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A Comprehensive Validation of Two Airflow Models – COMIS and CONTAM

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Abstract Several airflow and contaminant dispersion models have been developed to study air distribution in buildings. This paper reports the results of a comprehensive validation of two models: COMIS and CONTAM. The validation process was carried out at three different levels: inter-program comparison; validation with experimental data which was collected in a controlled environment; and finally, validation with field measurement data.
At the inter-program level, the airflow rates and pressure values predicted by COMIS and CONTAM for a four-zone paper building were compared with the airflow rates and pressures predicted by CBSAIR, AIRNET and BUS. The results show good agreement between these software programs.
The second level of validation compares the models' predictions with measured data collected in a controlled environment. Fan pressurisation, smoke and tracer gas tests were conducted to estimate the permeability of building envelope components, to locate cracks, and to determine the interzonal airflow rates between rooms. The results confirm that there is good agreement between predictions made by COMIS and CONTAM; there are, however, some differences between these models' predictions and the measured data.
The predictions made by these models were also compared with the results of a tracer gas measurement carried out in a residential building. The predicted and measured values were in good agreement.

Key words Air-flow; Multizone; Validation; Modelling; Laboratory and field measurements.

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Introduction

Several models have been developed to simulate the rates of airflow within buildings (Haghighat, 1988). These models range in complexity from single cell approaches, where the building interior is assumed to be at a uniform pressure, to multi-cell (multi-zone) methods, in which the interior of the building is divided into regions of differing pressures interconnected by leakage paths. The multi-zone models, being able to calculate the air movement between rooms, have an important application in indoor air quality studies. It is clear that, with the inter-zonal airflows being known, the dispersal of air contaminants within rooms may also be modelled.

An essential part of the development of any computer model is its validation. In the case of air infiltration models, errors or differences from the actual values can arise due to many factors. These errors can be due to: differences between actual weather conditions and those used in the simulation; the use of simplifying assumptions in the input data; differences in the actual building thermal characteristics and those used in the model; differences in the airflow mechanisms used by the model and the actual phenomena; and, finally, programming or logic errors (Walton, 1989).

Three types of test can be performed for the validation of computer models. These are comparative (inter-program), analytical and empirical tests. A comparative test involves the relative comparison of different models. It has the advantages of being inexpensive to carry out while being able to deal with any level of complexity. However, it has the disadvantage of being a no truth standard (Walton, 1989). A laboratory test involves an analytical solution, and has the advantages of being inexpensive and of being an exact truth standard. It has the disadvantages of not testing the actual model, and being limited to simple cases where analytical solutions can be derived. An empirical test involves the comparison to actual measured building data, and has the advantage of being able to handle any level of complexity. It is an approximate truth standard, but has the disadvantage of being expensive and time-consuming to carry out (Walton, 1989).

This paper reports the results of a comprehensive validation of two models: COMIS and CONTAM. The validation process was carried out at three different levels: inter-program comparison; validation with experimental data which was collected in a controlled environment; and finally, validation with field measurement data.

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Description of Models

The five models that were chosen for the study, COMIS, AIRNET, CONTAM94, CBSAIR and BUS, are all multi-zone air infiltration models. In all five models the building is described by a set of zones, in which the pressure varies hydrostatically but not dynamically, and the interconnections correspond to obstructions to airflow (Haghighat and Rao, 1991). The models are based on the conservation of mass in each zone of the building. A brief description of the models will follow.

COMIS

The COMIS program is a multi-zone air infiltration model, developed as a result of an international research collaborative effort under the auspices of the International Energy Agency (Feustel et al., 1990) and (Furbringer et al., 1995). The model can simulate crack flow, flow through large openings, single-sided ventilation, cross ventilation, and HVAC systems (Megri et al., 1994). The model also has the capability to calculate heat flow, and predict pollutant source strengths and concentrations for each zone. However, these latter options are not yet fully developed within the program, and hence will not be addressed in this study at this time. The study will therefore focus on the natural ventilation aspects of the program.

