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EXPERIMENTAL AND NUMERICAL ANALYSIS OF TRANSIENT AIR CHANGES IN BUILDINGS: A CASE STUDY

R. Borchiellini and M. Calì
Dipartimento di Energetica - Politecnico di Torino
Torino, Italy

SUMMARY

Air change rates calculated from the data obtained using tracer gas techniques are usually considered as constant in time, therefore their values represent the average in the time measurements interval.

In this paper the measurements performed in two identical detached test houses, using the decay technique, are described. The two houses, which were built by Italian main gas company, are very well equipped with instruments in order to acquire meteorological data and inside air temperatures; pressurization tests were also performed in the past.

After a quick glance at the mathematical formulation of the problem using the parameter estimation theory, the concentration measured values are here analysed by considering the air change rates as parameters which change in time.

The computed air change or air flow rates are plotted as time functions and are compared with the results obtained by assuming the parameter constant in time; uncertainties due to measurement errors and to calculation procedures are taken into account.

Finally it is shown how interesting considerations and information, on the validity of the experiment, can be obtained by the analysis of the results.

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NOMENCLATURE

c	vector of the concentration functions
C_d	covariance matrix of the experimental errors
C_D	C_d+C_T
C_P	covariance matrix of the a priori values
C_T	covariance matrix of the modelling errors
C_M	covariance matrix of the parameters
c_i^k	concentration of the k-th tracer gas in the i-th zone (m^3/m^3)
d	vector of the measured parameters
m	vector of the estimated parameters
M	number of tracer gases
N	number of zones (less outside zone)
Q	volume air flow vector
Q_{ij}	volume air flow rate from zone j to zone i (m^3/s)
Q_s	tracer volume gas flow rates
$Q_{s,i}^k$	k-th tracer gas flow rate in the i-th zone (m^3/s)
S	quadratic function defined in text
t	time (s)
T_i	temperature in the i-th zone (K)
T_s^k	temperature of k-th tracer gas injected (K)
V_i	volume of the i-th zone (m^3)
z	number of instants in which measurements have been performed
δ_{ij}	the Kronecker delta; $\delta_{ij} = 0$ if $i \neq j$, $\delta_{ij} = 1$ if $i = j$
σ	standard deviation
$\sigma()$	probability density function

INTRODUCTION

In March 1991 and 1992 tracer gas measurement were performed using the decay technique in two detached houses that because of their characteristics may be considered laboratory houses. The experimental apparatus used is a compact and mobile multi-tracer and multi-zone system developed at the Dipartimento di Energetica of the Politecnico of Torino.

By usually starting from the measured concentrations, the volume air flow rates or the air change rates are obtained as a value constant in time, that is, the calculated value is the mean value in the measurement period; a wider and fascinating approach is that of analyzing the measured data by considering the air volume flow rates as functions of time.

This work mainly refers to the Inverse Problem with the aim of describing the application of a general solution procedure that may be used with data obtained using different measurement techniques. The procedure here described satisfies these important requirements:

- it works well in both the hypotheses of constant flows and variable flows;
- it allows one to carry out the uncertainties related to the results;
- it is possible to use on line during the measurements.

The results obtained shown that interesting information can be provided by plotting the air flow rates versus time, especially if something unusual occurs during the measurements.

THE MEASUREMENT SITE

Number	Description
1	Bedroom S-E (CAMERA)
2	Bathroom (SERVIZI)
3	Bedroom N-E (CAMERA)
4	Corridor
4	Hall
5	Kitchen (CUCINA)
6	Bedroom N-W (SOGGIORNO)

