PROGRESS AND TRENDS IN AIR INFILTRATION
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WIND AND PRESSURE REQUIREMENTS FOR THE VALIDATION OF A MULTIZONE AIR INFILTRATION PROGRAM

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ABSTRACT

The validation process of FLOW, a multizone air infiltration program, has given plenty of information on which we report in this paper.

The methodology of validation is exposed and we describe specific problems which have been met and solutions which are proposed for most of them. The three first stages of a validation process are discussed : analytical verification, inter-model comparison and empirical validation.

A simple situation for a single cell has been calculated analytically and compared with the numerical FLOW simulation. A sensitivity test was applied for some parameters as wind speed, temperature, pressure for both FLOW and another program ESP-AIR, the results showing a very similar behavior.

The confrontation with full scale measurements has just started. But even if it is not yet possible to draw conclusions about the validity of FLOW, the work has learned us a lot to care of in future validations. It is shown that a new method should be used to log the wind data and that the Cp-values found in the litterature are not always suitable for the air infiltration calculation programs.

1. INTRODUCTION

In order to validate computer programs simulating air flows in multizone buildings we have collected data which are being organized in a data set [1].

We have tried to validate the program FLOW [2] which computes the air flows for a static situation in a multizone building modelled with a cubic network. This work has demonstrated all the complexity of the validation process in this domain.

In this paper, we present the many kinds of problems we have met and the solutions we propose.

We have not pushed the validation of FLOW to its end because this program is today obsolete and we prefer to validate the new program COMIS, now under development at the LBL [3].

2. THE VALIDATION PROCESS

2.1 Methodology

Following the ideas developed for the validation of thermal models by Judkoff and al. [4] in the USA as well as by Bowman and Lomas [5] in the UK a coherent validation methodology can be structured as it appears in figure 1.

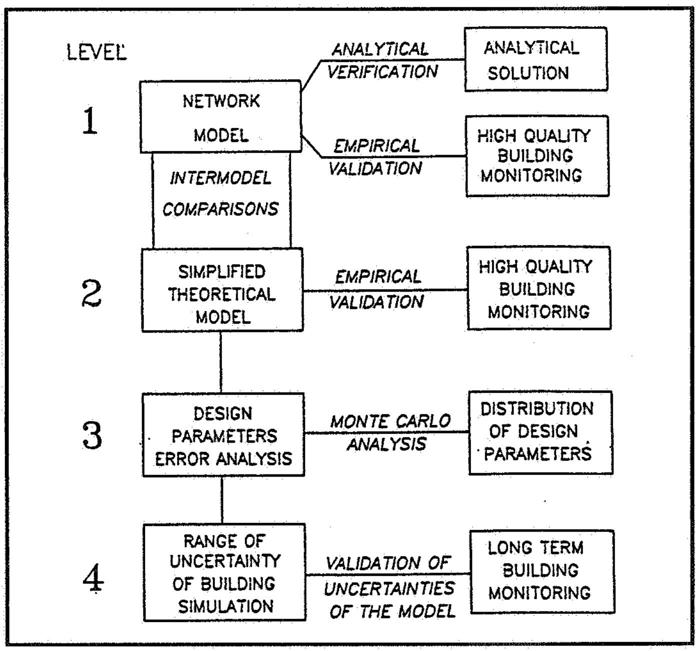

Figure 1 : Validation methodology for network models and simplified theoretical models [6].

The validation steps addressed in this work are :

1) the analytical verification
2) the inter-model comparison
3) the empirical validation.

In the analytical verification the calculation of a simple case is compared with program results.

The inter-model comparison is used to compare the advantages of various models or to appreciate the precision of a simplified model with respect to a more sophisticated one.

In the empirical validation measurements made "in situ" are compared to the computed results. On this level, many errors may influence the results and only a right error analysis can guarantee that the conclusion of the validation is reliable and not a piece of luck.

2.2 Error analysis in a validation process

The errors occurring in a validation process can be of two types :

1) internal errors
2) external errors

The internal errors issue from inaccuracies occurring in modelling the physical phenomena, writing the code, or in the numerical technique. The aim of the validation is to find these internal errors and to correct them. The external errors are contained in the data or coming from a bad use of the program and are to be avoided during the process of finding the internal errors.

Table 2 presents a comprehensive list of external error sources. It is an adaptation for the air flow model of the study of Bowman et al. [5].

Model Input Data	Climatic Data	• Some (or all) climatic data coming from a remote site • Frequency of measurement too low to define the variable (especially for the wind data) • Limited accuracy of measurements
	Site Data	• Cp imprecision problem
	Building Data	• Inadequate description of building geometry and construction • Uncertain workmanship • Use of handbook rather than measured physical properties • Temperature and permeability of adjacent unmodelled zones not defined • Limited accuracy of measured values
	Occupancy	• Interference with the building system • Badly defined occupancy profile • Uncertainty in modelling HVAC
	User Interface	• Blunders when entering data • Interpretation of poorly documented input data • Assuming values to replace missing data • Modification to the building description so that it can be modelled • Amended program coding so that the building can be modelled
Building Response Data	Data Logging	• Noisy, missing or spurious data • Frequency of measurement insufficient to define variable • Finite accuracy of probes and recording system
	Interference	• Internal features of structures altered by monitoring equipment
Comparison procedure	Data Comparison	• Transcription of measured data from charts, etc. • Differences between measured and predicted parameters • The location of the measurement and the prediction differ

Table 2 : External sources of errors occurring in a validation process.

