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An evaluation exercise of a multizone air flow model

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Abstract

In the IEA-ECBCS Annex 23 'Multizone Air Flow Modelling,' a sensitivity analysis procedure, that included both the Monte Carlo and Fractional Factorial analyses, was defined to evaluate COMVEN, a multizone air flow code. This procedure is here applied to evaluate COMVEN, when the simulation of the ventilation of a detached house is performed for the case of ventilation driven mainly by stack effect. The simulated values are compared to the measured values using the uncertainty range for each value; the confidence interval for the simulated values are obtained using the Monte Carlo method while the fractional factorial analysis has been used to identify the relative effects of the input parameters on the output accuracy. It is an interesting case which makes it possible to demonstrate the application of both sensitivity techniques.

Keywords: Building simulation; Experimental comparison; Monte-Carlo method; Factorial design; Sensitivity analysis; Tracer gas measurements

1. Introduction

The use of numerical models to simulate physical phenomena is continuously increasing. These models are usually run on computers using programs with a core numerical model and pre- and post-processors to manipulate the inputs and outputs.

The current problem for the user is therefore not only to perform the simulation but to correctly interpret the results and their accuracy. As many acceptable values can be used as input for the same parameters, the knowledge of the spread of the results, due to different input values, becomes one of the most important topics for the user. Furthermore, the assessment of this spread, that is, the confidence intervals of output data, is required when the comparison between simulated values and measured values is performed for validation purposes.

The sensitivity analysis is used to relate the input variation to the subsequent output variation. This technique consists of performing a set of code runs in order to explore the input data space. The number of runs that must be performed depends on the chosen method and on the kind of information required; this number can be minimised by optimally designing these runs.

In the IEA-ECBCS Annex 23 'Multizone Air Flow Modelling' [6] (see also Refs. [8,9] in the present issue), an extensive work was planned to evaluate COMVEN a multizone air flow code [3] and a sensitivity analysis procedure, including both the Monte Carlo and Fractional Factorial analyses, were defined [4,8,9]; the validation example presented here belongs to this framework.

This article aims to show a detailed example of the application of this sensitivity analysis procedure. This involves describing:

- the chosen input parameters and their uncertainty ranges;
- the strategy used to define the number of runs;
- the analysis of the simulation results and their uncertainties;
- the method used to compare the measured with the simulated values.

Both the Monte Carlo and fractional factorial analyses have been used to investigate the effects of the input variations and obtain information on the role played by the parameters on the model.

A comparison between the measured and simulated values is also presented for a detached laboratory house; the uncertainty of the simulated values has been obtained using the Monte Carlo method.

2. Measurements

All the measurements here illustrated were carried out using the tracer gas decay technique in a detached two

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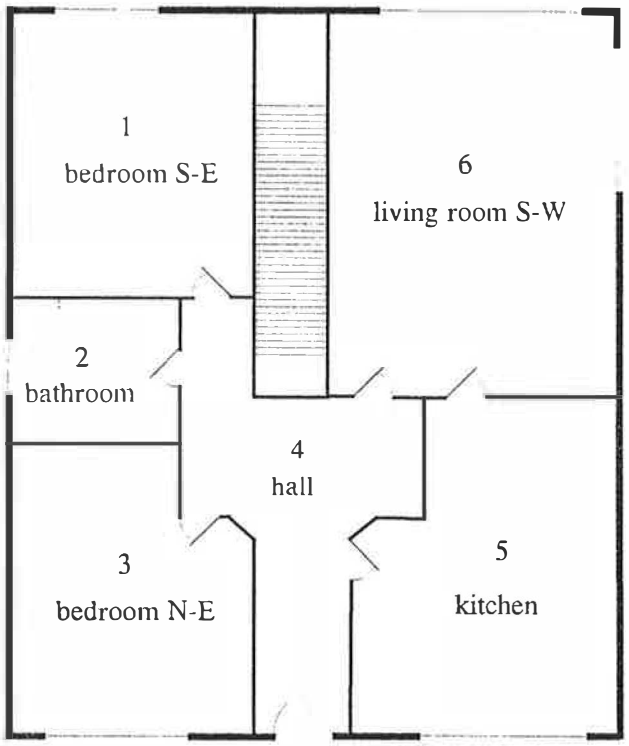

Fig. 1. Plant view of the detached house.

storey laboratory house [1,6] the underground floor hosts the centralised service equipment and the data acquisition and processing system; the ground floor (in which the tests were performed) has a floor area of 114 m^2, and is made up of two bedrooms, a living room, a bathroom and a kitchen. The attic space above the ground floor can be heated, so that the test floor may also reproduce the thermal conditions of an apartment in a multi-storey building. A plan view of the test area is shown in Fig. 1.

The experimental apparatus used for the tracer gas measurements has been developed at the Dipartimento di Energetica of the Politecnico di Torino [2].

The tracer gas measurements, here analysed, have been carried out over two different periods: October 1992 and January 1994. The main characteristics of the measurements are summarised in Table 1.

During the tests in October 1992 (see Table 1) the air change rate in the dwellings with a small gas-fire individual unit for space heating and service hot water production was measured in order to investigate the influence of purpose-provided ventilation openings (sized according to the national UNI-CIG 7129-72 standard) on the air changes and the IAQ. During these tests, the air supply area (ASA) of the purpose-provided opening was set respectively to 0%, 50% and 100%; the chimney cross-section (CCS) was varied from 25% to 100%.

The experimental measurements were carried out with one or two tracer gases (N_2O and or SF_6). When two tracers were used the concentration data was analysed with a two-zone model whereas in the other test (only one tracer gas) a single zone system was studied.

A network that represents the zones and their air flow exchanges must be defined in order to estimate the air flow from the tracer gas data. The networks used for the analysis of the tests and the calculated air flow rate are shown in Figs. 2–4. Here the word *zone* means a part of the space limited by a boundary that is fixed only during the test, whereas *rooms* are always fixed for all the tests, as shown in Fig. 1. Therefore a *zone* may be a room or a set of rooms.

The laboratory house has a meteorological station. The data is continuously monitored and saved in a storage unit (i.e., hard disk or tape device). The following data is

Table 1
Summary of experimental measurements in the Italgas houses

Test code	Date	Zone no.	Tracers	Notes
G3-04	7 Oct 1992	1	SF_6	ASA 100%; CCS 100%
G3-05	7 Oct 1992	1	SF_6	ASA 100%; CCS 50%
G3-06	8 Oct 1992	1	N_2O	ASA 100%; CCS 25%
G3-07	8 Oct 1992	1	N_2O	ASA 50%; CCS 100%
G3-08	8 Oct 1992	1	N_2O	ASA 50%; CCS 50%
G3-09	8 Oct 1992	1	N_2O	ASA 50%; CCS 25%
G3-10	8 Oct 1992	1	N_2O	ASA 0%; CCS 100%
G3-11	8 Oct 1992	1	N_2O	ASA 0%; CCS 50%
G3-12	8 Oct 1992	1	N_2O	ASA 0%; CCS 25%
G4-03	14 Jan 1994	2	N_2O	Only the internal doors of Room 5 are closed
			SF_6	The air samples in Rooms 1, 2, 3, 4 and 6 are mixed before reaching the analyser
				N_2O is injected into Rooms 1, 2, 3, 4 and 6
				SF_6 is only injected into Room 5
G4-04	14 Jan 1994	2	N_2O	Only the internal doors of Room 6 are closed;
			SF_6	The air samples in Rooms 1, 2, 3, 4 and 5 are mixed before reaching the analyser
				N_2O is injected into Rooms 1, 2, 3, 4 and 5
				SF_6 is only injected into Room 6

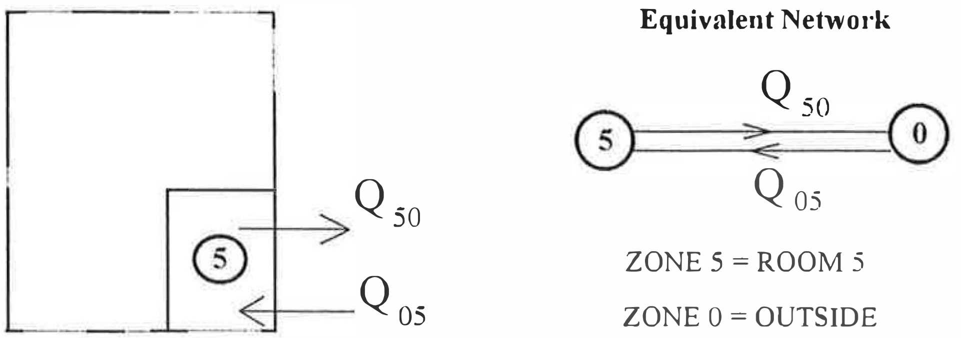

Fig. 2. Experimental network for the single zone tests from G3-04 to G3-12.

