- INFILTRATION, AIR FLOW DISTRIBUTION -
- AND MICRO-COMPUTATION -

ooo000ooo

- D. CACCAVELLI - J.J. ROUX - A. ROLDAN -

ooo000ooo

- LABORATORE EQUIPEMENT DE L'HABITAT -

I.N.S.A. DE LYON - BATIMENT 307

20, Avenue Albert Einstein

69621 - VILLEURBANNE CEDEX - FRANCE -

ooo000ooo

I - INTRODUCTION -

Nowadays, due to a greater insulation in the buildings, the amount of losses caused by unintentional air flows may vary from one-third to one-half of the total space conditioning load in residential building. It is important to all energy analysis computer programs to be able to value these infiltrations.

A wide variety of modelling techniques has been developed, estimating the hourly mean rate of air infiltration in dwellings. Generally, these can be divided into two categories. On the one hand, empirical approach of infiltration phenomena (1,2). On the other hand, the theoretical approach based on the basic principles of fluid mechanics. (3).

Empirical methods are easy to apply, but have some limitations. These methods are usually only applicable to buildings similar to the ones for which these methods have been made, and can not be extended to other kinds of buildings, or in other weather conditions.

More sophisticated methods of air infiltration predictions have a much wider range of applications but they require main frame computing facilities. If these methods are necessary to solve specific problems like water vapor condensation or contaminant migration, they are not appropriate to the estimation of ventilation rates applied to energy losses.

To all problems of energy consumption or confort intermediary models are more adequate.

Thus, we have developed an infiltration model, adapted from G.N. Walton's works (4) and we have integrated it in a micro-computer system of buildings transient thermal simulation (5). The aim of the model is the prediction of air infiltration and air flow between rooms inside a multi-room building.

In this paper natural ventilation which is characterized by occupant control will not be the interest of our study.

II - METHOD OF RESEARCH -

Presure difference caused by local weather conditions cause air flow through openings in the building envelope. The main factors which induce this pressure drop are :

- wind, which is an agent through its velocity and direction, produces higher-than-ambient pressures on the windward faces and lower pressures on the others.
- Stack effect which is created by temperature difference between indoor and outdoor air.
- Fan exhaust or pressurization.
- Chimney buoyancy forces generated by chimney temperature and by furnace operation are not treated.

Under this pressure drop, an air flow accross the unintentional openings of the shell takes place.

This air flow may either be a comer or a goer. It is unintentional because it depends only on weather conditions.

II.2 - Wind effect -

Wind generates a pressure field, over all the external surfaces of the dwelling, which changes in function of time.

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

$$(1) \qquad P(t) = \bar{P} + P'(t)$$

where $\bar{P}$ denotes the average pressure over time T and $P'(t)$, the sudden fluctuation.

This assumption is reasonable for time T of order 10 minutes (3). Nevertheless, we suppose that it remains acceptable to the time-step model we fixed (1 hour). The average pressure $\bar{P}$ over a facade can be linked to the mean wind velocity $\bar{V}$ at a reference point by the relation.

$$(2) \qquad \bar{P} = \frac{1}{2} \cdot \rho \cdot Cp \cdot \bar{V}^2$$

where :

$\bar{P}$ = average pressure, Pa

ρ = density of air, Kg/m3.

$\bar{V}$ = mean wind speed calculated at the top of each cell, m/s.

Cp = pressure coefficient

The mean wind speed varies with height and the vertical profiles of wind velocity vary with the roughness of terrain over which the wind is passing. For different types of terrain a simple formula can be used, based on PRANDTL's works to describe the wind speed variation (6).

$$(3) \qquad \bar{V}(Z) = k \operatorname{Log}\left(\frac{Z}{Zo}\right) \cdot \bar{V}\text{ meteo.}$$

where :

$\bar{V}$ meteo = mean wind speed measured at height equivalent to 10 m, m/s.

Z = height, m.

k, Zo = coefficients (see table 1).

