Numerical evaluation of the airtightness impact on energy needs in mechanically ventilated dwellings

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ABSTRACT

With the increasing need for higher energy efficiency in buildings, airtightness and ventilation systems choice become major performance issues in well insulated buildings. Buildings energy requirements lead to adapt ventilation strategies in order to reduce energy losses through mechanical balanced or extract ventilation. With the new French thermal regulation, the use of energy-efficient ventilation systems is implicitly required; low air infiltration is explicitly required in residential buildings through minimum airtightness levels. However, mean infiltration rate due to weather conditions could be significantly affected by the ventilation system choice. This work aims to evaluate the airtightness impact on energy needs depending on the mechanical ventilation strategies.

We have developed a numerical approach with the simulation tools TrnSys and COMIS, allowing us to model heat, airflow and pollutant transport (e.g., moisture) in each zone and to calculate the annual energy use for various envelope leakage distribution, mechanical ventilation systems, and climates. We have investigated for typical French dwelling the impact on the heating loads of: the location of infiltration openings on each façade (vertically and horizontally) and the ceiling; the zone configuration (1- or multi-zone model); the climatic conditions; and shielding conditions (exposed and surrounded by obstructions).

The numerical investigations show an increase of thermal needs from 2 to 17 kWh/(m².Year) per unit of air permeability index, depending on ventilation system choice, wind exposure category and climate zone.

KEYWORDS

Thermal simulation, airflow simulation, multi-zone, airtightness, ventilation system.

INTRODUCTION

With the increasing need for higher energy efficiency in buildings, thermal regulations are evolving towards more stringent rules at the European and national level. In France, the latest thermal Regulation (RT2012) requires all new buildings to be low-energy since 2013, with requirements on airtightness performance by pressure test. The air permeability “$Q_{4Pa\text{-}Surf}$” ($m^3/(h.m^2)$) is calculated as the ratio between the air leakage rate at 4 Pa and the envelope area of the building except the floor area “A_{TBAT}”. For the case of single-detached dwellings, it must be lower than 0.6 $m^3/(h.m^2)$.

In this context, airtightness and ventilation systems choice become major performance issues in well insulated buildings. Thus, demand ventilation systems (that control the airflow rate in response to ventilation needs) are nearly always used as they enable energy savings provided the structure is fairly air tight, while maintaining a good Indoor Air Quality.

The impact of airtightness on energy needs in mechanically ventilated dwellings in France was approached on the PABHI project by CETE de Lyon et al (2008). Simulations were realized on 9 new constructions. The increase of energy needs vary from 0.5 to 15 kWh/(m².Year) per unit of air permeability. However, these values were calculated with a simple method using crossing single-zone model, fixed wind exposure associated with wind pressure coefficients. The calculation of ventilation heat loss is based on an annual average air flow given by technical agreements for each system, delivered by the French Scientific and Technical Centre for Building (CSTB).

This work aims to evaluate the airtightness impact on energy needs using dynamic simulation of multi-zone building that enables modelling real behaviour of air inlets and outlets for different ventilation systems.

REVIEW OF VENTILATION SYSTEMS IN FRANCE

As indicated by Durier (2008) in its paper on ventilation requirements in France, the regulation concerning residential building ventilation mainly relies on the Ministerial Order of 24th March 1982 relating to air renewal in new dwellings. Its main requirements are:

- overall and continuous air renewal,
- air inlets (natural or mechanical) in main rooms, which can be adjustable or self-adjustable, but cannot be blocked,
- air exhausts (natural or mechanical) in wet room, such as kitchen, bathroom(s), toilet(s),
- ventilation system that must be able to ensure a minimum exhaust air flow rates greater than a limit depending on number of main rooms,
- individual adjustment devices which allow the reduction of exhaust air flow rates, provided that the total (and kitchen) exhaust air flow rates remain greater than a limit depending on number of main rooms.

These requirements have usually been achieved by using centralised mechanical exhaust systems to ensure a permanent displacement flow of fresh air into the building. The siting of the inlets and outlets ensures that air generally moves from dry rooms to wet rooms, so that moisture and other pollutants are removed at source and the whole dwelling is ventilated.