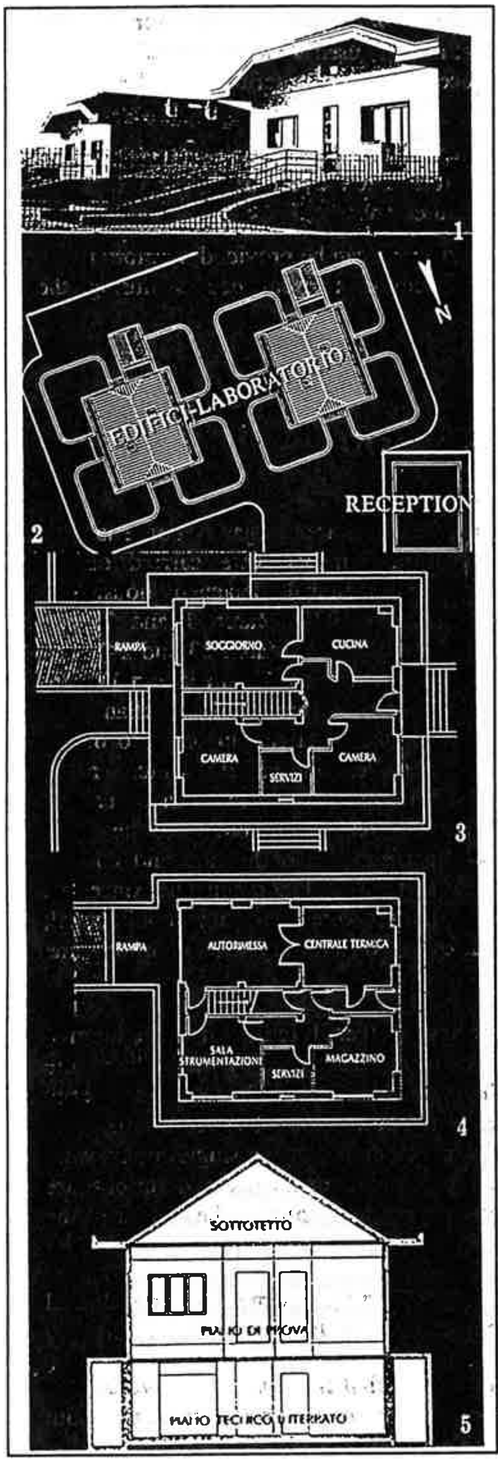
Table 1

The tracer gas concentration measurements were carried out in two identical detached houses in March 1991 (March 1 and 7) and March 1992 (March 23 and 24). The two houses (see figure 1 part 1) were built by the main Italian gas company, Italgas, in order to obtain two test-houses in which many different experiments can be carried out mainly in order to test the performance of heating and cooling systems and components; since the houses were designed and built equal, it is possible to measure the different behaviour of two different systems with the same operating conditions.

In order to perform these tests, the houses were very well analyzed as far as the thermal behaviour is concerned, all the characteristics of the materials used by the builder were well known, therefore, according to Italian standards, heat losses and energy consumption were carried out; thermal bridges were outlined and observed by means of infra-red thermography; tightness of the whole first floor and of the single rooms were defined using pressurization tests. The tracer gas measurements here described are included in this set of measurements carried out for characterizing the behaviour of the two houses.

The two building are three level houses (see figure 1 part 5): basement where technical rooms and instruments are placed; the first floor which is the test level and the loft.

The gas concentration measurements refer only to the first floor which is divided into six rooms; in table 1 a description and a number is given for each room; since the room



labels are written in Italian in figure 1 part 3, the English description is followed by the Italian translation in brackets in table 1.

In each room of the basement and of the first floor the air temperature is measured continuously; outside wind speed and direction, air temperature and humidity and solar radiation are recorded every five minutes.

EXPERIMENTAL APPARATUS AND MEASURED DATA

The decay technique was carried out in both March 1991 and March 1992 measurements; in March 1991 the experimental apparatus was that described in [1]: a compact and mobile multi-tracer gas system developed for multizone analysis and for on-site measurements.

The system is controlled by a PC computer laptop model based on an Intel 80C286 12 MHz processor and it utilizes two compatible I/O boards; only two infra-red photometers, for the measurements of the nitrogen protoxyde (N_2O) and sulphur hexafluoride (SF_6), have been included.

An upgraded version of the experimental apparatus was utilized in March 1992; compactness and portability characteristics have been improved in this version; the weight is reduced by means of the new type of solenoid valves; moreover the valves of each zone are assembled together in a single box that may be removed from

Figure 1 - View of the two identical houses, kindly provided by Italgas.

the rack at anytime, for each measurement therefore, it is possible to introduce only the number of boxes equal to the number of zones that are analyzed into the rack.

In each room on the first floor, the air was sampled by means of a vertical tube, with several hole in order to allow a simultaneous sampling for different height placed in the center of the zones; there is also a probe with a thermoresistance for air temperature measuring attached to the tube in order to be able to take the temperature influence as pointed out by Roulet [2] into account.

During the first day of the March 1991 experiments, two measurements took place: Test A and Test B. In both tests the air was sampled at the same time in each zone and mixed before reaching the gas analyzer; therefore only a single concentration was recorded (see fig 2) using a period of one minute.

