PROGRESS AND TRENDS IN AIR INFILTRATION
AND VENTILATION RESEARCH

10th AIVC Conference, Dipoli, Finland
25-28 September, 1989

Paper 6

EXPERIMENTAL STUDY OF AIR FLOW PATTERNS IN A THREE BEDROOM HOUSE

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ABSTRACT

This paper describes a set of experiments conducted in a three bedroom house in order to identify the leakage distribution of the building and the air flow rate through the on-purpose designed opening of the interior doors. Starting from the depressurization test in every zone, we were unable to track all the flow equation of every specific identified connection. We therefore propose to characterize the leakage between two zones by a unique general connection. Its flow behavior (K,n) is determined by an optmization under constraints of the results of the various tests. In the second phase, we study the aeraulic behavior of a slot, usually included in French doors and then we replace the existing interior doors by tight doors with a calibrated duct having a similar areaulic behavior $f(Q,\Delta P)=0$. In the absence of wind and temperature difference, we measure the air flow rate through the interior doors for differents mechanical extraction rates and compare them to the results of a pressure model simulation.

1. INTRODUCTION

In order to reduce the energy losses in buildings due to ventilation, innovative HVAC systems have been designed to satisfy the minimum air change rate at every instant according to weather and indoor conditions (humidity, temperature, concentration). A global ACH of 0.1-0.2 can be encountered. However, if we do not want to face some disorders such as air quality, condensation meldew problems, the optimum theoritical air flow path between the different rooms in the apartment should be respected. Our main question is to know if we can control the air pattern at such low air extraction rate. The answer to this question is conditionned by the building overall permeability and the leakage distribution between the various components including interior partitions. The first part of our study is devoted to identify the flow behavior of the air paths. Many studies have focused on enveloppe components but almost no research refers to interior ones. Unfortunately, the air flow pattern within the building can be largely modified in presence of leaky interior components. In the second phase of our study, we compare the experimental air flow rate through on purpose designed connections with the numerical air flow rate.

2. BUILDING PERMEABILITY

2.1 Experiment

Experiments are conducted on a new semi-detached house which respects the French building regulations. The reference building is a three bedroom house of 100 square meters, located in the suburbs of Lyon, France, on a well sheltered site. It has never been occupied and is equipped with a mechanical ventilation system. Automatic air inlets are casted in the frame of windows of the living room and bedrooms. Air Extraction takes place in the toilets, bathrooms and kitchen with a proportion of 1/5, 1/5, 3/5. The total mechanical extraction rate can be varied from 50 to 300 m3/h.

In order to characterize the leakage distribution of the house, a series of depressurization tests in the entiere building and in every aeraulic zone are realized. During the experiments, the wind speed is lower than 2 m/s and no temperature difference is notified between the outside and inside and within the interior zones. Otherwise, the test is rejected.

Some of the air connections : air inlet, shutter chest, window frame, light switch, wall-floor link, pipes,... are identified. After sealing of some of these detectable air paths, we reconduct some tests in order to analyse their specific behavior and their role.

2.2 Analysis

The results of the experiments are presented in Figure 1. We notice the major contribution of undectectable connections on the infiltration. The tighness of the house could have been drastically improved with a good quality of construction and adequate choice of building components. For example, the high quality window frame is associated with a poor shutter chest. No sealing joint between the interior partition and the floor of the bedroom has been installed. Some care seems to have been brought to the kitcken. At the opposite, the bathroom, the toilets and the hall present large undetectable infiltration in comparison with their volume. Running waterpipes and electrical wiring may represent some privilegeous air paths. Bedrooms have a similar behavior, bedroom ≠ 2 has a reduced surface of exterior enveloppe and is less leaky. The living room with the stairwell represents a large volume with important infiltration. However, the air flow rate per unit of volume is in the average of the building.