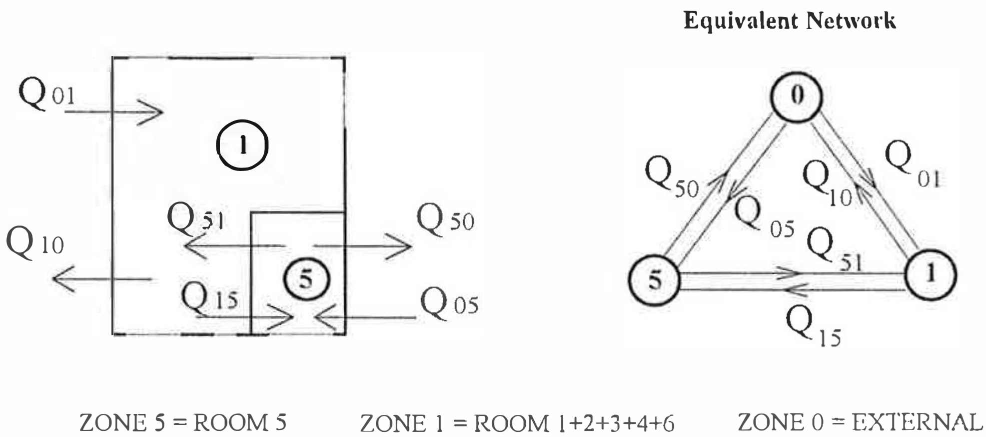

Fig. 3. Experimental network for the two-zone test G4-03.

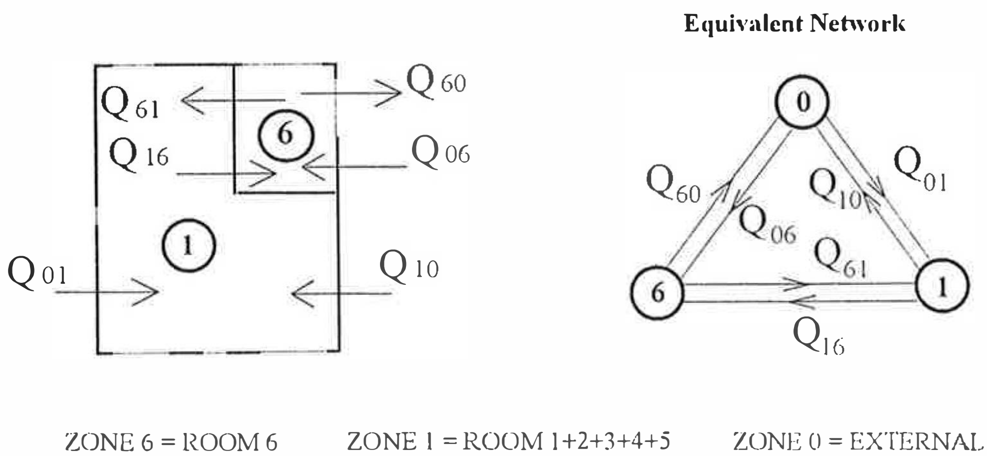

Fig. 4. Experimental network for the two-zone test G4-04.

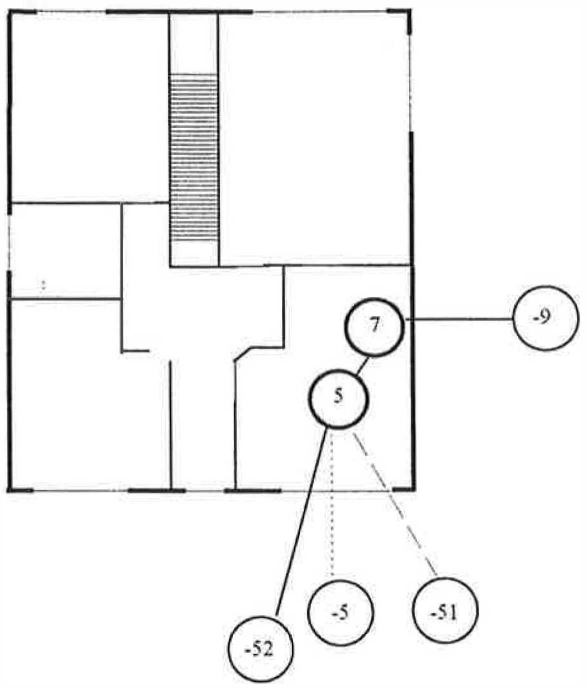

Fig. 5. COMVEN networks for tests from G3-04 to G3-12.

recorded for each time step: external temperature (°C), absolute barometer pressure (hPa), relative humidity (%), solar radiation (W/m^2), wind velocity (m/s), wind direction (degrees), rain (mm), time (s). The meteorological data were available only each 15 min for the measurement of October 1992 while for the last measurements (January 1994) the meteorological data were recorded each minute to improve the COMVEN comparison.

3. COMVEN air flow simulation

A network representing the air flow path must be defined when COMVEN is used to simulate the air flow behaviour inside the house during the measurements; Figs. 5 and 6 illustrate the COMVEN networks for tests G3-4–G3-12 (single zone tests with boiler) and G4-03–G4-04 (two-zone tests), respectively.

As far as tests G3-4–G3-12 are concerned (see Fig. 5), node 7 has been used to represent the gas fire unit (the boiler); it is connected to the external environment (node −9) by a link that corresponds to the chimney. A single resistance value ζ_{BV} [12] is used in this link to represent the butterfly valve position ($\zeta_{BV} = 3.4$ for CCS = 100%, $\zeta_{BV} = 14.4$ for CCS = 50% and $\zeta_{BV} = 100$ for CCS = 25%). The link between node 5 and node 52 represents the purpose provided ventilation opening.

The crack permeability for closed windows and doors are divided into two parts: half on the top and half on the bottom. There are therefore two external nodes for each window and the C_p pressure coefficient values are obtained from the COMIN C_p routine [10]. In Figs. 5 and 6 the dotted lines are the lower links and the dashed lines are the upper links.

The internal absolute humidity and the temperature in each room have been measured during the tests. The time variation of the internal temperature was described using the COMVEN temperature schedule option.

A series of pressurisation tests have been carried out in the Italgas house over the last few years [11]. The guarded zone method was used with two blower doors (the device consists of a variable speed fan and a means of sealing the

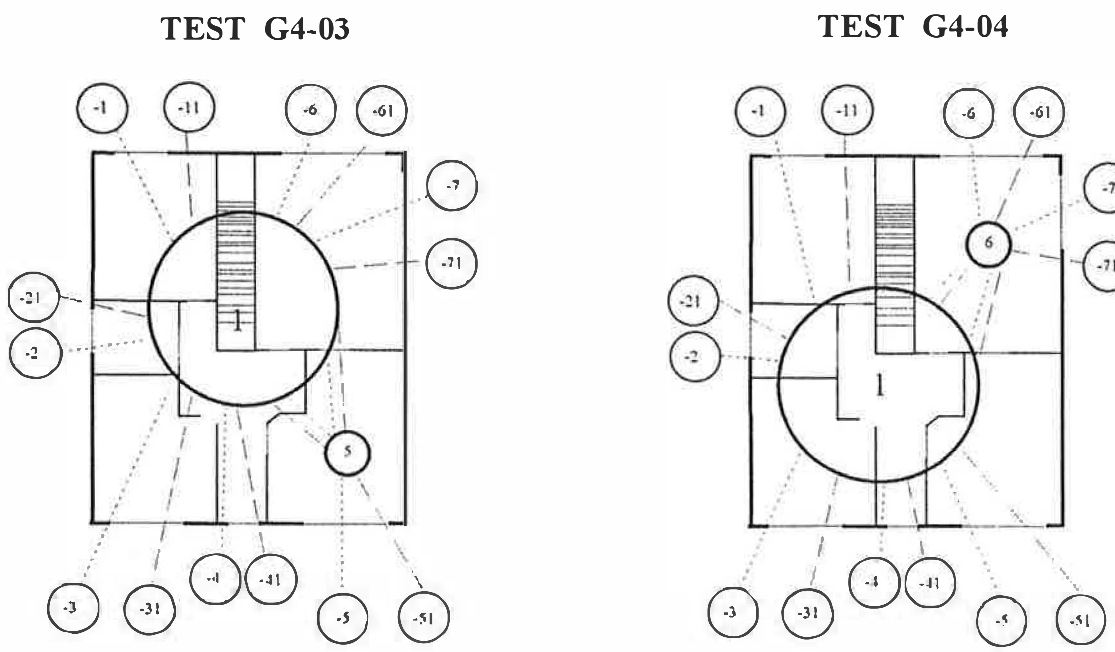

Fig. 6. COMVEN networks for tests G4-03 and G4-04.

fan into the doorway). These tests were performed mainly to define the wall permeability, that is, the characteristic of the cracks between the inside and outside. The values of the AIVC data base have been used for the crack coefficients of the internal doors [15].

4. Monte Carlo and fractional factorial analysis

4.1. Monte Carlo Analysis

A complete sensitivity analysis of the COMVEN results of each test has been performed using the Monte-Carlo method with the help of MISA (Multirun Interface for Sensitivity Analysis) [4,7].

The range used for the Monte-Carlo analysis is given in Table 2 for each class of parameters. This range, for the measured parameters, has been established on the basis of the measurement error, while for the parameters obtained from the literature (i.e., pressure coefficient) it has been defined in order to represent the variation that exists in bibliographic data.

As the parameter set must be defined for each test starting from the classes defined in Table 2, it is impossible to provide here a detailed description of all the parameters adopted for the eleven tests. Therefore only the number of parameters and the number of simulations used for each test is given in Table 3. Three hundred simulations for each analysis were considered to be sufficient to obtain accurate mean and standard deviation values, even though fewer values are usually considered [4], Fig. 7 shows the trend of the mean value and of the standard deviation during 1000 simulations performed for the G3-04 test (single zone test, ASA 100%, CCS 100%).

