Numerical evaluation of the airtightness impact on airflow pattern in mechanically ventilated dwellings in France

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ABSTRACT

The objective of this paper is to assess the impact of the envelope airtightness on airflow patterns for single detached dwellings depending on the ventilation system.
A numerical approach based on the energy simulation tool TRNSYS coupled to a multi-zone air-flow and contaminant transport model COMIS was used to analyze the local and global performance of four mechanical ventilation strategies in terms of energy and ventilation efficiencies. The following ventilation strategies were modelled: constant flow exhaust-only, humidity-sensitive exhaust-only with and without humidity-controlled inlets, and constant flow supply and extract. The multi-zonal approach allows studying the local disturbances in the functioning of these systems, which differs from most studies on the subject. The impacts of the location of leakages in the building envelope (facades and/or ceiling) were also investigated. Numerical results showed a significant impact of air permeability on the ventilation efficiency, with a different impact depending on the mechanical ventilation system. The wind effect exposes the building more frequently to the influence of crossing airflow, and as a result the normal distribution of fresh air from main rooms to wet rooms could be disturbed, with a risk of damaging indoor air quality. We also analysed the fresh air origin, by quantifying the amounts of airflows from leakages and inlet/supply units for each ventilation systems. Results show that in the case of humidity-sensitive ventilation systems, a specific attention should be given to the air permeability in order to maintain the desired airflow pattern from main rooms to service rooms.

KEYWORDS

Simulation, airflow displacement, airtightness, ventilation system.

1. INTRODUCTION

As building energy efficiency is becoming a major issue to reduce energy use and greenhouse gas emission, energy regulations are evolving towards more stringent rules at the national and European level. The European energy efficiency directive requires all new buildings to be nearly zero-energy by 2020. With the increased levels of fabric insulation, airtightness of the building envelope is expected to play an increasingly important role in buildings energy efficiency (Pan, 2010). However, energy saving targets in buildings must be achieved while maintaining good indoor air quality and comfort level. Therefore, the ventilation is a key concern in energy efficient buildings. It allows outdoor air to be intentionally provided to a space while stale air is removed. Ventilation is essential for securing acceptable air quality in buildings by diluting and removing indoor pollutants. At the same time, it accounts for 30%

or more of space conditioning energy demand (Liddament, 1996). Ventilation standards and regulations set the requirements for the minimum ventilation rates, with a possibility to reduce airflow during unoccupied period (Richieri, 2007). The ventilation needs can be achieved by natural or mechanical means. In countries with colder climates, mechanical systems are mostly used, which are either Exhaust-only or balanced, with or without heat recovery units (Dimitroulopoulou, 2012). In France, the following mechanical systems are typically used: Exhaust–only ventilation, balanced ventilation units with heat recovery, humidity sensitive exhaust ventilation, either integrated to air outlets (called "Ventilation Hygro A"), or to both air inlets and outlets (called "Ventilation Hygro B").

These systems ensure a permanent displacement flow of fresh air into the building. Air inlets are located in main rooms, which can be adjustable or self-adjustable, but cannot be blocked, and air exhausts in wet room, such as kitchen, bathroom(s), toilet(s). Ventilation system must be able to ensure a minimum exhaust airflow rates greater than a limit depending on number of main rooms. The siting of the inlets and outlets is intended to have the air move from main rooms to service parts (wet rooms), so that moisture and other pollutants are removed at source and the whole dwelling is ventilated (Durier, 2008)

Humidity-sensitive ventilation systems are generally based upon the modulation of the air-cross section – and so of the airflow – at the air inlets and outlets units level, using a mechanical sensor which directly drives the shutter set in the air stream. These systems can reduce the amount of the exhaust airflow to a low level of background ventilation during unoccupied periods or low activities. Several studies have confirmed that relative humidity sensitive ventilation is a good way of reducing building energy demand in residential buildings as the mean ventilation rate is reduced when the building is not used (Woloszyn, 2009). They are nearly always used in new French residences, as they appear to be cost-effective solutions to improve the energy performance and make it easier to meet current French energy regulation requirements.

