EFFECTIVE VENTILATION

9th AIVC Conference, Gent, Belgium
12-15 September, 1988

Poster 12

A SIMPLIFIED APPROACH OF AIR INFILTRATION IN MULTIZONES BUILDINGS

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SYNOPSIS

The specific value of different flows resulting from air exchanges between rooms or with the outside is not always important. An extensive model is not suitable when only estimations or tendencies have to be drawn (very time consuming).

So we developed a simplified infiltration model for predicting airflows in single rooms and between different zones of a building. We integrated this model into a building transient thermal simulation program set up to a micro-computer system.

So as to obtain this model, we used simplified assumptions. We planned those simplifications into two directions:

_ separate study of the actions induced by wind and stack effect,
_ sepatate study of mass and heat transfers.

In this way, our approach consists in searching for a satisfying compromise between an appreciable saving of time and consistent results.

The model is devised as follows :

_ a transitional step where the ingoing airflows are calculated once for all under the successive agency of wind and stack effect. this step leads to the storage of the different flows into matrices reflecting both effects.
_ a connecting step where airflows resulting from wind and stack effect are combined.

LIST OF SYMBOLS

A_j	= Physical open area, m^2
C_j	= Airflow coefficient, m^3/s at 1 Pa
C_P	= Pressure coefficient
g	= Acceleration of gravity, 9.81 m/s^2
K_j	= Leakage coefficient, $m^3/s.m^2$ at 1 Pa
$\overline{Pr}$	= Reference pressure, Pa
$\overline{Pv}$	= Average dynamic pressure, Pa
$\overline{Q_{exh}}$	= Net mass flow rate from an exhaust system, Kg/s
$\overline{Qm_j}$	= Mean mass flow rate through opening j, Kg/s
$\overline{Qv_j}$	= Mean volume flow rate through opening j, m^3/s
$\overline{V}$	= Average wind speed, m/s
$\overline{V_{met}}$	= Average meteorological wind speed, m/s
$\overline{z}$	= Height of calculated point, m
$\overline{\Delta P_j}$	= Mean pressure difference across opening j, Pa
ΔT	= Time step, s
βj	= Flow exponent
ρ	= Air density, Kg/m^3

1. INTRODUCTION

Nowadays, due to a better insulation of buildings, ventilation takes a great part in energy consumption[1].

However, we should not retain only energetic aspect. Whether ventilation is intentional (mechanical ventilation) or unintentional (infiltration) it has repercussion both on hygienic conditions (contaminant migration) and on risks of damaging the building (water vapor condensation).

It is necessary that we should provide the estimation of these ventilation rates taking into account a lack of clear information on some data (pressure coefficient, air permeability,...).

2. PRINCIPLES OF VENTILATION

Infiltrations through the building envelope are driven by a pressure difference across the shell.

The two motive forces primaly responsible for this pressure difference are :

_ wind through its velocity and direction produces higher -than-ambient pressures on the windward faces and lower pressures on the others,

_ stack effect caused by the temperature difference between indoor and outdoor air.

Under this pressure drop, an airflow across the unintentional openings of the shell takes place.This airflow may either be a comer or a goer.It is unintentional because it depends only on weather conditions. The renewal of air, which is due to volontary ventilation, is added in algebraic value to this crossing flow.

Now, we will study the action of these two motive forces.

2.1. Wind effect

Wind generates over all obstacles a pressure field which fluctuates in time .

The sudden pressure in a given point can be expressed by the relation :

$$P\ (z,t) = \overline{P_v}(z) + P'_v(z,t) \qquad (1)$$

where $\overline{P_v}(z)$ denotes the average pressure during ΔT and $P'_v(z,t)$, the sudden fluctuation .

However, during our calculation of air infiltration, only the notion of average pressure is kept (ΔT=3600 s) .

The average dynamic pressure $\overline{P_v}$ over a building is linked to the mean wind velocity $\overline{V}$ at a reference point by the relation

$$\overline{P_v}(z) = \frac{1}{2}\rho . C_p . \overline{V}(z)^2 \qquad (2)$$

The average wind speed on a specific location is linked to the wind speed measured at the nearest meteorological station by a logarithmic relation[2] :

$$\overline{V}(z) = k . Log_e . \left(\frac{z}{z_0}\right) . \overline{V}_{mét} \qquad (3)$$

where $k, z_0(m)$ are constants which depend on surface roughness . They have been assessed for different terrain classes (Table 1) .