	TERRAIN PARAMETERS FOR STANDART TERRAIN CLASSES				
	Ocean or other body of water	Flat terrain with isolated obstacles	Rural area	Urban Indus-trial or Forest area	Center of large city
Zo (m)	0,005	0,07	0,3	1	2.5
k	0,166	0,202	0,234	0,266	0,292

Table 1 : Terrain parameters for standard terrain classes

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 (7).An experimental study by J. GANDEMER (8) 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. 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 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 the angle of incidence of wind , for a small building.

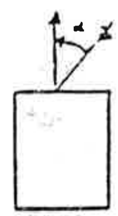
	α	0	30	60	90	120	150	180	
Country terrain without surroundings	Façade Roof	0,70 - 1,00	0,60 - 0,50	0,10 - 0,50	- 0,80 - 1,00	- 0,65 - 0,50	- 0,45 - 0,50	- 0,25 - 1,00	
Country terrain with surroundings	Façade Roof	0,30 - 0,30	0,25 - 0,45	- 0,05 - 0,45	- 0,30 - 0,30	- 0,30 - 0,45	- 0,25 - 0,45	- 0,15 - 0,30	
Suburban with surroundings	Façade Roof	0,40 - 0,50	0,35 - 0,70	- 0,05 - 0,70	- 0,50 - 0,50	- 0,50 - 0,70	- 0,40 - 0,70	- 0,25 - 0,50	

Table 2 : Pressure coefficient versus wind direction

The interpolation has been realized by using FOURIER's series limited to the 6th rank (9) . Figure 1 shows the accuracy of interpolation obtained according to coefficients in table 2.