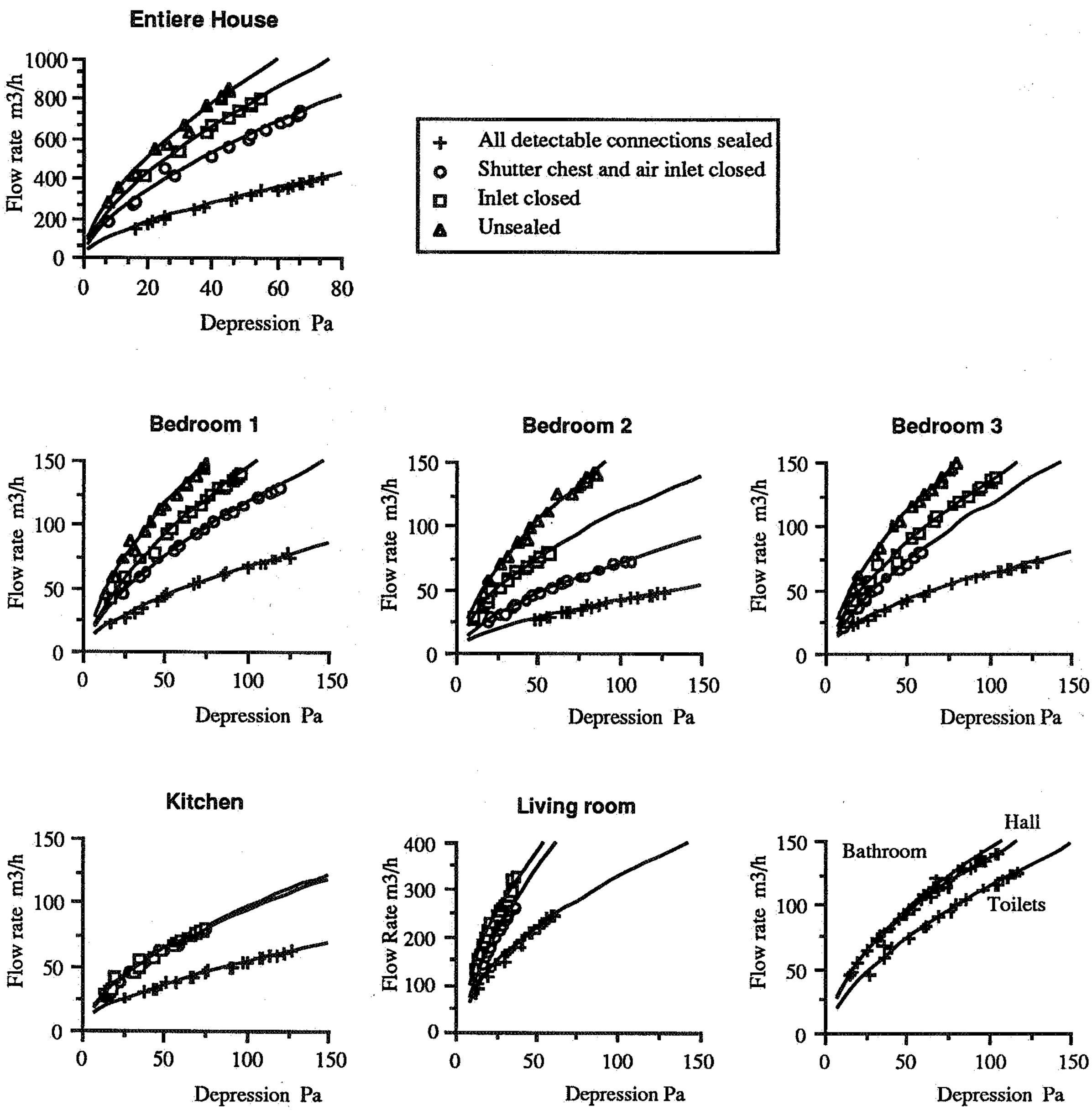

Figure 1: Results of depressurization tests

The leakage characteristic of this house is representative of new built houses in France. At 1 Pascal, the air flow rate per unit of volume is equal to 0.24 in the 0.24-0.48 range (table 1) which is the result of an extensive survey on 70 houses in France[1].

On purpose designed air inlet do not represent the major source of incoming air.

	massive buildings exterior insulation		massive buildings interiorinsulation		light building	wood frame building
	simple	multi-family	simple	multi-family	simple	multi-family
Average	0.25	0.11	0.36	0.17	0.39	0.74
Variance	0.08	0.10	0.12	0.15	0.18	0.38
Number of Houses tested	6	20	54	21	15	19

Table 1 : Permeability per unit of volume at 1 Pascal[1]

3. Leakage distribution

Many of the pressure models require a precise description of the air connections between the different zones. For example, in ESPAIR, the geometry of the connection (width, length, area) should be mentionned as well as its type : crack, opening or large opening. The methodology adopted in the experiment was conceived to identify the behavior of detectable air paths by making the connection inactive and then active. Let us identify the aeraulic behavior of some components.

3.1 Power Law

In the same buiding configuration, let us take two depressurization tests : one with the connection A sealed and the other unsealed.

From test 1 (resp 2), we get a series of couples (ΔP1,Q1) (resp (ΔP2,Q2)).

If we suppose that the connection A follows a power law, we have different possible methods to identify it :

. Look for tests at same depression ΔP and fit a power curve through the points (ΔP,Q1-Q2)

. Suppose the test 1 and 2 follow a power law : $Q1 = K1\ \Delta P^{n1}$ and $Q2 = K2\ \Delta P^{n2}$ then identify $Q = Q1 - Q2 = K\ \Delta P^{n}$

. Suppose that the zone with all detectable connections sealed follows a law of type $Q = K\ \Delta P^{n}$. Then, suppose that the unsealing of a connection adds a new power law. For a specific building configuration, the depressurization test can be expressed in the following way :

$$Q_{old} = \Sigma\ K_i\ \Delta P^{ni}$$

If we unseal a new connection j, $Q_{new} = Q_{old} + Kj\ \Delta P^{nj}$.

(Kj,nj) are determined by a curve fit of the data ($Q_{new}-Q_{old}$,ΔP_{new}).

Due to the limited number of tests at the same depression, method 1 has limited applications and the results are really sensible to the quality of the few measurements. Methods 2 and 3 give better results because of the higher number of measured points.

	Undetectable Permeability		Wall-Floor link		Shutter chest		Air inlet	
	K	n	K	n	K	n	K	n
bedroom 3	3.32 *3.32*	0.622 *0.622*	1.07 *1.20*	0.723 *0.689*	1.49 *3.26*	0.586 *0.500*	1.78	0.651
bedroom 1	2.93 *2.93*	0.662 *0.662*	*1.63*	*0.695*	2.42	0.530	3.30 *3.30*	0.500 *0.500*

Table 2 : Behavior law of some connections determined by:
- Method 1 - *Method 3*

We note that the results are not convergent. It appears such a large discrepancy between the impact of the various connections that determining the behavior of small connections is almost impossible. We can also point out that the shutter chest are really leaky. Their theoritical value suggested by the French standard is ten times less that the measured one. The identical air inlets do not present the same behavior. Moreover, many laws for specific components are unrealistic :
- n is lower than .5
- the unsealing of a connection decreases the flow rate at the same ΔP.

