CONTROL AND PERFORMANCE OF INNOVATIVE VENTILATION SYSTEMS IN LOW ENERGY BUILDINGS: A STUDIED CASE

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ABSTRACT

As part of a project aiming at assessing ventilation in low energy buildings, this study analyses the performance of innovative ventilation systems used in a single-family building. Five ventilation systems are investigated by simulation using SIMBAD Building and HVAC Toolbox. The results then show better performance in terms of energy demand and indoor air quality (IAQ) for balanced ventilation systems, either permanent or intermittent management. The investigated demanded-controlled ventilation (DCV), which strategies based on CO_2 level and on combined CO_2 and humidity, levels lead to less good but acceptable IAQ. They also allow important reduction of energy demand compared to exhaust-only ventilation system.

KEYWORDS

Innovative ventilation, low-energy building, indoor air quality.

INTRODUCTION

Low-energy buildings are built with well-insulated envelope in order to reduce the energy demand. In France, the conventional primary energy consumption should be inferior to 50 kWh/m^2/year for the residential low-energy buildings. This consumption takes into account the energy demand for heating, which includes the energy demand of ventilation and infiltration, space lighting, air-conditioning, ventilation auxiliaries and hot water production. The up-coming French thermal regulation RT2012 will apply this specification for the new built buildings. Nevertheless, the regulation on ventilation does not specially deal with low-energy buildings. One then can wonder about the energy impact of ventilation in such buildings. This concept of buildings brings out additional questioning on the link between innovative ventilation systems and indoor air quality (IAQ). The main concern is: which ventilation systems are suitable for low-energy buildings? The adequate ventilation system should meet the energy requirements while providing acceptable indoor air quality.

Researchers are trying to elaborate proper answers to that question. Huynh [1] recently analyzed this dilemma and Maier et al. [2] showed the energy and IAQ benefits of mechanical ventilation in low-energy buildings. Besides, Karlsson et al. [3], investigating residential buildings, noted that the set-point temperature, the building orientation and U-values as well as the local climate are factors that can influence the energy demand. Mahdavi et al. [4] compared passive and low-energy residential buildings: according to the authors, both type of buildings can achieve good indoor CO_2 level and meet the energy requirements. Moreover, Koffi et al. numerically assessed the IAQ and energy performances of different ventilation systems in a single-family building [5] and a low-ernergy apartment [6].

In the same framework, the present study aims to assess the performance of ventilation systems supposed to bring accurate responses to these questions. Final propositions of the project would give indications about the suitable way of the management of ventilation in low-energy buildings according to the use of the building. For this purpose, existing mechanical exhaust-only and balanced ventilation systems are designed in a single-family building. In addition, three demanded-controlled ventilation (DCV) systems are studied. They are respectively based on: 1) CO_2 concentration and humidity level, 2) CO_2 concentration and presence detection, and 3) day and night airflow rates management. The simulations are carried out in a French local climate. This paper analyzes the impact of these ventilation strategies on the indoor air quality and the energy demand.

METHODS

The simulated building

The study is about a single-family low-energy house presented by Figure 1; we used the weather data of Trappes, a French city near Paris. SIMBAD Building and HVAC Toolbox [7] is used for the simulations. This tool implements multizone and nodal building models in MATLAB/Simulink environment and combines heat and mass transfer equations; the airflow model is described by Koffi et al. [5]. Table 1 presents the thermal properties of the building walls which are designed to achieve the energy requirements of low-energy buildings. Besides, the envelope air leakage is set to 1.70 ach at 50 Pa pressure difference (i.e. 0.6 m^3/h per square meter of envelope under 4 Pa) for limiting air infiltration.