	TERRAIN PARAMETERS FOR STANDARD TERRAIN CLASSES				
	Ocean or other body of water	Flat terrain with isolated obstacles	Rural area	Urban, industrial area	Center of large city
z_0	0.005	0.07	0.3	1	2.5
k	0.166	0.202	0.234	0.266	0.292

Table 1 : Terrain parameters

Pressure coefficients vary according to different parameters :
_ shape and size of the building,
_ exposure of the building,
_ kind and direction of the wind .

These pressure coefficients are determined by testing a scale model of the building in a boundary layer wind tunnel.

An experimental study by J. GANDEMER[3] led to the setting up of a detailed mapping of pressure coefficients for each facade. This study has been made for each parameters combination before-mentioned (figure 1)

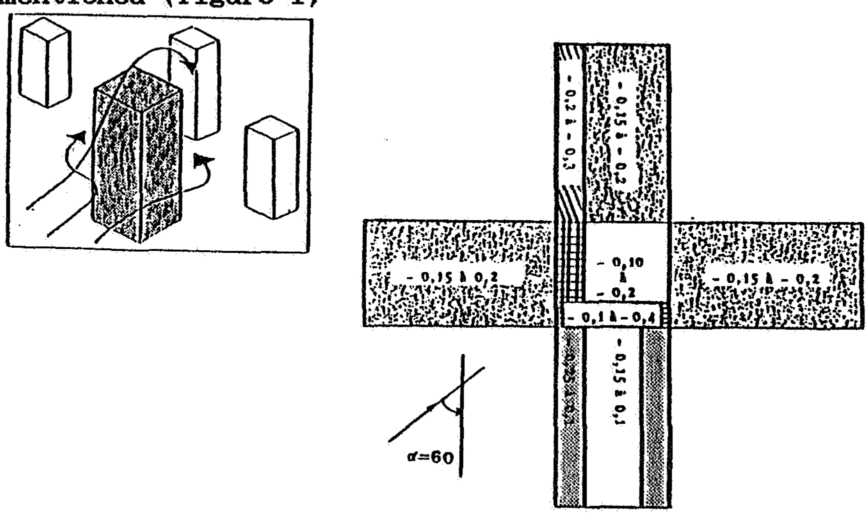

Figure 1 : Mapping of pressure coefficients according to J. GANDEMER for a tall building .

In this way, these results (pressure coefficients) are difficult to exploit. Moreover, an assumption was made which consists of defining, for each facade, a mean pressure coefficient. Thus, we have established[4] nine configurations of pressure coefficients corresponding to three kinds of building-single-family house, small building and high-rise building), two kinds of wind according to terrain roughness (open country terrain and suburban terrain) and with or without neighbour surroundings. Table 2 shows the discrete values of pressure coefficients according to the angle of incidence of wind for a tall building.

Tall Building	α	0	30	60	90	120	150	180
Country terrain without surroundings	F	0.6	0.6	-0.05	-0.8	-0.6	-0.5	-0.4
	R	-0.9	-0.6	-0.6	-0.9	- 0.6	-0.6	-0.9
Country terrain with surroundings	F	0.2	0.1	-0.2	-.035	-0.3	-0.25	-0.2
	R	-0.35	-0.3	-0.35	-0.3	-0.25	-0.3	-0.35
Suburban with surroundings	F	0.25	0.1	-0.2	-0.4	-0.4	-0.35	-0.3
	R	-0.5	-0.4	-0.4	-0.5	-0.4	-0.4	-0.5

Table 2 : Pressure coefficient versus angle of incidence of wind (°) ;(F=Facade, R=Roof)

From pressure coefficient values obtained each 30 degrees, that is twelve values by symmetry, the interpolation according to the angle of incidence of wind on the facade is realized by using a FOURIER's series[5] limited to the 6th rank.