The parameter set illustrated in Table 2 can be split into three subsets:

1. parameters that refer to the building structure (e.g., cracks, room volume, etc.);
2. parameters that refer to the indoor and outdoor environment (temperature, humidity, etc.);
3. parameters used in boiler simulation for single zone tests G3-04–G3-12 (e.g., single resistance value of the butterfly valve, etc.).

The first subset is characterised by parameters which are not time dependent (ageing problems are not taken into account) while in the second subset the parameters change continuously according to the environmental conditions. The third subset contains the parameters used to define a component that is not included in COMVEN.

In the last subset a major role is played by the single resistance value (ζ_{BV}) of the butterfly valve installed in the chimney as it strongly influences the flow in the chimney. The variation of the mean value of flow Q_{05} (that corresponds to the air change rate in Room 5) and the variation of the standard deviation have been analysed using the Monte Carlo method when ζ_{BV} goes from 0 to 1000. The temperature of Room 5 and of the combustion gases are set respectively to 24°C and to 91°C and the outdoor temperature is set to 18°C (these are the mean values during the tracer gas measurements).

The results of this analysis are shown in Fig. 8. The flow is affected by the single resistance value mainly when ζ_{BV} is in the range [1–100], in which the values used to simulate the three different butterfly valve positions are located. The greatest slope is between $\zeta_{BV} = 1$ and $\zeta_{BV} = 10$. Further investigations are shown in the fractional factorial analysis paragraph to explain this fact. For $\zeta_{BV} > 1$ the ratio between the standard deviation and the mean value is proportional to the logarithmic value of ζ_{BV}. The uncertainty range is therefore quite constant.

The influence of the magnitude of the uncertainty in the input value (input range) of ζ_{BV} on the mean value of the flow Q_{05} has also been investigated by means of the

Table 3
Number of parameters and simulation used for the Monte-Carlo analysis

Test	Parameters	Simulation
G3-04–G3-12	32	300
G4-03 and G4-04	40	300

Table 2
Parameter range for the Monte-Carlo analysis

Parameter	Range	Parameter	Range
Crack permeability (C_s) [kg/s @ 1 Pa]	±25%	Indoor humidity [g/kg]	±10%
Crack exponent (C_{exp}) [–]	±10%	Pressure coefficient (C_p) [–]	±50%
Duct diameter [m]	±0.50%	Altitude meteo station [m]	±1%
Duct roughness [mm]	±50%	Wind exponent [–]	±10%
Duct length [m]	±0.50%	Surrounding building height [m]	±10%
Single resistance [–]	±5%	Outside temperature [°C]	±1 [°C]
Single resistance butterfly valve [–]	±25%	Outdoor humidity [g/kg]	±10%
Zone temperature [°C]	±1 [°C]	Atmospheric pressure [kPa]	±0.50%
Zone volume [m^3]	±5%	Wind speed [m/s]	±0.3 [m/s][a]

[a]As the wind speed is very close to zero (often the wind speed is zero), this error range has been used in the tests here analysed to take the possibility of wind speed fluctuation into account.

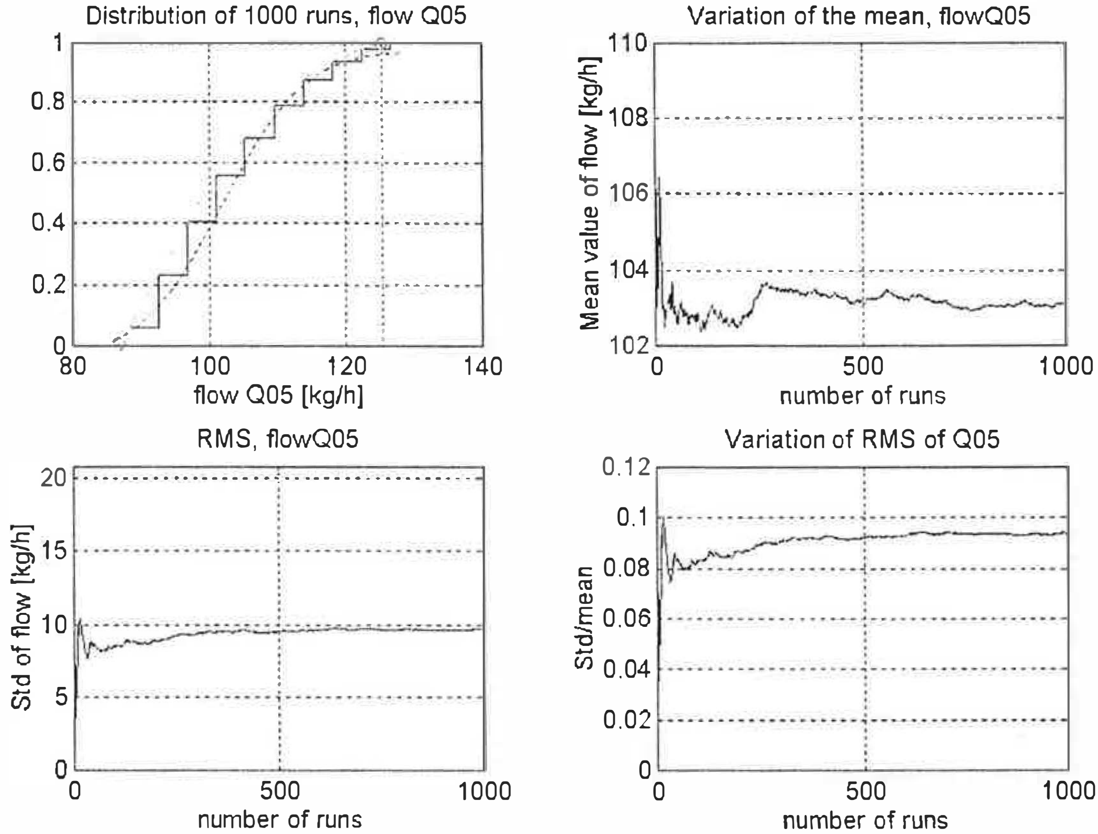

Fig. 7. Relation between the number of runs and the mean value and standard deviation. The first graph presents the cumulative probability distribution of the Q_{05} flow. The second graph is the evolution of the mean of Q_{05} when the number of simulations is increased. In this case the stabilisation of the mean requires many more runs than that which is given in literature on the Monte Carlo design. The two last graphs show the evolutions of the absolute and the relative value of RMS, respectively. In this case, the RMS stabilizes itself after 500 runs at around 9%.

Monte Carlo method; the results (see Fig. 9) show that the mean value is only slightly affected by the ζ_{BV} input range while the ratio between the standard deviation and the mean value of the flow is strictly related to the ζ_{BV} input range, especially for the $\zeta_{BV} = 3.4$ case. This behaviour can easily be explained by taking the previous shown variation (Fig. 8) of Q_{05} for ζ_{BV} values in the range [1–10] into account.

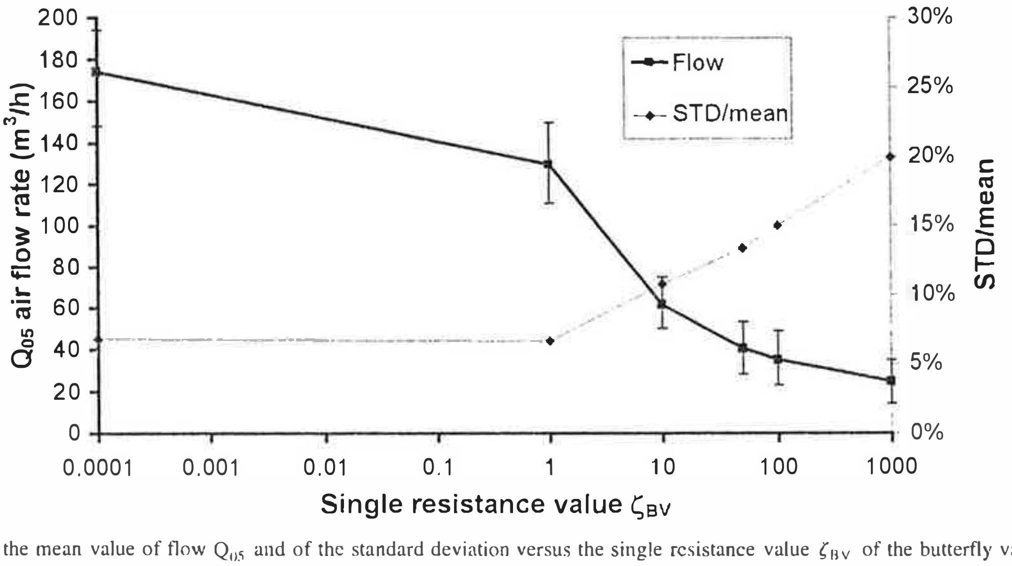

Fig. 8. Variation of the mean value of flow Q_{05} and of the standard deviation versus the single resistance value ζ_{BV} of the butterfly valve. The standard deviation is obtained after 300 Monte Carlo simulations taking into account the uncertainty of 32 parameters. The intervals around the mean correspond to the confidence interval of 99% probability.