The couple (K,n) is so sensitive to the measurements that any perturbation (a sudden wind, a solar spot,...) may induce an unrealistic (K,n). Moreover, the accuracy of the equipment is limited in the low ΔP range. It is surprising to note that the depressurization test facility is not well appropriate at low depression which is the usual situation in buildings. Some improvements should be brought in the selection of the equipment such as accurate flow meter, precise manometer, stable extraction rate, ... Then, instead of verifying that the wind speed is lower that 2 m/s, it would be preferable to measure the pressure difference between two facades.

Then, the progressive unsealing of components is not an appropriate methodology because a poor intermediate test implies poor following tests. The influence of any connection should be evaluated with a reference test even at the cost of a lengthly procedure.

However, an identification of each component behavior does not seem to be promoted to a large success: air paths are difficult to identify, control of experimental conditions is limited, the behavior of minor connections is really sensitive to perturbations and obscured by the finite accuracy of the equipment. We propose a more global approach to take benefit of depressurization tests.

3.2 Optimization under constraints

We divide the building in zones where the pressure and temperature are uniform as it is common in pressure models. Then, we suppose that the air paths between two adjacent zones can be gathered and modeled in a unique law of type $Q = \Delta P^n$. The physical connections between two zones may be of different types : small or large cracks, small openings, smouth or rough surfaces,.... Moreover, they are usually difficult to identify. This method represents a global approach that may simplify the building description.

Now, the problem is to identify the couple (K,n) for every global connection.

Let us take the building configuration when all the detectable connections are sealed.

For every zone i, we have made k(i) tests which should respect the following equation.

$$\sum_{j=1}^{nzones} m_{ij} \left(K_{ij} \, \Delta P_{ik}^{\,n_{ij}} - Q_{ik} \right) = 0$$

with m_{ij} = 1 if zones i and j are adjacent
= 0 otherwise
$(\Delta P_{ik}, Q_{ik})$ results of the depressurization test k in zone i

K_{ij} permeability coefficient of the connection between zones i and j
n_{ij} exponent coefficient between zones i and j
nzones total number of zones

Therefore, we get $M = \sum_{j=1}^{nzones} k(j)$ equations with $N = \sum_{\substack{i > j \\ i = 1,nzones}} m_{ij}$ unknowns.

For our specific configuration, $M \approx 200$ and $N \approx 60$. The non linear system is overdetermined. Moreover, the unknowns should respect some constraints such as:

$$K_{ij} > 0 \text{ and } 0.5 < n_{ij} < 1.$$

The problem can be reformulated as a minimization problem with constraint and Kühn and Tücker theorem is usually applied to solve it. However, the programming is quite lenghtly. Lau[2] has suggested a new approach to solve this kind of problem. The principle is based on the Monte Carlo method : a simple random search technique. (See appendex 1)

This method is straightforward programming but is time consuming and has been applied to our problem. A reduced and confident interval for the constraints improve the convergence speed and the quality of the results. A more detailed study is necessary to access the pertinence of this method. However, it looks promising.

Figure 2 shows the perfect matching between the pressurization test and the numerical results. Figure 3 illustrates the flow rate under a 10 Pascals pressure difference in every connection. As mentionned before, we notice interconnection between toilets, hall and bathroom due mainly to ducts. The living room presents an important leakage area.

In a second stage, we use the Lau's method to determine the behavior law of the air path when no connection are sealed. We get the same good matching than in the first stage.

We therefore conclude to the feasibility of the proposed method. From individual depressurization tests, we can identify the flow behavior of global components separating two zones. According to the values of (K,n), we can comment on the permeabilty of the connections and the type of the defaults. Now, we should be able to visualize the air flow pattern within the house under various conditions.