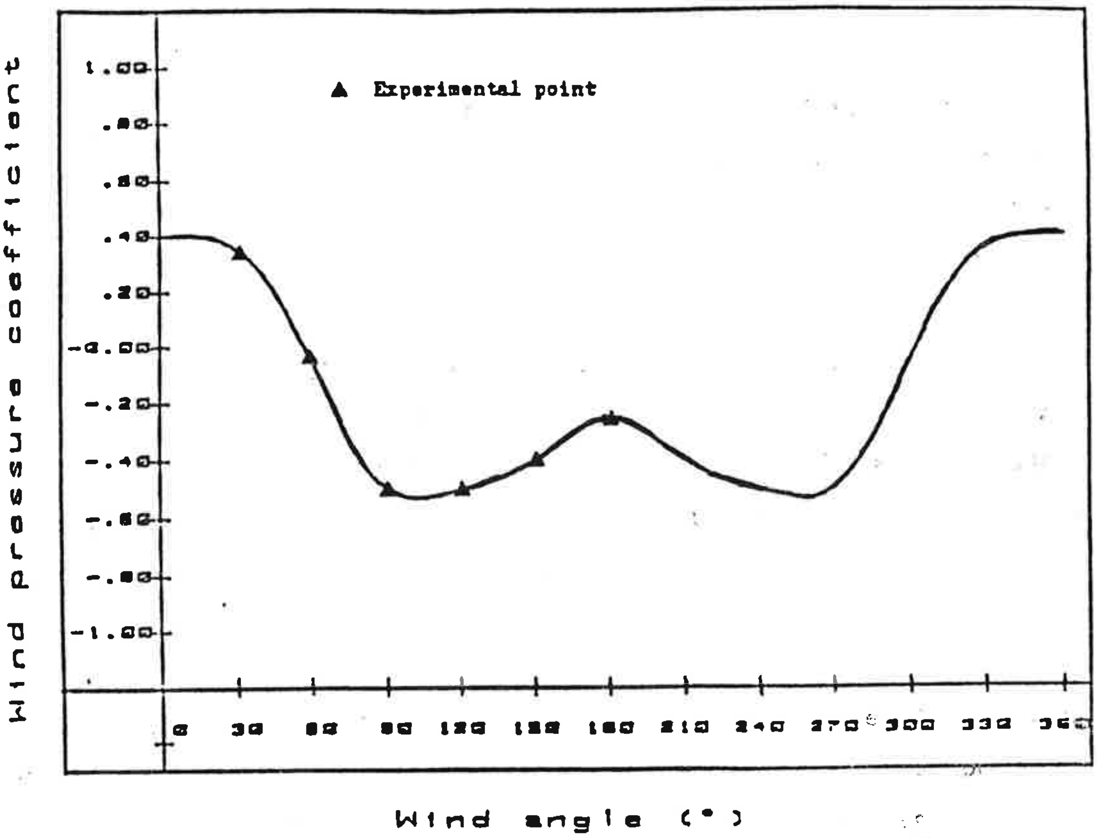


Figure 1 : Averaged pressure coefficients for a configuration :
- Small building - Suburban terrain - With surroundings -

II.2 - Stack effect -

Temperature differences between inside and outside or between two rooms cause air density differences, producing pressure differences, that drive infiltration.

The mean pressure difference, $\Delta\overline{P}_S$, accross a surface belonging to the shell, calculated at a height h is :

$$(4) \quad \Delta\overline{P}_S = Pr_{in} - \rho_o . g . h . T_o . \frac{(T\ int - T\ out)}{(T\ int . T\ out)}$$

where :

Pr_{in}	= internal reference pressure at reference height (h = o) Pa,
T int, T out	= inside and outside air temperatures, K
$\Delta\overline{P}_S$	= mean pressure difference due to stack effect, Pa
T_o	= Absolute temperature, 273.1 K.
ρ_o	= air density, 1.293. kg/m3.
h	= height, m.
g	= gravitational constant, 9.81 m/s,2

If the surface separate the two horizontally adjacent room, then the mean pressure drop accross this surface is :

$$(5) \qquad \Delta \overline{P}_S = P_{r2} - P_{r1} - \rho_o\, g.h.T_o.\frac{(T1 - T2)}{(T1 \cdot T2)}$$

where :

P_r1, P_r2 = reference pressures of room 1 and 2 at reference height, Pa.

T1, T2 = internal air temperatures of room 1 and 2, K.

During the heating season, the warmer inside air rises and flows out of the building near its top. It is replaced by colder outside air which enters the building near its base. During the cooling season, the flow directions are reversed.

Recent works on prediction models for single-family houses (10) demonstrate the strong influence of the stack effect on the infiltration rate. This effect is even more important for high-rise buildings because of the magnitude of the building height.

III.3 - Flow Equation -

This equation characterizes the relationship between mean flow rate through openings and mean pressures acting accross them. All effects of external flow turbulence are therefore neglected.

The relationship to all kinds of openings can be expressed as :

$$(6) \qquad Qi = Ci\,(\Delta \overline{P}i)^{\beta i}$$

where :

Qi = volume flow rate of air through opening i, m3/h

Ci = air flow coefficient, defined as the volume flow rate of air at a pressure difference of 1 Pa, m3/h. at 1 Pa.

$\Delta \overline{P}i$ = mean pressure difference accross opening i caused by wind and temperature difference, Pa.

β_i = flow exponent.

The flow exponent value depends on the character of the air flow. This one is laminar when the viscous forces are role domination because of rough and narrow openings.

For larger openings, the kinetic forces are rôle domination thus, the air flow is turbulent. This means that for lower pressures βi tends towards 1 whereas, for important pressures βi tends towards 0.5.

Many authors (10,11) have suggested an intermidiary value, $\beta i = 0.67$ to characterize the typical pressure implied in infiltration phenomena (from range 0 to 10 Pa). According to our point of view, this value is under-estimated because it is the fruit of experiments used to be made with more important pressure drop than those induced by natural infiltration. (Swedish airtighness standards recommend pressurization test normalized at 50 Pa).

Howewer, we used this value in our calculating program.

Two forms of flow equation are used to describe the air flow through the different types of openings :

For the large openings (for example, an air vent), the air flow is turbulent and the equation is :

$$(7) \qquad Q_i = C.\ Ai \sqrt{\frac{2\Delta \bar{P}i}{\rho}}$$

where :

C = discharge coefficient

Ai = physical open area, m2

ρ = air density, kg/m3

$\Delta \bar{P}i$ = mean pressure difference calculated in the middle of the openings, Pa.