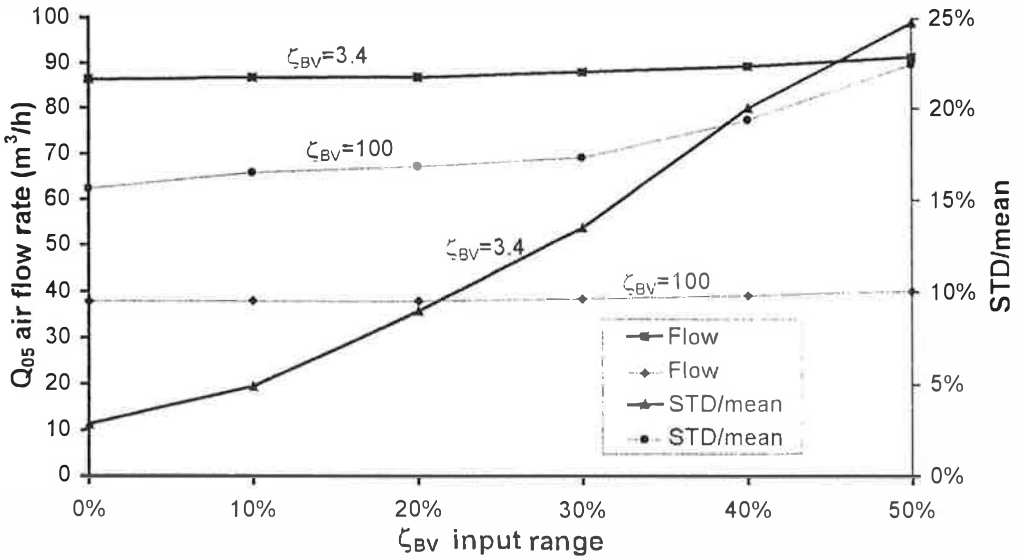

Fig. 9. Variation of the mean value of flow Q_{05} with an increase of the input variation amplitude.

Different behaviour of the building ventilation may be induced mainly by changes in the values of the parameters of the second subset. The Monte Carlo method has therefore been applied to investigate the following.

– The variation of the mean value of the Q_{05} flow and its standard deviation when the temperature differences between the room and the combustion gases leaving the boiler varies (see Fig. 10). This temperature difference is obtained by varying the temperature of the combustion gases while the temperature of Room 5 is set at 24°C and the outside temperature is set at 18°C (these are the mean values during the tracer gas measurements). The influence of this temperature difference on the Q_{05} flow does not seem to be significant.

– The variation of the mean value of the Q_{05} flow and the standard deviation when the temperature differences between the room and outside varies (see Fig. 11). This temperature difference is obtained by varying the outside temperature while the temperature of Room 5 is set at 24°C and the temperature of combustion gases is set to 91°C (these are the mean values during the tracer gas measurements). The results show the influence of this temperature difference on the Q_{05} flow.

4.2. *Fractional factorial analysis*

The first fractional factorial analyses of the COMVEN results for the detached house examined here are illustrated

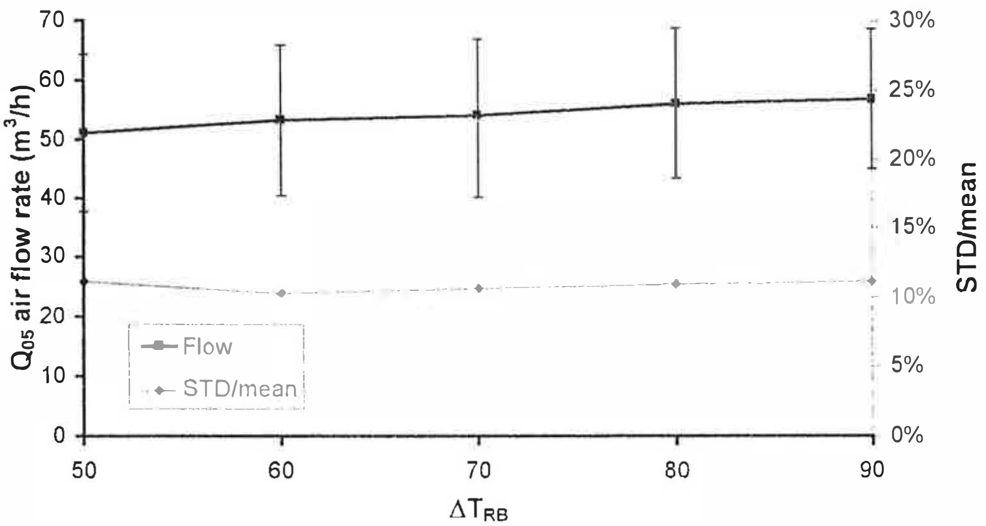

Fig. 10. Mean value of flow Q_{05} versus the temperature difference between the room and the combustion gases exiting from the boiler. The standard deviation is obtained after 300 Monte Carlo simulations taking into account the uncertainty of 32 parameters. The intervals around the mean correspond to the confidence interval of 99% probability.

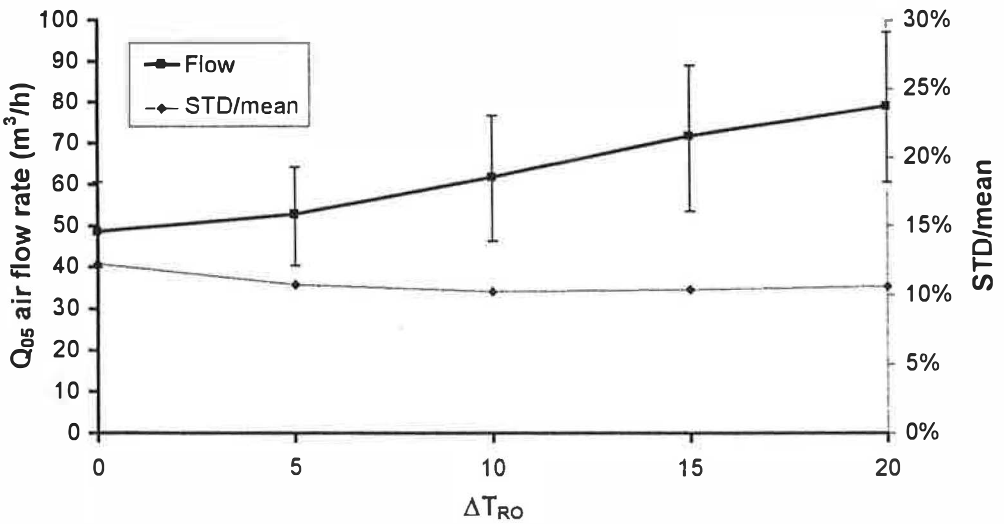

Fig. 11. Mean value of flow Q_{05} versus the temperature difference between the room and the outside. The standard deviation is obtained after 300 Monte Carlo simulations taking into account the uncertainty of 32 parameters The intervals around the mean correspond to the confidence interval of 99% probability.

in Ref. [5]. This kind of analysis is used to improve the understanding of the COMVEN simulation for all the measurement tests performed because it provides a feed back on the input.

Performing a fractional factorial design allows one to fit the results to a linear empirical model which corresponds to a Taylor development of the model (Eq. (1)) [6].

$$\begin{aligned} Y(\vec{x}) &= Y(x_0) + \sum_i \frac{\partial Y}{\partial x_i}\Delta x_i + \sum_i \frac{\partial Y}{\partial x_j}\frac{\partial Y}{\partial x_j}\Delta x_i \Delta x_j \\ &+ \cdots \\ &= \alpha_0 + \sum_i \alpha_i \Delta x_i + \sum_i \alpha_{ij}\Delta x_i \Delta x_j + \cdots \end{aligned} \tag{1}$$

The main effects α_i that correspond to the partial derivatives, indicates the sensitivity of the model to the parameter x_i. The relative effect α_i/α_0 allows one to break away from the units and a make comparison between the parameters.

For the case presented here, a $2^{(32-26)}$ fractional factorial design has been used as the influence of 32 parameters has to be investigated and the expected interactions do not pass 2 by first order interactions. A 48-run Placket and Burman (Hadamard) design has also been used to evaluate the main effects of 40 parameters. The change of these influences (evolution of the sensitivity) is shown in graphs that give the results of the sensitivity analysis with the fractional factorial design.

For tests G3-04–G3-12 (single zone tests with boiler), the fractional factorial analysis was performed to investigate the variation of the relative effects due to ζ_{BV} changes. The results are illustrated in Fig. 12 only for the air flow rates from Zone 5 to the outside (Q_{50}) and for the air flow rates from the outside to Zone 5 (Q_{05}). The remaining flow, that is, the flow through the chimney, is the difference between these previous two.

For flow Q_{05} only the relative effects greater than at least 4% at one point, are shown in Fig. 12. In the same figure and for the same parameters, the relative effects for flow Q_{50} are also shown. In this case the relative effects of the window crack, ζ_{BV}, temperature of zone 5, and outdoor temperature are the greatest effects for flow Q_{50}, while the relative effect of the exponent is of the same magnitude as others that have not been plotted here (i.e., surrounding building height). The effect of the temperature of the combustion gases that leave the boiler is not included in the most important effects, this being in agreement with the results shown in Fig. 10.

There are no important effects for Q_{50} when ζ_{BV} is less than 1, while for Q_{05} and ζ_{BV} less than 1, the effects of the window crack and of ζ_{BV} are significant and the effects of the exponent and of the outdoor temperature are not zero. Furthermore, one can notice that the $\zeta_{BV} = 10$ value is very important for the effect trends; in fact for this value of ζ_{BV} all the effects for Q_{50} have a maximum in the absolute value. For Q_{05} a maximum and a minimum of the absolute value are observed respectively for the ζ_{BV} and the window crack effects while for the other effects the value $\zeta_{BV} = 10$ corresponds to a noticeable change in the slope.

The physical reason for this complicated behaviour can be found if one observes the variation of the mean value of Q_{50} versus ζ_{BV} shown in Fig. 13. One can notice the following.