The model is user-friendly to a certain degree, namely because of the fact that the data input is facilitated by an interactive, menu-driven routine. Each of the menus deals with a specific type of information that is required by the model. This information ranges from optional data, such as building description and occupant schedules, to necessary data such as airflow components. The most important information to be supplied within the airflow components menu is the crack flow coefficient and the corresponding flow exponents. Within the zone menu, it is necessary to define the number of zones in the building, and the option also exists to assign temperatures to each zone, as well as different reference heights. In addition, one must enter linkage data in order to define which zones the individual crack elements span.

The model also can include the effect of wind on air infiltration. Two options are possible. The wind pressure coefficients can be input directly, or the model can automatically calculate them based on input of wind speed and direction, building orientation, the terrain properties, and the reference height for the wind speed.

The program assumes that air is an ideal gas, and therefore its state depends only on temperature and pressure. The airflow through cracks is expressed by the power law. COMIS then establishes the ventilation rate in the building by the solution of a nonlinear system of equations with the use of numerical techniques such as the Newton-Raphson method.

AIRNET

AIRNET is an airflow model developed by Walton (Walton, 1989). The model can simulate airflow elements such as openings, ducts and fans. It does not have the capability to evaluate pollutant concentrations and heat flow, as does the COMIS model.

The data input is done through data files. This model can also take into account the effect of wind on air infiltration. However, the user has the sole option of directly entering the wind pressure coefficients into a data file. The model does not have the capability to automatically evaluate these coefficients as does the COMIS model.

The data required by this model consist of first defining the zones or nodes, their respective reference heights, and their respective air temperatures. Secondly, the crack data or flow components data is input. Like COMIS, AIRNET can simulate various types of airflow components, but only the power law elements will be considered here; therefore, the flow coefficients and the corresponding flow exponents are required as input. Here, AIRNET differs from COMIS because every AIRNET flow element model includes both nonlinear and linear correlations. The linear relation is used in evaluating derivatives when ΔP approaches zero to avoid a divide-by-zero. This is based on the physical nature of airflow through an orifice which becomes laminar at every low Reynolds numbers. A proper model of flow at a low Reynolds number would require a flow element model which treats the laminar-turbulent transition in some detail as well as data to support that level of detail.

The resulting mass balance equations are a nonlinear system of equations, thus requiring iterative solution techniques. AIRNET uses a simple under-relaxation coefficient, typically 0.75, to achieve convergence. A value of 1.0 will not converge in many cases.

An inter-model comparison was performed by Herrlin (Herrlin, 1992) between MOVECOMP and AIRNET. The main focus of the comparison was their mathematical solvers. Because these solvers were used in two distinct programs, all input data were carefully checked for uniformity. The output was identical for all four test cases (ranging from 2 to 45 zone structures).

CONTAM

CONTAM94 combines most of the capabilities of AIRNET (Walton, 1989), CONTAM-87 (Axley, 1987, 1988), and ASCOS (Klote, 1981). The CONTAM model performs inter-zonal air movement and contaminant dispersal analyses for buildings (Walton, 1993). The program is quite user-friendly, in that the user can define the airflow network in terms of a simplified floor plan of the building. In CONTAM94 the input processing, simulation, and graphic review of the results are merged into a single program. This program can access all available memory if needed for very large simulations.

CONTAM94 includes several types of flow elements: openings allowing only one-way flow (e.g. cracks), openings allowing two-way flow (e.g. doorways), and elements which force airflow (e.g. fans). Interactive menus are provided for entering data for these elements based on direct entry of equation coefficients for various physical descriptions. CONTAM uses exactly the same solution of the airflow network as AIRNET. AIRNET and CONTAM both use Equation 1b flow model with the additional linear (laminar) portion. CONTAM94 also added the Equation 1a (see below).

CBSAIR

CBSAIR is a research program developed to verify the theoretical multi-zone airflow model (Haghighat et Rao, 1991). The derivation and solution of the model uses matrix representations. Like other models, CBSAIR considers a building as nodes connected by openings. Only the power law flow relationship is implemented at present, although arbitrary flow equations are included in the theoretical model.

The computer implementation is done in MATLAB, a software package that directly uses matrices as basic variables in expressions. The input file is in the MATLAB programming code. The data is entered as vectors or zonal connections, zone reference heights and temperatures, opening locations, power law coefficients and exponents, wind and exponents, wind-pressure coefficients, and reference wind speed.