However, as for balanced ventilation, humidity sensitive ventilation systems induce globally a weaker under-pressure that can be lower than the weather induced pressure (Liddament, 1996). Therefore the total (and local) air change rate could be more subjected to variations due to the air infiltration through the building envelope. Unlike ventilation process, air infiltration is the uncontrolled airflow into the building through unintentional gaps and cracks in the building envelope (Liddament, 1996) (Dimitroulopoulou, 2012).

The air infiltration rates depend on the airtightness of the envelope, the wind speed and direction, and the air temperature (stack effect). When the pressures acting across air inlets of the ventilation systems located in the building envelope are dominated by weather conditions, these inlets can also become routes for undesired air infiltration. This additional outdoor air entering the building will lead to an increase of energy consumption (Pan, 2010) (Chan, 2013). Also, it may distort the intended airflow pattern resulting in parts of the house being inadequately ventilated and leading to poor air quality and a risk of moisture problems (Liddament, 1986).

Thus a poorly implemented ventilation strategy, combined with an inappropriately designed building envelope, may adversely affect both energy efficiency and indoor climate (Pan, 2010) (Liddament, 1996). Airtightness improvement in mechanically ventilated building allows a better indoor air quality (QUAD BBC; 2009).

Until now, models developed to calculate the impact of air permeability on heating demand used calculation methods based on annual average air-infiltration EN ISO 13789 (EN ISO 13789, 2007) or on an hourly calculation of standard EN NF 15242 13789 (EN NF 15242, 2007) also used by French regulation calculation method with a monozonal configuration. These both methods do not take into account the dynamic behaviour of the local humidity-

controlled air inlets and outlets in main and service rooms as function of wind exposure and envelope airtightness. As a result, both methods lead to substantially different results.
Our work aims to go one step further by evaluating the airtightness impact on energy needs (Richieri, 2013), as well as airflow patterns whose topic is especially discussed in this paper. A dynamic simulation tool of a multi-zone building was developed, including controlled-loop of air inlets and outlets for different ventilation systems. The relationship between airtightness, ventilation system is investigated. Also the impact on air flow pattern is discussed.

2. METHODOLOGY

2.1. Studied configuration

Building description

The building considered is a typical French single-detached dwelling with 119 m² of living area, and inhabited by a 4-person household (a couple and two children). Thermal and airflow zoning covers 11 connected areas according to the following detail:

- **main rooms**: Living-room; Office; 3 bedrooms;
- **service rooms**: Kitchen; Bathroom; WC;
- **auxiliary rooms**: storeroom (without water point), corridor;
- **highly ventilated attic**.

Figure 1 shows the plan view of the dwelling. Main thermal properties of walls and windows are described in **Error! Reference source not found.**.

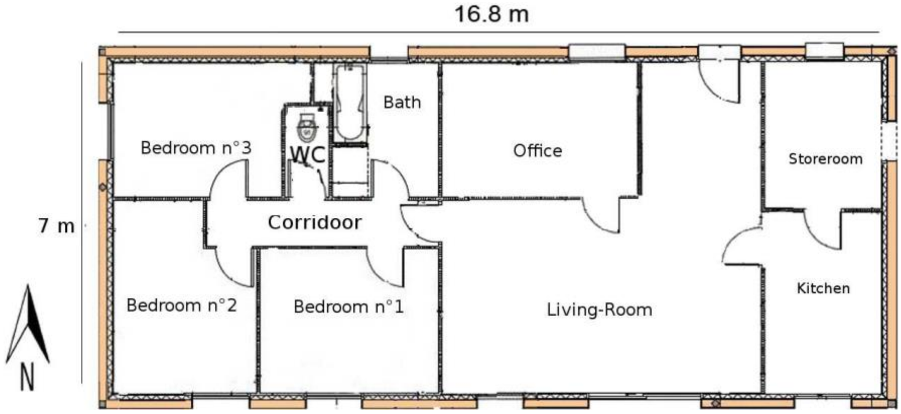

Figure 1: Plan of the dwelling

Table 1: Envelope composition

Wall	Composition	U value W/(m².K)
External Wall	20 cm hollow brick + 10 cm glass wool insulation	0.21
Upper Ceiling	1.3 cm gypsum + 27 cm glass wool insulation	0.14
Floor	4 cm concrete + 9 cm Polyurethane + 12 cm concrete	0.24
Living Room Windows	Low emissivity double-glazing with aluminium frame	1.7
Other Windows	Low emissivity double-glazing with PVC frame	1.4
Pitched Roof	Clay roof tile (High ventilated attic)	5.6

