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► **To cite this version:**

Juslin Koffi, Jean-Jacques Akoua, Francis Allard. Experimental Validation of a Numerical Multizone Airflow and Pollutant Transfer Model. 10th REHVA WORLD CONGRESS “Sustainable Energy Use in Buildings”, May 2010, Antalya, Turkey. pp.73. hal-00486173

**HAL Id: hal-00486173**

**<https://hal.science/hal-00486173>**

Submitted on 25 May 2010

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# Experimental Validation of a Numerical Multizone Airflow and Pollutant Transfer Model

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## SUMMARY

In order to get a useful tool for global and long-term assessment of the performances of ventilation systems, the experimental house MARIA and ventilation systems are modeled in MATLAB/Simulink environment. This paper quickly describes the multi-zone airflow and pollutant transfer model and deals with the validation by experimental means.

Firstly, tracer gas methods are used to evaluate pollutant transfer within the real house. Then, numerical investigations are performed with the developed airflow tool by using some measured parameters as input data. Comparisons between the numerical and experimental results show that the evolution of the concentrations is adequately modeled. However, concentrations from the model were high enough. Then, a parametric study is carried out in order to determine the influential factors and better represent the experimental house by an airflow model; it finally appears that the internal airflow connections and the envelope air leakage should be better known.

## INTRODUCTION

Ventilation and air leakage count for about 30 % of the energy consumption of buildings. Maintaining an acceptable indoor air quality while reducing energy consumptions has become a compromise for the professionals of building ventilation. In this framework, CSTB has built an experimental house (MARIA: *Mechanized house for Advanced Research on Indoor Air*) equipped with mechanical exhaust, balanced and natural ventilation systems. In addition, the virtual laboratory SIMBAD Building and HVAC Toolbox (*SIMulator of Building And Devices*) is developed in MATLAB/Simulink environment [1], with the support of the University of La Rochelle, for the management of buildings energy demand; we also with this tool developed airflow and pollutant transfer models.

For advanced studies of ventilation systems, MARIA is modeled using SIMBAD. This paper aims to show an example of the validation of the multizone airflow and pollutant transfer model of MARIA.

A simulation tool can be evaluated by analytical evaluation, inter-model comparison and experimental comparison [2]. The latter method is the most complete and complex way to evaluate a tool; it consists in the comparison between measurement results and results obtained with the investigated tool. These procedures are used for validating simulation tools like COMIS [3]. Besides, Bossaer et al. [2] experimentally examined the reliability of COMIS in the field of internal air flows and pollutant transfer. Such studies are performed by Blomsterberg et al. [4] and Koinakis et al. [5] with different ventilation systems and show good agreement in various cases.

In the present study, different pollution scenarios by tracer gas are carried out in the actual building for three existing ventilation systems. Then, simulations are done by considering measured indoor and outdoor parameters as input data. Finally, comparisons are made between the experimental and the numerical concentrations and parametric studies are performed to illustrate the influence of some factors on the results.

## METHODS

The investigations are carried out in the experimental house MARIA [6] by means of tracer gas methods [7]. This house consists of four bedrooms, a bathroom and a shower at first-level, a living-room, a kitchen and toilets at ground-level, all linked by a hall (Figure 1). There is also a basement is connected to the hall by a closed door. The pollution source is simulated by a release of sulfur hexafluoride ( $\text{SF}_6$ ) at 2 ml/s flow rate for 5 hours, respectively in the living-room, the kitchen and bedroom 3. The concentrations are measured in six rooms: the living-room, the kitchen, the hall, bedrooms 3 and 4, and the bathroom. This scenario is applied for mechanical exhaust and balanced ventilation systems, and natural ventilation. Detailed results of this investigation can be found in [8].