In practice, to satisfy these French requirements, the following mechanical systems are used:

- Single exhaust ventilation (called “Ventilation Auto”),
- Balanced ventilation units with heat recovery,
- Humidity sensitive ventilation, either integrated to air outlets (called “Ventilation Hygro A”), or to both air inlets and outlets (called “Ventilation Hygro B”).

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 exhausted airflow to a low level of background ventilation during unoccupied periods or low activities. However, as for balanced ventilation, they induce a weaker under-pressure that can be lower than the weather induced pressure (Liddament M., 1996). Therefore the total air change rate is more subjected to variations due to the air infiltration.

METHOD

A numerical approach based upon the coupled thermal and airflow network model TRNSYS-COMIS is adopted. It allows the calculations of 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).

Presentation of the building and occupancy patterns

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 of the dwelling. Main thermal properties of wall and windows are described in TABLE 1

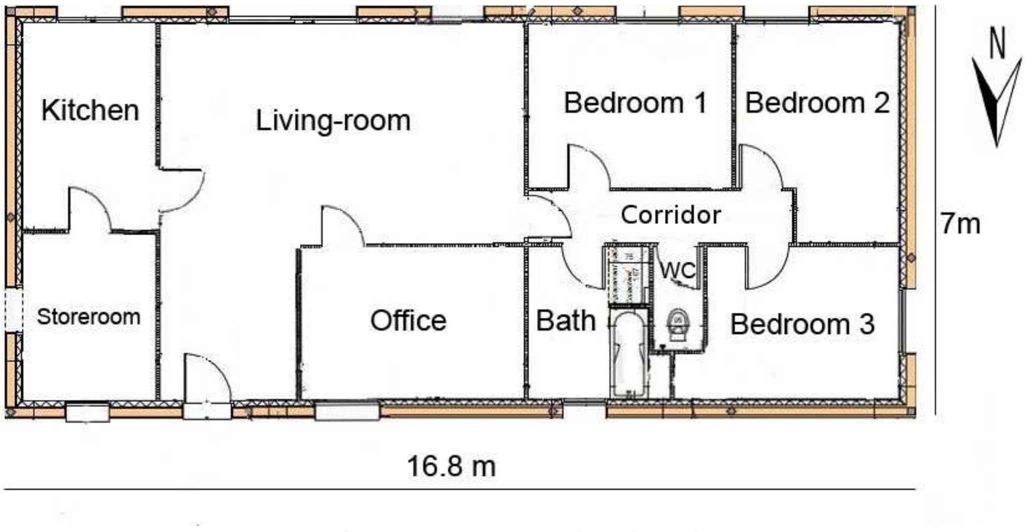

Figure 1: Plan of the dwelling

TABLE 1: Wall composition

Wall	Composition	U value
External Wall	20 cm hollow brick + 10 cm glass wool insulation	0.21 W/(m^2.K)
Upper Ceiling	1.3 cm gypsum + 27 cm glass wool insulation	0.14 W/(m^2.K)
Floor	4 cm concrete + 9cm Polyurethane + 12cm concrete	0.24 W/(m^2.K)
Living room Windows	Low emissivity double-glazing with aluminium frame	1.7 W/(m^2.K)
Other Windows	Low emissivity double-glazing with PVC frame	1.4 W/(m^2.K)
Pitched roof	Clay roof tile (High ventilated attic)	5.6 W/(m^2.K)

Dwelling is supposed to be heated from 1st October to 20th May with an 20.4℃ ambient temperature during occupied period (18h-9h on weekdays and all the week-end). Set point temperature is 3℃ reduced during unoccupied period (weekdays).