2.3 Problems met and solutions

2.3.1 Frequency of wind data measurements

In the following we assume that wind data are available on site, either by a procedure of transferring meteo data from the remote station [18] or by measurements on site.

The air infiltration model calculates the air change rates averaged over fixed time intervals (here 15 minutes). In order to do so, wind data must be converted into pressures. The averaging of wind pressures over a particular time interval, is a problem.

Indeed, weather data measurement installation set up for building thermal auditing are often not able to collect measurements in a time interval shorter than 15 minutes.

Under these conditions the wind measurements are often of poor quality. On one hand, instantaneous measurements every 15 minutes are insufficient to model the air flows in buildings and on the other hand mean values have no physical meaning. As an example, we imagine the situation where the wind blows half of the time interval from the south and half from the north, then the following situations are possible :

1. The averaging process handling separately the wind speed, $V(t)$ and its direction, $\theta(t)$, results in an average direction which is east or west, and an average speed which is non zero.

   $$\{\theta(t_i), V(t_i)\} \rightarrow \overline{V}, \overline{\theta}$$

2. The averaging process computing the vectorial sum gives an average vectorial wind close to zero.

   $$\{\vec{V}(t_i)\} \rightarrow \langle\vec{V}\rangle$$

In each case the average wind is of no use to calculate the surface pressures and to simulate air flows reliably. To avoid this problem, an appropriate technique has been developed at the LESO.

But before explaining it, it is necessary to define the two kinds of time intervals occurring in a weather data logging process.

1. The sampling period is the time between two measurements of the same variable (typically 1 minute or equal to the recording period).

2. The recording period is the time after which the averaged, integrated or instantaneous measurement is recorded on the data logger tape (typically 15 to 30 minutes).

Usually the sampling period is equal to the recording period for the slowly varying observables (e.g. temperature) and the sampling period is shorter than the recording period for the quickly varying variables as wind speed or wind direction.

In such conditions, the appropriate technique to have satisfactory wind data consists of :

- Measuring the wind speed $V(t)$ and direction $\theta(t)$ at the highest possible sampling frequency.
- Summing the wind speed $V(t)$ sorted on the wind direction sectors (commonly eight sectors of 45°). As shown in the Annex 1, we shall compute :

$$V_{Jk} = \Big(\sum_{\{\theta_J \le \theta(t_{ik}) < \theta_{J+1}\}} [V(t_{ik})]^{2n} \Big)^{1/2n} \qquad (1)$$

with

$J = 1, 2, ..., 8$ (sectors)
$k = 1, 2, ..., K$ (recording time)
$i = 1, 2, ..., I$ (sampling time)

and

V_{Jk} : geometrical average wind speed in the sector J for the recording period k, $[ms^{-1}]$

θ_J : limit angle between the sector J-1 and J

$V(t_{ik})$: instantaneous wind speed at the sampling time i of the recording period k, $[ms^{-1}]$

$\theta(t_{ik})$: instantaneous wind direction at the sampling time i of the recording period k.

The geometrical average is justifiable by the fact that the pressure on the façade is proportional to the square of the wind speed and the flow to the power n of the pressure difference (n = .65 is taken). Therefore :

if $$Q = C\left(Cp \frac{1}{2} \rho \; V^2 \right)^n \qquad (2)$$

then $$\langle Q \rangle = C\left(Cp \frac{1}{2} \rho \right)^n \langle V^{2n} \rangle \qquad (3)$$

- recording the V_{Jk} every recording time
- modelling the flows in accordance with the measurements

$$Q_{lm} = \frac{1}{I} \sum_{J=1}^{8} C_{lm} \left(Cp(\theta_j) \frac{1}{2} \rho \; V_j^2 \right)^n \qquad (4)$$

Q_{lm}	:	the flow between the nodes l and m, $[m^3 h^{-1}]$
C_{lm}	:	the permeability coefficient between the nodes l and m, $[m^3 h^{-1} Pa^{-n}]$
$Cp(\theta_j)$	:	the pressure coefficient for the sector J representing the pressure difference between l and m, [-]

$$Cp = \frac{\Delta P_{lm}}{q}$$

2.3.2 The pressure coefficients

Getting satisfactory pressure coefficients (shape factors) is a very complex problem. The authors do not have the pretension to solve it, but summarize the specific problems for air infiltration codes validation.

Figure 3 gives the air flows, for the eight wind directions, in a room of the LESO building for two sets of Cp-values. The first set was measured in a wind tunnel at the LBL and the second is the default set of the FLOW program. Q_{in} is the flow entering the room from the inside of the building while Q_{out} is the flow entering from the outside. The dramatic discrepancy between the two sets of computed air flows is obvious. This example gives all its importance to the following discussion.