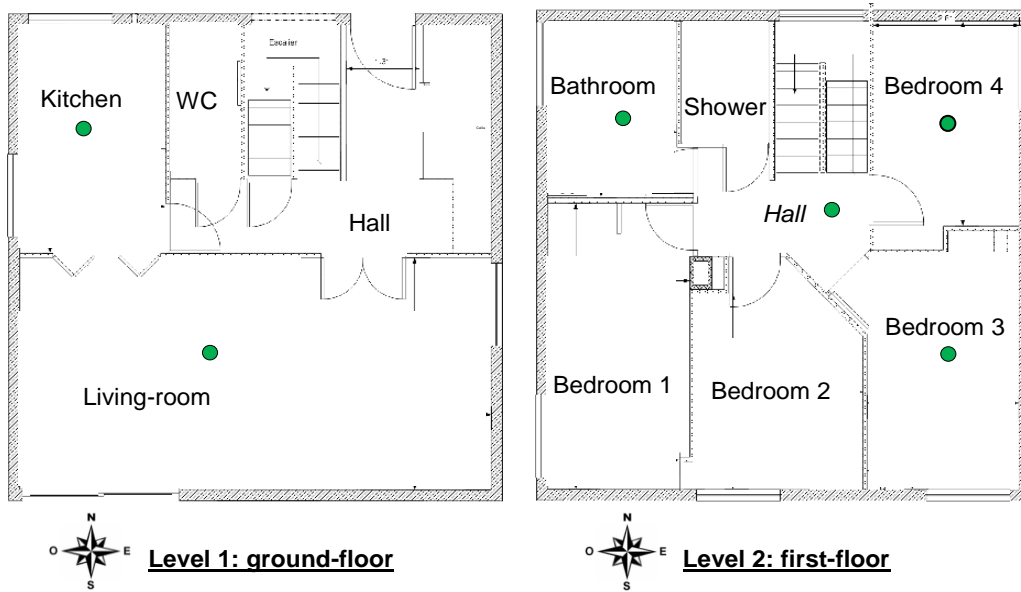


Figure 1. Experimental measurement in the house.

Modeling the experimental house MARIA aims to get a building model for long-term assessment of the IAQ and energy impacts of the applied ventilation system. For doing this, thermal models (walls, windows, heating devices...) of SIMBAD Toolbox are used on the one hand for achieving heat transfer [1]. On the other hand, airflow components, based on orifice model, are modeled in MATLAB/Simulink environment for calculating mass transfer:

$$\dot{m} = \rho K \Delta p^n, \quad (1)$$

For ventilation components such as air inlets or outlets, the reference airflow rate  $q_{v0}$  is given by the constructor at a reference pressure  $\Delta p_0$ :

$$\dot{m} = \frac{\rho_0 q_{v0}}{\sqrt{\Delta p_0}} \times \sqrt{\frac{\rho}{\rho_0} |\Delta p|}, \quad (2)$$

For the building air leakage, the parameters  $K$  and  $n$  in equation (1) can be determined by experimental means using the blower-door or tracer gas methods. When one gets only the whole envelope air leakage  $P_{\Delta p_0}$  ( $m^3/s/m^2$ ), this value can be used for each façade as follows:

$$\dot{m}_{leakage} = \rho P_{\Delta p_0} A_{façade} (\Delta p / \Delta p_0)^n, \quad (3)$$

where  $A_{façade}$  ( $m^2$ ) is the surface area of the considered façade.

Equation (3) supposes homogenous repartition of the air leakage on all façades, what is not always the case in actual buildings. In the model, each façade is connected by two air leakage components for taking into account an eventual neutral plane on the building façades.

Allard et al. [9] shows the importance of including the influence of humidity ratio on the air density. In this program, the air density depends on node temperature, pressure and air humidity according to an equation based on the ideal gas law:

$$\rho = \left( \frac{\rho_0 T_0}{T} \right) \frac{P}{P_0} \frac{1 + \omega}{1 + \omega (M_a / M_v)}, \quad (4)$$

where  $\omega$  ( $kg/kg$ ) is the humidity ratio,  $P$  ( $Pa$ ) the absolute pressure,  $T$  ( $K$ ) the indoor air temperature. Wind and stack effect together with fans are the driving forces of air movement within the building. The inside pressure is given by the hydrostatic equation:

$$p_i = p_{i,0} - \rho_i g h_i, \quad (5)$$

where  $p_{i,0}$  is the reference pressure of the zone.

The stack effect is included in every flow element through the pressure difference:

$$\Delta p_{therm} = -g(\rho_j h_j - \rho_i h_i), \quad (6)$$

Wind pressure on the external nodes is calculated by:

$$p_w = C_p \times \frac{1}{2} \rho_{ext} U_w^2, \quad (7)$$

where  $U_w$  ( $m/s$ ) is the measured wind speed.