2.2. Stack effect

Temperature difference between inside and outside or between two rooms causes air density variations. These variations produce in their turn pressure differences and hence either infiltration or exfiltration across the shell (figure 2).

Stack effect pressure, calculated at a height z, between zones (i) and (m) is written as follows :

$$P_i(z) - P_m(z) = Pr_i - Pr_m - (\rho_i - \rho_m) . g . z \qquad (4)$$

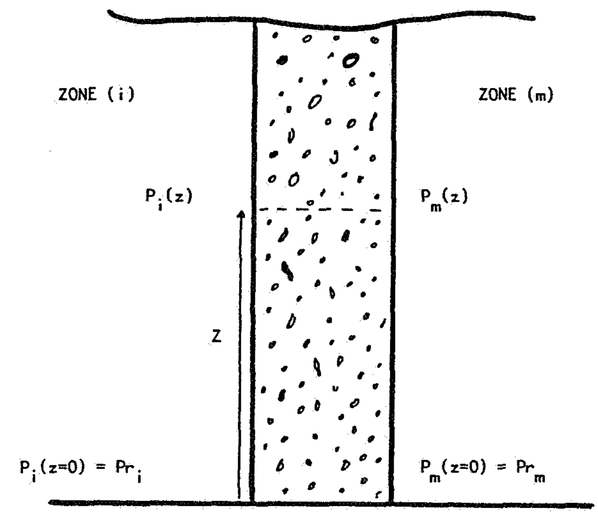

Figure 2 : Definition of different pressures.

2.3. Combined effects of wind and temperature difference

The effects of wind and temperature difference usually act simultaneously to induce unintentional air infiltrations inside a building.

The combined action of these two motive forces is not simple because on the one hand, it depends on the building and on the other, on meteorological conditions of the site.

It is the study of this action which defines the main calculation procedures of airflow.

From equations (2), (3) and (4), the pressure difference calculated at a height z, between zones (i) and (m), under the simultaneous action of wind and stack effect is as :

$$\overline{\Delta P} = P_i - P_m = Pr_i - Pr_m - (\rho_i - \rho_m).g.z + \frac{1}{2}\rho_i.C_p.\overline{V}^2(z) \quad (5)$$

with :

$$\begin{cases} Pr_i = 0 \text{ if room (i) is outside } (P_{atm} = 0 \text{ Pa}). \\ C_p = 0 \text{ if room (i) is inside.} \end{cases}$$

2.4. Flow equation

This equation characterizes the relationship between mean flow rate through openings and mean pressure difference acting on these openings.

To all kinds of openings, the relationship can be expressed as :

$$\overline{Qv_j} = C_j.(\overline{\Delta P_j})^{\beta_j} \qquad (6)$$

The flow exponent value depends on the character of airflow and hence on the kind of openings. For rough and narrow openings, the airflow is laminar whereas, for larger openings it becomes turbulent. This means that for low pressure differences, β_j tends towards 1 whereas, for more important pressure differences β_j tends towards 0.5 .

Many authors[6] have suggested on intermidiary value, β_j = 0.67 to characterize the typical pressure difference implied in dwelling houses (from 0 to 10 Pa).

Two forms of flow equation are generally used to describe the airflow.

* For intentional openings (air vents, ventilation grilles, ...) we can write :

$$\overline{Qv_j} = C_d.A_j.\sqrt{\frac{2.\overline{\Delta P_j}}{\rho}} \qquad (7)$$

The discharge coefficient C_d is a function of the Reynolds number and the ratio of the openings size to the entire surface. But in our calculations, C_d is assumed to be equal to 0.6.

* For unintentional openings (cracks, crevices, background leakage areas, ...) the equation is :

$$\overline{Qv_j} = K_j.A_j.(\overline{\Delta P_j})^{0.67} \qquad (8)$$

This equation is normally applied to every leakage component. But the location of the background leakage (leakage between the sill plate and the fundation, frame-wall leakage, electrical outlets, plumbing penetrations, ...) is rather difficult to obtain for an existing building and impossible to predict during the design process. Therefore, we assume that the leakages are uniformly distributed on each facade of the building. With this assumption a single crack permeability coefficient will characterize the leakage of each facade. So, the solution of equation (8) is easier to obtain than before by reducing the amount of complex computer programming and by removing the input of the exact location of the observable cracks.