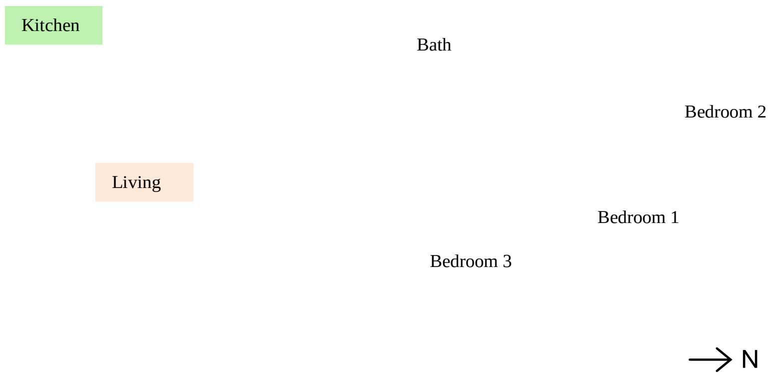

Figure 1. The studied building.

Layer	U ($W/m^2.K$)	R ($m^2.K/W$)
External walls	0.16	6.1
Ceiling	0.10	10.1
Floor (over a crawl-space)	0.17	5.6
Floor (on ground)	0.23	4.3
Inter-storey floor	0.36	2.5
Internal walls	0.20	4.8
Windows	1.2	-

Table 1. Thermal properties of the wall layers.

The house is occupied by four persons according to occupancy schedules similar to those described by Mansson et al [8]: two adults sleep in bedroom 1 and two children in bedrooms 2 and 3. Each occupant releases in the occupied space some amounts of water vapour, carbon dioxide and sensible heat depending on its age and metabolism. In addition, water vapor is generated during cooking breakfast (50 g/pers), lunch (150 g/pers) and dinner (300 g/pers), as well as shower (300 g/pers for 20 minutes), clothes washing (200 g for 2 hours) and drying (1000 g for 20 hours). Besides, some emission models of volatile organic compounds (VOCs) due to building materials and to activities like cooking, cleaning, smoking and incense burning are simulated using extisting database PANDORE [9] and IA-QUEST [10].

The studied ventilation systems

Five existing or newly designed ventilation systems are studied in the defined building in order to achieve both energy requirements and acceptable indoor air quality in low-energy building:

1) System MI-0 is the permanent exhaust ventilation commonly is in French homes. It deals with mechanical air exhaust from the kitchen (45 m^3/h), the bathroom (30 m^3/h) and the toilets (15 m^3/h). The fresh air enters the living-room and the bedrooms through self-regulated air-inlets. During cooking, the airflow rate is raised to 120 m^3/h in kitchen for half an hour; then, the total exhaust flow rate is raised from 105 m^3/h to 180 m^3/h.

2) MI-1 is a balanced ventilation system with both mechnical supply and exhaust ducts. The exhaust flow rates are the same as for strategy MI-0. The input airflow rate is 20 m^3/h in each bedroom and 45 m^3/h in the living-room. During cooking, the airflow rate is set to 120 m^3/h in the kitchen and the living-room. Furthermore, in order to reduce the energy demand, strategy MI-1 deals with 0.85 heat recovery efficiency on the exhaust air for pre-heating the supply air.

3) MI-2: this exhaust system deals with CO_2-sensors in the main rooms and combined CO_2 and humidty-dependant exhaust devices in the service rooms.

4) MI-3: we simulate this exhaust system using again CO_2-dependant air-inlets in the living-room and the bedrooms as well as strategy MI-2. However, MI-3 is distinguished from MI-2 by the use of presence detection sensors in the exhaust rooms. In fact, the airflow rate is set to a minimum value in each exhaust room until it is occupied; then, the system extracts the maximum airflow rate for half an hour once the occupant has lived the room.

5) MI-4 is a balanced demanded controlled ventilation strategy based on occupant presence in the whole building. During daytime, the maximum airflow rate, 70 m^3/h, is supplied in the living-room while only 8 m^3/h is input in each bedroom. At night, the system supplies 30 m^3/h per bedroom and 10 m^3/h in the living-room. If there is nobody in the house, the global input and output airflow rates are reduced to 25 m^3/h. As well as strategy MI-0, this system deals with heat recovery which efficiency is set to 0.85.

During lunch and dinner, the exhaust airflow rate in the kitchen is boosted to 120 m^3/h for 30 minutes. Systems MI-0 and MI-2 distribut this additional airflow along with the pressure differences on the façades. Moreover, strategies MI-3 and MI-4 use a balanced hood in the kitchen during cooking, supplying and exhausting 105 m^3/h airflow rate for 30 minutes. In order to prevent the dispersion of the released pollutants, the removal efficiency of the hood is set to 2 and the heat exchanger efficiency is 0.35.