Ventilation systems

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. The second is a mechanical balanced ventilation with a 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. Finally, two strategies of mechanical humidity-controlled ventilation are modelled following technical agreement specifications (CSTB, 2009). “Humidity-controlled Hygro A” is composed of self-regulated air-inlets in main rooms 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		
	Living room	**Bedrooms & office**	**Kitchen**	**Bathroom**	**Toilet**
Self-adjusting exhaust ventilation	2 x (22 m^3/h)	30 m^3/h	45 m^3/h	30 m^3/h	30 m^3/h
Balanced ventilation	35 m^3/h	18 m^3/h	45 m^3/h	30 m^3/h	30 m^3/h
Humidity-controlled Hygro A	2 x (22 m^3/h)	30 m^3/h	12-45 m^3/h at RH 50-83%	10-45 m^3/h at RH 25-60%	30 m^3/h
Humidity-controlled Hygro B	2 x (6-45 m^3/h) at RH 45-60%	6-45 m^3/h at RH 45-60%	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’)

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 3 presents the values of the heat and moisture ratios of the activities that have been considered in the calculation. The humidity ratios represent the total amount of moisture per week that has been calculated from ratios mentioned by CSTB (2003) and Annex 27 of IEA ECBCS (2002). For example, the CSTB gives a ratio of 500 g/person for shower. 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 0.28 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.

TABLE 3: Heat and Humidity ratio of different sources

Sources	**Heat ratio**	**Humidity ratio**
Occupant metabolism : sleeping	0.7 met	15.2 kg/week
Occupant metabolism : seated at rest	1 met	
Occupant metabolism : seated light activity	1.2 met	
Artificial lighting	1.4 W/m² of floor area	-
Domestic appliances	5.7 W/m² of floor area	-
Cooking	-	11.0 kg/week
Showering	-	14.0 kg/week
Drying cloths	-	7.0 kg/week
Floor cleaning	-	0.5 kg/week

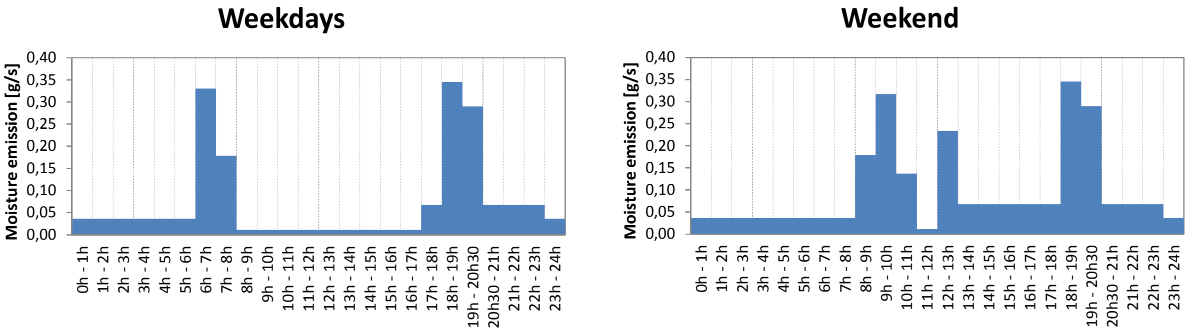

Figure 2: The sum of total moisture emission schedules for all zones

Climates and Wind exposure

Three French regions with distinct climates have been considered for the study, according the climate distinction used for energy requirements: continental, oceanic and Mediterranean. Besides, as the wind has a significant impact on the air infiltration, two different locations have been considered for the Mediterranean climate. The locations are the following:

- Continental climate : Strasbourg
- Oceanic climate: Poitiers
- Mediterranean climate: Nice
- Windy Mediterranean climate: North Corsica

Both locations (Nice and North Corsica) have close insolation and temperatures, but significantly different wind regimes. This is confirmed through the analysis of wind speed and direction distribution as illustrated on Figure 3.