– For $\zeta_{BV} \leq 1$, the mean value of Q_{50} is always zero, i.e., the driven force is the chimney stack effect and all the

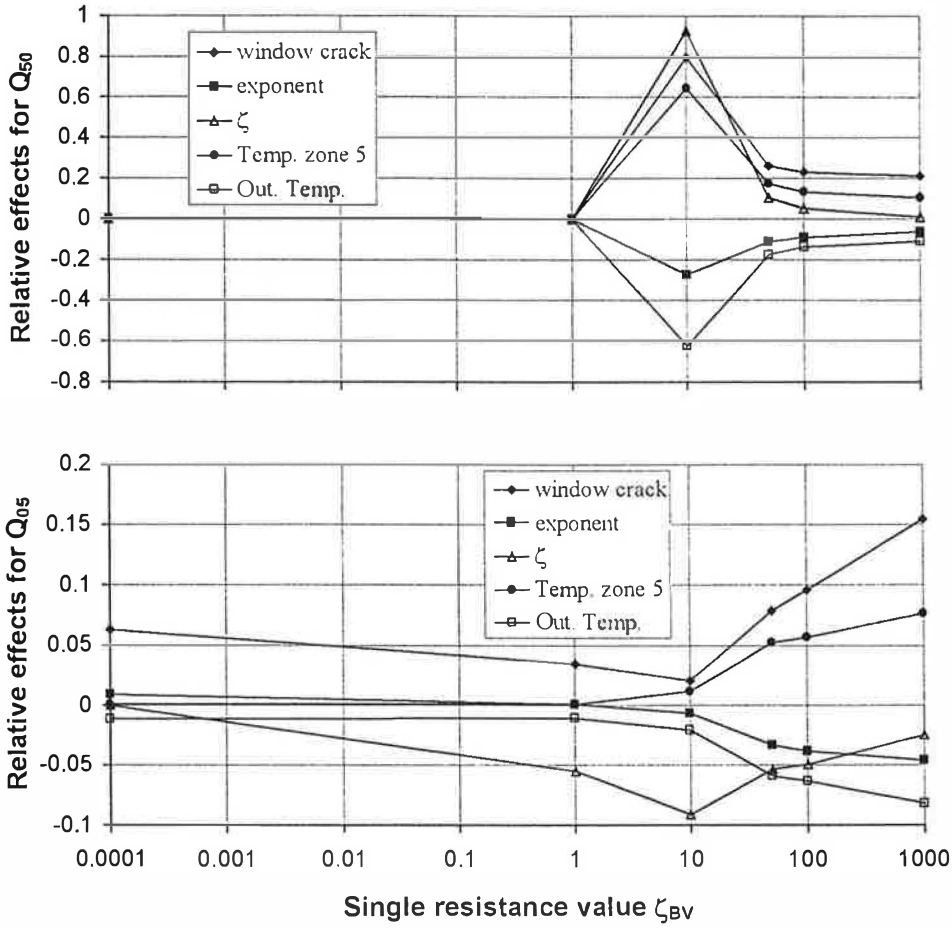

Fig. 12. Main relative effects for air flow rates Q_{50} and Q_{05}.

flows from the outside into Zone 5 exit through the boiler chimney. The main parameters, in this situation, are the window crack and the single resistance value ζ_{BV} in the chimney.

– For $1 \leq \zeta_{BV} \leq 10$, a flow Q_{50} may exist however its value is very low, that is, in this range of ζ_{BV} the chimney stack effects is not always the only driven force and the stack effects in Zone 5 can cause a flow from Zone 5 to the outside. For any change in the parameter values it is therefore possible to switch from the situation in which the chimney stack effect is the only driven force to the other situation. This explains the increasing value of the relative effects for Q_{50} shown in Fig. 12.

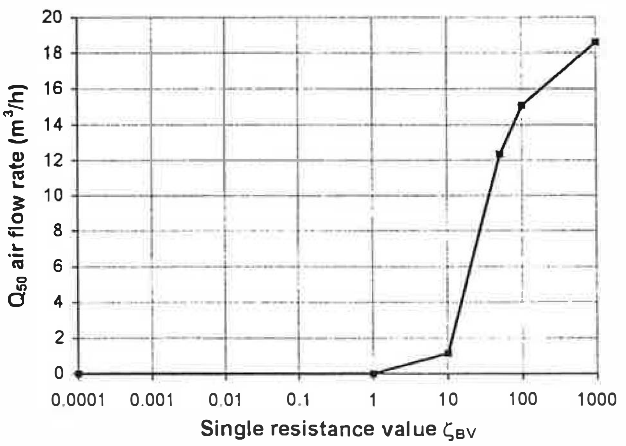

Fig. 13. Influence of the single resistance ζ_{BV} variation on the simulated air flow rate from Zone 5 to the outside.

– For $\zeta_{BV} \geq 10$, flow Q_{50} increases, that is, the existence of this flow cannot be disputed by changes in the parameter values and the relative effects for Q_{50} therefore decrease while for Q_{05} the effects of the zone temperature, the outside temperature and the window crack become important.

The sensitivity analysis has also been performed for the two-zone tests G4-03 and G4-04. The relative effects for all the flows are shown in Figs. 14 and 15 where only the relative effects that are greater than 15%, for at least one flow, are taken into account.

For test G4-03 (two-zone test: kitchen and the remaining rooms) five main parameters are identified: three crack characteristics and the temperatures of the two zones. The air exchange between Zone 5 and the outside is mainly influenced by the crack permeability of the window while the air exchange between the two zones is influenced by all the five parameters. Small effects are found for the total

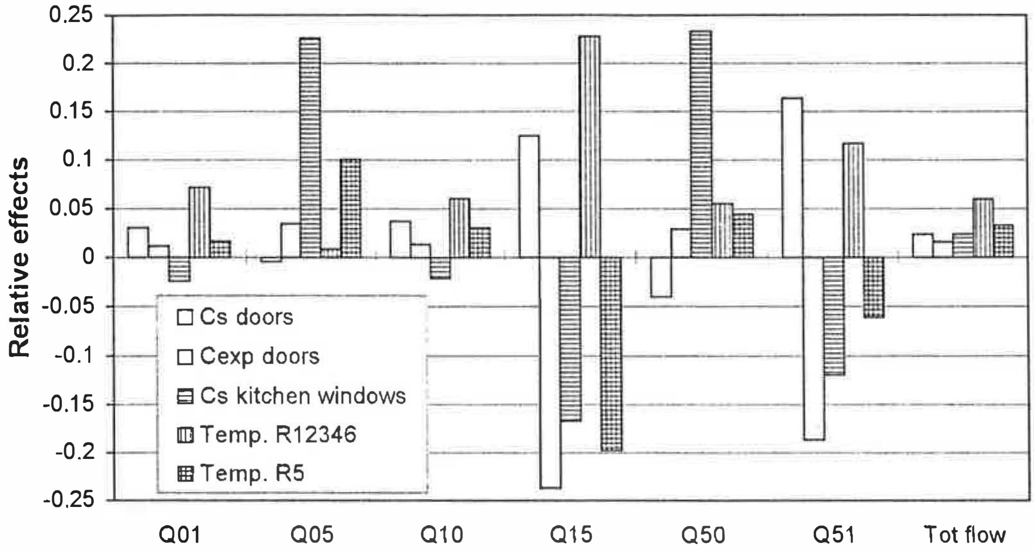

Fig. 14. Relative effects for test G4-03.

flow that corresponds to the global air change and for the air exchange between Zone 1 and the outside. This fact means that the effects are distributed quite uniformly among all the parameters and therefore not only these previously mentioned five parameters affect these flows.

For test G4-04 (two-zone test: living-room and the remaining rooms) eight main parameters have been identified and these all refer to crack characteristics, that is, to the building structure description. As for tests G4-03, the air exchange between the two zones is influenced by all the parameters here taken into account and the main effects are related to the exponent of the doors. No important effect can be recognised for the other flows as the effects are very low and well distributed.

When, in Section 4.3, the measured and the simulated values are compared, the comments on the results of the sensitivity analysis of these two-zone tests have to be considered in order to clearly understand the comparison.

4.3. Monte Carlo analysis versus fractional factorial analysis

In the previous paragraphs the results obtained from the Monte Carlo and the fractional factorial analyses have been shown and some considerations on the features of these two methods for performing the sensitivity analysis of a computer model can now be outlined.

The Monte Carlo method allows an easy identification of the uncertainty of the results due to the input variation

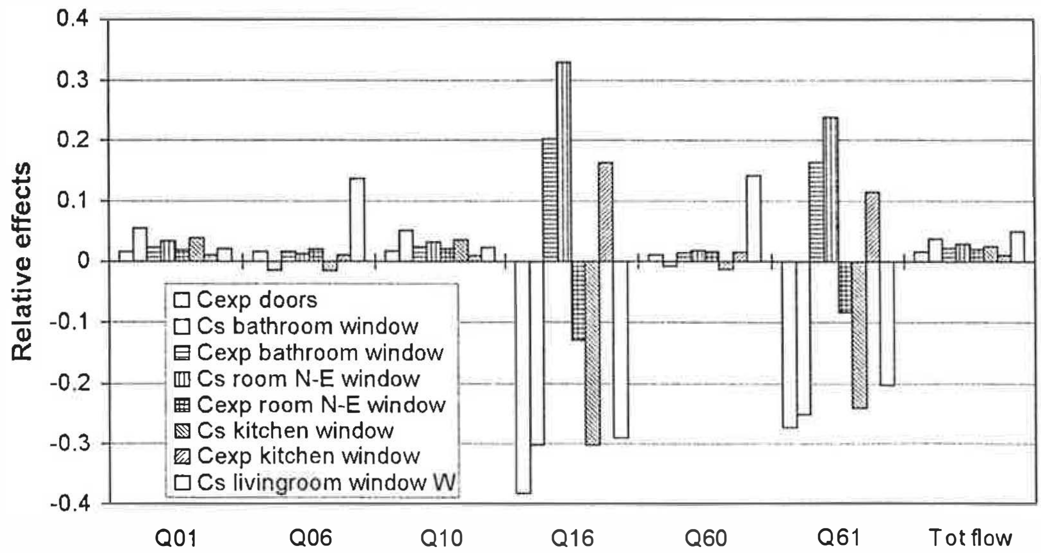

Fig. 15. Relative effects for test G4-04.