Table 2 summarizes the control factors of the studied ventilation systems.

Syst.	**Type**	**Control factor**	**Cooking airflow rate (m^3/h)**
MI-0	Exhaust-only	Permanent	120
MI-1	Balanced	Permanent	120
MI-2	Exhaust-only	CO_2 + humidity	120
MI-3	Exhaust-only	CO_2 + presence detection	45+105 (balanced hood)
MI-4	Balanced	Time clock + presence	45+105 (balanced hood)

Table 2. Control factors of the studied ventilation systems.

ENERGY CONSUMPTION

Table 3 and Figure 2 present the final energy consumptions for the studied ventilation systems. This energy demand includes the heating energy in which contains the energy loss due to ventilation and infiltration. The fan energy, which is a funtion of the total airflow rates, is the electrical consumption of fans and eventually hoods: then, it has been multiplied by 2.58 when calculating the final energy demand of fans. Thus, balanced ventilation systems MI-1 and MI-4 engender the highest demand. Besides, the consumption of strategy MI-3, using a hood, is silghtly superior to that of systems MI-0 and MI-2.

The maximum energy demand is obtained with exhaust-only ventilation, strategy MI-0, which is considered as the reference system in this study. The heating energy demand for the latter system is 2733 kWh, i.e. 20.7 kWh/year per square meter of surface (in final energy). In addition, without any airflow reduction or heat recovery, the energy demand due to ventilation is 1980 kWh (i.e. 15 kWh/m^2): then, ventilation accounts 72% for of the energy demand. This part is very high as far as the building is well-insulated and emphasizes the necessity of using heat recovery or reducing as well as possible the airflow rates by means of the control of ventilation.

	Final energy (kWh)		
Syst.	**Heating**	**Ventilation**	**Fan**
MI-0	2733	1980	115
MI-1	1263	390	313
MI-2	2061	1211	93
MI-3	1688	865	118
MI-4	1228	350	309

Table 3. Final energy demand (kWh).

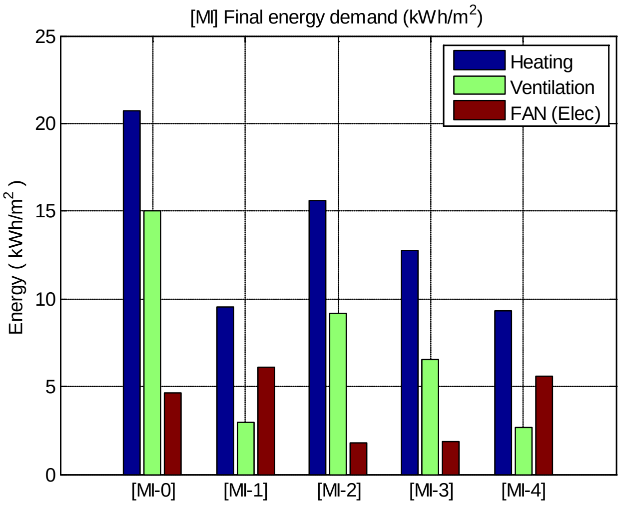

Figure 2. Comparison of final energy demand (kWh/m^2).

Benefits of ventilation heat recovery

Balanced ventilation strategies MI-1 and MI-4 are used for assessing the benefits of heat recovery. The results show a better performance since the ventilation energy is limited to 390 kWh with strategy MI-1 and 350 kWh for MI-4, representing more than 80% savings compared to the ventilation energy of system MI-0. As consequence, the heating energy demand is highly reduced to 1263 kWh with MI-1 and 1228 kWh for MI-4; the savings due to heat recovery represent more than 53% of heating energy demand of the reference system. But in fact, both systems lead to quit similar savings but one can note a slight advantage to use strategy MI-4, due to the airflow control.