The discharge coefficient, C, is a function of the Reynolds number and the ratio of the openings size to the entire surface. But for the considered openings, C is assumed to be equal to 0.6.

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

$$(8) \qquad Q_i = Ki\ Li\ (\Delta \bar{P}i)^{0.67}$$

where :

Ki = Leakage coefficient, m3/h. m at 1 Pa.

Li = Lenght of crack, m.

$\Delta \bar{P}i$ = mean pressure differences accross the crack, Pa.

This equation is normally applied to every leakage component.
But the location of the background leakage (leakage between the sill plate and the foundation, electrical outlets, plumbing penetrations...) is extremely difficult to obtain for an existing building and virtually impossible to predict for a projected building. Therefore we assume that the leakages are uniformally distributed on each facade of the building. With this assumption a single crack permeability coefficient will characterize the leakage on each facade and solutions to equation (8) are easier to be obtained than before by reducing the amount of complex computer programming and by removing the input of the exact location of the observable cracks.

There are two ways to know the crack permeability coefficient of each facade :

. First, the permeability coefficient can be obtained by adding together all the leakage sites belonging to the facade. The values of some leakage coefficient have been determined through experiments (12, 13) so we have good data to describe their functional forms in particular for gaps around closed windows and doors. Moreover, other experiments (12) have shown that this kind of leakage stands for less than one-third of the entire leakage in the building drawbacks.

. Secondly, the permeability coefficient can also be obtained by measuring air leakage of the shell. The technique generally used is the fan pressurization method (10) which is independant of weather conditions.
Figure 2 shows the air leakage of 40 buildings on the basis of their features (detached houses, townhouses).

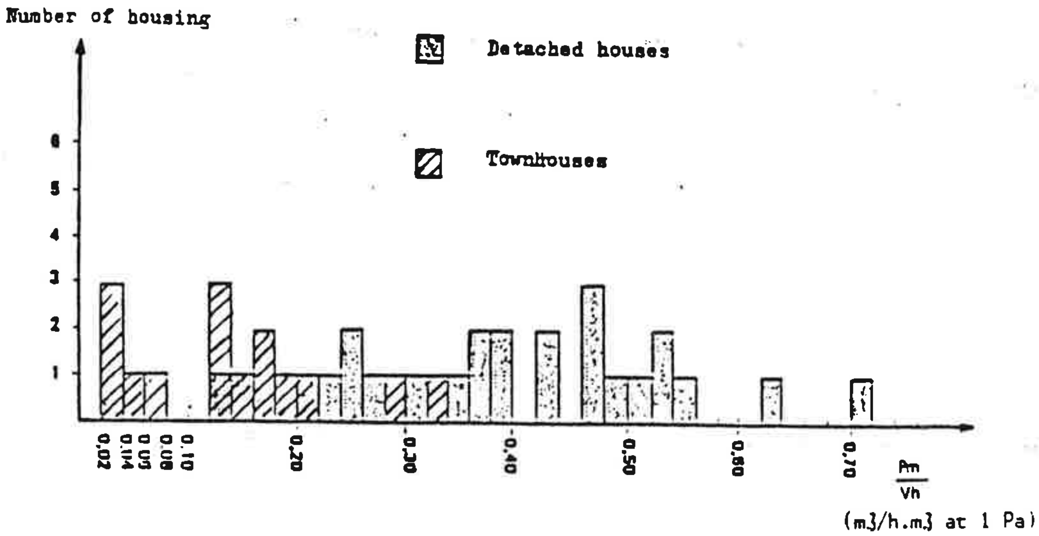


Figure 2 : Histogram of air leakage rate (normalized by the building volume) of 40 differents houses in France .

The value of the crack permeability coefficient of each facade is obtained by dividing up in proportion to the surfaces. If this method provides a quite good estimation of the whole leakages of the building, it affords no data about the inter-room leakage. In addition, we can not use it in projected buildings.