The dwelling is supposed to be heated by radiator and thermostatic valves (set à 20.4°C – corresponding to the French regulation reference) from 1st October to 20th May during occupied period (18h-9h on weekdays and on weekends). The internal temperature is 3°C reduced during unoccupied period (Monday – Fridays from 09h to 18h)

Ventilation systems description

Four ventilation systems are modelled in accordance with national requirements on ventilation as indicated in Table 2. The first one is "self-adjusting mechanical exhaust ventilation". Service rooms are equipped with self-adjusting air-outlets, and main rooms by self-adjusting air-inlets integrated in facades. The second is mechanical balanced ventilation with an 80% efficiency heat exchanger. The exhaust airflow rates are the same as the self-adjusting mechanical exhaust ventilation. The pre-heated fresh air is distributed in main rooms by air supply units. Finally, two strategies of mechanical humidity-controlled ventilation are modelled following technical agreement specifications (CSTB, 2014). "Humidity-controlled Hygro A" is composed of self-regulated air-inlets in main rooms integrated on facades and humidity-controlled air-outlets in service rooms. For "Humidity-controlled Hygro B", both air-inlets and air-outlets are relative humidity controlled. All mechanical systems enable boosting airflow rate in the kitchen (135 m^3/h) during cooking.

Table 2: Ventilation systems characteristics

System	**Inlets**				**Outlets**				
	Type	**Living room**	**Bedrooms & office**	**Total**	**Type**	**Kitchen**	**Bathroom**	**Toilet**	**Total**
Self-adjusting exhaust ventilation	Facade air inlets	2 x (22 m^3/h)	30 m^3/h	164 m^3/h	Air exhaust units	45 m^3/h	30 m^3/h	30 m^3/h	105 m^3/h
Balanced ventilation	Air supply units	35 m^3/h	18 m^3/h	107 m^3/h	Air exhaust units	45 m^3/h	30 m^3/h	30 m^3/h	105 m^3/h
Humidity-controlled Hygro A	Facade air inlets	2 x (22 m^3/h)	30 m^3/h	164 m^3/h	Air exhaust units	12-45 m^3/h at RH 50-83%	10-45 m^3/h at RH 25-60%	30 m^3/h	52-120 m^3/h
Humidity-controlled Hygro B	Facade air inlets	2 x (6-45 m^3/h) at RH 45-60%	6-45 m^3/h at RH 45-60%	36-270 m^3/h at RH 45-60%	Air exhaust units	10-45 m^3/h at RH 24-59%	10-40 m^3/h at RH 36-66%	5 m^3/h (30 m^3/h; 30')	25-90 m^3/h

2.2. Simulation tools

Our approach is based upon the coupled thermal and airflow network model, using the commercially available simulation tools TRNSYS (building energy simulation) and COMIS (airflow network) (Feustel, 1999). It allows us to calculate heat transfer, airflow and pollutant transport (e.g., moisture) in a multi-zone building under transient boundary conditions. Besides, it enables dynamic modelling of closed-loop control for different systems (especially humidity sensitive ventilation system). TRNSYS has been validated for the calculation of transient heat exchange through the surfaces composing a zone (Voit et al., 1994). Also, COMIS has been validated for air and contaminant flows resulting from infiltration through cracks and ventilation systems (Furbringer, 1996).

Moisture generation

Moisture vapour is produced through activities such as cooking, showering or washing/drying clothes, or through metabolic processes such as respiration and sweating. Moisture is produced at various times according to occupation in different locations and in variables

quantities. More generally, elevated levels of humidity are related with other pollutants such as CO_2 (produced by the metabolism) and cooking odours.
Consequently, moisture vapour and sensible heat schedules were created for each zone according to the activities of a 4-person family (2 adults and 2 children) - activities related to human metabolism and domestic. For each schedule, the amount of water vapour and sensible heat were calculated hour by hour. Table 4 presents the values of the heat and moisture ratios of the activities that have been considered in the calculation.