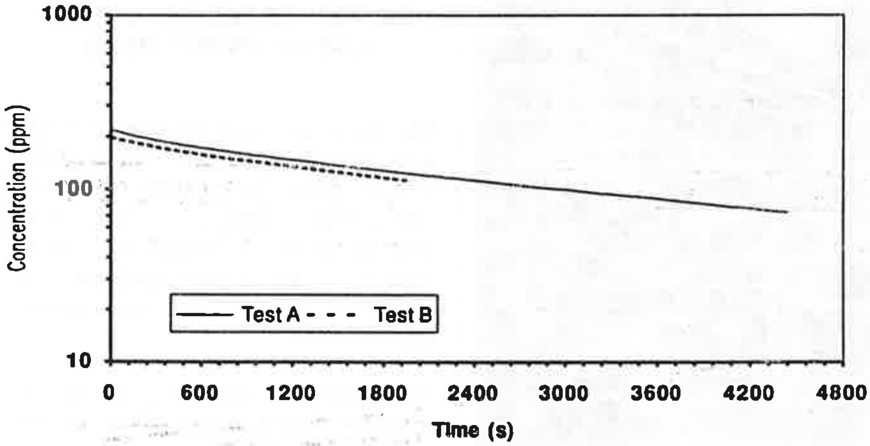


Figure 2 - Measured concentrations in Test A and B

During the second day of the March 1991 experiments, three measurements were carried out: Test C, Test D, Test E. The air was sampled in one zone at a time and as many concentrations as zones were recorded (see fig. 3, 4, 5).

On the first day of the March 1992 experiments, two measurements were carried out: Test F and Test G. The measurements were performed in the same way as for Test A and Test B. In test F the outside door was opened 1000 seconds after the beginning of the test and it was closed again after 600 seconds. The window shutters (external roller type) were closed after 1440 seconds from the beginning of the Test G; as the gas injection the N_2O concentration went over the full-scale value and windows and outside door were opened in order to quickly decrease the N_2O concentration; the measurement started as soon as the door and windows were closed without waiting the new mixed condition.

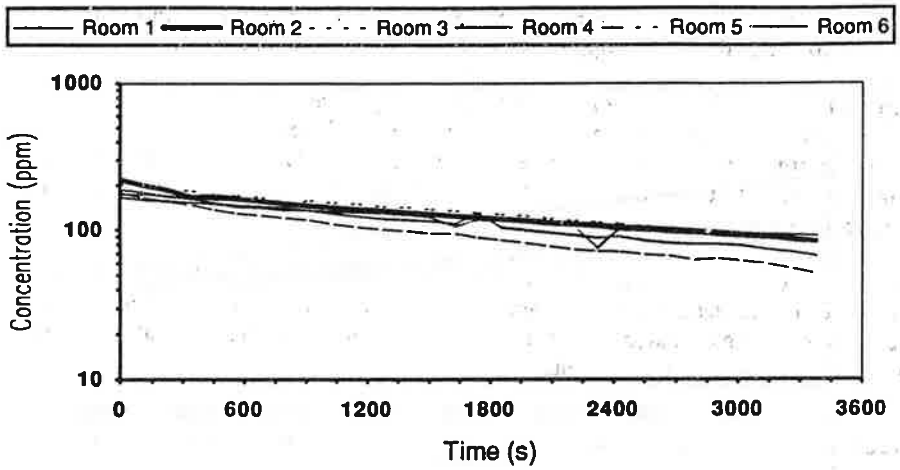


Figure 3 - Measured concentrations in Test C

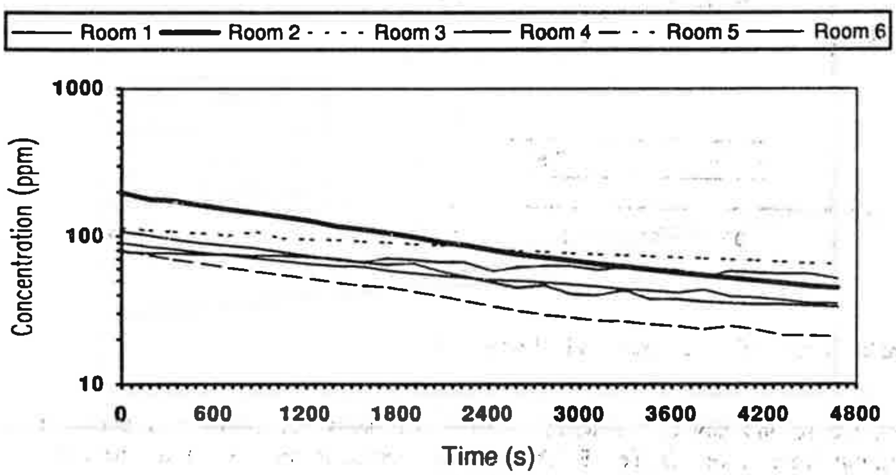


Figure 4 - Measured concentrations in Test D

Test H took place on the second day of the March 1992 experiments, and it concerns the second house (called A) while all pervious measurements are carried out in house B. The decay technique was utilized as in Test A and Test B, but in this test two tracers were used, therefore in the following paragraph, Test H (SF_6) here denotes values concerning the analysis of the SF_6 concentration data and Test H (N_2O) values concerning the analysis of the N_2O concentration data; a window in room 6 was opened after 1500 seconds and closed after 600 seconds.