Our approach, which is in between, is based on "theoretical air leakage" calculated for the building from usual data, mainly leakage coefficient values of gaps around closed doors and windows. "Theoretical air leakage" is linked to "real air leakage" by correlations over building features (detached houses, townhouses,) (11), building type of construction (brick-veneer, concrete masonery,...). Our interest is on the processing of this method in particular to find out accurate correlations which is not easy.

II.4 - Solution of the flow equations

For each room, the air mass balance between infiltration and exfiltration must be satisfied. The mass air flow conservation for the room (i) can be written :

$$(9) \qquad \sum_{J} Q_j - Q_{exh}(i) = 0$$

where :

Q_j : Comer or goer air flow through large openings or cracks, kg/s.

Q_{exh} (i) = Net mass flow out of the room (i) from an exhaust system, kg/s

Q_{exh} is assumed to be independant of pressure generated inside or outside the dwelling.

The consequence of the non-linearity of the flow equations is that the air mass balances form a system of non-linear algebraic equations in which the unknowns are the reference room pressures.
The resolution of this system at each step-time requires an iterative method.
The Newton's method generalised to the systems of equations (14) was used.
We obtained an acceleration of the convergence by using a suitable under relaxation coefficient.
With such an approach a large computer capacity is necessary. This is inconsistent with the use of a micro-computer, so we were driven to make the following assumptions :
The first assumption is related to the infiltration processing.We split the infiltration problem into two distinct parts. On the one hand, the wind regime where the driving forces are the dynamical effects of the wind, on the other hand, the stack regime where the driving forces are the air density differences.
The effects of mechanical systems are included in this last part. In this approach the two regimes are separately studied. For each of them we have to resolve a system of non-linear algebraic equations but this time, because of the uncoupling of the effects, the resolution is quicker than before.
The air mass flow resulting from the two driving forces must be combined to arrive at the total infiltration.

For each room, the whole air flow is obtained by :

$$(10) \qquad Q_T(i) = \sqrt{Q_s^2(i) + Q_w^2(i)}$$

where :

Q_T (i) : infiltration from both wind and stack regimes, kg/s
Q_w (i) : infiltration from the wind regime, kg/s
Q_s (i) : infiltration from the stack regime, kg/s

The second assumption is based on the following observation : we have noticed that in climatic files some variables like wind velocity or wind direction often have the same values. With the complex air infiltration model as defined before, this remark is not taken into account, the same calculation is executed each time it's required.
So we have used a set of outside climatic values from which the infiltration rates will be back-calculated.
For the wind regime, the set of values made up of wind speed from 0 to 10 m/s, wind direction varying from 0 to 360 degrees with step 20, and external temperature taken as the average temperature during the period of the study.
For the stack regime, only external temperature variations are taken into account, internal air temperature of each room is assumed to be constant.
For each regime and for each set of values, the infiltration rates are back-calculated and saved into a file.

III - RESULTS -

The development of our model made it necessary to simplify the complex process of air infiltration calculating. We propose to study the effects of these assumptions upon a dwelling on air mass flow as well as on thermal behaviour
This study will be made by a comparison with a comprehensive model developed in the "Laboratoire Equipement de l'Habitat" by A. ROLDAN (15) which will be our referring model.

The studied building was built in 1969 near LYON (FRANCE). It is 10.95 m x 16.45 in plan (figure 3a). and 8 m in height (figure 3b).

The building is divided into four thermal zones :

One part of the ground floor and the two upper stories make the three first zones and the other part which is entrance lobby, maintenance rooms and stairwell make the fourth zone.

Each story is composed of two apartments separated by a stairwell. The description of one apartment is similar to the others : the floors and partitions walls are concrete. The facades are made of a partially insulated concrete breast-wall, a large bay-window and a noninsulated rolling-shutter.

The doors connecting each room are supposed closed.