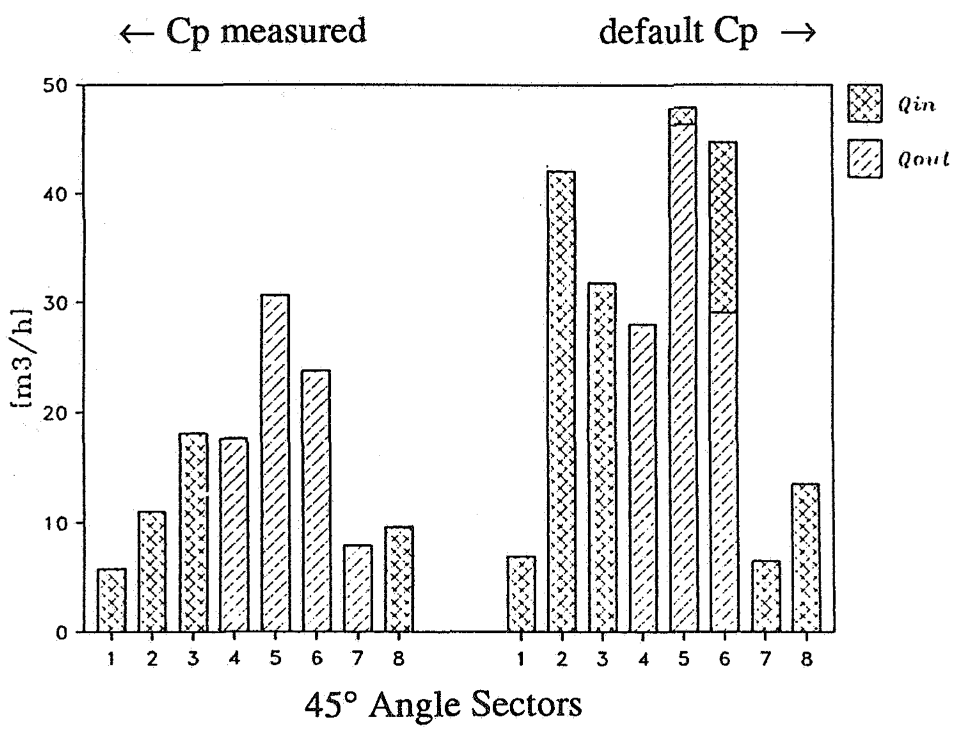

Figure 3 : Calculated air flows entering a room of the LESO building for a wind of 10 $[m\ s^{-1}]$ for eight wind directions and two sets (right - left) of Cp-values.

The items to be discussed are definitions of the Cp-values, sources of Cp-values, representative location of the Cp-values and representativity of the Cp-values themselves.

The definitions of the Cp - values

Several definitions exist for the pressure coefficients depending on their use, the geometry of the building and the habits of the professionals in a given country.

The Cp is always the ratio of a local pressure p to a dynamic pressure q :

$$q = 0.5\ \rho\ V^2 \qquad (5)$$

$$p = Cp\ q \qquad (6)$$

where ρ is the air density, [kg m^{-3}], and V is the wind speed, [m s^{-1}].

The definitions differ by the use of different extreme or average values for p and q [7] and, because the high sensitivity of the nodal air flow simulation program to them, it is a very critical point in the validation process. The two most common definitions are presented and commented below.

Cp used with one reference dynamic pressure

The dynamic pressure q is taken at a reference point

$$p(x, y, z) = Cp\ \ q(x_0, y_0, z_0) \qquad (7)$$

where z_0 : the reference height.

Definition (7) is better adapted to low rise buildings simulated with a constant wind profile. This profile can be used when the wind flow is driven down by the building. In this case (fig. 4) it is possible to observe, at low level, winds as fast as at roof level.

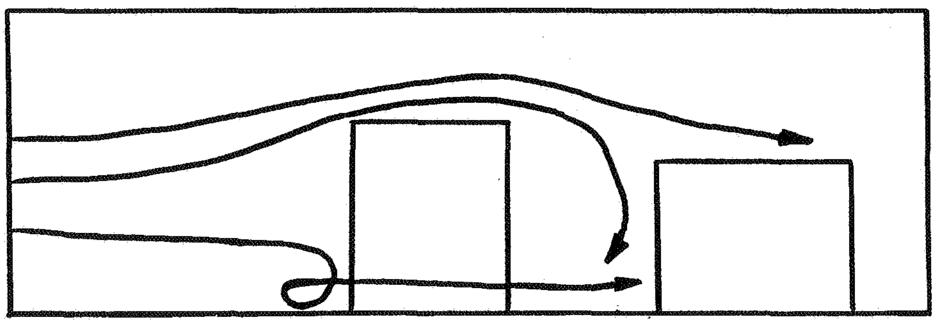

Figure 4 : The wind flow driven down by the building.

The reference point may be placed in various locations, each having advantages and disadvantages as discussed in reference [19]. Various positions on the roof or upstream are possible choices.