Impact of ventilation control

When using demanded-controlled ventilation strategies based on CO_2 and presence (MI-3), and on both CO_2 and humidity (MI-2), one can also expect to decrease greatly the total energy demand through the control of ventilation airflow rates. MI-2 generates 2061 kWh energy demand against 1688 kWh for MI-3: the savings due to these control strategies are respectively 24.5% and 38.2%. Besides, the energy part of ventilation will represent from 51% (MI-3) to 59% (MI-2) of the corresponding heating energy demand, that less than ventilation impact of MI-0 but more than that of balanced strategies.

In the present study, CO_2-DCV MI-3 results in a better energy performance than the combined CO_2 and humidity strategy MI-2. The main reason of this difference is a difference in the design of these strategies. In fact, system MI-2 uses, in the exhaust rooms, the maximum airflow rate between that generated by CO_2 level and that due to humidity ratio. Not at all, strategy MI-3 deals with presence-dependant airflow control in these rooms. This situation results in higher energy expense by MI-2.

Finally, according to the requirements, the studied ventilation systems seem to be suitable for use in such a low-energy building for the considered local climate. Balanced ventilation strategies MI-1 and MI-4 are the strategies offering the best performance in terms of energy demand. Even strategy MI-0 leads also to acceptable results. Nevertheless, we can note high losses through ventilation and infiltration which is, most of the time, difficult to control. One should then read this conclusion carefully. In fact, the energy analysis does not consider the use of electricity. Therefore, the conclusion is not valid if electricity is used as energy for heating the space. The energy demand could have also been influenced by the set up temperature: we used 20°C, without any schedule, instead of 19°C as usually recommended. This change was done in order to get maximum levels of the energy demand.

ANALYSIS OF INDOOR AIR QUALITY

CO2 level and exposure to VOCs

Figure 3 and Figure 5 present the daily CO_2 concentrations in bedroom 1 and the living-room. The first room is generally the most polluted one: in fact, two adults occupy it during the night. In addition, Figure 4 and Figure 6 present the cumulative occurrence of CO_2 in these rooms, by calculating the ppm-hours. This index represents the product of the CO_2 concentrations, respectively superior to guideline values of 1000, 1500 and 2000 ppm, and the total duration over the heating period. This index is calculated only when the rooms are occupied in order to deal with exposure.

Using the reference system MI-0, the concentration in the bedroom 1 can exceed 1500 ppm and 1200 ppm in the living-room during the night. As shown by the CO_2 index, the concentration are lower than 2000 ppm. The second system, MI-1, brings out better air quality compared to MI-0 (and also CO_2 DCV and CO_2 and humidity-controlled ventilation). With this strategy, one can expect to ensure CO2 concentrations lower than 1500 ppm. The main benefits with system MI-1 reside in adequate and permanent air input in the bedrooms and the living-room. In addition, due to air exfiltration occurring from these rooms, a noticeable part of the emitted pollutant is exhausted outdoors without crossing the building, so that the pollutant levels are somewhat lower than with MI-0.

Strategy MI-4 is designed to always bring the fresh air where necessary according to a night/day schedule. This concept brings the best indoor air quality during the occupancy periods as shown by the CO_2 indexes. Globally, the carbon dioxide level in the bedrooms rarely reaches 1200 ppm with this system. The concentration difference with the other systems can reach 300 to about 1300 ppm. There is a real benefit to increase the airflow rate in the occupied rooms.

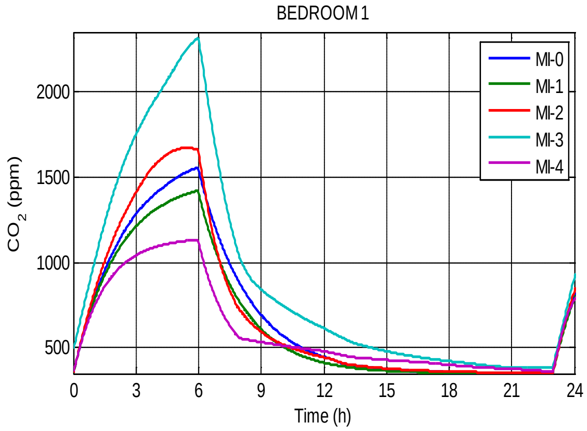

Figure 3. CO_2 concentrations in bedroom 1.