Table 3: Humidity ratio of different sources

Sources	**Humidity ratio**
Occupant metabolism : sleeping	15.2 kg/week
Occupant metabolism : seated at rest	
Occupant metabolism : seated light activity	
Cooking	11.0 kg/week
Shower	8.4 kg/week
Drying cloths	7.0 kg/week
Floor cleaning	0.5 kg/week

The humidity ratios represent the total amount of moisture per week that has been calculated from ratios mentioned in (Furbringer, 1996) and (Brogat, 2003). For example, a ratio of 300 g/person for a shower is used. In our case, we have considered in the bathroom 4 showers per day – 2 in the morning and 2 in the evening. Thus, an emission of 0.195 g/s has been defined in the bathroom from 06:00 till 07:00 and from 18:00 till 19:00 during weekdays. Figure 2 illustrates the sum of total moisture emission schedules for all zones for weekdays and weekend (Fig2).

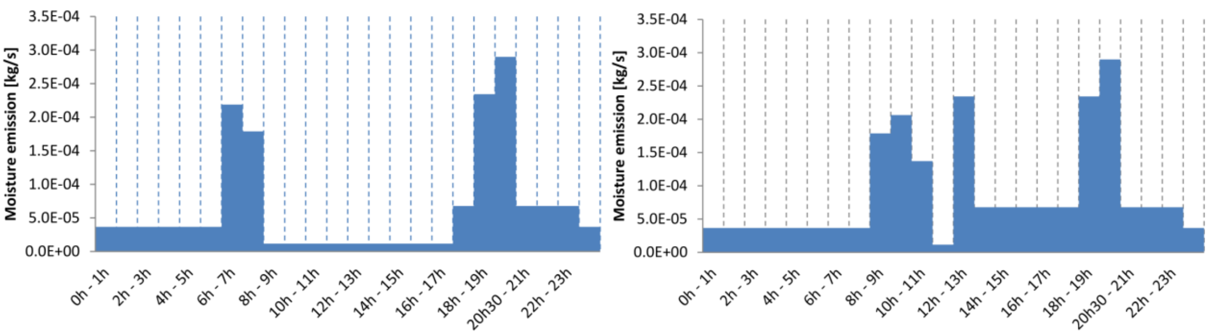

Fig. 2: Sum of total moisture emission schedules for all zones during Weekdays (left) and Weekends (right)

Flow paths through building components

The building is considered as a zone network linked by airflow components such as cracks on envelope, inlets and outlets of ventilation systems, and internal circulations between 11 zones. For each main room, inlets are located in accordance with plans, positioned at 2.2 m height. Specific behaviour of self-adjusting or humidity sensitive inlets is modelled as defined in Table 2. As the attic is generally highly ventilated, we added large cracks for the pitched roof with the following characteristics: 0.5 for the flow exponent, and 0.3 kg/(s.$Pa^{0.5}$) for the flow coefficient (CSTB, 2006).
Leakages are distributed over the 227 m² building envelope (A_{Tbat}). In each zone, two cracks have been defined on external walls at 0.63 m and 1.88 m height, and one crack on the ceiling at 2.5 m height as recommended in (EN ISO 13789, 2007). The flow exponent of cracks is equal to 0.65. The zones are interconnected by 90 cm wide doorways considered as closed during simulations. To ensure air circulation from dry to wet rooms, each doorway is

considered with a 1 cm undercut for all inner doors and 2 cm undercut for the kitchen door, according to (XP P50-410, 1995). The door undercut is modelled as a large crack with 0.5 flow exponent.

Wind pressure coefficients

As wind pressure coefficients (Cp) depend on the surrounding ground and the wind angle relative to each facade, we have considered two exposure conditions: "exposed" and "surrounded by obstructions". The local wind velocity depends on the surface roughness and the height. The wind profile used by Comis follow a power law detailed in (Anon, 1991), with a roughness coefficient of 0.17 for exposed condition. The wind pressure coefficients Cp depend on four parameters: the spatial location on the building envelope, the building shape, the surroundings and the wind direction. The Cp values are considered in accordance with (Liddament, 1996) for the shielding conditions "exposed".