The ventilation systems are modeled with their actual airflow characteristics: fans are approximated by polynomial equations resulting from the actual airflow curves. The total pressure drop in ductworks is given by the expression:

$$\Delta p_{duct} = \left( \frac{\lambda L}{D_H} + \sum_i \zeta_i \right) \frac{1}{2} \rho V_{duct}^2, \quad (8)$$

Here, the friction and minor loss coefficients,  $\lambda$  and  $\zeta$ , are calculated by different equations from [10] according to the nature and the geometry of the ducts. Once the airflow rates are known, the pollutant mass balance in the  $i^{th}$  zone of a multizone building with  $N_z$  zones, connected to zone  $j$  through  $Nk(j,i)$  airflow elements, is given as follows:

$$\rho_i \frac{dm_i}{dt} = S_i + \sum_{j=0}^{N_z} \sum_{k=1}^{Nk(j,i)} \dot{m}_{jik} C_j - \sum_{j=0}^n \sum_{k=1}^{Nk(i,j)} \dot{m}_{ijk} C_i, \quad (9)$$

The model of MARIA consists of 11 zones which are the actual rooms. The hall is connected to all zones via closed doors represented by orifice model; apart from the kitchen and the living-room, no air flow link is considered between the other zones. Such a configuration allows all the air flows transiting by the hall and avoids, for instance, pollutant transfer between habitable rooms. As shown by equation (5), height reference is the floor level of each zone. The model is compared to CONTAM and shows good agreements: the maximum error is lower than 5% in most of cases [11]. This means the equations are correctly modeled so that the airflow model can be considered accurate with regard to CONTAM.

For comparison with experimental results, tracer gas methods are used in the same conditions as for the experiments. The model uses the measured indoor and outdoor air temperatures and humidity ratios as well as wind speed and direction as input data for the simulations. The envelope air leakage is equal to the experimental value of  $0.9 \text{ m}^3/\text{h}/\text{m}^2$  [11]. The mechanical airflow rates are the measured ones. The model then calculates inside pressures and pressures in the ducts, the airflow rates and pollutant concentrations. We present here the results of injection in the living-room and the kitchen for mechanical exhaust and balanced ventilation systems with inner doors closed.

## RESULTS

Figure 2 compares tracer gas concentrations in the living-room (the injection room) from the model and the experiments for mechanical exhaust ventilation. The maximum concentration level is about  $830 \text{ mg}/\text{m}^3$  while the experimental results in only  $530 \text{ mg}/\text{m}^3$ . It clearly appears that, in this case, the concentration from the model is very high compared to the experimental result. This difference leads to up to  $120 \text{ mg}/\text{m}^3$  concentration difference on the pollutant transfer towards the kitchen. A similar observation can be made in the bedroom 4 where the experimental concentration reaches about  $55 \text{ mg}/\text{m}^3$  against almost  $10 \text{ mg}/\text{m}^3$  with the model. However, the model shows a good pollutant transfer towards the hall, the bathroom and bedroom 3 at the first level.

For injection in the kitchen (Figure 3), there is a better agreement between the results; almost no pollution is observed in the other rooms for both experiments and simulations. Besides, one can observe similarities in the variation of the concentrations for all cases.

Such observations are made for comparison using mechanical balanced ventilation and natural ventilation. But the differences are the lowest for the first system and the highest for the second one. It then appears that the better the airflow rates are controlled, the lowest the divergence between results are. This is indeed illustrated by the agreement between experimental and numerical concentrations in the kitchen.

The observed deviations in concentration levels are likely to result from different causes: modeling assumptions (perfect mixing, input data such as inner air flow path, building air leakage, pressure coefficients, etc.) and measurement uncertainties (concentration, airflow rates, pollutant injection rate, temperature, humidity...).

We try to check out the influence of each parameter by different tests. Results show that the  $\text{SF}_6$  injection rate has little influence as far as, to get the curves superposed, it would varied between 0.9 and 1.7 ml/s along with the ventilation system and the emission room. Besides, measurement uncertainties seem to be meaningless. As there is no pressure coefficient measurement for MARIA,  $C_p$  values from literature are used [10]; this choice could have influenced the results.