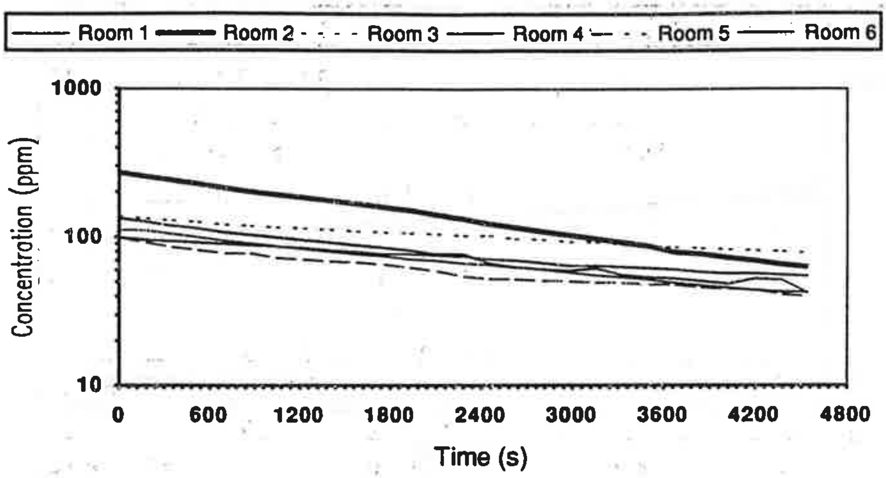


Figure 5 - Measured concentrations in Test E

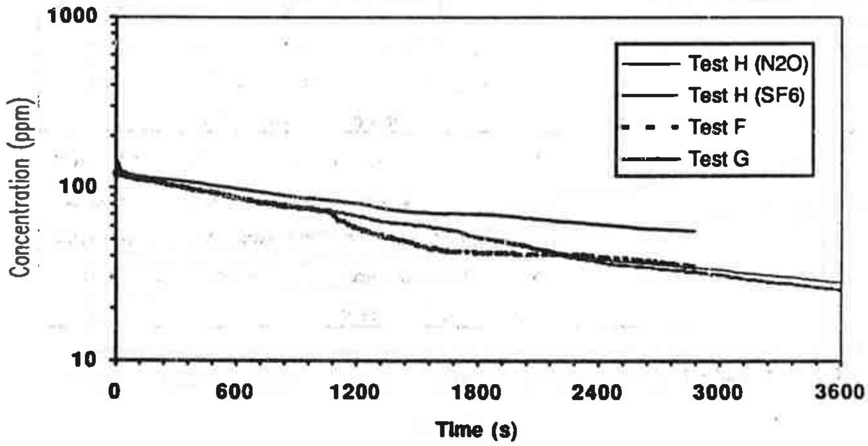


Figure 6 - Measured concentrations in Test F, G and H

Figure 6 shows the measured tracer gas concentrations versus time; table 2 summarizes the characteristics of the measurements.

Test	Period (s)	Technique	Notes
A	4440	Decay	The samples in the six zones are mixed before reaching the analyzer; all doors between the zones are open.
B	1980	Decay	The samples in the six zones are mixed before reaching the analyzer; all doors between the zones are open.
C	3480	Decay	Only the door between zones 5 and 6 is closed; period for washing pipes and analyzer with fresh air: 20 s.
D	4820	Decay	All door between zones are closed; period for washing pipes and analyzer with fresh air: 30 s.
E	4689	Decay	Only the door between zones 5 and 6 is open; period for washing pipes and analyzer with fresh air: 30 s.
F	2880	Decay	The air samples in the six zones are mixed before reaching the analyzer; all doors between the zones are open; only the door between zones 5 and 6 is closed. Outside door open from 1000 to 1600 seconds.
G	2875	Decay	The air samples in the six zones are mixed before reaching the analyzer; all doors between the zones are open; only the door between zones 5 and 6 is closed. Rolling shutter closed after 1440 seconds.
H	3680	Decay	The air samples of the six zones are mixed before reaching the analyzer; all doors between the zones are open; only the door between zones 5 and 6 is closed. N_2O and Sf_6 are used. The window in room 6 open from 1500 to 2100 seconds.