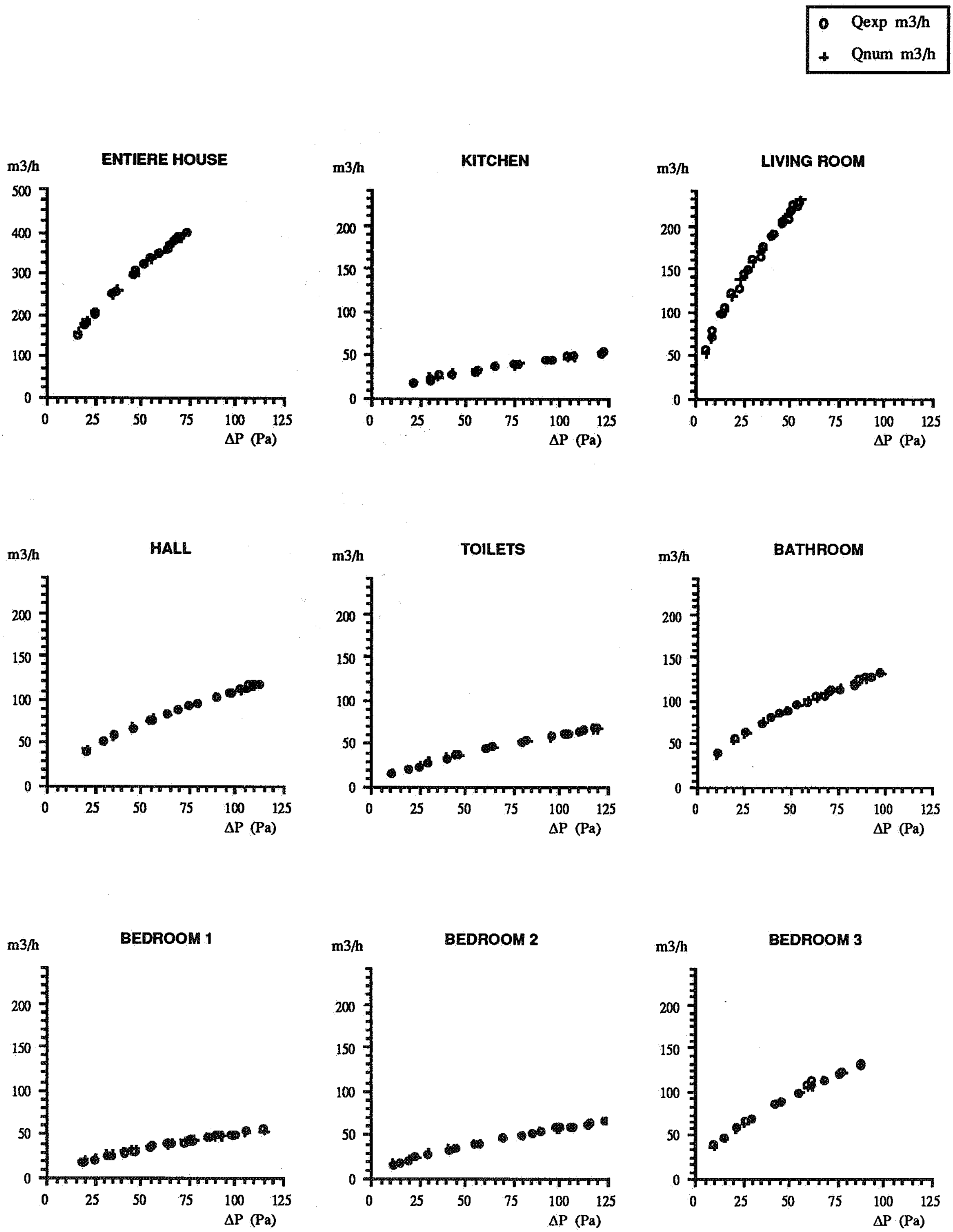

Figure 2: *Results of depressuration Test in every room. Comparaison with numerical results obtained by Lau's determination.*
- All detectable air paths Sealed.

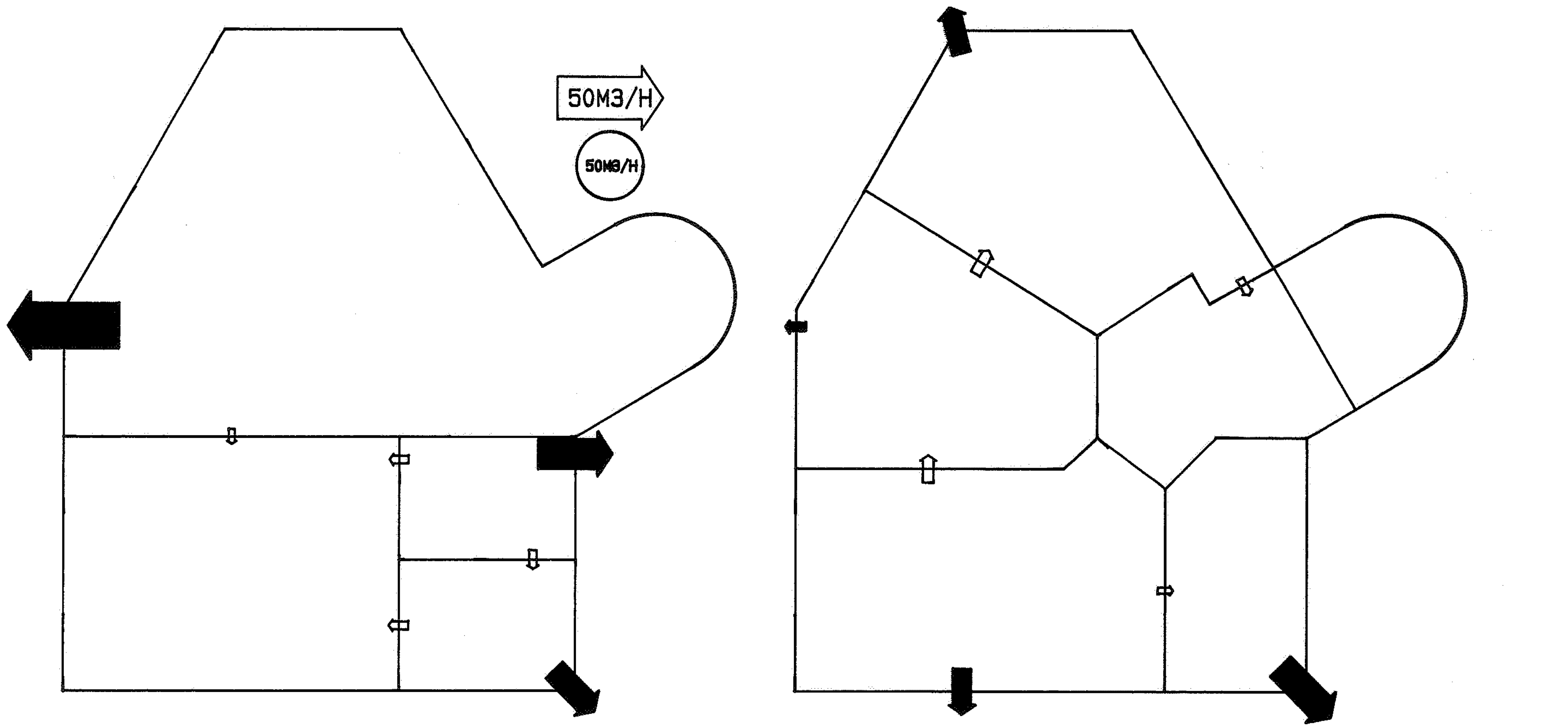

Figure 3: Illustration of the Flow rate under every global connection at 10 Pa pressure difference

3. Interior doors

In the previous tests, interior doors are substituted by tight door with a mounted fan that creates the depression. Therefore, the influence of this element is not included in the general laws and should be evaluated.