3. RESULTS AND DISCUSSION

3.1. Impact of air permeability on heating needs

Simulation is done for the four ventilation systems using the multi-zone model with the oceanic climate of Poitiers (HDD 18°C 2321°C.Day). Figure 4 illustrates the results of energy needs and figure 5 the energy needs sensitivity towards air permeability.

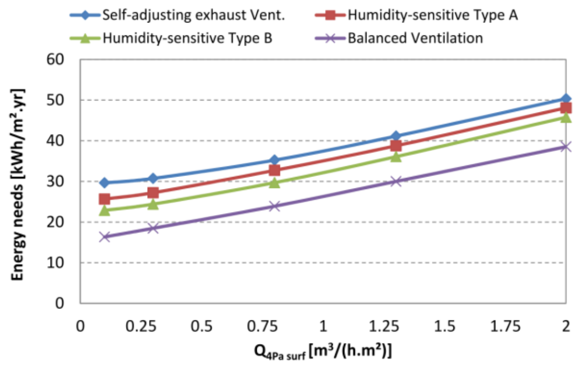

Figure 3: Influence of ventilation systems on energy needs

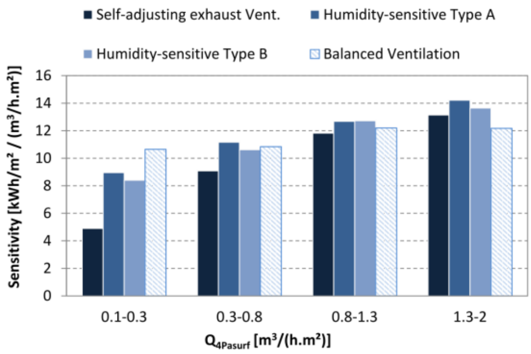

Figure 4: Sensitivity of energy needs for different ventilation systems

As expected, energy needs increase with air-permeability. The balanced ventilation enables the higher energy savings followed by humidity sensitive and self-adjusting ventilation (specific electricity for fans is not countered). A clear distinction can be based upon the level of air permeability:

- For good airtightness (air permeability below 0.3 $m^3/(h.m^2)$), the sensitivity of balanced ventilation (11 kWh/(m^2.Year) per unit of air permeability) is the highest followed by humidity sensitive ventilation (8 kWh/(m^2.Year) per unit of air permeability), and self-adjusting extract ventilation (5 kWh/(m^2.Year) per unit of air permeability). This can be explained by a weaker under-pressure in the case of balanced and humidity sensitive ventilation systems - that can be lower than the weather induced pressure. This exposes the building more frequently to the influence of crossing airflow, and as a result the total air change rate becomes higher.
- For higher air permeability (above 0.8 m3/($h.m^2$)), the energy needs increase in the same amount (12 to 14 kWh/(m^2.Year) per unit of air permeability) whatever the ventilation systems. This can be explained by a leakage air renewal which significantly exceeds the air renewal related to the different ventilation systems.

3.2. Impact on air flow pattern

As observed with the previous simulations, the wind effect could disturb the normal distribution of fresh air from main rooms to wet rooms, with a risk of damaging indoor air quality. In fact, inversion of airflow pattern contributes to the dispersion of air pollutants or odours from service rooms to main rooms. In order to analyse this phenomenon, the yearly occurrences of airflow disruption (flow inversion: service rooms -> main rooms) have been countered during the occupancy period. For example, an occurrence of 10% means that the flow direction is correct 90% throughout the year, regardless of the wind conditions. Figure 5 illustrates the occurrences of airflow inversion for the four ventilation systems.