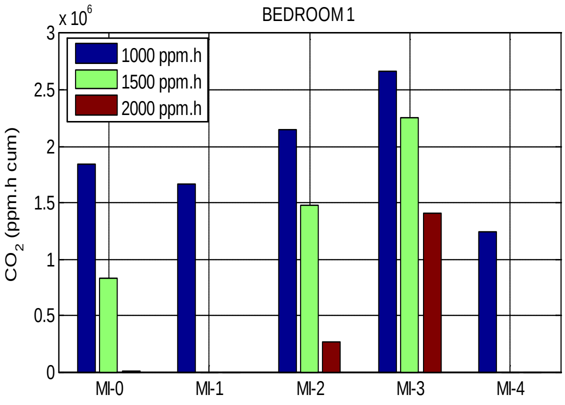

Figure 4. CO_2 index in bedroom 1.

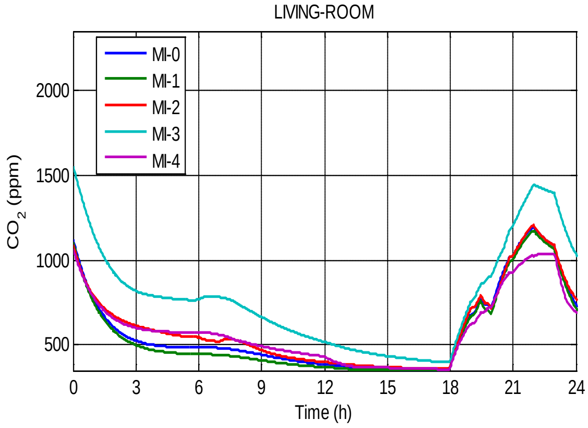

Figure 5. CO_2 concentrations in the living-room.

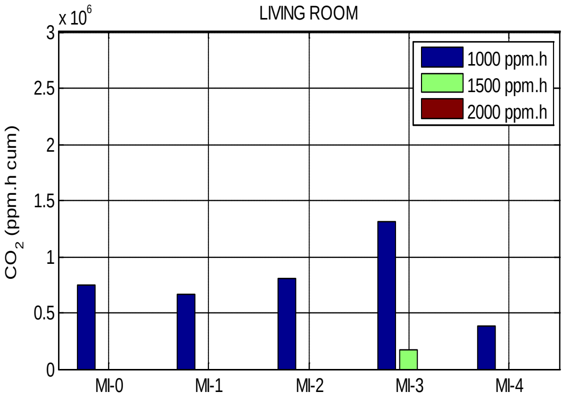

Figure 6. CO_2 index in the living-room.

On the contrary, the CO_2 and presence DCV MI-3 leads to the highest pollution in this study; the concentrations frequently exceed 1500 ppm in the living-room during the week-ends and 2000 ppm in bedrooms. This result seems to be inconsistent with the objective of that system. In fact, during the night, strategy MI-3 only depends on CO_2 concentrations in the bedrooms; the exhaust airflow rates are set to their minimum values as the corresponding rooms are not occupied. Then, the increase of CO_2 concentrations has a very reduced effect on the renewal airflow rate of the building. What happen are an enhancement of the flow rates through the air inlets and a diminution of the infiltrations in the bedrooms. During the day, the airflow rates are increased only when one or more exhaust rooms are occupied. This strategy should have integrated CO2-dependence in the exhaust rooms.

The combination of humidity control and CO_2 control in the exhaust rooms helps to improve the air quality. Then, with strategy MI-2, one can note a real decrease of the CO_2 concentration and index in the rooms. The occurrence of concentrations higher than 2000 ppm is thus divided by a factor greater than five compared to MI-3; this solution seems to be more adapted. Globally for the studied systems, the 1000 ppm guideline seems impossible to avoid. One solution can be the increase of the demanded airflow rate, for instance using system MI-4; however, this way of doing is likely to penalize the energy savings.

A parallel can be made with VOCs through the analysis of formaldehyde concentration (Figure 7 and Figure 8). The level of this contaminant is kept almost constant in the bedrooms when using strategy MI-1 as the airflow rates are constant. Some slight variations are visible with MI-0 during cooking periods.