The modelling and solution aspects involve a one-to-one implementation of the theoretical model in the matrix form. Zonal pressure updates use the built-in matrix inversion function with an accelerated solution scheme, similar to that of AIRNET. Due to MATLAB's interactive environment (in addition to the programming capability), data and results can be displayed and manipulated easily. Modification of the program is also very easy and fast. This program is best suited for in-house use. A sensitivity analysis procedure for airflow in buildings is also included in CBSAIR (Rao and Haghighat, 1993).

BUS

The ventilation system was modelled by a network. The nodes were connected to each other by one-dimensional flow elements. The improved SIMPLE algorithm (Juslin and Siikonen, 1983) was used to solve the mass balance equations at every node, and the momentum equations of each flow element. These equations are linearised and solved iteratively using a fully implicit method. Convergence of the program was tested by test runs. The simulated steady-state mass flow rates and pressures were checked by analytical calculations. The results were found to satisfy both the mass balance equations for every node and the momentum equations for each flow element when a simple test case is simulated (Tuomaala, 1993).

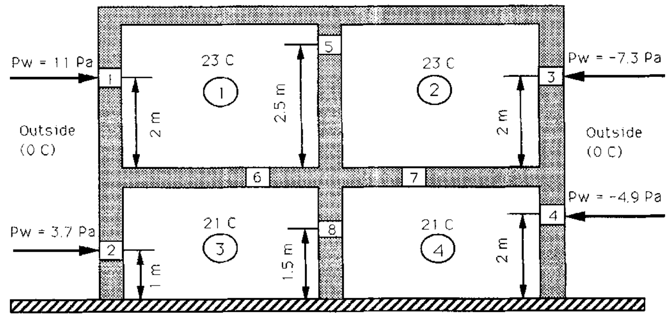

Fig. 1 A four-room building (node numbers are inside the circles, and flow element numbers are inside the squares).

Test Case and Results

Paper Building

The test case for comparison is the same as the one used by Haghighat and Rao (Haghighat and Rao, 1991). It consists of a four-room building with eight airflow paths. The building and room dimensions, opening characteristics, temperature distribution, and wind-induced pressures are shown in Figure 1. The power law flow elements are selected, and the values of the parameters for each element are presented in Table 1.

The coefficients used in the flow equations depend on the exact form of the equation used in the simulation

Table 1 Flow element parameters for the test case

Flow element number	C ($m^3 s^{-1} Pa^{-n}$)	n
1	0.005	0.65
2	0.008	0.65
3	0.007	0.65
4	0.009	0.65
5	0.015	0.5
6	0.020	0.5
7	0.020	0.5
8	0.015	0.5

program. COMIS Fundamentals (Feustel et al., 1990) identifies three possible flow equations:

$$W = \rho Q = K_a C_a \rho (\Delta P)^n \quad (1a)$$

$$K_a = (\frac{\rho_0}{\rho})\, n\, (\frac{v_0}{v})^{2n-1}$$

$$W = K_b C_b \rho^{1/2} (\Delta P)^n \quad (1b)$$

$$W = K_c C_c (\Delta P)^n \quad (1c)$$

$$K_c = (\frac{\rho_0}{\rho})^{n-1} (\frac{v_0}{v})^{2n-1}$$

$$K_b = (\frac{\rho_0}{\rho})^{n-\frac{1}{2}} (\frac{v_0}{v})^{2n-1}$$

The flow coefficients, C_i, are assumed to be determined under standard conditions (20°C and 101.3 kPa), and the temperature adjustment factors, K_i, are used to adjust the computed flows if the actual state of the air is different. For pure viscous flow, the flow rate increases as much as 30% at –20°C. The viscosity in this case represents about 40% of the increase.

BUS and CBSAIR use form (1a) of the flow equation, and AIRNET utilizes form (1b). CONTAM94 employs both forms (1a) and (1b) of the flow equation and relates the form (1b) to the orifice equation ($Q=C_dA\,[2\,\Delta P/\rho]^{1/2}$) so that $C_b=2^{1/2}\,A\,C_d$, relating the flow coefficient to physical quantities.

Form (1a) can be converted to form (1b) in one of the following ways:

$$C_b = \rho^{1/2} C_a \quad (2)$$

$$A = (\frac{C_a}{C_d})(\frac{\rho}{2})^{1/2} \quad (3)$$

by assuming a value for C_d (e.g. 0.6), or:

$$C_d = (\frac{C_a}{A})(\frac{\rho}{2})^{1/2} \quad (4)$$

by assuming a value for A (e.g. C_a).