Table 2 - Measurement characteristics

SOME CONSIDERATIONS ON THE THEORETICAL APPROACH

The well known equation that describes the time concentration evolution for the k-th tracer gas in the i-th room is:

$$\frac{V_i}{T_i}\cdot\frac{dc_i^k}{dt}=\frac{\left|Q_{s,i}^k\right|}{T_s^k}+\sum_{j=0}^{N}\frac{\left(c_j^K-c_i^k\right)}{T_i}\cdot\left(1-\delta_{ij}\right)\cdot\left|Q_{ji}\right| \tag{1}$$

It is assumed that the main hypotheses that allow its formulation are also known [2, 3].

After some rearrangements in equation (1) it is possible to write a system of equations with (M+1)N equations and (N+1)N different air flows; this system can be written in the following general form:

$$F(Q, Q_s, c, \dot{c}, t) = 0 \tag{2}$$

These equations represent the mathematical model of the tracer concentration evolution used by the researchers in the last fifteen years; it is now possible to take two different approaches into account:

a - DIRECT MODEL SOLUTION or FORWARD MODELLING (FM) where the time variations of the concentration for each tracer are carried out starting from the knowledge of:
  - all volume air flows;
  - the volume tracer injection rates;
  - the zone temperatures
  - the tracer temperatures.

b - INVERSE MODEL SOLUTION or PARAMETER ESTIMATION or INVERSE MODELING (IM) where it is assumed that the time variations of the concentration for each tracer is observed; a set of parameters is carried out starting from these values and adding other information.

Two main concepts are involved when using the inverse problem theory: "state of information" and "probability"; the meaning of these two concepts can be clearly identified in every book on this topic; the books written by Beck [4, 5] and Tarantola [6] are taken into account for the basic definitions of this work.

Since a probability density function is associated to each information it is possible to define the following covariance matrices:

C_T covariance operator describing the estimated modeling errors for a model $\mathbf{m}$;
C_d covariance operator describing estimated experimental errors, which may depend on the observed values $\mathbf{d}_{obs}$;
C_D C_T+C_d;
C_P covariance operator describing uncertainties on "a priori" values of model parameters $\mathbf{m}_{prior}$;

Tarantola [6] states that all this information may be joined in order to define a probability density $\sigma(\mathbf{d}, \mathbf{m})$ representing the "a posteriori" information; furthermore, if the probability density function representing the experimental uncertainties, forward modelling uncertainties and the "a priori" information on model parameters are Gaussian, the "a posteriori" information in the model space is given by [4, 5, 6]:

$$\sigma_M(\mathbf{m}) = \text{const} \cdot \exp(-S(\mathbf{m})) \tag{3}$$

$$S(\mathbf{m}) = \frac{1}{2}\left(\left(g(\mathbf{m}) - \mathbf{d}_{obs}\right)^t C_D^{-1}\left(g(\mathbf{m}) - \mathbf{d}_{obs}\right) + \left(\mathbf{m} - \mathbf{m}_{prior}\right)^t C_P^{-1}\left(\mathbf{m} - \mathbf{m}_{prior}\right)\right) \quad (4)$$

where the forward model:

$$\mathbf{d}_{cal} = g(\mathbf{m}) \quad (5)$$

In multi-zone air flow problems **d** is the measured concentrations while **m** is usually the volume air flow rate even if the volume tracer gas injections or the zone volumes could be considered as parameters; therefore equation (5) is here replaced by equations (2).

Solving the Inverse Problem means carrying out the **m** value maximizing $\sigma_M(\mathbf{m})$; where **m** is usually considered as a vector constant in time [7, 8, 9 10]. Therefore, the calculated value of **m** is the mean volume air flow value in the measurement period. This method is here denoted as Constant Parameter Method (CPM).

In this paper the measured concentration values are analyzed using both the hypotheses of constant parameters and parameter functions of time; when the second hypothesis is considered, the value of **m** for each time is carried out using the sequential method (SM) described in [11] in which the parameters at time t_a, are estimated using measurements performed in times t_a, t_{a+1},....., t_{a+r-1}; therefore for a=1 and r is equal to the number z of the measured instants, the value of **m** obtained has the same meaning of that obtained using CPM.

Furthermore this approach, based on the concepts of the state of information and probability, allows one to easily define the standard deviation for each estimated parameter as:

$$\sigma_i = \sqrt{C_{M,ii}} \quad (6)$$

ANALYSIS OF EXPERIMENTAL RESULTS

The method defined in the previous section has been applied to analyze the concentrations measured and given in the previous figures; the parameter set is here the air volume flow rates that in this special case is a set including only one component: the outside volume air flow rate.