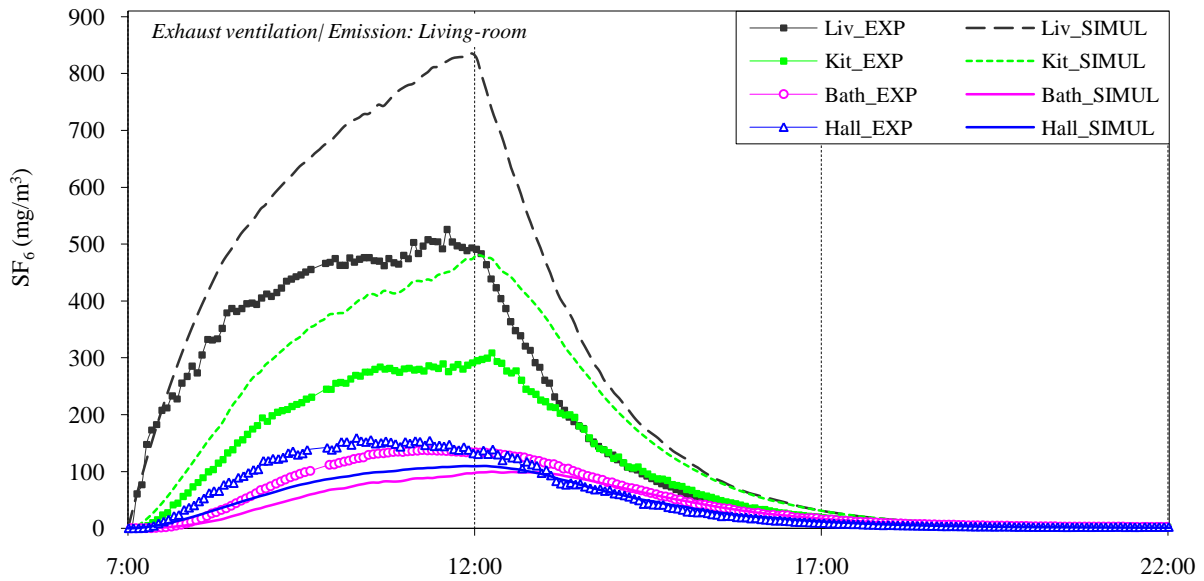


Figure 2. Exhaust ventilation - SF<sub>6</sub> concentrations for injection in the living-room (Case A).



Figure 3. Exhaust ventilation - SF<sub>6</sub> concentrations for injection in the kitchen (Case A).

The results for both inner air flow paths and air leakage distribution on the façades are presented in the paragraph below.

### Influence of air leakage

Initially in the simulations, the envelope air leakage is the same whatever the façade is. Here, we suggest a new distribution based on some observations in the building: rooms with windows are likely to be less tight (Table 2). Besides, as no test value is available for inter-zonal air leakage, we increase orifices at the bottom of the inner doors to take into account internal connections such as cracks around ducts, wires or plug-in crossing the walls in addition to the links at the border of the doors (Table 1).

Figure 4, Figure 5 and Figure 6 compare concentrations for injection in respectively the living-room and the kitchen for mechanical ventilation systems.

Table 1. Change in air flow paths under internal doors.

Air flow path	Case A (cm)	Case B (cm)
Service rooms/ Hall	2.0	2.0
Bedrooms/ Hall	1.0	1.5
Living / Hall	1.0	1.75
Living/ Kitchen	1.0	1.5

Table 2. Distribution of air leakage on rooms' façades.

Room	Air leakage on façades (m <sup>3</sup> /h/m <sup>2</sup> )			
	Case B0	Case B1	Case B2	Case B3
Bedrooms	0.9	0.99	1.035	1.035
Living-room	0.9	1.305	1.35	1.395
Kitchen	0.9	0.7	0.5	0.5
Bathroom, Shower, WC	0.9	0.2	0.2	0.1
Hall	0.9	0.2	0.2	0.2
Basement	0.9	0.9	0.9	0.9
Total infiltration at 4 Pa (m <sup>3</sup> /h)	151	150	151	151

The maximum SF<sub>6</sub> level in the living decreases from 830 mg/m<sup>3</sup> initially (Case A) to 750 mg/m<sup>3</sup> in Case B0 and to 665 mg/m<sup>3</sup> in Case B1. With change in inter-zonal air flow links and heterogeneous distribution of air leakage, the façades are less tight causing important crossing-flows. However, concentrations vary weakly from Case B1 to Case B3 because the permeability margin of variation is very narrow from Case B1. It means that internal air connections are more influential on pollutant spread than envelope air leakage distribution; it is the reason why the pollutant spread is very low in most of the cases. The concentration is less sensitive to permeability with balanced ventilation; in fact, infiltration is less important in this configuration and internal pressure equilibrium is no more sensitive to inner permeability.

Pollutant spread towards the kitchen also decreases along with the changes. However, the transfer upstairs (bedrooms, bathrooms, and hall) is still under-estimated despite a slight increase: the distance between the experimental results and the numerical ones is always significant in all rooms.