Two methods may be used to know the crack permeability coefficient of each facade :

_ by measuring air permeability of the shell. To determine this permeability, one of the methods is the fan-pressurization[7]. the average air leakage through each facade is obtained by dividing air permeability in proportion to the surface of the facade.

_ by adding all individual components belonging to the facade. In design process, we will use the second method.

3. CALCULATION METHOD

The specific value of different flows resulting from air exchanges between rooms or with the outside is not always important. An extensive model is not suitable when only estimations or tendencies have to be drawn (very time consuming).

So we developed a simplified infiltration model for predicting airflows in single rooms and between different zones of a building. We integrated this model into a building transient thermal simulation program set up to a micro-computer system[8].

So as to obtain this model, we used simplified assumptions. We planned those simplifications into two directions:

_ separate study of the actions induced by wind and stack effect,
_ sepatate study of mass and heat transfers.

In this way, our approach consists in searching for a satisfying compromise between an appreciable saving of time and consistent results.

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_ a transitional step where the ingoing airflows are calculated once for all under the successive agency of wind and stack effect. this step leads to the storage of the different flows into matrices reflecting both effects.
_ a connecting step where airflows resulting from wind and stack effect are combined.

We will use a standardized description form[9] based on GER ALMETH's work to outline this model.

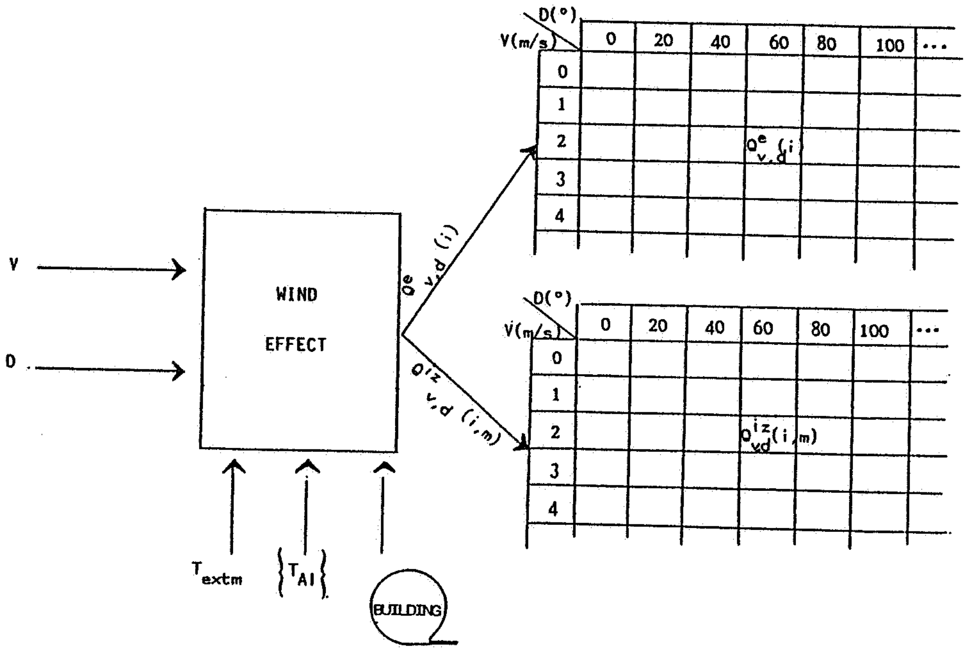
Now, we will study both phases.

3.1. Transitional step

This step depends only on characteristics of the building and weather conditions. The computation time is mainly a function to the number of zones.

3.1.1. Airflows driven by wind effect

The ingoing airflows through each zone are back-calculated for both inputs : wind speed and its direction. Other inputs (inside and outside air temperatures) are assumed to be constant during the studied period.



Nomenclature

Inputs	V	: Wind speed, m/s
	D	: Direction of wind/south, °
Outputs	$Q^e{}_{V,D}(i)$	: Net mass flow from the outside towards the inside of zone(i),Kg/s.
	$Q^{iz}{}_{V,D}(i,m)$	: Net mass flow from zone (m) towards zone (i), Kg/s.
Parameters	T_{extm}	: Mean outside temperature during the studied period, °C
	$\{T_{AI}\}$	: Air temperatures vector.