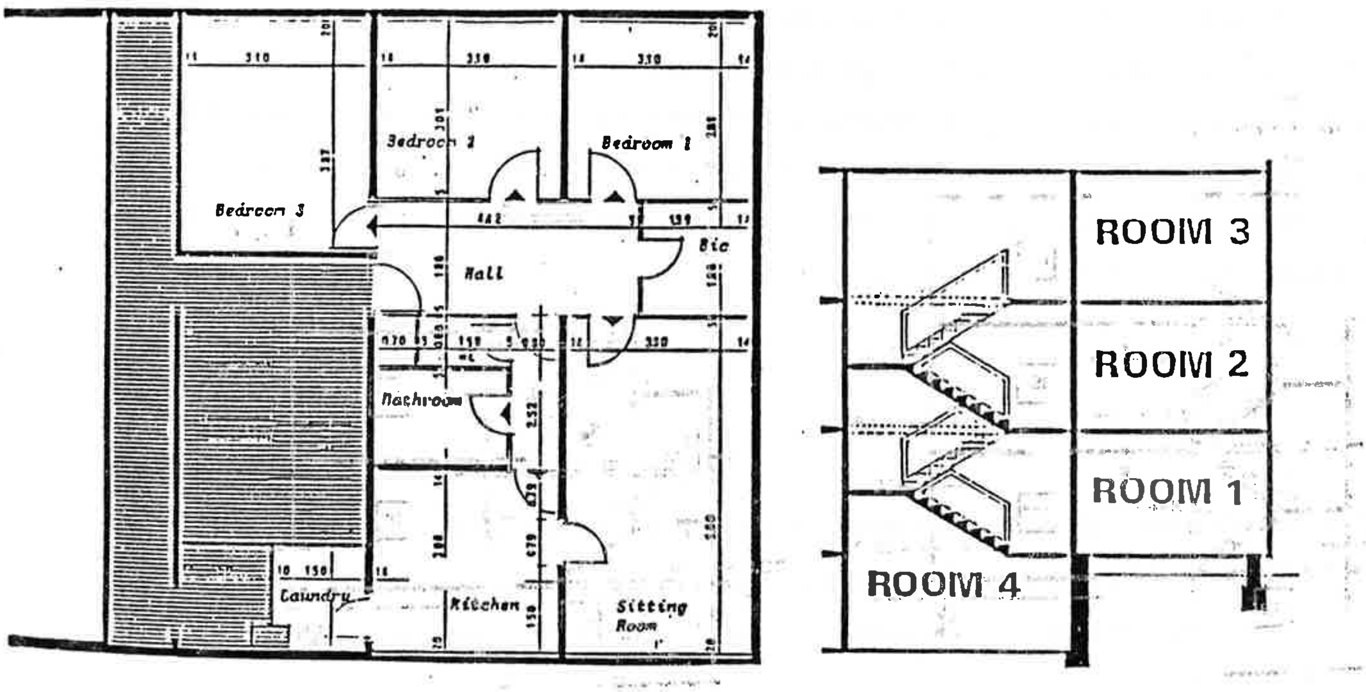


Figure 3 (a) : Typical floor plan, (b) staircase section.

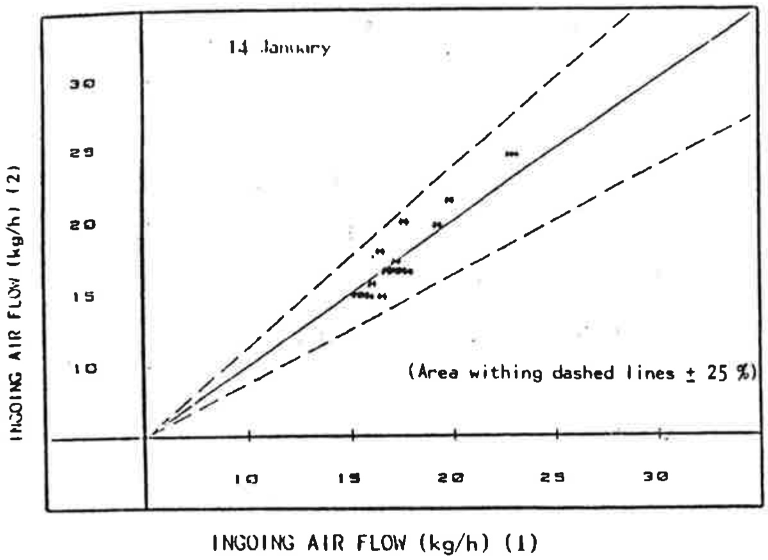


Figure 4 : Referring model (1) versus simplified model (2)
The solid line is the locus of points that represents perfect agreement.