Even when closed, interior doors should be designed to facilate the air transfer between the various zones of a house. They can be equipped with a grille, a shaft or a void at the lower level. At the extreme, we trust on the poor tightness of this building component to represent the least air resistance path. Usually, these origins combine each other to offer a priveligeous track for the air.

In the second phase of our study, our objective is to identify under real conditions how much air transit through the doors at various extraction flow rates. Unfortunately, it is almost impossible to measure the flow rate through a typical door. So, we propose to substitute the existing door by an airtight door with a calibrated pipe which has the same aeraulic behavior. Moreover, it is easier to evaluate the volume flow rate in a pipe. Our approach can be divided in three phases :

- identifying the behavior of a slot of various depths and width encountered under interior French doors
- selecting the diameter of the pipe to be representative of an interior door
- measuring the flow rate through the pipe.

3.1 Behavior of a slot

In am airtigth box (figure 4), we have tested cracks of 200 mm length with various width, 3 mm to 10 mm, and various depth, 4.7 mm to 34.7 mm. Our results are presented in term of a power law as it is usual (figure 5). We note that the permeability, K, at 1 Pa increases linearly with the width (figure 6) bus it almost constant with the depth (figure 7). The flow exponent is almost constant with the depth and a width superior to 3 mm (figure 8 and 9).