As well are for CO_2, strategy MI-4 leads to the lowest pollution level in the bedrooms during. The concentrations decrease to a minimum value when the occupants are in these rooms. When they are of out the building during the day, the VOCs level increases until reaching the maximum level among the studied systems: however, this does not matter as far as the main concern of IAQ should be the occupants' exposure. Finally, we can note that strategy MI-3 fails to provide air quality as good as the other systems according formaldehyde concentrations; the level of this pollutant increases during the night and reaches levels more than three times compared MI-0.

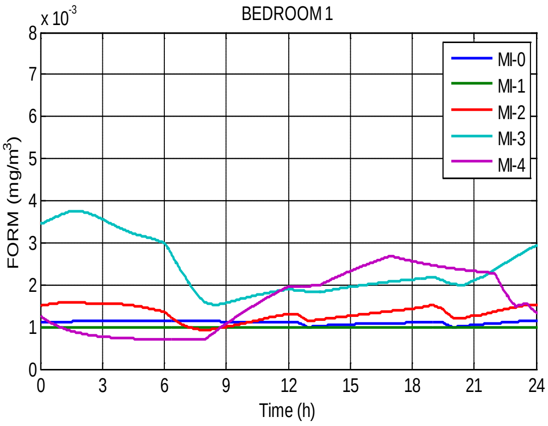

Figure 7. Formaldehyde concentrations in bedroom 1.

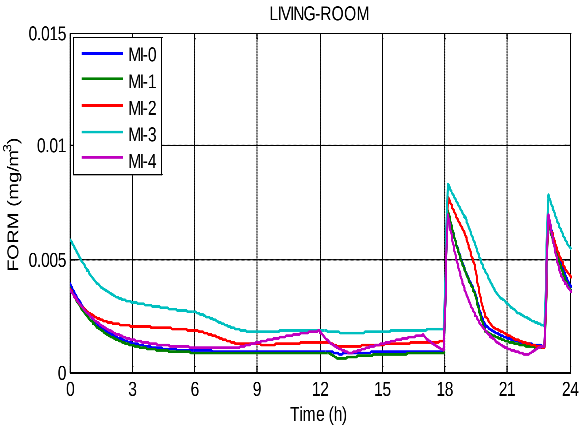

Figure 8. Formaldehyde concentrations in the l*iving-room*.

Humidity level

The daily evolution of relative humidity in the kitchen is illustrated by Figure 9. Figure 10 presents the cumulated number of hours over the heating period for which the relative humidity is higher than 75%. Only the bathroom and the kitchen are mainly concerned by this index; the maximum RH can reach 100% especially during cooking and shower. In the bedrooms, the humidity is most of the time lower than 60%, but can sometimes exceed this value especially with strategy MI-3; in winter, the lower values can touch 20% mainly due to outside low absolute humidity.

In the kitchen, strategies MI-0, MI-1 and MI-2 lead to comparable RH index values, representing about one hour per day. The observed differences may result from difference of internal air transfer and mainly from the humidity ratio in the living-room which is less important with MI-1. On the contrary, MI-3 and MI-4, using higher pollutant removal efficiency, allow a noticeable decrease the humidity level too.

In the bathroom, the humidity level remains higher with strategies MI-3 and MI-4 than with the other systems. This is mainly due to reduced airflow rates when the occupants are out of the building while water vapour is still released from clothes washing and drying. For MI-3, this happens as soon as nobody is in the concerned exhaust rooms. The airflow rate reduction lasts for 23 hours per day with MI-3 against 7 hours with MI-4; that difference in the basic factor of the RH index difference, about 270 hours, between these systems. Finally, the humidity ratio is kept at minimum level with strategy MI-2: the RH remains superior to 75% for about 630 hours against more than 950 with hours with MI-0 and more than 1600 hours for MI-3 and MI-4. Due to control by humidity and CO_2 concentration, MI-2 can in fact bring airflow rate up to 45 m^3/h in the bathroom while the other strategies are limited to 30 m^3/h.