Cp used with dynamic measure profile

The dynamic pressure q is considered at the same height as the pressure p (fig. 5).

$$p(x, y, z) = Cp \; q(z) \tag{8}$$

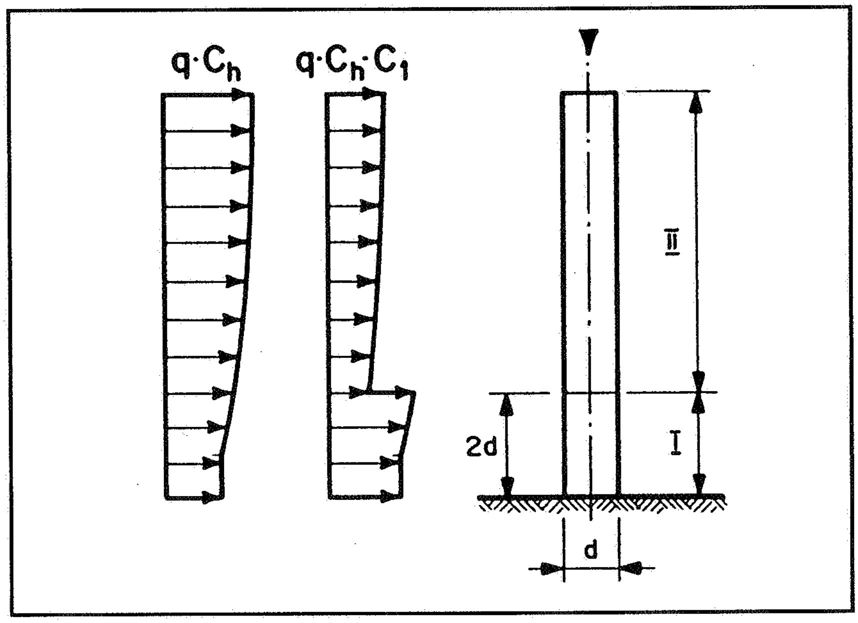

Figure 5 : Dynamic pressure q profile for a high-rise chimney [12].

The wind at the height z is calculated from the exponential law (9)

$$\frac{V(z)}{V(z_0)} = \frac{z^\alpha}{z_0^\alpha} \tag{9}$$

with the exponent α depending on the terrain roughness [8] so that

	0.18	in flat open land
$\alpha \approx$	0.23	in country
	0.36	in urban centers

These exponents are taken from reference [9], but it seems that every author has his own values.

Definition (8) is adapted to high rise buildings when the difference in the wind speed between the basement and the roof is important [10]. But aerodynamicians know a lot of details, which can have their weight in the choice of the appropriate Cp [11]. It would be a gain of time to have a decision tree (an algorithm) to choose the right definition and to avoid subjective screening.

Sources of Cp-values

As sources of Cp-values it is possible to use handbooks [12], simulation codes and wind tunnel measurements. Usually the handbook values are measured in wind tunnels, and sometime on site (full-scale measurements). The numerical codes which simulate tri-dimensional flows are still in development.

When picking Cp-values from a handbook care shall then be taken of which definition, which reference point and which safety margin have been used to obtain those results. In addition the buildings presented in handbooks are measured in open land situation and the influences of adjacent obstructions present in the real situation have to be estimated.

The adaptations of the values from handbooks to those expected by the computer program are theoretically possible if the information is precise enough, but it is better to ask help from a specialist, since for some locations in a building, the Cp values are calculated using special methods which are not explicitly mentioned in handbooks.

Without taking these precautions, every effort to obtain high quality results can be ruined by one or two badly estimated pressure coefficients [7].

For the wind tunnel measurements care should be taken of the correct simulation of the wind as a turbulent boundary layer. Because of the non-stationarity of the wind, its simulation should reproduce carefully the speed and direction profile, the turbulence intensity and the turbulence spectrum.

Representative location of a Cp-value

When a façade is submitted to a pressure field the resulting air flows depend on the permeability distribution.

To illustrate this problem, figure 6 presents different zones on a façade of a cube with respect to Cp-values.

Many typical situations are possible as a portion of the untight element may belong to one zone or another. This point emphasizes the advantage of programs which model the façades element by element.

In addition, the areal average shall be studied in agreement with the pressure distribution on the façade. For example the interpolation of Cp-values between two points is not possible because the pressure field on the building is not monotonic. Indeed, Cp-values vary more strongly horizontally than vertically, especially for high-rise buildings. Moreover, values given in handbooks are often calculated for civil engineering purpose. Therefore they are not representative of an average but more often only valid at a particular location [11]. In order to obtain Cp-values which serve as areal coefficients it is better to measure them as such. Reference [9] gives an example of a scale model built to perform areal and pneumatic averages.

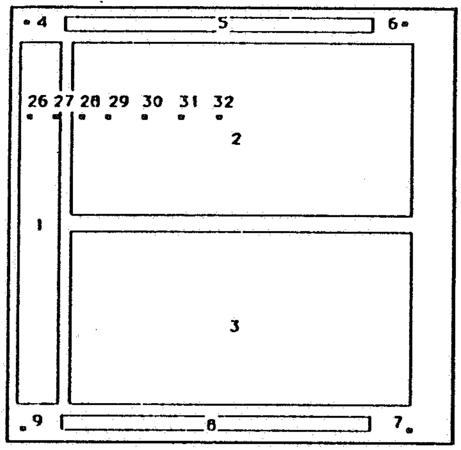

Figure 6 : Areal partition of the leeward side of a cube for wind pressure distribution. The numbers correspond to the probes [9].

Representativity of the Cp for the air flow simulation of buildings

The decisive proof of the quality of a theory is the confrontation with the reality. And here is the critical point for the Cp-values. Full scale and wind tunnel measurements agree only for windy and open, flat, situations for simply shaped buildings [13].

Usually the results for full scale measurements have so large confidence intervals (they can reach the magnitude of the value itself) that any conclusion can be taken [14]. Some specialists doubt the possibility to represent the pressure on a façade by a single value [15].