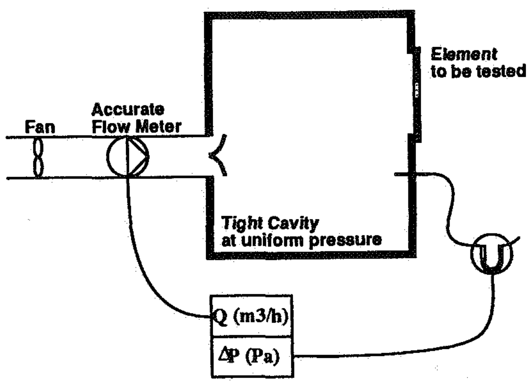

Figure 4: Test Facility to characterize the flow behavior of typical elements

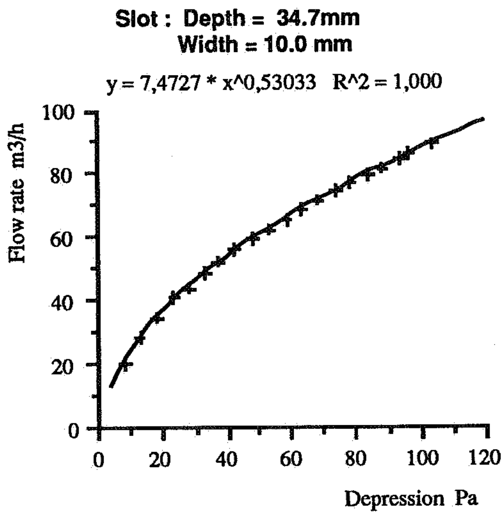

Figure 5: Behavior law of a slot

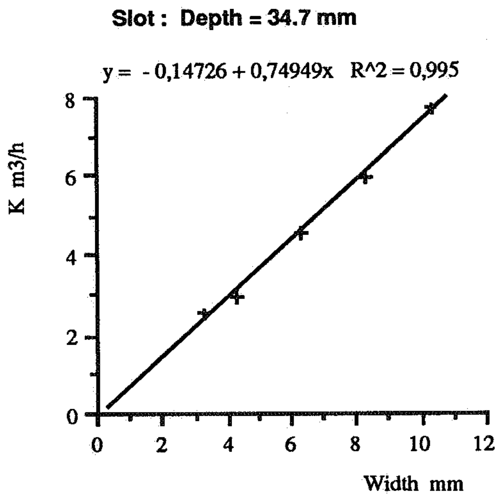

Figure 6: Variation of the permeability at 1 Pa with the width

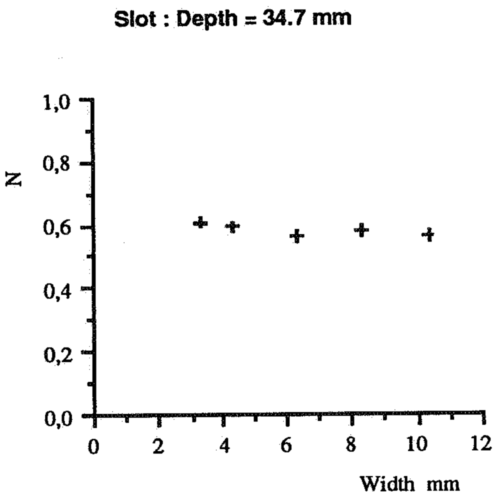

Figure 7: Variation of the flow exponent with the width

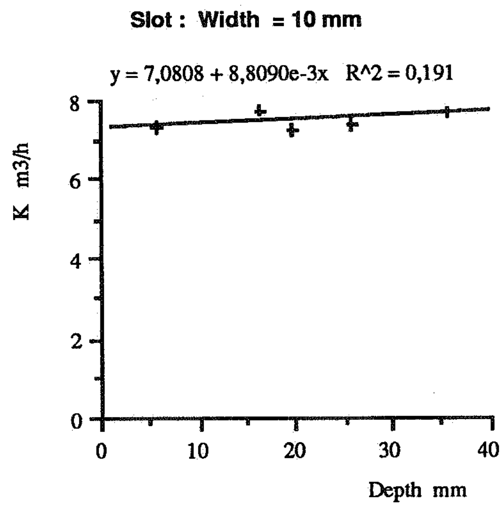

Figure 8: Variation of the permeability at 1 Pa with the width

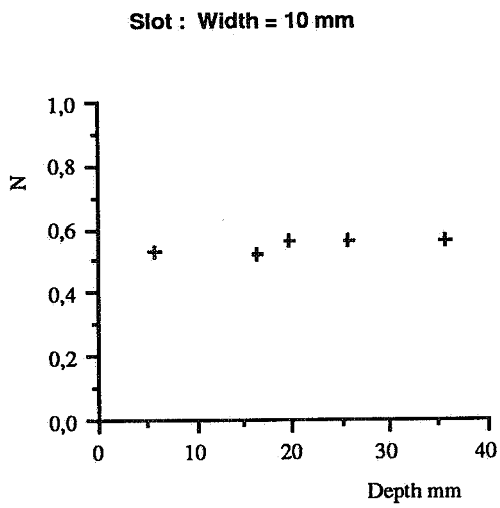

Figure 9: Variation of the flow exponent with the width

3.2 Behavior of a pipe

The depression through a closed door in a house is often around 10 Pa. So, we compare the behavior of a 104 mm diameter pipe and an 800 mm length crack of 10 mm width in the range of 0 to 10 Pa. We notice that the flow exponent and the permeability are quasi identical. The curves of the pipe and the crack are situated between the curves of an interior door without an opening at the bottom and an interior door with an 10 mm opening (figure 10). We conclude that the suggested pipe is representative of French interior doors. All interior doors are substituded by an airtight door with the calibrated pipe.

3.3 Determination of the flow rate through a pipe

In the laboratory, we verify that the velocity distribution is uniform over the outlet section of the pipe. Thus, the flow rate is equal to the product of the velocity by the section area. The measured and the calculated flowrate are in a good agreement (figure 11).

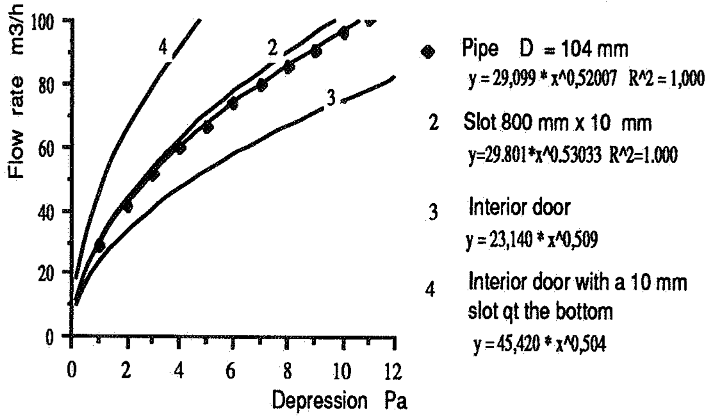

Figure 10 : Comparison of the behavior law of pipe crack and doors

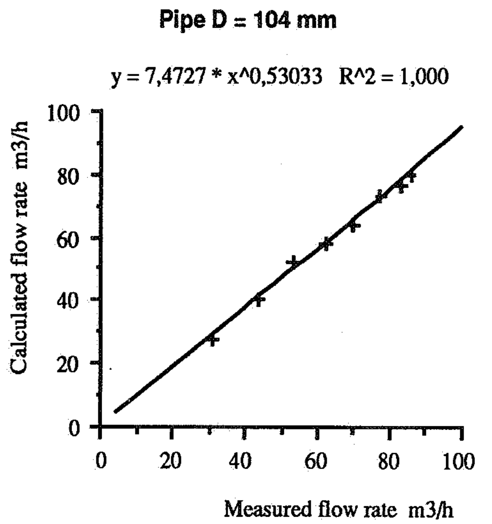

Figure 11 : Comparison of the measured and calculated flow rate in a pipe

4. MULTIZONE AIR MOVEMENT

4.1 Experiment

For different total extraction rates and building configurations, we measure the flow rate through interior doors in the absence of wind and temperature differences. This gives us an image of the flow pattern within the house. In an ideal flow diagram, all the air should transit through the on purpose designed opening in the interior door. Figure 12 illustrates that when the infiltrations of a room are high, controlling the air flow pattern become tricky.

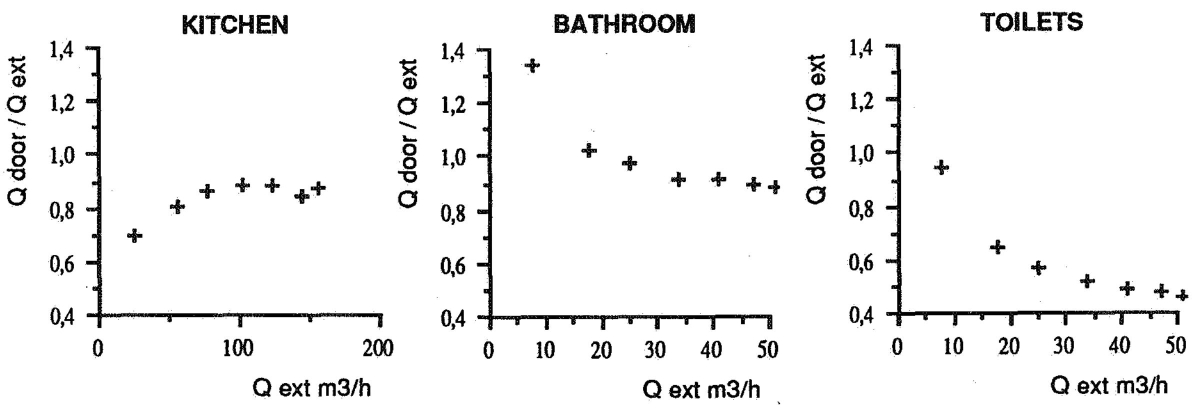

Figure 12: Evolution of the flow rate through the door / extracted flow rate in the room

