leakage and temperature differences since simulations are performed for a cold season. Thus, evidence appears that natural ventilation, with 15% overconsumption, is the least energy-efficient studied system.

Infiltrations occur for all the studied systems and mainly for exhaust strategies due to depressurization within the dwelling. Airtight envelopes are therefore indispensable for achieving better performances, especially for the control of fresh airflow rates in the case of strategy “Hygro B”. In the same way, although balanced ventilation has certainly little influence on infiltration, the efficiency is decreased as infiltrating air is not pre-heated and no recovery is possible on the out-flowing air.

Balanced ventilation also appears to be an accurate strategy for assuring healthy IAQ since the fresh air is supplied at constant rate. Humidity-controlled ventilation provides less accurate IAQ, mainly in the main rooms where CO<sub>2</sub> guideline values are in general reached or exceeded. In addition, the results show the impact of the occupancy through metabolic pollutants concentrations in the adults' room, excepted for balanced ventilation.

The present results are to be considered in relation to the simulations assumptions since the study is carried out for only a single climate area and in a specific type of individual home. They are nevertheless a springboard for apprehending the long-term behavior of the ventilation systems with regards to the chosen assessment criteria. The study also highlights the potentialities of the developed building model. This one appears as a helpful tool for assessing the performances of ventilation strategies. The developed model is likely to be used as an integrated design tool of ventilation systems in new buildings: it can be helpful for the design and implementation of innovative ventilation strategies via parametric studies, for example in low energy buildings. It needs for this purpose further development.

## ACKNOWLEDGEMENT

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