The reason for such a situation comes from the problem of the pressure measurement and also from the fact that in the low wind situation, which is most frequent in Switzerland, buoyancy induced airflow around the building can be similar to the wind effect.

Annex 2 presents a simplified calculation where it is demonstrated that in a middle sized building (three floors) a temperature difference of 3° C between two façades, caused by radiation from the sun, induces a convective flow of about 1 m/s.

In conclusion the Cp-values, if they are the right ones, probably allow the calculation of the wind effect on the building but not the effective pressure in the most frequent situation when the wind velocity is low and the sun shines.

3. THE PROGRAM FLOW

The program FLOW was developed by H.E. Feustel at the LBL [2] and was available to us when COMIS [3] started. FLOW is constituted by a FORTRAN code and data files as shown in figure 7.

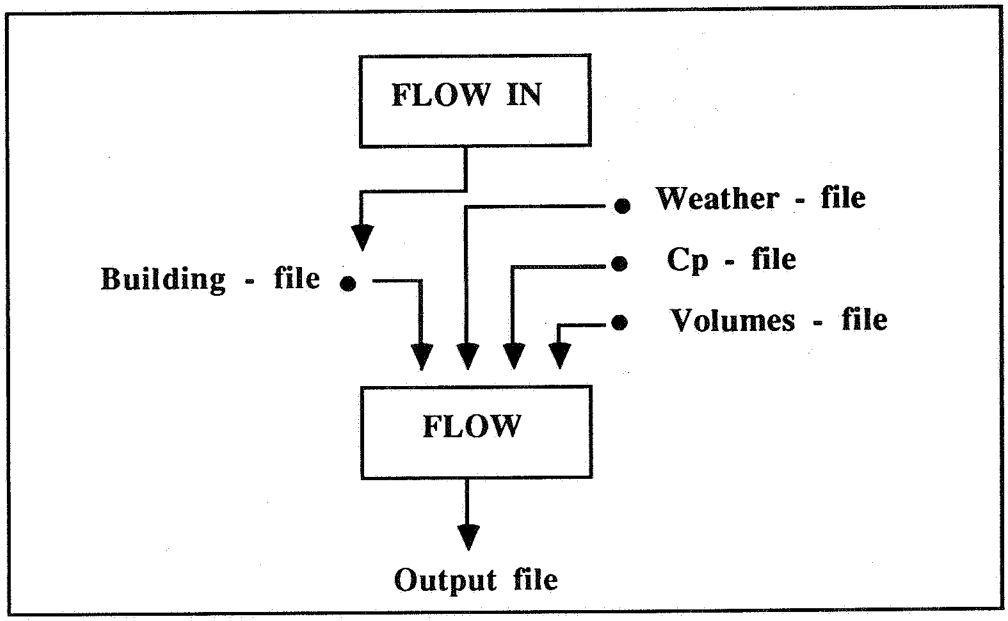

Figure 7 : The file structure of FLOW.

The main program computes the flows by a Newton algorithm for a cubic network of permeabilities connecting the nodes which correspond to the rooms and the outside.

The weather file contains outside temperature, wind speed and wind direction at the reference point for every time step. These values are taken into account as boundary conditions by the program which computes these static situations one after the other.

The output file contains basically the flows between every node and its six neighbors.

4. THE VALIDATION OF THE PROGRAM "FLOW"

The first three levels specified in figure 1 have been taken into account.

4.1 The analytical verification

For this level, the results of the code are compared with an analytical solution for a few simple cases. The test cases have to be chosen in order to be able to test all the algorithms in the code both separately and interacting with one another. Every case which can be handled by the program should be investigated.

For this study the two air flow driving processes were investigated separately :

1. The infiltration due to wind
2. The infiltration due to the stack effect

Each can be investigated in different situations, where different parts of the code are used. This method has allowed us to find many programming bugs. It is very important to begin with these very simple cases because it is easier to find the problematic points that way.

Annex 3 presents the calculation of a simple case of wind induced infiltration.

In table 8 analytical results are compared with computed ones, after correction of the program.

Parameters and variables		Analytical	Computed	Remark
$C_{windward}$ $C_{leeward}$	[m^3 h^{-1} Pa^{-n}] [m^3 h^{-1} Pa^{-n}]	20 40		given
T_{ext} T_{int}	[°C] [°C]	0 0		given
ρ_{ext} ρ_{int}	[kg m^{-3}] [kg m^{-3}]	1.293 1.293	1.27 1.2	FLOW assumes special ρ
Wind speed P_{static}	[m/s] [Pa]	8.8 50	8.87 50	adapted to have the same P_{stat} $\frac{1}{2}\rho\ V^2$
P_{int} m Q	[Pa] [kg / h] [m^3 / h]	2.8 266.48 209.83	2.80 266.33 221.94	

Table 8 : Comparisons between analytical solution and the computed results for wind induced infiltration.

The principal remark concerns the air density calculation. The program runs with two air densities :

Outside the building : $\rho_{ext}(T) = 1.27 - 0.05\ T$ (10)

and inside : $\rho_{int}(T) = 1.2$ (11)

It is very important to give this kind of information in the instructions for use, otherwise there is a huge loss of time in debugging the program and finding clues to interpret the differences between the computed and the analytical results.