For injection in the kitchen with both systems, the concentrations are less sensitive to the permeability so that the pollution level remains close to the experimental values since the exhaust airflow rates are identical. On the contrary, it seems to be a slight accumulation of SF<sub>6</sub> in the kitchen.

In all cases, the concentrations dynamics is nevertheless in accordance with the experiments: decrease phases show similar air change rates in the studied rooms. These results mean that effort must be done to get the actual values of the two influential factors for each room of the building. The impact of the studied factors on concentrations is clearly visible: this confirms that the major cause of differences is undoubtedly the inadequacy of the representation of inter-zonal air links combined with inadequate distribution of the envelope permeability.

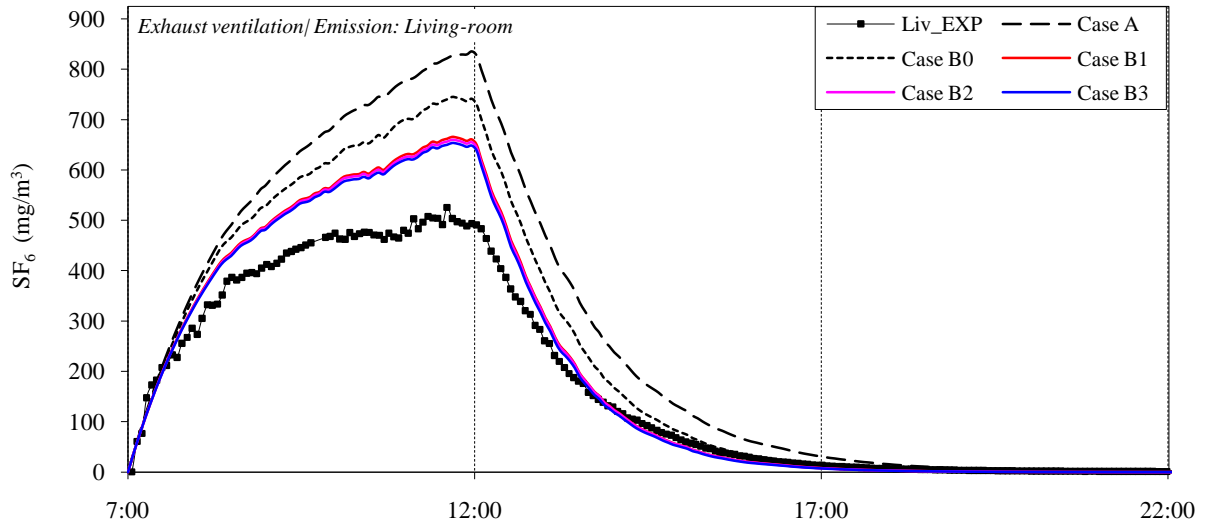


Figure 4. Exhaust ventilation – Influence of air leakage on SF<sub>6</sub> concentration in the living-room for injection in the living-room.

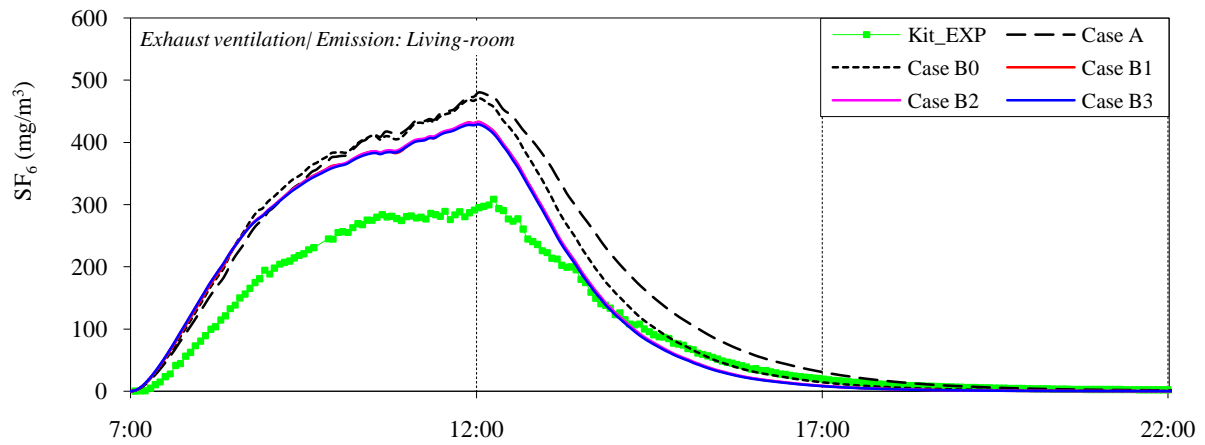


Figure 5. Exhaust ventilation – Influence of air leakage on SF<sub>6</sub> transfer towards the kitchen for injection in the living-room.