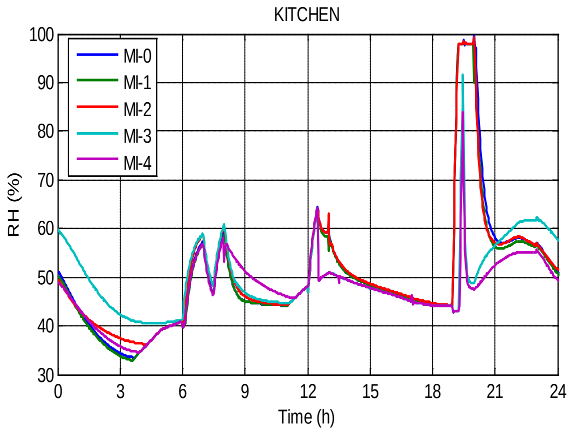

Figure 9. Relative humidity in the kitchen.

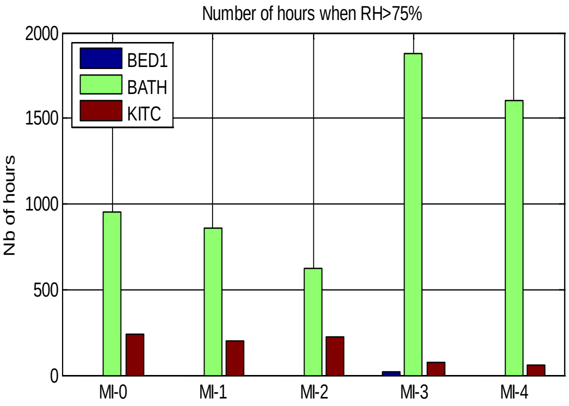

Figure 10. Relative humidity index (RH>75%) in the exhaust rooms.

CONCLUSION

This study deals with the assessment of innovative ventilation systems in a low-energy house. The analysis of the results brings out many differences among the studied strategies. The energy consumption, which is the first criterion for evaluating low-energy buildings, seems to be acceptable in the present study. In almost all the studied cases, the energy allowed for heating is kept in the range of the requirements as far as no electricity is used for this purpose.

Another observation is that, for the studied cases, the impact of ventilation can represent a considerable part of the total energy demand, about 30% for balanced ventilation systems, and from 50 up to 72% with exhaust-only strategies. This is mainly due to the combined effect of a well-insulated envelope and uncontrollable infiltration in spite of a supposed airtight envelope; it may be very interesting to investigate the energy consequence of the envelope air leakage. Besides, the results showed that 0.85 heat recovery efficiency can lead to more than 80% savings in energy demand with balanced ventilation strategies. In the same way, using demanded-controlled ventilation systems based on CO_2 and presence detection (MI-3), and on both CO_2 and humidity (MI-2), can help make savings from 24 to 38% on the energy demand.

The analysis of the indoor air quality clearly brings out differences in the performances of the studied systems according to the control factors. Exhaust-only DCV strategies (MI-2, MI-3) fail at times to bring the expected air quality. The difficulty with in their operating mechanism is that the input airflow rates depend on parameters, which values do not, most of the time, match with those of the exhaust rooms. Then, when the exhaust airflow rate is maximum, and if the CO_2 concentrations in the bedrooms or the living-room are not high enough to provide the corresponding airflow rates, these strategies can promote a lot air infiltration.

For the analyzed parameters (CO_2, water vapor and VOC), balanced ventilation systems MI-1 and DCV based on presence MI-4 bring the better performances during the occupancy periods compared to the exhaust systems. The ccontrol of ventilation through presence carried out in strategy MI-4 shows that it is possible to reduce the energy demand while performing good indoor air quality. However, the performance of this strategy would depend on the influence of the occupants who should be aware of the operating of the ventilation system.

The results thus outline the importance of ventilation control: if adequately performed, ventilation control appears as a good way of providing good air quality in order to prevent damages on the occupants' health. The most important way of controlling air quality seems the adjustment of ventilation to the demand. Nevertheless, this analysis does not consider the impact of all the simulated pollutants. Further studies would bring more detail about this through the use a built of indoor quality criteria.

ACKNOWLEDGEMENTS

This study is carried out with the financial support of ANR, the French National Research Agency, and the assistance of AirH, CSTB, CETIAT, INERIS and Allie'Air.

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