4.2 Comparisons with numerical results

Using a modified version of ESPAIR, we calculate the air flow pattern with the house for various extraction rate, supposing the behavior laws of the connections determined by Lau's method. For every experiment, we compare the measured and the simulated flow rate through the interior doors. We get a good agreement for the interior doors located at the ground floor even for the toilets that are really leaky. For the first floor, the results are in a poor agreement. Limited air flow rates and air moving downward the stairs may explain it. Moreover, any temperature difference may induce a strong convective flow that is not taken in account in our numerical approach.

Figure 13 represents the air flow pattern for a total extraction rate of 250 m3/h. We note that the ideal flow diagram for a ventilation system is quite well respected. However, this is a strong short circuiting in the bathroom and in the toilets. Permeability of interior components has a limited effect on the flow paterns because of a reduced pressure difference between interior zones in comparaison with the pression difference between inside and outside.

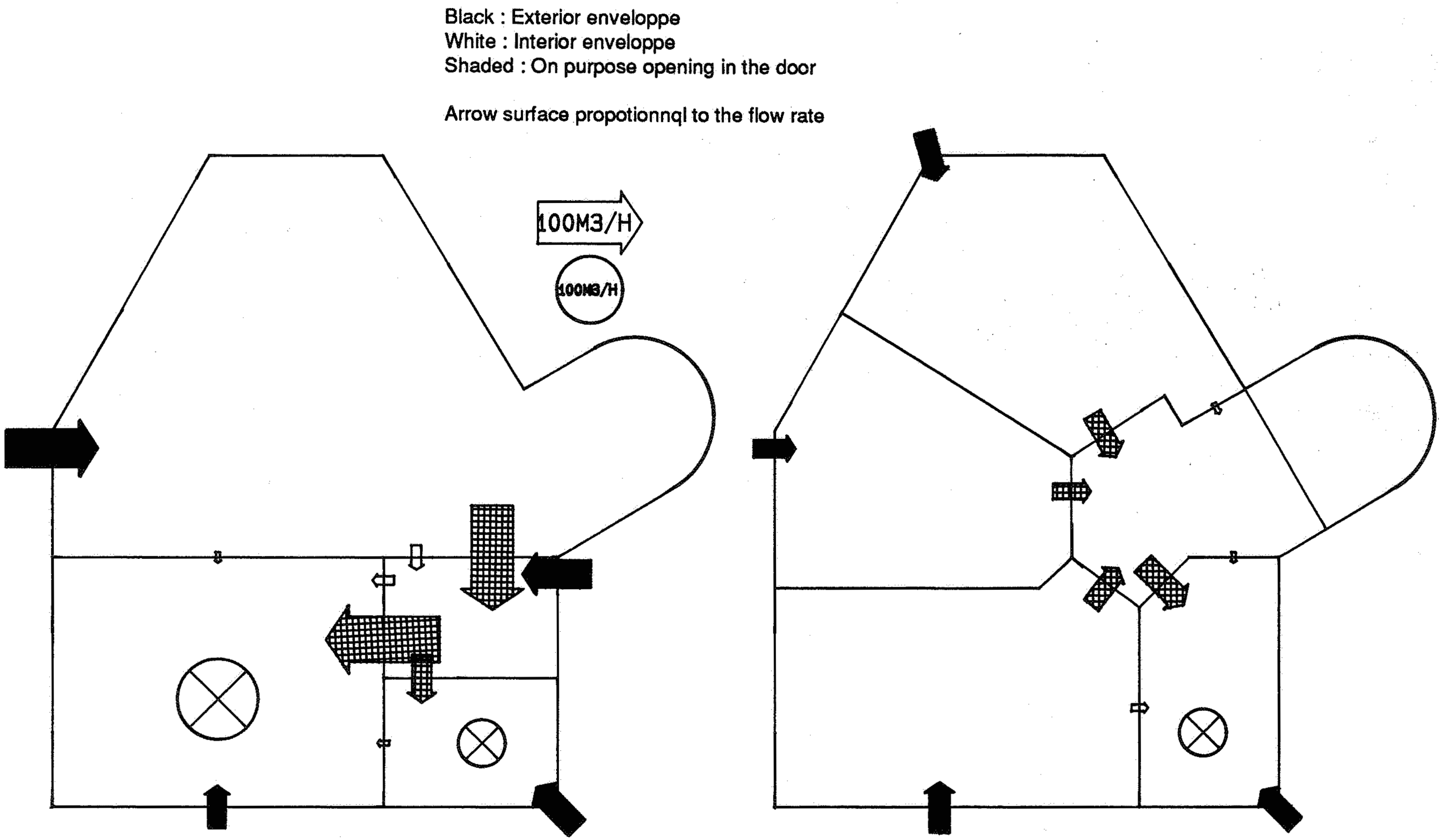

Figure 13 : Air flow pattern within the building

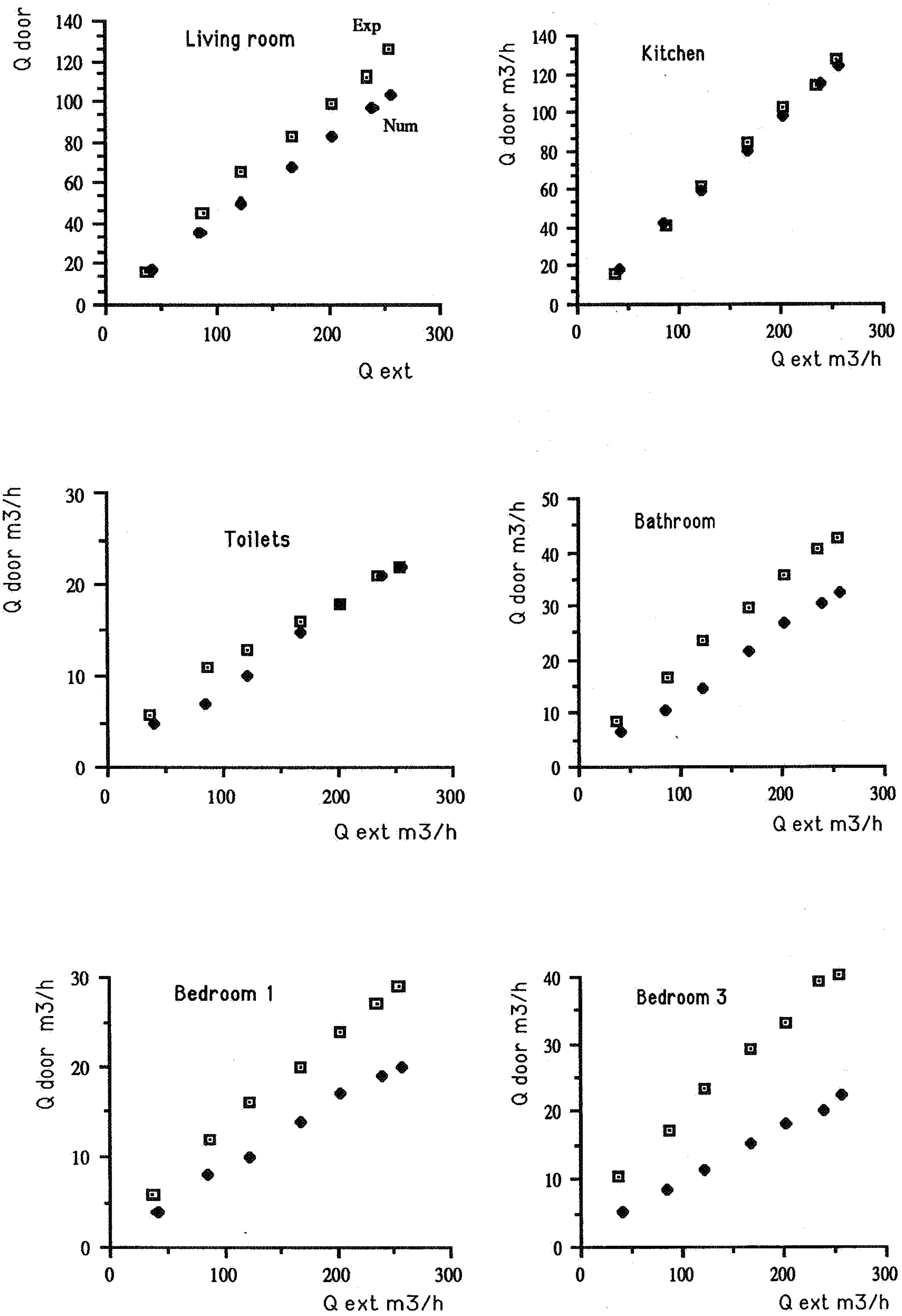

Figure 14 : Air flow rate through the interior doors

5. CONCLUSIONS

This study allows us to characterize the permeability of global components from depressurization tests by using an innovative numerical approach. After identification of the flow behavior of a typical interior door and their substitution by an equivalent pipe, we study the air flow pattern within the building under various extraction rates. The initial flow diagram is respected but less air than expected transits through the interior doors because of the poor level of tightness of the exterior enveloppe. A reduced ventilation rate results in the living room and in the bedrooms. More work is needed to take benefit of all the experiments and to fully characterize the building from a ventilation point of view.