We limited the set of outside climatic values in order not to obtain oversized matrices :

_ wind speed varies from 0 to 10 m/s with 1 m/s step.

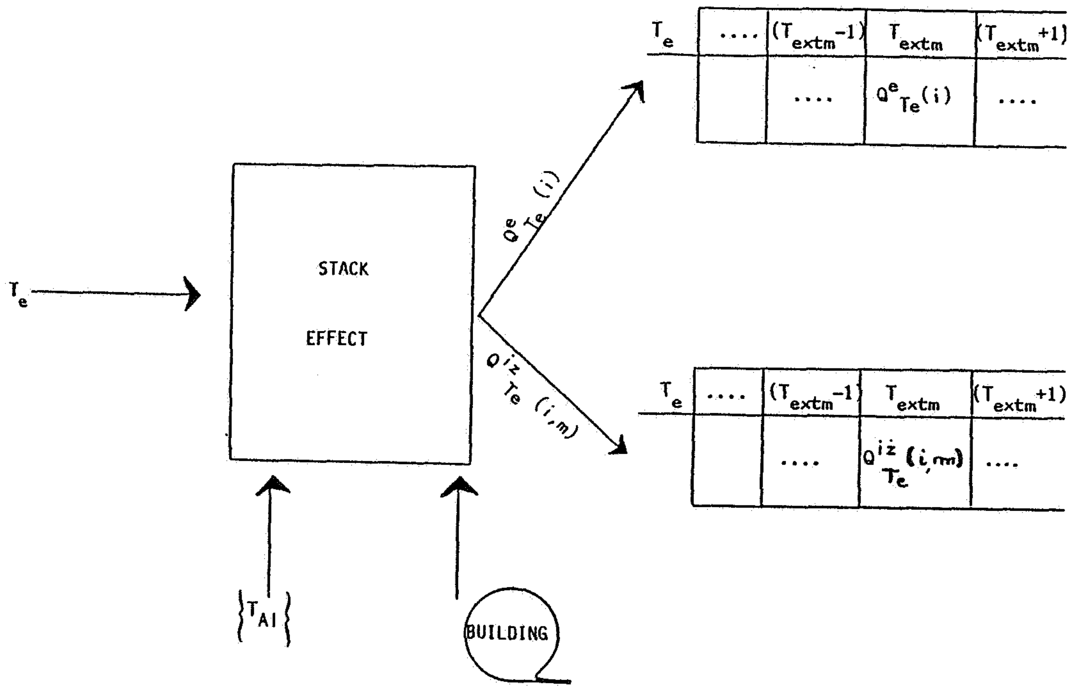
_ wind direction varies from 0 to 340° with 20° step.

This restriction is in agreement with meteorological values provided by climatic files.

The calculation method of airflows driven only by wind is summed up in table 3.

3.1.2. Airflows driven by stack effect

The ingoing airflows through each zone are back-calculated according to a single input variation : outside air temperature. The other inputs (inside air temperatures) are assumed to be constant during the studied period.



Nomenclature

Input	T_e	: Outside air temperature, °C
Outputs	$Q^e{}_{Te}(i)$	: Net mass flow from the outside towards zone(i), Kg/s
	$Qi^z{}_{Te}(i,m)$	: Net mass flow from zone (m) towards zone (i), Kg/s.
Parameters	$\{T_{AI}\}$	: Air temperatures vector

The outside air temperatures variation are obtained from mean outside air temperature during the studied period : T_{extm}. $(T_{extm} - 7) \leq T_e \leq (T_{extm} + 7)$ which means 15 different values for T_e.

The calculation method of airflow driven only by stack effect is summed up in table 3.

3.2. Connecting step

In our simplified method, we have separated wind and stack effects in order to study separately their actions on a building. Now, we have to combine these two effects.

R. CADIERGUES[10] as shown that the combined effects of wind and temperature difference is usually between :
_ the effect which corresponds only to the predominant force,
_ the effect which corresponds to the adding of the two motive forces.