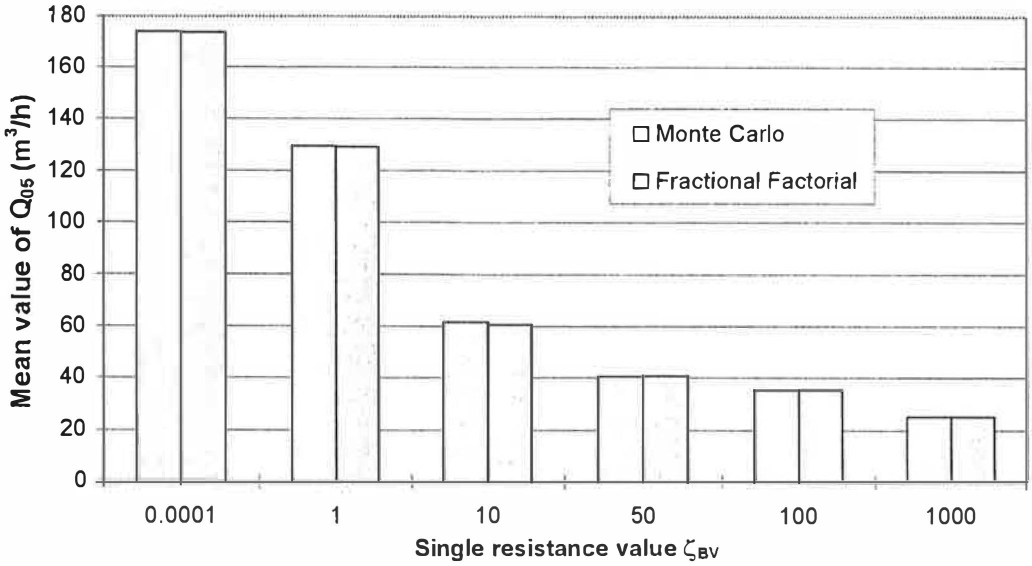

Fig. 16. Comparison of the mean values obtained from the Monte Carlo and fractional factorial analysis.

even though it requires more runs of the computer model than the fractional factorial analysis for the presented cases. It is possible to perform an investigation of the influence of the variation of the parameters on the results (see Figs. 8–11) but it requires a great deal of effort and computer time. Moreover, only the effects of the variation of a single parameter or the mixed effect of one group of parameters can be estimated.

Fractional factorial analysis requires a more accurate preparation phase for the definition of the plan of the experiments and does not allow a straightforward identification of the uncertainty range of the results due to the input variation but it is very effective in allowing a detailed analysis of the effects of the input parameter on the output (see Figs. 12, 14 and 15). When using this kind of analysis it is therefore possible to clearly investigate the model behaviour and its relation to the physical phenomena.

Finally, the comparison between the mean value of the Q_{05} flow obtained with the Monte Carlo and the fractional factorial analyses is shown versus the ζ_{BV} value in Fig. 16. In this case the mean values of Q_{05} found using the two methods are very close; this means that the same results are obtained for the physical phenomena and for the model here studied by exploring the input data space with a good random sampling or with a sampling in the corner of the input domain. A more detailed discussion on both technique features can be found in Ref. [7].

5. Measured versus simulated values (comparison)

In this section, a comparison between the measured and simulated air flows is illustrated by means of diagrams in which the confidence interval of 99% probability is represented for each value.

The measured flows are estimated from the time histories of the tracer concentrations, by solving an inverse problem [13,14]. In the approach here used the air flows are considered to be functions of time. That is, for each instant at which the concentrations are measured, a value of the air flow rates is estimated and a standard deviation is associated to this value [1]. The value of standard deviation is related to the experimental uncertainties, to the correlation existing among the estimated flows and to the derivative of the concentration with respect to the air flows [16]. Therefore, the standard deviation may be different for different times of the same air flow function and may also change from one parameter to another in the same parameter set, estimated from the same concentration data.

The simulated flows are the COMVEN flows. For the two-zone tests G4-03 and G4-04, the air flows have been calculated many times, while the confidence interval has been calculated once for each test and then used for the remaining times.

Fig. 17 refers to the single zone tests with a boiler (G3-04–G3-12). The simulated net flow of Zone 5 and the measured value are compared in this figure. This flow corresponds to the air flow from the outside to Zone 5 (Q_{05}) for these tests. The Air Supply Opening (ASO) and the Chimney Cross-Section (CCS) are specified in each test in order to simplify the understanding of the influence of the purpose-provided ventilation opening and of the butterfly valve position on the room ventilation.

When the CCS is 50%, one can notice a better agreement between the measured and simulated values (differences between 5% and 7%) than those obtained for a CCS of 25% and 100%. The simulated air flows are

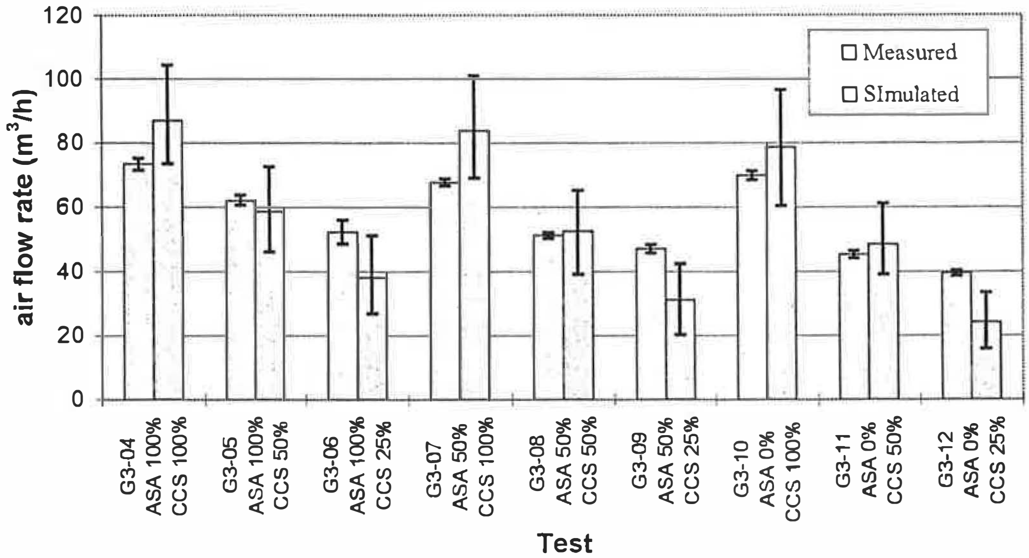

Fig. 17. Simulated and measured air flow rates for tests G3-04–G3-12; ASO = Air Supply Opening and CCS = Chimney Cross-Section. The uncertainty intervals around measured and simulated values correspond to the confidence interval of 99% probability.

underestimated by 27% to 39% for a CCS of 25%. Instead, for a CCS of 100%, the simulated air flows are overestimated by 12% to 24%.

The analysis of these results shows the strong influence of the chimney stack effect on the room ventilation and therefore special attention should be given to the choice of the single loss coefficient that represents the butterfly valve as many different values can be found in the literature. An agreement close to that found when the CCS is 50% could, in fact, be reached for the simulation results of the remaining tests by only changing the values of the single loss coefficient of the butterfly valve. For these reasons a wide error range (25%) for this parameter was used in the Monte-Carlo analysis (see Table 2).

There are only two tests in which the error range of the simulated value and the error range of the measured value do not overlap: G3-09 (ASA 50%, CCS 25%) and G3-12 (ASA 0%, CCS 25%). In both tests the CCS is 25%. This corresponds to the maximum value of the single loss coefficient that represents the butterfly valve. A greater error range than 25% should probably be used for such high values of the single loss coefficient since a high variation of the single loss coefficient is associated to a small error according to the knowledge of the valve position when a valve is almost closed (see Fig. 18). From the results given in Fig. 12, one can observe that even the effects of the window (crack permeability and exponent) become significant for $\zeta_{BV} = 100$ and therefore this discrepancy could be due to a wrong estimation of these input parameters.

The tests of January '94 were performed without the gas fire unit and the purpose-provided opening. As for the measurements of October '92, the wind velocity was very low or even zero. These tests refer to a system in which the air flows are mainly driven by thermal buoyancy due to a temperature difference between the inside and the outside. For this reason the temperature difference is plotted together with the measured and simulated total flow rate for the two-zone tests G4-03 (two-zone test: kitchen and the remaining rooms) and G4-04 (two-zone test: living-room and the remaining rooms) in Fig. 19.