6. APPENDIX

Reformulated Problem :

$$\text{minimize} \quad \sum_{i=1}^{nzones} \sum_{k=1}^{k(i)} \left| \sum_{j=1}^{nzones} m_{ij} (K_{ij} \, \Delta P_{ik}^{n_{ij}} - Q_{ik}) \right|$$

Subject to :

$$S_{ij} \leq K_{ij} \leq T_{ij}$$
$$Q_{ij} \leq n_{ij} \leq R_{ij}$$

Lau's method:

Step 1

- For each variable K_{ij}, n_{ij}, generate a random number in a given interval of constraints.Evaluate the objective function.

Step 2

- Repeat step 1 i1 times and memorize the best random vector that minimizes the objective function.

Step 3

- Shrink the constraint interval around the best random vector.
- Go to step 2 until step 3 has been applied i2 times. Then, the final solutionis the best random vector.

7. ACKNOWLEDGEMENTS

The work described in this paper was funded by the French Energy Agency (AFME) and the French Department of Construction. We would like to thank M. Kilberger and V. Richalet from CETE-France for conducting the on-site experiments.

8. REFERENCES

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Discussion

Paper 6

Peter Wouters, (Belgian Building Research Institute, Belgium)

I agree with you. But our objective was to measure the flow rate through on purpose openings (grille of the interior doors). On the second point of your question, a compensated flow meter would have been more appropriate. However, simultaneous measurements would require seven of them, and I suppose you know the price of each of them?

B. Fleury (ENTPE LASH, France)

The measurement of internal leakages with your pipe technique doesn't allow to estimate the leakages through the walls or between walls and doors. A compensated flow meter might be more accurate and quicker.