All the results here given are carried out using the single room hypothesis which means taking all the six zones as a whole into account; as far as Test C, Test D and Test E are concerned, the six measured concentrations were used to obtain a single mean value that was considered as a single measured concentration as for the results obtained in Test A and Test B.

Test	Air change rate (1/h)	Standard deviation σ (1/h)	Air change rate (1/h)	Standard deviation σ (1/h)	Air change rate (1/h)	Standard deviation σ (1/h)
A	0.8511	0.0934	0.8632	0.0104	0.9418	0.0017
A(*)	0.7240	0.1113	0.7508	0.0019	0.7266	0.0039
B	1.0118	0.0754	1.0138	0.0173	1.0836	0.0041
B(*)	0.8754	0.0812	0.8997	0.0053	0.8884	0.0072
C	0.9012	0.0500	0.9136	0.0126	0.9467	0.0036
D	0.7239	0.0633	0.7829	0.0153	0.7751	0.0051
E	0.7502	0.0474	0.7772	0.0085	0.7830	0.0040
F	1.5523	0.0694	1.8292	0.0152	1.8373	0.0021
G	1.2216	0.0480	1.0428	0.0075	1.5031	0.0014
H(N_2O)	1.4475	0.0759	1.5370	0.0045	1.6172	0.0016
H (SF_6)	1.5793	0.0793	1.6613	0.0043	1.7410	0.0016

Table 3 - Results obtained for Test A + H

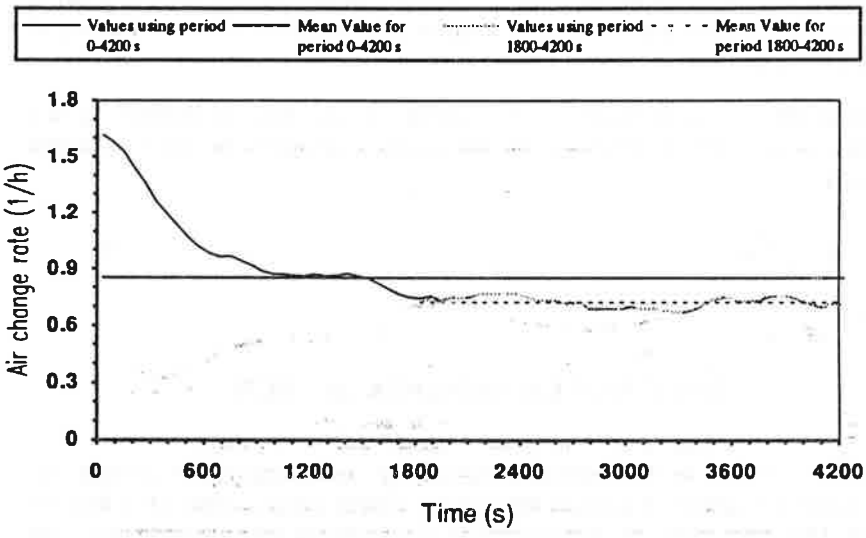


Figure 7 - Computed air change rate for Test A

CPM and SM have been applied to analyze the data acquired during the experiments; the results obtained are given in Table 3 where: the second and the third column refer to the mean value of the results obtained with the SM here proposed (see fig. 7 + 12); the fourth and the fifth column refer to the results obtained with CPM using an analytical direct model and Marquard method to improve convergence; the sixth and the seventh column show the result obtained using the here explained SM with r=z. In Table 3 the symbol "(*)" defines the values obtained using only a sub-set of the measurement period.