In both these tests the error ranges of the air flow rate do overlap and a correlation does exist between the experimental air flow trend and the temperature difference trend. Furthermore, for test G4-04 the mean value of the simulated and the experimental flows are very closed.

For test G4-03 the differences between simulated and calculated values are very small (see Fig. 20), the greatest error is in flow Q_{01} (from −10% to +20%) while in the other flows (Q_{05}, Q_{51} and Q_{15}) the error is smaller. The

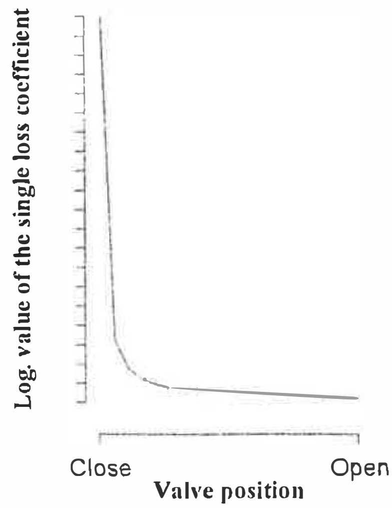

Fig. 18. Single loss coefficient of a valve.

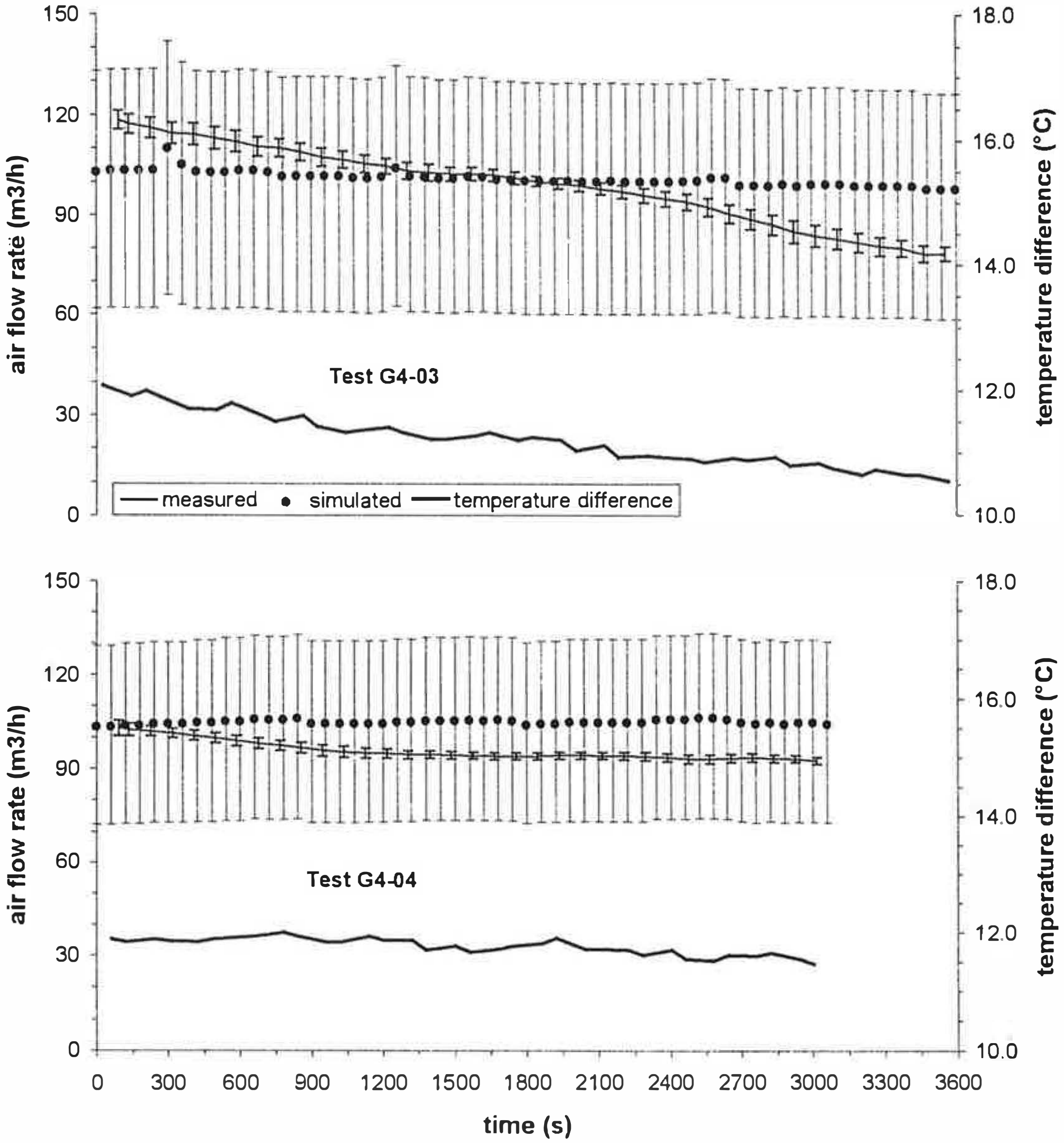

Fig. 19. Total flow rate for tests G4-03 and G4-04. The uncertainty intervals around measured and simulated values correspond to the confidence interval of 99% probability.

error range of the simulated flows and of the measured flows always overlap in this test.

For test G4-04 (see Fig. 21) the simulated flow Q_{16} is about 70% less than the measured value and the error ranges in this case never overlap. There is no obvious reason for this discrepancy. Fig. 15 shows that the most important parameter for this flow is the crack exponent of the doors, therefore it is only possible to assume that the literature value used to describe the internal door cracks, was in this case, not close to the actual value. The same crack exponent of the doors was used for the simulation as in the previous G4-03 test but in this previous case, Fig. 14 shows that the relative effect of these parameters is less than that found for test G4-04.

The simulated Q_{61} and Q_{01} flows are very close to the measured flows and the error ranges overlap. Q_{06} is over-estimated by more than 100% but the error range of the simulated values includes the measured value for about half of the measurement period. The mean measured value of the measurement period is within the error range of the mean simulated value. The time behaviour of flow Q_{06} can be explained by observing (see Fig. 22) that the temperature difference between Zone 6 and the outside (ΔT_{6-0}) decreases during the measurement period and is greater than the temperature difference between Zone 1 and the outside (ΔT_{1-0}). Furthermore, the ΔT_{6-0} value approaches the ΔT_{1-0} value and therefore the changes in the ΔT_{6-0} are more significant for the air flow behaviour than the changes in ΔT_{1-0}. Once again the results of the sensitivity analysis are useful to understand this disagreement between the measured and simulated values. As Fig. 15 shows, the temperature effect is not one of the main

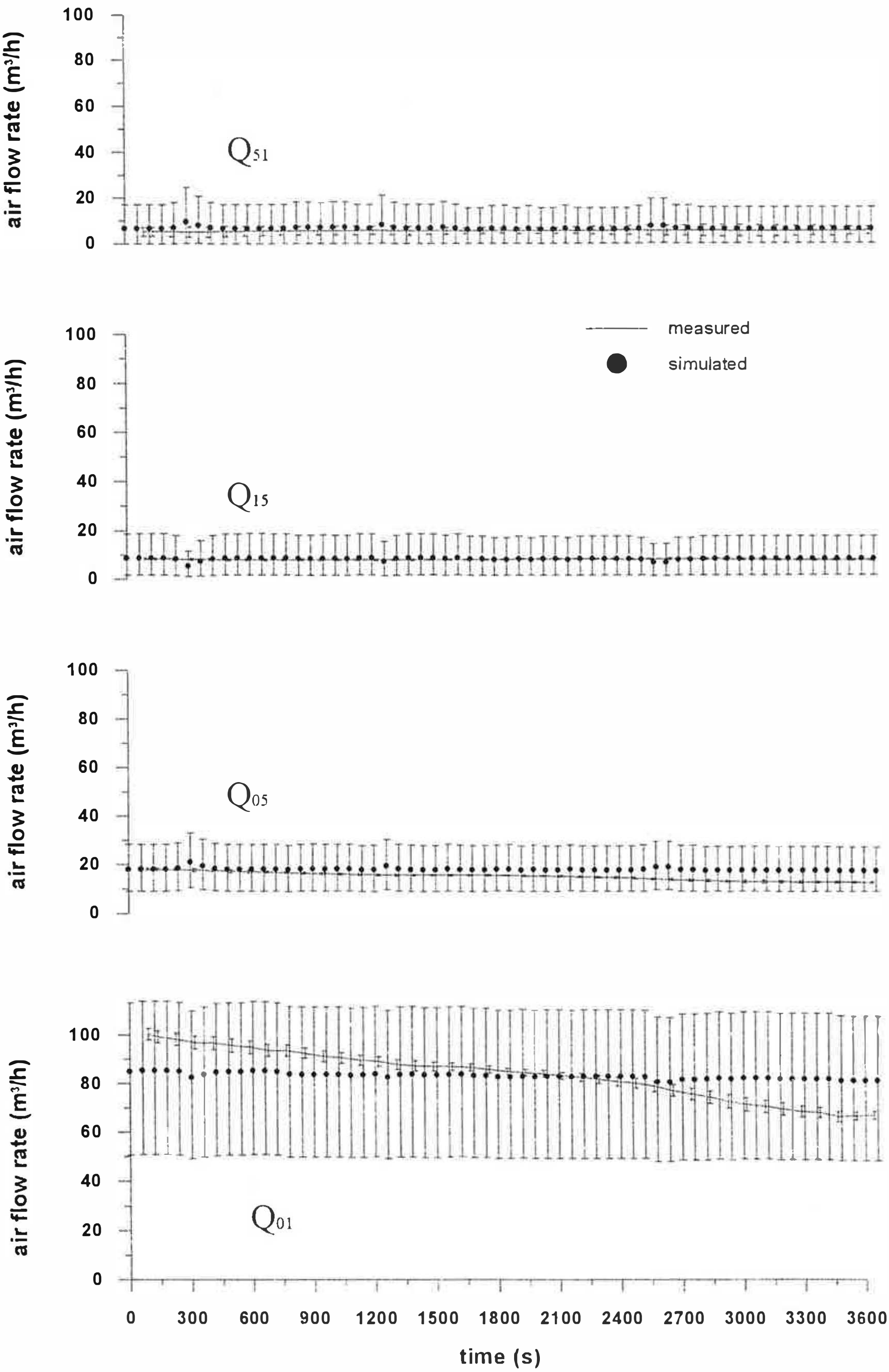

Fig. 20. Simulated and measured air flow rates Q_{51}, Q_{15}, Q_{05} and Q_{01} for test G4-03. The uncertainty intervals around measured and simulated values correspond to the confidence interval of 99% probability.