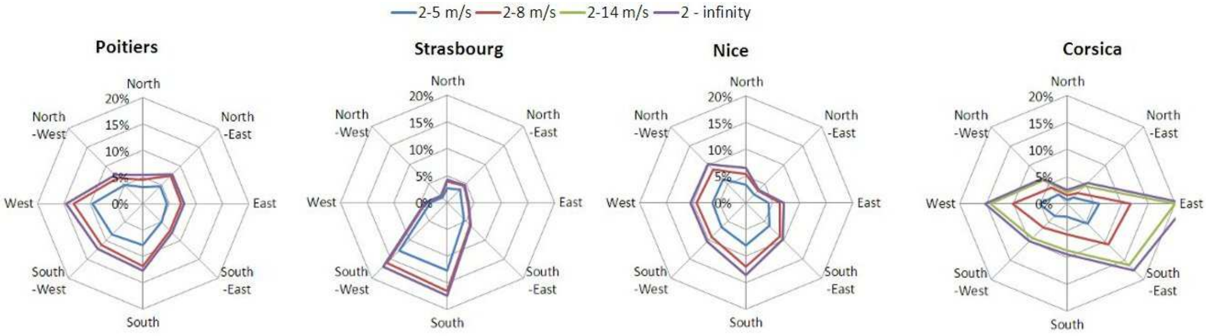

Figure 3: Wind Rose for four locations

As wind pressure coefficients (Cp) depend on the surrounding ground and the wind angle relative to each façade, we have considered two shielding conditions: “exposed” and “surrounded by obstructions”. The Cp values are considered in accordance with the AIVC guide on ventilation (Liddament M., 1996).

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 by the standard EN NF 15242 (2007). The cracks characteristics are as follows:

- fixed 0.65-flow exponent,

- flow coefficient calculated from the global building coefficient $Q_{4pa\ surf}$ proportionally the ratio of the façade area to the total envelope area A_{Tbat}.

The zones are interconnected by 90 cm wide doorways considered 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 NF P 50-410 (1995). The door undercut is modelled as a large crack with 0.5 flow exponent.

Besides two particular cases have been considered in order to evaluate the influence of modelling parameters on airflow rates:

- a simplified single-zone model with a heated single well-mixed zone without internal partitions (e.g.. internal doors always open).
- a leakage distribution with cracks only on vertical façade.

INFLUENCE OF AIRTIGHTNESS ON BUILDING HEATING LOAD

Simulation 1: Airflow Network modelling

A first set of simulation is done with Poitiers climate and “wind exposed” condition. The ventilation Hygro B system is used because of its specific behaviour depending on local humidity. Figure 4 presents the results of single and multi-zone models for the two leakage distributions (facade/ceiling and facade only).

Figure 4 illustrates a negligible difference between single-zone and multi-zone simulation for the facade/ceiling distribution, both in energy needs and trends. When leakages are distributed only on facades, the heating needs for the single-zone model are 6 kWh/(m².yr) @ 2 m^3/(h.m²) higher compared to the multi-zone model. It also induces a higher sensitivity (17 against 13 kWh/(m².Year) per unit of air permeability). The single-zone model amplifies the crossing airflow through building, especially leakages only distributed on facades.

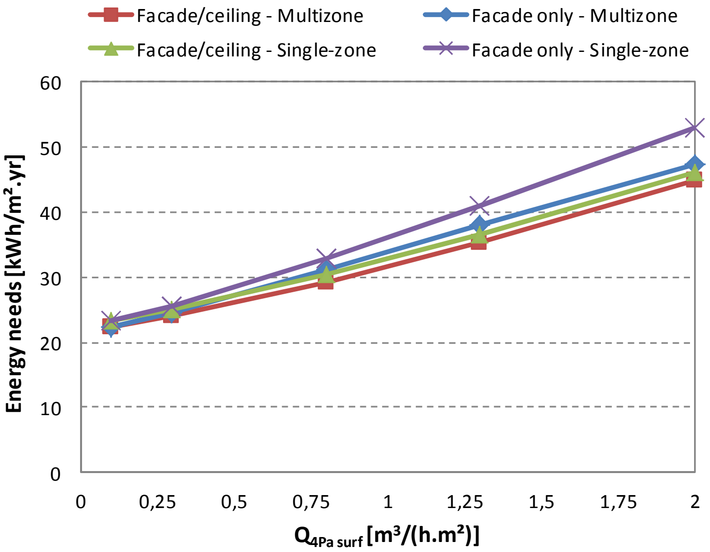

Figure 4: Influence of airflow Network modelling

Simulation 2: Ventilation systems

A second set of simulations is done for the four ventilation systems using the multi-zone model with Poitiers climate and “wind exposed” condition. Figure 5 illustrates the results of energy needs and Figure 6 the energy needs sensitivity towards air permeability.