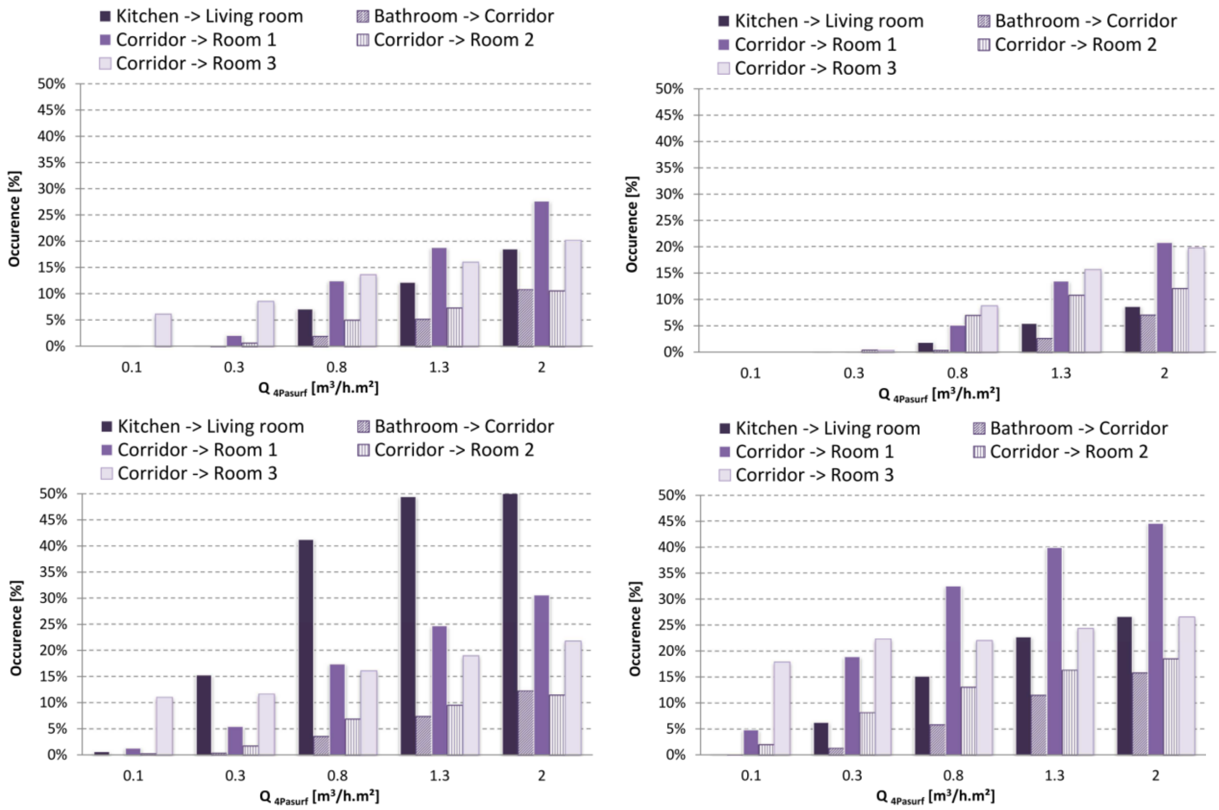

Figure 5: Occurence of Airflow inversion for self-exhaust ventilation (up-left) – balanced ventilation (up-right) - Humidity sensitive Hygro A (down-left) and Hygro B (down-right)

From **Error! Reference source not found.**figures 5, we can conclude the following:

- an increased risk of airflow inversion and pollutants dispersion from service rooms in the case of humidity sensitive ventilation systems, particularly if the airtightness is not clearly improved, with an occurrence from 10 to 25% (Hygro B), up to 45% (Hygro A);
- a significantly lower risk with balanced ventilation system, and self-adjusting extract ventilation, even if airtightness is close to 0.8 $m^3/h.m^2$;
- the factors disturbing correct airflow circulation are principally weaker under-pressure due to modulation of the fan speed extractor, and the facade self-adjusting air inlet located downwind. Thus, the most affected ventilation system is the humidity sensitive ventilation Hygro A with fixed air-cross section, and the less affected is balanced ventilation system;
- a poor airtightness (> 1.3 $m^3/h.m^2$) causes a heterogeneous air renewal of the rooms, yet all equipped with the same natural or mechanical air-inlet. The prevailing winds in Poitiers are from the southwest sector. Therefore, room No. 3 located downwind has the highest occurrences;

- only excellent airtightness would ensure an accurate and uniform air flow.