At first it was not obvious that the difference in volume flows was only due to the differences in assumed densities. Such a detail cannot be found in an empirical validation process, because it is hidden under the large amount of possible causes.

4.2 Inter-model comparison

The inter-model comparison was made between the programs FLOW and ESP-AIR [16]. The simulated building is a cube. Its parameters are presented in the table 9 and the table 10 gives the weather data.

Side	Permeability C $[m^3 h^{-1} Pa^{-n}]$	n [-]	Cp (0°)
South	1	1	β
East	1	1	- 1/3 β
North	1	1	- 1/3 β
West	1	1	- 1/3 β
Roof	0	-	0

Table 9 : Building parameters for the inter-model comparison.

Run -	Wind speed $[m\ s^{-1}]$	Wind dir.	T_{int} [°C]	T_{ext} [°C]	β
1	20	South	20	20	1.5
2	20	South	20	0	.5
3	1	South	20	20	.5
4	1	South	20	0	1.5
5	14	South	20	10	1.0

Table 10 : Weather data parameters for the inter-model comparison and sensitivity study.

The weather data parameters have been chosen to explore regularly the experimental space and perform an optimum sensitivity test with a minimum of runs. The parameter β is artificial and serves to modify the magnitude of the pressure coefficients. Table 11 presents the results.

These results are similar and follow the same variations. A more detailed study would be necessary to explain the differences and define a confidence interval for each result.

Run	FLOW [m^3/h]	FLOW [kg / h]	ESP-AIR [m^3/h]	ESP-AIR [kg / h]
1	342	410	360	413
2	132	158	127	156
3	.28	.34	.30	.35
4	.99	1.19	.95	1.17
5	123	148	120	143

Table 11 : Results from FLOW and ESP-AIR.

The parametric study has shown that the two programs are most sensitive to the wind speed. Fitting a polynomial on the four first runs, the following relative coefficients were found :

Constant	:	1
Windspeed	:	1
Temperature	:	0.44
β (Cp)	:	0.44

In the constant are hidden non-studied parameters including the permeability distribution and the pressure distribution.

The influence of the wind speed is very large and this is an argument to take into account when considering the quality of the wind measurements (see chapter 2.3).

This inter-model comparison should be continued further, with other situations. We intend to do it with the COMIS program [3]. However, this level of the validation allows us anyway to study the sensitivities of the programs to several variables.

5. CONCLUSIONS

The validation process of the multizone air infiltration programs FLOW and ESP-AIR has shown a high sensitivity of this kind of nodal model to the wind and hence to the pressure coefficients Cp. Available wind data are in general not adapted to the requirements of air infiltration modelling. A new scheme for the measurement and simulation of wind data is proposed suggesting that considerable progress in wind simulation is possible.

Cp-values available in the literature are not adapted to the purpose of air infiltration calculation. They generally do not give an areal average pressure coefficient in a realistic situation, including boundary layer flow, natural convection flow and surroundings.

Before comparing full scale measurements and computed results, we submitted the code to analytical validation in many very simple situations. It was found an easy way to debug the code.

Future research should include the coupling effects of wind and buoyancy on air infiltration.

A few remarks. It is felt that time can be gained by joining the authors of the program, the measuring staff and the validators in a same place during the program validation.

It seems to be scientifically advantageous that the program author and the validator are two different persons. The review will be more censorious that way and the result will be better.

Finally and obviously, it is very important to remember that the validation of a program is a hard and very time consuming work.

6. APPENDICES

ANNEX 1 - A SATISFACTORY AVERAGING METHOD FOR WIND DATA

The mean flow Q_k between two nodes at the limit of the network during the period k is modelled by a sum on 8 sectors of the mean flows Q_{Jk}

$$Q_k = \frac{1}{I} \sum_{J=1}^{8} Q_{Jk} \qquad \text{(A1)}$$

The demonstration is done by showing that this model is equal to the sum (A7) of the instantaneous flows Q (t_{ik}). The flow Q_{Jk} is defined so that :

$$Q_k = \frac{1}{I} \sum_{J=1}^{8} C \; [Cp\,(\theta_J)\,\frac{1}{2}\,\rho \;(V_{Jk})^2]^{\,n} \qquad \text{(A2)}$$

where

Q_k	:	average flow during the period k, [$m^3\ h^{-1}$]
I	:	number of measurements during the period k (recording period)
C	:	permeability coefficient, [$m^3\ h^{-1}\ Pa^{-n}$]
n	:	exponent, [-]
Cp (θ_J)	:	pressure coefficient for the sector J, [-]
ρ	:	air density, [$kg\ m^{-3}$]
V_{Jk}	:	integrated wind speed for the sector J during the period k
Q_{Jk}	:	integrated flow during the period k for the sector J.