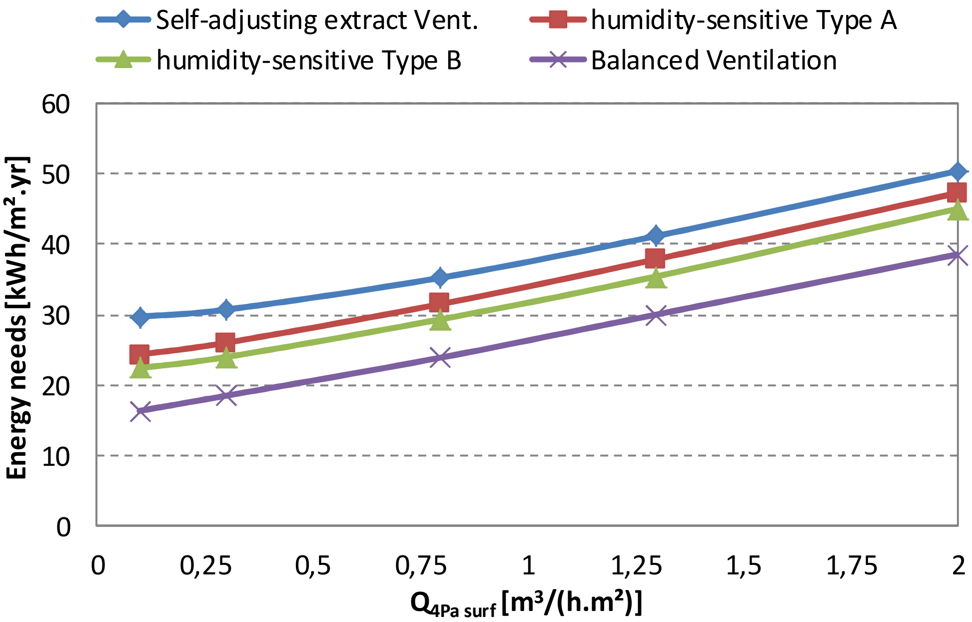

Figure 5: Influence of ventilation systems

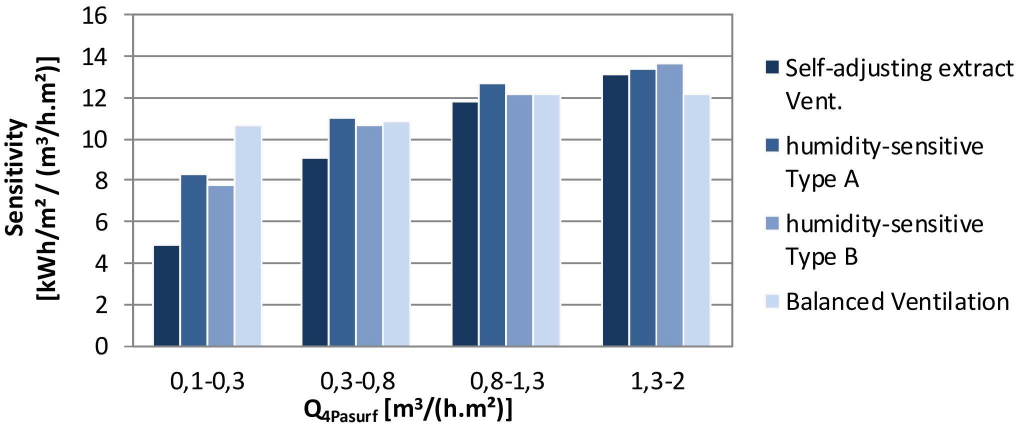

Figure 6: Sensitivity of energy needs for different ventilation systems

As expected, energy needs increase with air-permeability. The balanced ventilation enables the higher energy savings followed by humidity sensitive and self-adjusting ventilation.

When we analyse the sensitivity of energy needs towards air permeability, 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/(m².Year) per unit of air permeability) is the highest followed by humidity sensitive ventilation (8 kWh/(m².Year) per unit of air permeability), and self-adjusting extract ventilation (5 kWh/(m².Year) per unit of air permeability index). This can be explained by the weaker underpressure 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 $m^3/(h.m^2)$), the energy needs increase in the same amount (12 to 14 kWh/(m².Year) per unit of air permeability) whatever the ventilation systems. It can be explained by a leakage air renewal which significantly exceeds the air renewal related to the different ventilation systems.