The air vented from the home by exhaust fans must be replaced by outside air. This new air comes into the home either through controlled inlets, supply units or through air leakage. Many of the air leaks come from undesirable locations such as crawl spaces, attics, or cross insulation lining and may threaten air quality by pulling gas pollutants or dust into the home.
In order to analyse the impact of leakages distribution on airflow pattern, an heterogeneous leakages distribution has been tested with 30% of total leakage areas being grouped on bathroom envelope (instead of 6% with an uniform distribution as in the previous simulations). Figure 6 shows a comparison of the occurrences of airflow inversion between uniform and heterogeneous leakages distributions for the case of humidity sensitive hygro B ventilation system (most widely distributed) and an airtightness of 0.8 $m^3/(h.m^2)$ (reference used before the last French regulation RT2012).

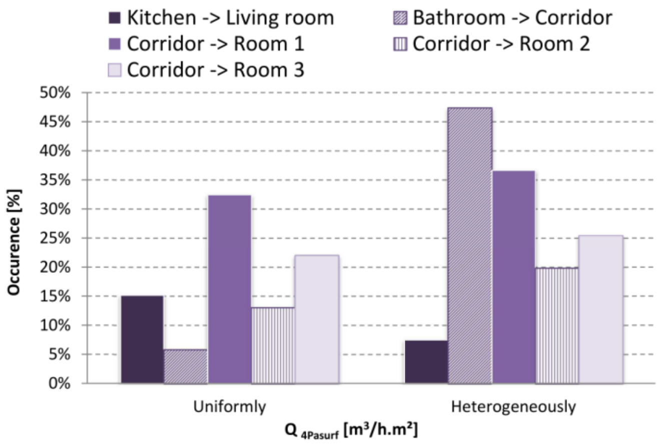

Fig. 6 Comparison of airflow inversion between uniform and heterogeneous leakages distribution

The leakages distribution method does not cause noticeable difference on heating needs between a uniform and heterogeneous distribution (respectively 31.6 kWh/m² against 31.8 kWh/m²). However, the ventilation efficiency is significantly affected. The occurrence of airflow inversion in bathroom (from bathroom to corridor) rose from 6% to 47%, pulling humidity into the main rooms. In the kitchen, the occurrence of airflow inversion is slightly decreased. Therefore, leakages located in wet rooms could significantly disturb the overall air-renewal into the dwelling.

3.3. Impact on air renewal through inlet and supply units

A last set of simulations has been performed to analyse the fresh air origin, by quantifying the amounts of airflows from leakages and inlet/supply units for each ventilation systems. Two calculations have been done with Comis under the following stationary conditions:
- Case n°1 without wind and thermal drift effects (indoor and outdoor temperatures at 20°C)
- Case n°2 with a 4 m/s wind speed oriented SSW, and a 10°C thermal drift (indoor temperature at 20°C and outdoor temperature at 10°C). The results are presented on Figure. 7 7.