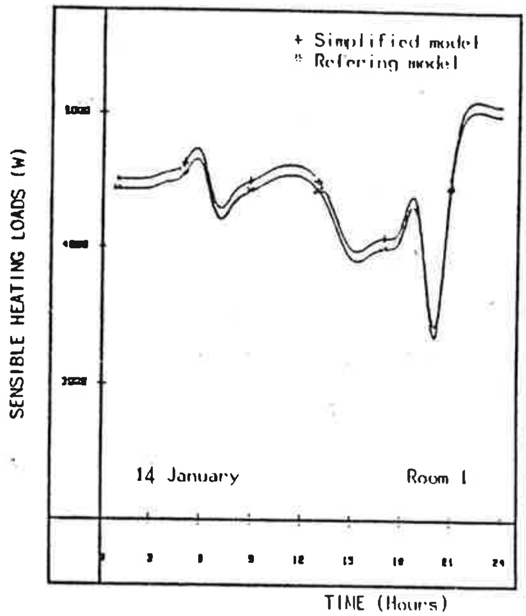


Figure 5 : Comparative load profile

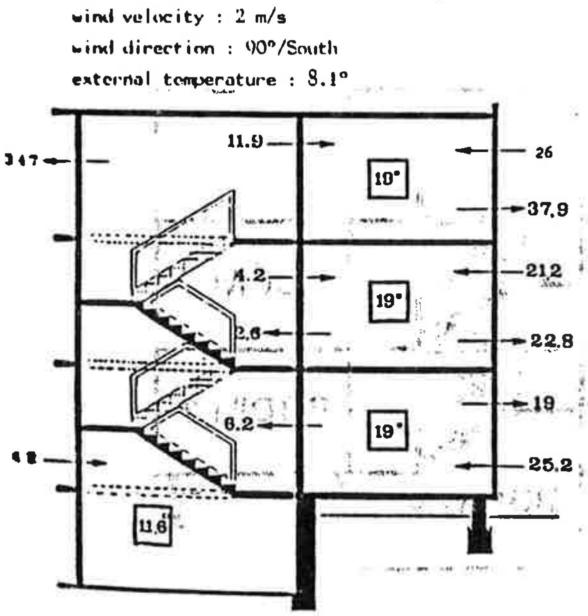


Figure 6a : Infiltration air flows (kg/h) through the building without mechanical exhaust.

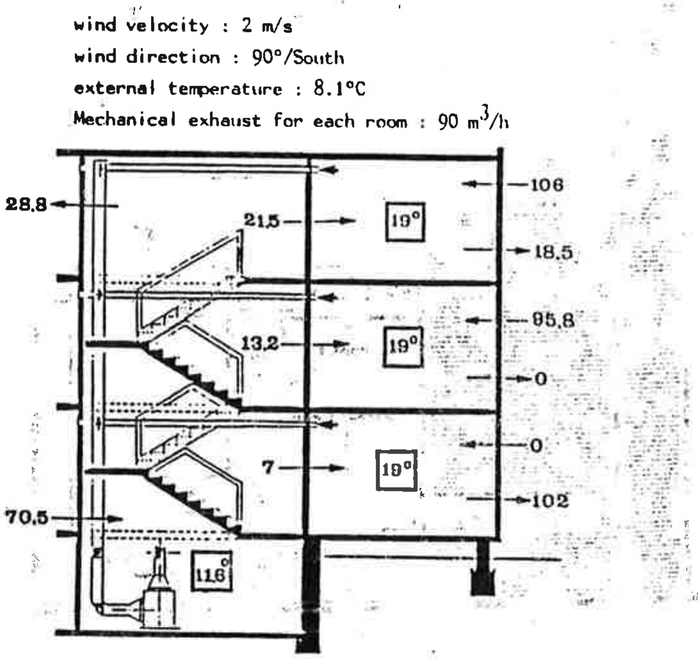


Figure 6b : Infiltration air flows (kg/h) through the building with mechanical exhaust (except for the room 4).