Let us define

$$(V_{JK})^2 = \left[\sum_{\{\theta_J \leq \theta(t_{ik}) < \theta_{J+1}\}} (V(t_{ik}))^{2n} \right]^{1/n} \quad (A3)$$

which is the averaging method compatible with the model (A2), as shown below. Placing (A3) in (A2) we obtain :

$$Q_k = \frac{1}{I} \sum_{J=1}^{8} \sum_{\{\theta_J \leq \theta_{ik} < \theta_{J+1}\}} \left(C \left(Cp(\theta(t_{ik})) \frac{1}{2}\rho \right)^n (V(t_{ik})^{2n}) \right) \quad (A4)$$

recomposing the two sums

$$Q_k = \frac{1}{I} \sum_{i=1}^{I} C \left[Cp(\theta(t_{ik})) \frac{1}{2}\rho \; (V(t_{ik}))^2 \right]^n \quad (A5)$$

$$Q_k = \frac{1}{I} \sum_{i=1}^{I} Q(t_{ik}) \quad (A6)$$

The precision between the real flow and the modelled one depends on the number of measurements. The greater is I, the more accurate will be the simulation.

ANNEX 2 - THERMAL WIND AROUND A BUILDING

The scope of this calculation is to estimate the magnitude of the air flow between two façades at different temperatures.

This difference can be caused by the radiation on one façade (front façade subscript F) and the shadow on the other (back façade subscript B). We imagine the building in the form of a parallelepiped of height h. From the Bernoulli equation, it is possible to write :

$$P_B + \frac{1}{2} \rho_B V_B^2 = P_F + \frac{1}{2} \rho_F V_F^2 \quad (A7)$$

to simplify the problem let us assume that V_B is close to zero. Then

$$\Delta P = \frac{1}{2} \rho_F V_F^2 \quad (A8)$$

and for two colums of air at different temperatures the maximum pressure difference is :

$$\Delta P = h \; g \; \Delta\rho \quad (A9)$$

then it is possible to estimate the velocity V so that :

$$V = \sqrt{\frac{\Delta\rho}{\rho} g\, h} = \sqrt{\frac{\Delta T}{T} g\, h} \qquad \text{(A10)}$$

As a numerical example, ΔT is 3 [°C] and h = 10 [m] would give

$$V = \sqrt{(3/300)\ 9.81 \cdot 10} = 1 \text{ [m/s]} \qquad \text{(A11)}$$

that means that for a wind velocity of 5 m/s, a value of Cp = 1 can be affected by up to 20 % and a Cp = 0.2 by up to 100 %.

It is interesting to recall that the same characteristic velocity is found by recognizing that the internal Froude number must be close to unity (i.e. buoyancy forces are in equilibrium with the inertial forces) [17]; this is a restatement of equation (A10).

ANNEX 3 - CALCULATION OF THE SIMPLE CASE OF WIND INDUCED INFILTRATION FOR THE ANALYTICAL VALIDATION

A3.1 The building

The monozone building is described as follows :

C_W	:	windward exfiltration coefficient [$m^3\ h^{-1}\ Pa^{-n}$]
C_L	:	leeward exfiltration coefficient [$m^3\ h^{-1}\ Pa^{-n}$]
Cp_W	:	windward pressure coefficient
Cp_L	:	leeward pressure coefficient
n	:	exponent coefficient
V	:	wind speed [$m\ s^{-1}$]
P_W	:	windward pressure, [Pa]
P_L	:	leeward pressure, [Pa]
P_I	:	internal pressure, [Pa]

Figure 12 gives a schematic view of the building-test 1

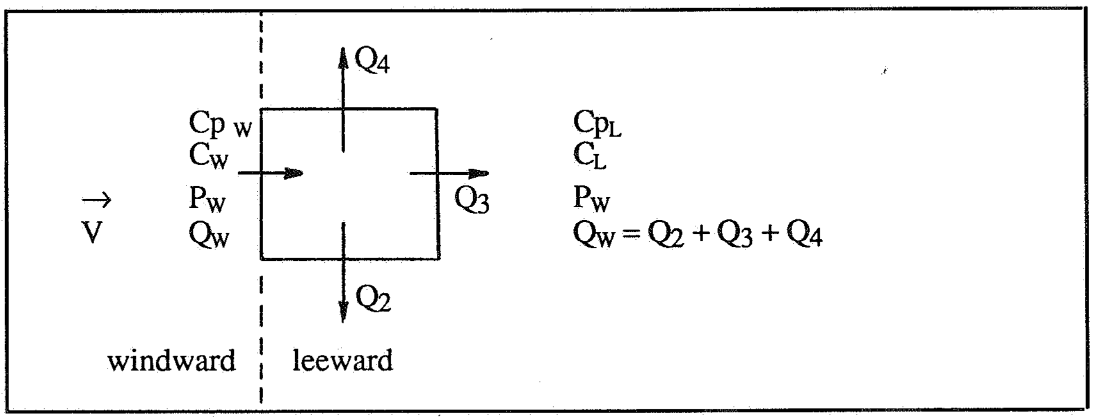

Figure 12 : A schematic view of the building-test 1.