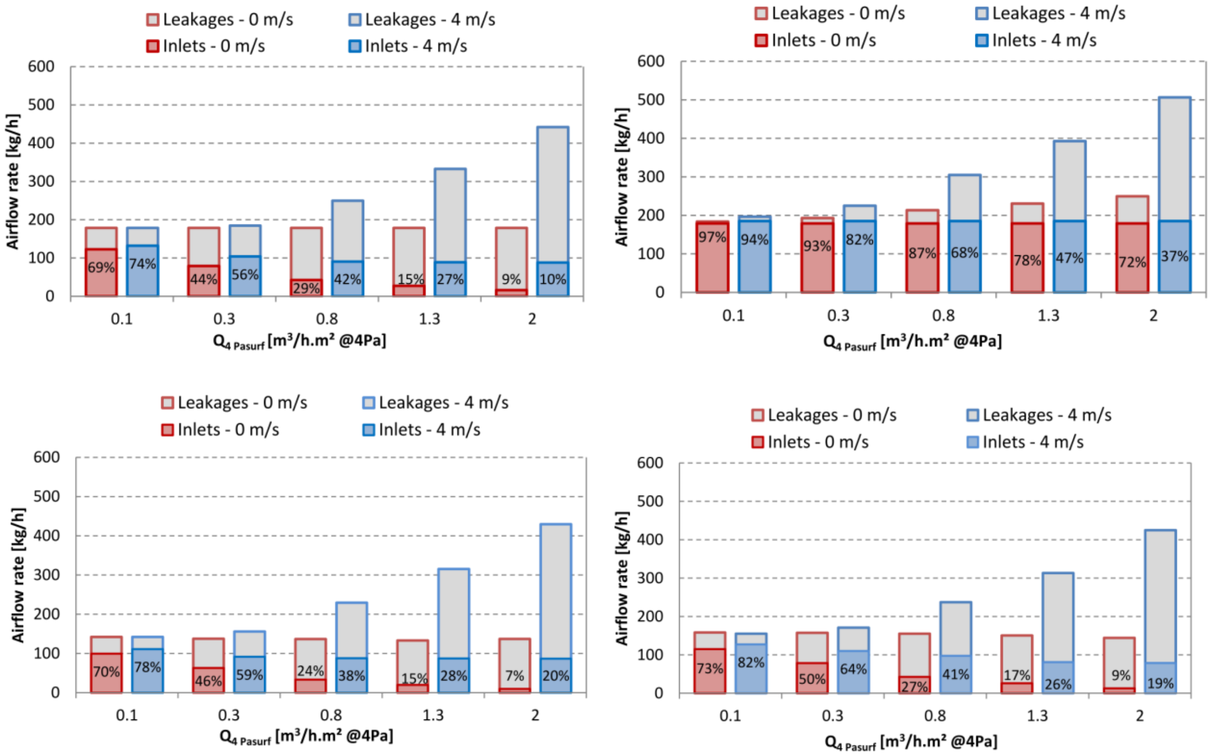

Figure. 7: Airflow rate through leakages and Inlets for self-exhaust ventilation (up-left) – balanced ventilation (up-right) - Humidity sensitive Hygro A (down-left) and Hygro B (down- right)

Under the wind effects, outside air flow and leakage rate increases with the airtightness degradation. With air-inlets, the outside air cross mainly air leakages than air-inlets. Among the exhaust ventilation systems, the proportion of outside air from leakages seems slightly higher with humidity controlled ventilation Hygro A, compared with the other two systems. For example, with a poor airtightness of 1.3 m^3/(h.m²) @ 4 Pa, the proportion of outside air from the air inlets is between 15 and 30% with exhaust ventilation systems, against 45 to 80% with balanced ventilation systems, depending on weather conditions. For an excellent airtightness less than 0.3 m^3/h.m² @ 4 Pa, the proportion of outside air from supply units is always greater than 80% with balanced ventilation, against 45 to 60% with exhaust ventilation.

As a result, with a poor airtightness, dispersion of pollutants (chemical pollutants and dust) could be probably more important with exhaust ventilation systems compared with balanced ventilation systems. Therefore, an excellent airtightness treatment seems to be recommended for all mechanical ventilation systems to ensure proper functioning of hygienic ventilation (with ensure the good functioning of the ventilation systems). A good airtightness improves the performance of Exhaust-only ventilation system by giving more authority to the air inlets (lower flows through leakage is compensated by a better control of inflows).

4. CONCLUSIONS

A multi-zonal model TRNSYS-COMIS has been developed to study the envelope air-tightness influence on the functioning of four ventilation systems. The numerical investigations illustrate the influence of air-tightness on heating demand and ventilation efficiency. For a French oceanic climate, heating demand increase in the same amount (12 to 14 kWh/(m².Year) per unit of air permeability, whatever the ventilation system choice. Demand control ventilation systems - such as humidity controlled exhaust systems - seem to be more sensitive to air permeability, especially in terms of airflow control. With a low airtightness performance (Q4pasurf > 0,3 m^3/h.m²), the simulations indicate that normal airflow pattern is clearly disturb and could contribute to the dispersion of air pollutants or odours from service rooms to main rooms. At the same time, airtightness default on envelop (local crack) seems induce heterogeneous air renewal of the main rooms.

5. ACKNOWLEDGEMENTS

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