Figure 4 shows the comparison between referring model and simplified model as regards to the hourly ingoing air flow to room 1 the 14th January (meteorological station at CARPENTRAS, FRANCE). We can notice that the difference between the two models never exceeds 10 % while the wind velocity varies from 0 to 6 m/s.

Figure 5 translates the results of the figure 4 in comsumption terms indeed we can observe a similar evolution for both models.

These results are very encouraging because they show that good agreement could be achieved with the two methods.

Figure 6 a shows the air flow distribution in the building without any mechanical systems. A two way flow occurs in the room 2 due to the stack effect between rooms 2 and 4.

Figure 6 b . shows the air flow distribution in the building in the same climatic conditions but with an air extraction in each apartment (0,5 a c h). We observe that the air extraction is not disturbed until the room. 2, but the infiltration effect begins to be felt in room 3.

CONCLUSION -

Infiltration is a complex process affected by many parameters, the values of which are difficult to accurately predict.
There is a need for further experimental work to provide more reliable data for the improvement of design procedures.

REFERENCES -

(1) G. REEVES - M.F. Mc BRIDE - C.F. SEPSY
Air infiltration model for residences
ASHRAE Transactions, Vol 85 Part. 1, 1979.

(2) J.E. PETERSON
Estimating air infiltration into houses
ASHRAE Journal - Janvier 1979.

(3) D. W. ETHERIDGE - D.K. ALEXANDER
The British Gas Multi-Cell Model for Calculating Ventilation
ASHRAE Transactions - Part 2, PP. 808 - 818 - 1980.

(4) G. N. WALTON
Calculation of inter-room air movement for multi-room building
Energy analysis
NBSIR - 81-2404 - Washington - D.C. 20234 - Nov. 1981.

(5) J.J. ROUX
Proposition de modèles simplifiés pour l'étude du comportement
thermique des bâtiments
These Docteur-Ingenieur - INSA LYON - AVRIL 1984.

(6) G. GUYOT
Les profils de vitesse de vent au voisinage du sol
PROMOCLIM E, N° 1 - MARS 1976.

(7) C. KARAKATSANIS, M.N. BAHADORI, B.J. VICKERY
Evaluation of pressure coefficient and estimation of air flow
rates in buildings employing wind tower
SOLAR ENERGY, VOL 37, N° 5 PP. 363-374 - 1986.

(8) J. GANDEMER
Champ de pression moyenne sur les constructions usuelles
Cahier du C.S.T.B. - N° 187 - Cahier 1492, Mars 1978.

(9) R.W. HAMMING
Numerical methods for scientifists and engineers
Mc GRAW-HILL Book Company - 1973

(10) M.H. SHERMAN, D.T. GRIMSRUD, R.G. DIAMOND
Infiltration - Pressurization correlations : Surface pressure and terrain effects.
ASHRAE Transaction, Part 2, 1979.

(11) M. KILBERGER
Perméabilité à l'air des logements neufs.
CETE LYON, 83/110 HEB, 1983.

(12) ASHRAE Fundamentals 1985
Chapter 22 PP. 22.1, 22.18.

(13) DTU Règles Th K 77
Règles de calcul des caractéristiques utiles des parois de construction.

(14) W.F. STOECKER
Design of thermal systems, Mc Graw-Hill, 1971.

(15) A. ROLDAN
Etude thermique et aéraulique des enveloppes du bâtiment
Influence des couplages internes et du multizonage.
Thèse de Doctorat, INSA LYON, DECEMBRE 1985.