ASHRAE[11] suggests the following correlation :

$$Q^e_T(i) = Q_{max} \cdot \left(1 + 0.24 \cdot \left(\frac{Q_{min}}{Q_{max}}\right)^{3.3}\right) \qquad (9)$$

where :

$Q^e_T(i)$ = Net mass flow from the outside towards zone (i) under the combined action of wind and stack effects, Kg/s.

with :

$$\begin{cases} Q_{max} = \text{MAX}\ (Q^e_{V,D}(i),\ Q^e_{Te}(i)) \\ Q_{min} = \text{MIN}\ (Q^e_{V,D}(i),\ Q^e_{Te}(i)) \end{cases}$$

We preferred to use a simplified relation :

$$\begin{cases} Q^e_T(i) = \sqrt{(Q^e_{V,D}(i))^2 + (Q^e_{Te}(i))^2} \\ Q^{is}_T(i,m) = \sqrt{(Q^{is}_{V,D}(i,m))^2 + (Q^{is}_{Te}(i,m))^2} \end{cases} \qquad (10)$$

	WIND EFFECT	STACK EFFECT
WIND VELOCITY	$\overline{V}(z) = k.\text{Log}_e.(\frac{z}{z_0}).\overline{V}_{met}$	
PRESSURE DIFFERENCE	$\overline{\Delta P} = Pr_i - Pr_m + \frac{1}{2}\rho_i.C_p.\overline{V}^2(z)$ with : $Pr_i = 0$ if room (i) is outside; $C_p = 0$ if room (i) is inside.	$\overline{\Delta P} = Pr_i - Pr_m - (\rho_i - \rho_m)g.z$
FLOW EQUATION	$\overline{Qv_j} = C_j.(\overline{\Delta P_j})^{\beta_j}$	$\overline{Qv_j} = C_j.(\overline{\Delta P_j})^{\beta_j}$
MASS BALANCE EQUATION FOR EACH ZONE	$\sum_j \overline{Qm_j} - Q_{exh} = 0$	$\sum_j \overline{Qm_j} = 0$
SOLUTION OF THE FLOW EQUATION	Standard Newton' method generalized to a system of non-linear algebraic equations.	

Table 3 : Simplified method of calculation of air infiltration in buildings.

4. COMPARISON OF OUR MODEL WITH EXPERIMENTATION

We have compared numerical results obtained from our simplified model with an experimental study undertaken in residential suburb of Ottawa, Canada, by the Division of Building Research (D.B.R.).

This energy research project, called MARK XI, was first conducted on the instrumentation[12], then on the measure of airtightness[13] in four detached two-storey houses.

In particular, we are interested in the standard construction which architectural design is shown in figure 3.

SECTION A-A FRONT ELEVATION

Figure 3 : Architectural design of the standard house.

37 air infiltration measures were made during 1978-1979 heating season[14]. Air infiltration rates were measured using the tracer-gas decay method[15], with CO_2 as the tracer-gas. This involves introducing a small amount of CO_2 into the house and measuring the decay of its concentration with time, using an infrared gas analyser. Whereas, air permeability was measured for different pressure drops across the envelope, using the fan-pressurization method. We have estimated air permeability of standard house (normalized by the building volume) at $K_{meas}=.234$ $m^3/h.m^3$ at 1Pa .

Table 4 sums up a part of experimental tests. It describes climatic conditions under which these measures were made. Either the results are numerical or experimental, they are set out as air infiltration rates.