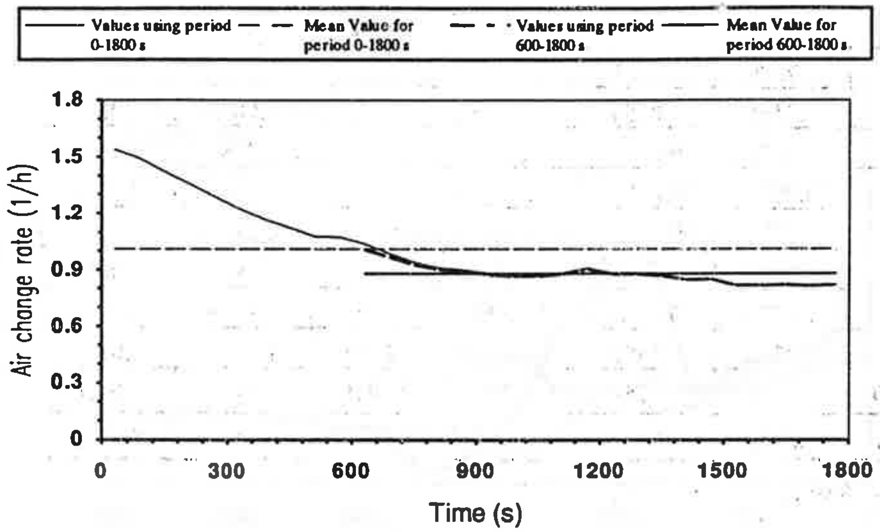


Figure 8 - Computed air change rate for Test B

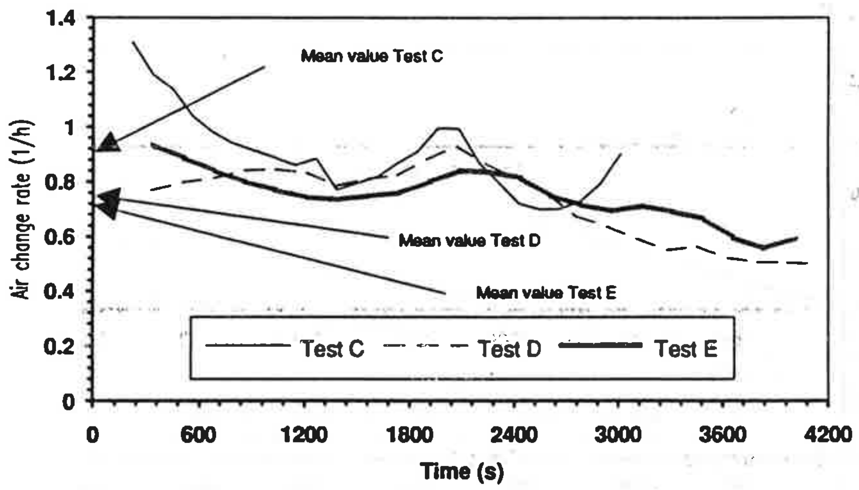


Figure 9 - Computed air change rate for Test C, D and E

For Test A ÷ E, the results of the Table show a good agreement between the mean value of the parameter as a function of time and the value obtained using the constant parameter hypothesis. In the case of Test F and G the system was disturbed during the measurement therefore the difference between the mean value of the parameter as a function of time and the value obtained using the constant parameter hypothesis is grater than in Test A + E.