Version 1.3 of COMIS, which uses form (1c) of the flow equation, and CONTAM94 are used in this paper. In COMIS, the density is calculated at the air leakage temperature in the crack as a function of different parameters (cf. Table 2) (Feustel et al., 1990), (Megri, 1993):

where:

$$A = \frac{\dot{m}c}{\alpha X}[(t_{in,0}-t_0) + \frac{\dot{m}c}{\alpha X}(t_i-t_0)] \quad (5)$$

$$B = [(t_i - t_0)(\frac{1}{2} - \frac{\dot{m}c}{\alpha X})]$$

Table 2 Air leakage temperature for different types of crack

Crack	Mean temperature
Door or single-pane window	$t_{in}=t_0+0.136\,(t_i-t_0)$ $t_{ex}=t_i-0.363\,(t_i-t_0)$
Prime and storm windows	$t_{in}=t_0+(0.121+0.193\gamma)\,(t_i-t_0)$ $t_{ex}=t_0+(0.371+0.450\gamma)\,(t_i-t_0)$
Small cracks	$t_{in}=t_0+A\,(1-e^{(-\beta x)})+B$
Wide cracks	$t_{in}=C-\alpha_n+\beta_n-\gamma_n$

$$\alpha_n = \frac{\lambda}{L\dot{m}c}\sum_{n=0}^{n=\infty}\frac{A_n}{\sinh(n\pi)}\mathrm{Cos}\,(n\pi X) \quad (5)$$

$$\beta_n = \sum_{n=0}^{n=\infty}\frac{B_n}{1+e^{-2\pi n}}\mathrm{Cos}\,(n\pi X)\,(e^{-2n\pi}-1)$$

$$\gamma_n = \sum_{n=0}^{n=\infty}\frac{D_n}{\mathrm{Cosh}\,(n\pi)}$$

$$C = t_0 + \frac{\alpha_n\beta_n\gamma_n}{\mathrm{Cosh}\,(n\pi)}$$

where

R_o: thickness of the wall

t_i: room air temperature

t_{in}: air leakage temperature (infiltration)

t_{ex}: air leakage temperature (exfiltration)

t_0: outside temperature

γ: temperature factor for infiltration and exfiltration condition $(t\text{-}t_0/t_i\text{-}t_0)$

In CONTAM94, AIRNET, and CBSAIR, the density is that of the fluid flowing through the flow path. Therefore, in all programs the density depends on the flow direction in a non-isothermal case.

In Table 3, the simulated mass link flow rates, zone pressures and link pressure differences for COMIS, AIRNET, CONTAM94 (form 1b) and CBSAIR are given. Table 3 also shows the results from BUS predictions (Tuomaala, 1993). As shown, there is good agreement between the results obtained from these models. The zone pressures are measured at floor level on the first floor and at the height of three meters on the second floor. In Table 3, the zone flow rate is the mass flow rate into the zone (infiltration) or out of the zone (exfiltration). The pressure values are within a 5% agreement of each other, for both the zones and the links, except for link 7 where the difference is about 13%. For example, in the COMIS model (version 1.3), the stack pressure between links 6 and 7 is an interpolation between the