Simulation 3: Climatic conditions

A third set of simulation is done to analyse the impact of climatic conditions for the case of Humidity-controlled ventilation Hygro B. Figure 7 illustrates the results of energy needs and Figure 8 the energy needs sensitivity towards air permeability.

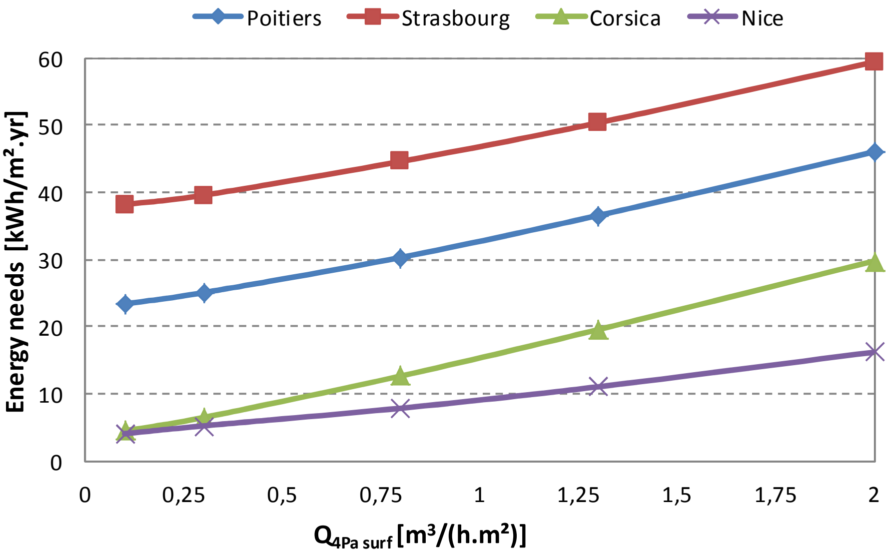

Figure 7: Influence of the climate

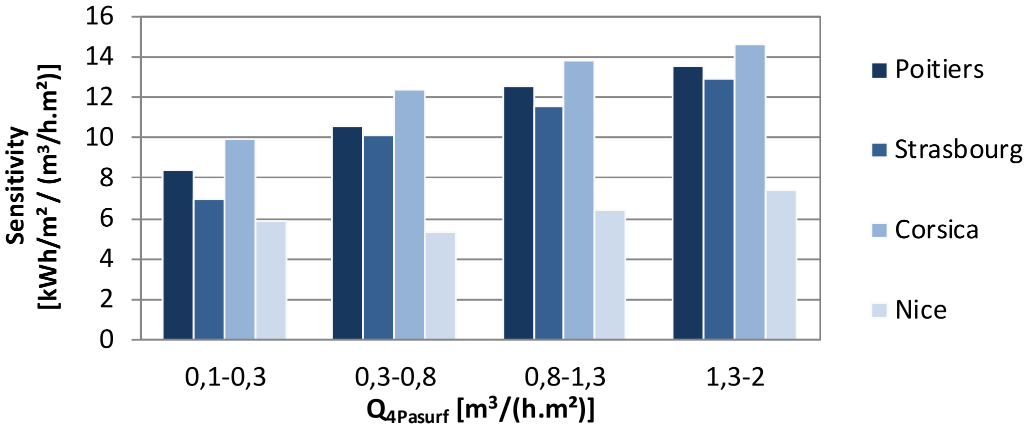

Figure 8: Sensitivity of energy needs for different climates

An expected increase of energy needs according to climatic conditions is observed - the continental climate of Strasbourg with the highest values followed by oceanic (Poitiers) and mediterranean (Nice and North Corsica) climates. For the mediterranean climate where the heating demands are very low, the impact of air permeability becomes dominant as it increases. For example in Nice, the heating demand increases by 63% from a very good airtightness (0.1 $m^3/(h.m^2)$) to a minimum mandatory of 0.6 $m^3/(h.m^2)$.