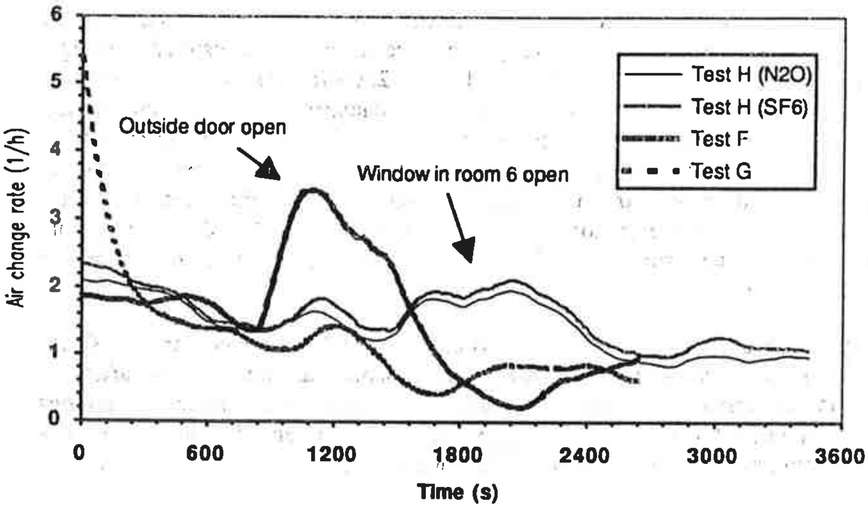


Figure 10 - Computed air change rate for Test F, G and H

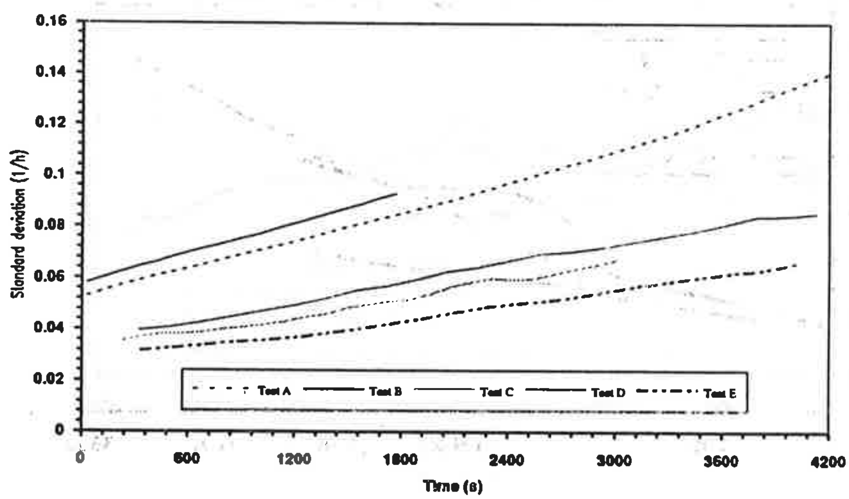


Figure 11 - Standard deviation for computed air change rate for Test A, B, C, D and E

The air change rates functions of time, obtained with the here proposed procedure, for the eight tests are given in figure 7 ÷ 10; the uncertainties defined by (6) are given in figure 11 ÷ 12.

As far as the results obtained for Test A and Test B (see fig. 7) are concerned, it must be emphasized that in both cases the initial values are very high and the behavior is very different from a constant value; it seems to become stable only after the middle of the measurement period. For these two tests, the parameters were also estimated using a shorter period than the measurements period (1800 - 4200 s for Test A and 600 - 1800 s for Test B); in figure 7 it is clear how the mean value changes using these new periods. In order to explain the initial quick variation in the first 600 s, the following hypothesis can be made: a non uniform mixture was obtained when the measurements started, therefore the tracer dilution in the surrounding volume of the sampling area contributes to the lowering of the concentration. Taking the parameter as a function of time into account to analyze these situations allows one to obtain further information on the validity of the experiment.

Similar considerations can be made by analysing the results obtained for Test G for which it should be remembered that the measurements start immediately after the windows and the outside door are closed; moreover, it seems that stationary conditions are never reached for this test during the measurement period and therefore the effects due to the closing of external roller shutter are not clear either.

Figure 10 shows how the results obtained with the hypothesis of parameter changing in time, allows one to recognize that something has happened during the measurement such as a window or a door opening.

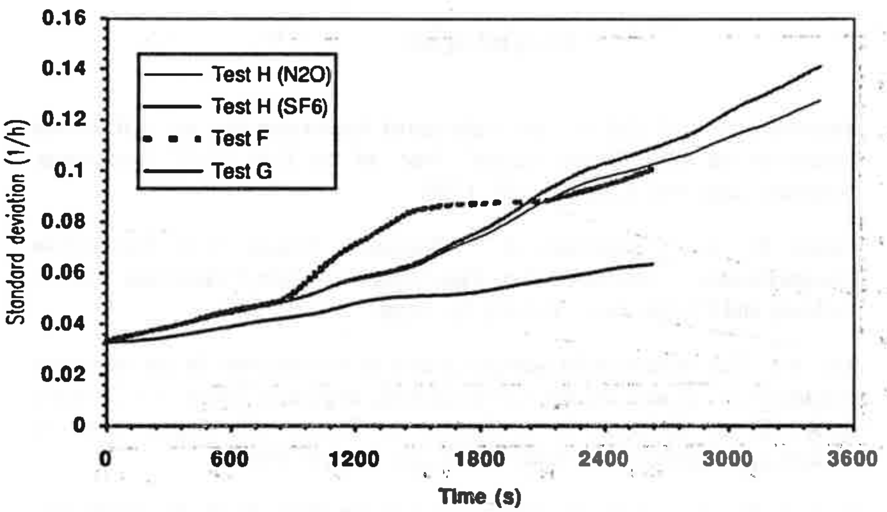


Figure 12 - Standard deviation for computed air change rate for Test F, G and H

CONCLUSION

In this work SM is applied to analyze the data obtained during the measurements in two detached houses; the air flow rate and its standard deviation are carried out as functions of time obtaining useful information on the behaviour of the system during the experiments. The effects of different initial concentrations in rooms when a single zone analysis is performed, as pointed out in Test A and B, are now being investigated by the authors.

Therefore the use of the Inverse Problem Theory together with the hypothesis of parameters changing in time seems a very powerful tool to analyze the data obtained with tracer gas measurements and even if the results here given refer to a single zone case, this approach as explained in [11] can be applied to the multi-zone case and the authors are already working in this field.

ACKNOWLEDGMENTS

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