A 3.2 Analytical solution

The wind induced infiltration process is represented by the following equations :

- Exfiltration law

$Q_W = C_W (P_W - P_I)^n$ with $0.5 < n < 1$ (A12)

$Q_L = C_L (P_I - P_L)^n$ (A13)

- Wind induced pressure

$P_W = Cp_W \, q$ (A14)

$P_L = Cp_L \, q$ (A15)

- Static pressure

$q = 0.5 \, \rho \, V^2$ (A16)

- Mass conservation

$\rho \, Q_W = \rho \, Q_L$ (A17)

from 6 it is trivial to obtain by (A12) and (A13)

$$C_W (P_W - P_I)^n = C_L (P_I - P_L)^n \qquad (P_W > P_I > P_L) \qquad \text{(A18)}$$

by raising (A18) to the power $\frac{1}{n}$

$$(C_W)^{1/n} (P_W - P_I) = C_L^{1/n} (P_I - P_L) \qquad \text{(A19)}$$

and we get

$$P_I = \frac{(C_W)^{1/n} P_W + (C_L)^{1/n} P_L}{C_W^{1/n} + C_L^{1/n}} \qquad \text{(A20)}$$

$$P_I = q \frac{Cp_W (C_W)^{1/n} + Cp_L (C_V)^{1/n}}{C_W^{1/n} + C_L^{1/n}} \qquad \text{(A21)}$$

and finally we get

$$Q_L = Q_W = C_W C_L \frac{(P_W - P_L)^n}{(C_W^{1/n} + C_L^{1/n})^n} = C_{eq} (P_W - P_L)^n \qquad \text{(A22)}$$

A 3.3 Numerical results

The following data are used :

C_W = 20 [m³/h Paⁿ]

C_L = 40 [m³/h Paⁿ]

n = 0.65

Cp_W = 0.8 → P_W = 40 [Pa]

Cp_L = $0.2 \rightarrow P_L = -10$ [Pa]
V = 8.8 [m/s]
ρ = 1.2929 (T = 0 [°C]) (kg / m³)
q = $1/2\ \rho\ V^2 = 50$ [Pa]

The use of equation (A21) gives :

$$P_{int} = 50 \left(\frac{0.8\ (20)^{1/.65} - 0.2\ (40)^{1/.65}}{20^{1/.65} + 40^{1/.65}} \right) = 2.8\ \text{[Pa]} \qquad \text{(A23)}$$

The flows are now obtained from equation (A22)

$$Q_W = 20\ (40 - 2.8)^n = 209.83\ [m^3/h] \qquad \text{(A24)}$$

$$Q_L = 40\ (-10 - 2.8)^n = 209.82\ [m^3/h] \qquad \text{(A25)}$$

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8. BIBLIOGRAPHY

[1] J.-M. Fürbringer, R. Compagnon
"Weather and aeraulic data set for validation - The LESO Building, Part. 1 Content of the data set" internal report, LESO, EPFL, Lausanne, Switzerland (1989).

[2] H.E. Feustel
"Beitrag zur theoretischen Beschreibung der Druck und Luftmassen stromverteilung in natürlisch und maschinell gelüfteten Gebäuden". Forschritt-Berichte der VDI-Zeitschriften, 1984, Reihe 6, Nr 151.

[3] International Workshop COMIS. 1988, 1989
Conjunction of Multizone Infiltration Specialists at Lawrence Berkeley Laboratory.

[4] R. Judkoff and al.
"A methodology for validating building energy analysis simulations", draft report, SERI / TR-254-1508 Golden, CO, USA (1983).

[5] N.T. Bowman and K.J. Lomas
"Empirical validation of dynamic thermal computer models of buildings", Building Services Engineering Research and Technology, Vol. 6 (4). pp. 153 - 162, London, UK (1985).

[6] J.-L. Scartezzini, J.-M. Fürbringer, C.-A. Roulet, H.E. Feustel,
"Data needs for purpose of air infiltration computer code validation" proc. 8th AIVC Conference, Ueberlingen (1987).

[7] G. Barnaud
"Effets locaux-pression interne" in "Aerodynamique", CSTB editor, REFF Vol. II, France.

[8] A.G. Davenport
"The relationship of wind structure to wind loading" in proc. "Wind effects on buildings and structures" National Physical Laboratory, Teddington, UK (1963).

[9] J.A. Hertig et al.
"Essai en soufflerie à couche limite en vue de mesurer les coefficients de pression pour les tableaux de la norme SIA 160 révision 1988" (LASEN, EPFL, Lausanne, Switzerland (1989).

[10] Y. Lee et al.
"Distribution of wind - and temperature - induced pressure differences across the walls of a twenty-storey compartementalised building" Jour. of Wind Eng. and Ind. Aerody. 10 (1982) Amsterdam, Netherlands.

[11] Private discussion with J.-A. Hertig, Lasen, EPFL, Lausanne, Switzerland.

[12] SIA Standard 160 "Action sur les structures porteuses". Ed. SIA, Zurich, Switzerland, (1989).

[13] J. Gusten
"Full-scale wind pressure measurements on low-rise buildings"
in proc. "1984 Wind pressure workshop" TN AIC 13.1.

[14] A. Gadilhe
Intermediate thesis report, LASH, Lyon, France (March 1989).

[15] Private discussion with H. Phaff, TNO, Delft (NL).

[16] J. Clarke, D. McLean, Abacus
"ESP. A building and plant energy simulation system" Version 5, release 3
University of Strathclyde, Glasgow, UK, (1986).

[17] J.S. Turner
"Buoyancy effects in fluids", Cambridge University Press, UK (1973).

[18] J.A. Hertig, J. Ehinger
"Analysis of the influence of topography on the exposure of buildings"
proc. 10th AIVC Conference, Gent (1988).

[19] Carolyn Allen
"Wind pressure data requirements for air infiltration calculations"
TN AIC 12, UK (1984).