Concerning the sensitivity, the lowest value was observed for the mediterranean climate of Nice (6 $kWh/(m^2.Year)$ per unit of air permeability) due to its warmer climate. Strasbourg and Poitiers have a higher sensitivity (around 14 $kWh/(m^2.Year)$ per unit of air permeability) due to their colder climates. However North Corsica shows the highest sensitivity despite the mild temperatures of its mediterranean climate (up to 15 $kWh/(m^2.Year)$ per unit of air permeability). This can be explained by the strong wind conditions of North Corsica as compared to Nice. Therefore, the impact of air permeability on energy needs depends on both average exterior temperature and wind conditions.

Simulation 4: Wind exposure

In order to evaluate the impact of shielding conditions, a fourth set of simulations is done for two configurations: “exposed” and “surrounded by obstructions”. Figure 9 illustrates the results of energy needs for multi-zone model with a humidity-controlled system Hygro B with Poitiers and North Corsica’s climates.

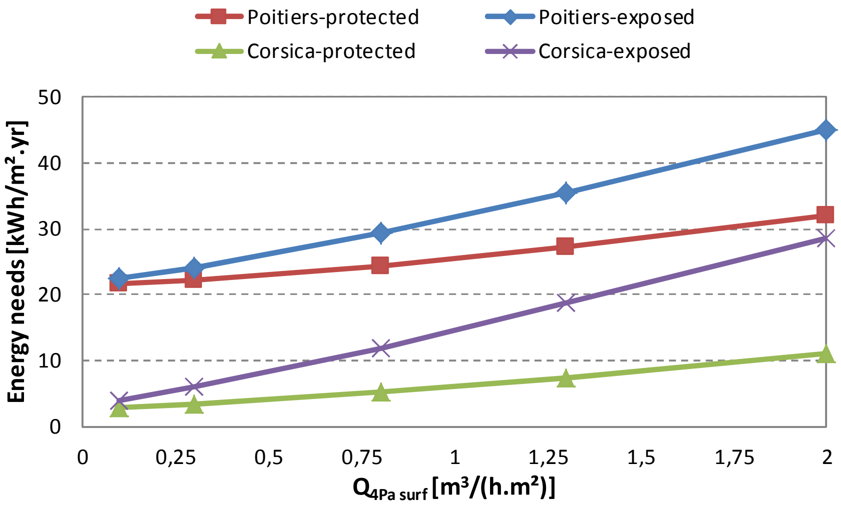

Figure 9: Influence of the wind exposure

For these two climates, wind exposure significantly influences energy needs. For the case of buildings surrounded by obstructions, the impact of air permeability on energy needs is 3 times lower in Corsica, and 2.5 times in Poitiers than exposed buildings.

CONCLUSION AND FUTURE WORK

In order to evaluate the impact of air permeability on energy needs in buildings, a typical French dwelling has been studied for different ventilation systems in three French climates. The numerical investigations show an increase of heating load from 2 to 17 kWh/(m^2.Year) per unit of air permeability index, depending mainly on shielding conditions and climatic zone. Thus, a good treatment of airtightness is essential for low energy building whatever the French climate, including the mediterranean area exposed to strong wind conditions.

Ventilation systems that induce weak under-pressure in buildings - such as humidity control and balanced exhaust systems - are more sensitive to air permeability, especially for very good airtightness levels. However, for higher air permeability, the impact is the same whatever the ventilation system.

Concerning the modelling approached, single- and multi-zone model give close results for different ventilation systems, including humidity sensitive ventilation (hygro B). However, caution should be exercised in case of strong wind conditions and leakages distributed only on the facades (and not on the ceiling), as single-zone models amplify the crossing air flows. Also, the choice of pressure coefficients, which are affected by surrounding obstructions, influences significantly energy needs.

This study focused on the heating impact of building air permeability. However, we foresee to use the multi-zone model to study the impact of airtightness on local indoor air quality.

ACKNOWLEDGEMENTS

This work has been financed by the French Ministry of Housing. The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the Ministry.

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