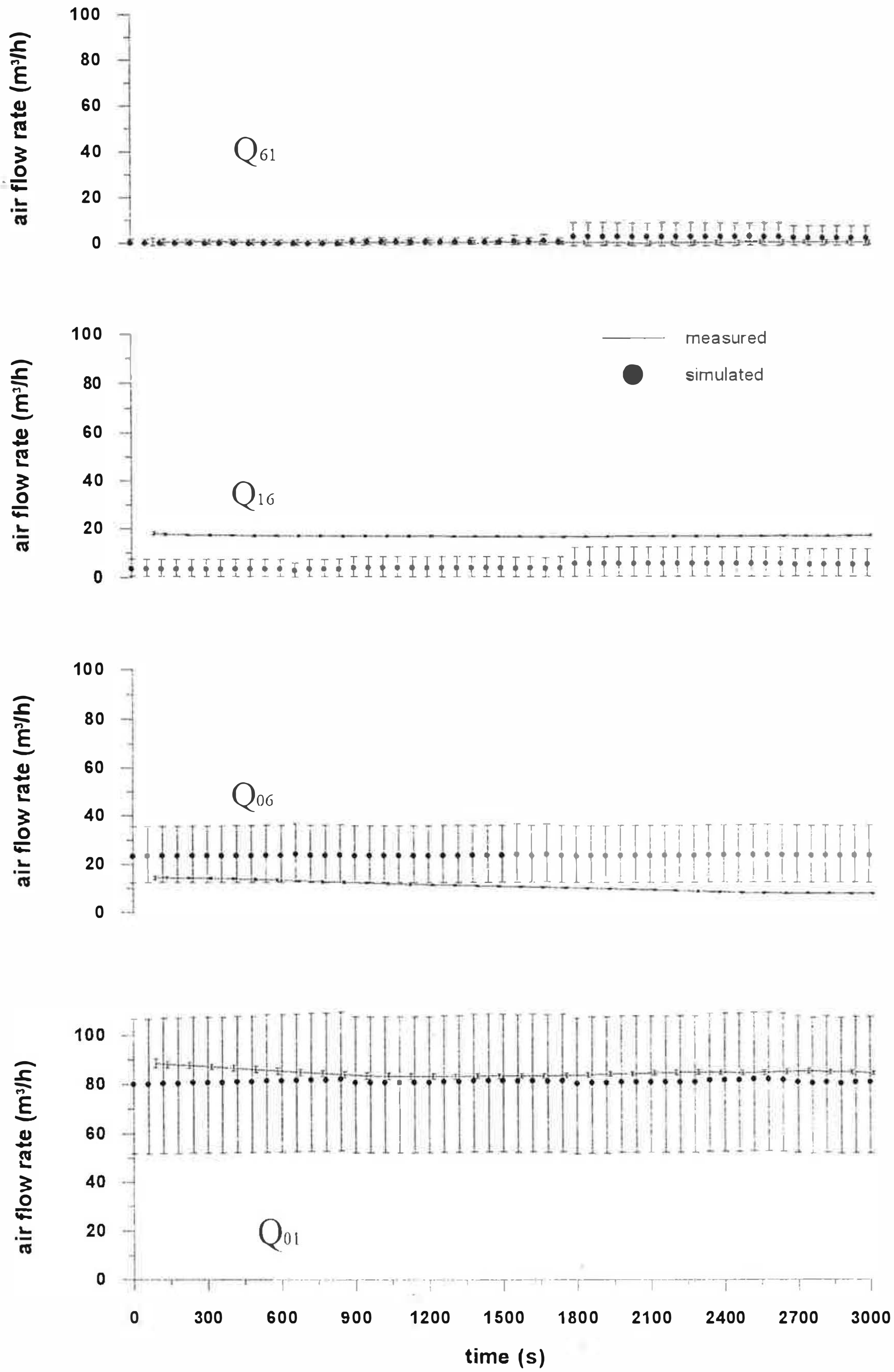

Fig. 21. Simulated and measured air flow rates Q_{61}, Q_{16}, Q_{06} and Q_{01} for test G4-04. The uncertainty intervals around measured and simulated values correspond to the confidence interval of 99% probability.

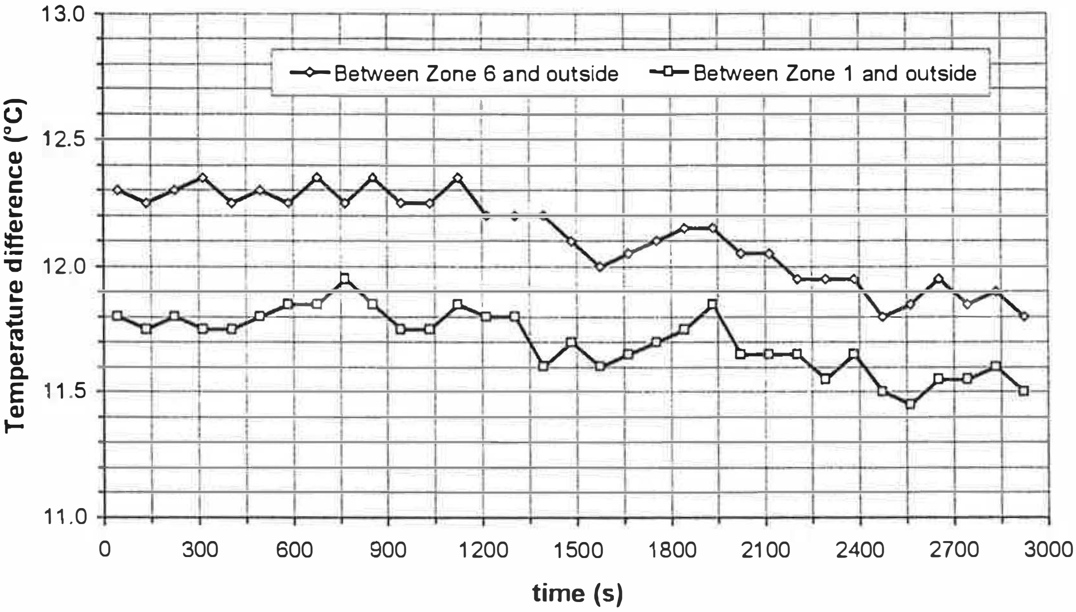

Fig. 22. Time behaviour of the temperature difference between Zone 6 and the outside and between Zone 1 (rooms 1, 2, 3, 4 and 5) and the outside during test G4-04. The temperature used for Zone 1 is the mean temperature of rooms 1, 2, 3, 4 and 5.

important effects and the COMIS results therefore are not able to follow the evolution of the system for this simulation.

6. Conclusion

The validation procedure defined and developed in the framework of the IEA-ECBCS Annex 23 'Multizone Air Flow Modelling' for a network air flow model has been applied to study the COMVEN behaviour when it is used to simulate a detached house.

A complete sensitivity analysis has been performed using both the Monte Carlo and the fractional factorial analyses. The information obtained using these two methods shows that the Monte Carlo method is useful for a global analysis of the sensitivity of the model but it is not so powerful when a detailed investigation, related to the physical meaning, is needed. On the contrary, the fractional factorial analysis allows a good understanding of the model behaviour and its relation to the physical phenomena.

The sensitivity analysis has been used to associate an uncertainty range to the simulation results of COMVEN for a comparison with the measured values in order to show a valuable validation procedure for this model.

As far as the COMVEN model is concerned, the possibility of simulating devices (i.e., boiler) which are not included in the COMVEN data base has been shown in the single zone tests with boiler G3-04–G3-12, but special attention has to be paid to the single loss coefficients.

Furthermore, the sufficient agreement obtained in the two-zone G4-03 and G4-04 tests, allows one to consider COMVEN as a useful tool for analysing the air flow inside a detached house when thermal buoyancy is the main force that causes the air flows.

Finally, it is important to remark on the role of the error range associated to the simulated value in this comparison. Most of the values of simulated air flow rates are far from the measured values (even greater than 100%) and only the overlapping of the error ranges has allowed one to state that simulated results can match the measured values (in fact to avoid a significant discrepancy). For this reason the utility of models such as COMVEN for air flow simulation is closely related to the knowledge of the associated error range and a sensitivity analysis is required for all types of simulation either within a design or a validation process.

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