TEST Nº	AIR TEMPERATURE Inside (°C)	Outside (°C)	WIND VELOCITY (m/s)	WIND DIRECTION	MEASURED VALUES ($m^3/h.m^3$)	CALCULATED VALUES ($m^3/h.m^3$)
1	22.4	4	4.83	N	.219	.225
2	20.4	-12.7	1.65	N	.264	.258
3	20.7	-2.6	3.93	NW	.274	.234
4	22	-10.6	10.55	NW	.415	.355
5	20.2	.5	2.19	W	.168	.208
6	23.4	-3.4	6.12	W	.301	.256
7	21.8	-4.4	4.43	W	.210	.241
8	21	-4.7	9.61	W	.222	.345
9	22.6	-5.5	5.63	W	.271	.262
10	22.5	-7.4	4.69	W	.267	.256
11	19.8	-9.3	5.68	W	.255	.273
12	22.6	-9.6	5.23	W	.265	.261
13	23.1	-10.6	6.00	W	.303	.280
14	21.3	-12.2	6.30	W	.292	.286
15	21.4	3.9	1.07	W	.155	.199
16	22	.2	7.38	S	.316	.262
17	22.4	3.7	6.48	S	.270	.240
18	20.0	-9.0	5.95	SW	.256	.274
19	22.2	3.8	8.05	E	.214	.293
20	22.4	-1.0	7.64	E	.281	.300
21	22.0	-4.7	8.00	E	.260	.309
22	21.0	-5.6	1.43	E	.236	.228

Table 4 : Experimental conditions and obtained results.

We plotted on a graph (figure 4) , measured infiltration points on x-axis and calculated infiltration points on y-axis. The solid line is the locus of points that represent perfect agreement; the dashed lines define an area of acceptable agreement based on the measurement incertainties (± 25%).

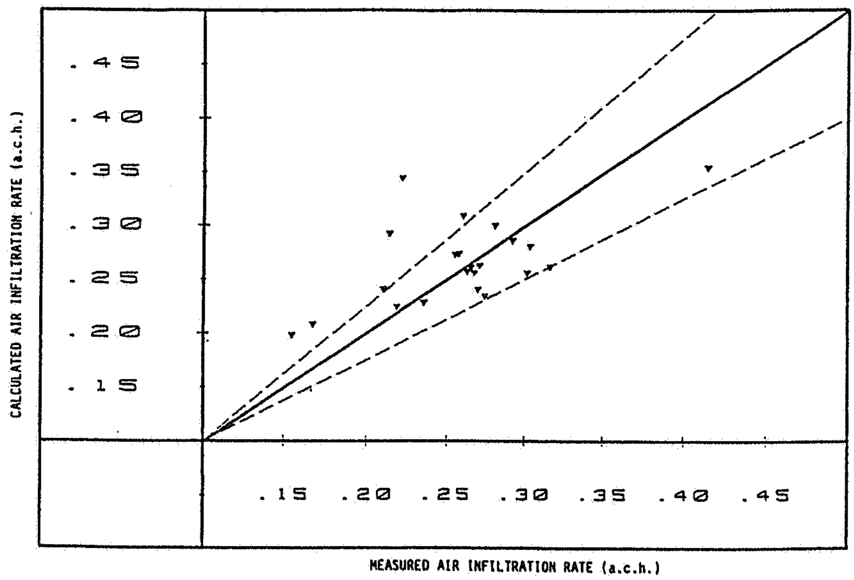


Figure 4 : Comparison between calculated and measured air infiltration rates.

We note a good agreement between experimental and predicted results. The points which are further off the solid line correspond to high level velocity of wind (test n° 4, 8, 16). Two kinds of interpretation, which are not inconsistent, may explain these differencies.

_ air infiltration measures by using a tracer-gas decay method depend on climatic conditions. With a strong wind ($\geq$ 7 m/s), these measures may be erroneous.

_ we assumed that only an average pressure coefficient on each facade may characterize the wind impigement on a building. This assumption is not valid when the dynamic pressure becomes predominant in the infiltration process.

This comparison could not be taken as a validation for our model since it is applied to a particular kind of dwelling house. It may be interesting that other cases may be studied especially air exchanges between rooms. Unfortunately, we do not know if any experimentation of this kind was made before.

5. CONCLUSION

We studied a simplified model which treats air mass transfers in a partitioned building.

This model was made to analyze the tendencies in a aided architectural design context. So, we privileged the quickness of computation running instead of a wide investigation scope.

This study must be balanced by noting that, even if physical principles and general laws which induce ventilation phenomena are known, it exists a great incertitude concerning different data (pressure coefficients, air permeability , ...)

ACKNOWLEDGEMENTS

This work was supported by "l'Agence Française pour la Maitrise de l'Energie" under contract N° : 6.04.0025.

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