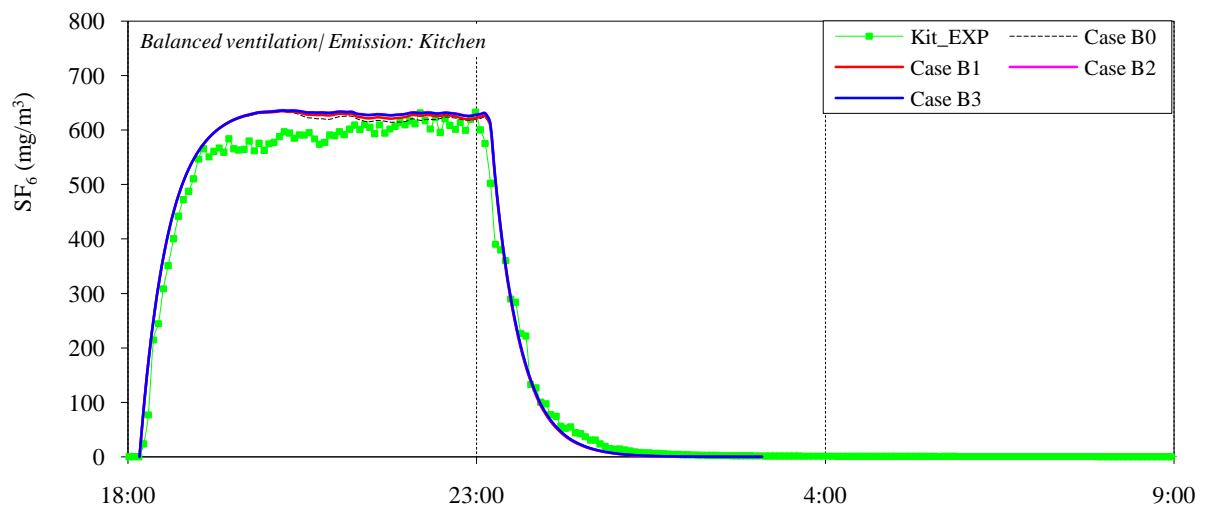


Figure 6. Balanced ventilation – Influence of air leakage on SF<sub>6</sub> concentration in the kitchen for injection in the kitchen.



## DISCUSSION

The comparisons between tracer gas concentrations from simulations and experiments show many disparities. The numerical results show pollutant accumulation in the release rooms and little pollutant transfer within the building, excepted towards the kitchen. In fact, while modeling the experimental house MARIA, several settings could not be considered.

It is certain these errors are due to under-estimation of air flow connections which may effectively have a critical impact on pollutant spread since they influence inner pressure equilibrium. Indeed, the building envelope air permeability is evenly distributed due to lack of measurements by façade. As demonstrated by the results, heterogeneous distribution contributes to approach the measured pollution levels. In addition, the complexity to assess with certitude the internal air flow paths results in numerical under-estimation of inter-zonal air exchanges and pollutant transfer compared to experimental results. Unfortunately, no experimental values of these parameters are available for simulations.

As shown by results for injection in the kitchen, measurement uncertainties on tracer gas concentrations and airflow rates cannot explain the observed discrepancies. Furthermore, pressure coefficients from the literature were used in the model; it can be quite useful to determine experimentally these coefficients to represent the real wind pressure on MARIA.

The major difficulty in modeling an actual building is undoubtedly the considerable number of influential parameters on the air change rate. Unfortunately, most of these parameters are not directly accessible through measurements. The multitude of unknown factors prevents indeed an accurate determination of the impact of each parameter as well as their interaction. However, it stands out from this study that a better modeling of the experimental house MARIA requires both the knowledge of the air permeability of every façade and an accurate evaluation of air connections between the rooms.

## ACKNOWLEDGEMENT

This study is carried out as part of a PhD thesis at the CSTB building research centre of Marne-la-Vallée (Paris, France), and is directed by Pr. Francis Allard of University of La Rochelle (France) and Dr. Jean-Jacques Akoua from CSTB.

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