Table 3 Inter-comparison programs

Zone	Pressure (Pa)					Flow rate (kg/s)				
	COMIS	AIRNET	CONTAM1b	BUS	CBSAIR	COMIS	AIRNET	CONTAM1b	BUS	CBSAIR
1	−36.722	−37.2741	−37.3	−37.124	−37.12	0.02597	0.02627	0.0262	0.0265	0.0266
2	−38.803	−39.4120	−39.4	−39.309	−39.33	0.03133	0.03200	0.0319	0.0321	0.0322
3	−2.091	−1.9882	−2.0	−1.8420	−1.80	0.02699	0.02760	0.0275	0.0278	0.0279
4	−4.082	−4.0736	−4.1	−3.9763	−3.96	0.02540	0.02604	0.0260	0.0264	0.0265
Link										
1	8.64	8.3134	8.3131	8.104	8.31	0.02437	0.02471	0.02471	0.02514	0.02521
2	4.91	4.7843	4.7840	4.59	4.78	0.02699	0.02760	0.02760	0.02789	0.02787
3	−7.68	−7.8443	−7.8440	−7.976	−7.85	−0.03133	−0.03200	−0.0320	−0.03215	0.03220
4	−2.59	−2.6350	−2.6349	−2.74	−2.63	−0.02003	−0.02031	−0.02031	−0.02088	0.02088
5	2.08	2.1379	2.1377	2.21	2.14	0.02597	0.02627	0.02627	0.02657	0.02660
6	0.00444	0.00425	0.00425	0.004	0.0043	0.00160	0.00157	0.00157	−0.00143	0.00139
7	0.0499	0.05679	0.05679	0.055	0.057	0.00536	0.00573	0.00573	−0.00558	0.00560
8	1.99	2.0852	2.0852	2.16	2.08	0.02540	0.02604	0.0260	0.02646	0.02647

Table 4 Inter-comparison between programs

Zone	Pressure (Pa)				Flow rate (kg/s)			
	PLR (b)	PLC (a)	PLR (T)	PLC (T)	PLR (b)	PLC (a)	PLR (T)	PLC (T)
1	−37.271	−37.077	−37.124	−37.126	0.02627	0.02658	0.02656	0.02656
2	−39.408	−39.287	−39.309	−39.310	0.03200	0.03216	0.03214	0.03214
3	−1.9881	−1.7932	−1.8420	−1.8421	0.02760	0.02783	0.02780	0.02780
4	−4.0732	−3.9529	−3.9763	−3.9765	0.02604	0.02645	0.02634	0.02634
Link								
1	8.3131	8.1170	8.1664	8.1663	0.02471	0.02520	0.02510	0.02510
2	4.7840	4.5891	4.6379	4.6379	0.02760	0.02783	0.02780	0.02780
3	−7.8492	−7.9724	−7.9490	−7.9491	−0.03200	−0.03216	−0.03214	−0.03214
4	−2.6349	−2.7553	−2.7318	−2.7318	−0.02031	−0.02087	−0.02076	−0.02076
5	2.1377	2.2105	2.1845	2.1846	0.02627	0.02658	0.02656	0.02656
6	0.00425	0.00331	0.00369	0.00369	0.00157	0.00138	0.00146	−0.00146
7	0.05679	0.05410	0.05386	0.05386	0.00573	0.00558	0.00558	−0.00558
8	2.0852	2.1597	2.1344	2.1344	0.02604	0.02645	0.0263	0.02634

stack pressure when the flow is positive and when it is negative. This interpolation is necessary to prevent convergence problems. The airflow rates for the links are in agreement by roughly 13%. The CONTAM94 model was then used to investigate the impact of the flow equation form on the model's predictions of mass link flow rate and pressure difference. Table 4 gives the values of the simulated mass link flow rates and pressure differences for PLR (refers to form 1b), PLR(T) (form 1b with temperature adjustment), PLC (refers to form 1a), and PLC(T) (form 1a with temperature adjustment).

The major causes for the differences observed in Tables 3 and 4 are the form of the mass flow equation used or the numerical manipulation used to avoid convergence problems. The AIRNET and PLR results are in excellent agreement since they use the same model. The temperature adjusted calculations agree almost exactly - as they should. The PLC model is better than the PLR model if no temperature adjustment is made. Temperature adjustment is faster with the PLR model since it is not needed when $n=1/2$. This is not a difficult test for the nonlinear equation solver. The problems occur when the flow coefficients for the different paths differ by several orders of magnitude. This test has been useful in confirming that the flow equations have been correctly used in the programs. The test is not a difficult challenge from the point of view of execution time - the solution is computed in less than the 0.05 seconds resolution of the timing algorithm.

Experimental Validation

Laboratory and field measurement tests were also conducted to further validate these models. A prerequisite for the validation of the airflow calculations with these models is the knowledge of air leakage through every component, air temperatures, and the ventilation rates.

Controlled Climatic Environment Test - OPTIBAT

The second level of validation was done by comparing the models' predictions with measured data. However, to eliminate the error due to differences between actual weather conditions and those used as input, the experiment was carried out in a controlled environment: OPTIBAT (Figure 2). OPTIBAT is an experimental

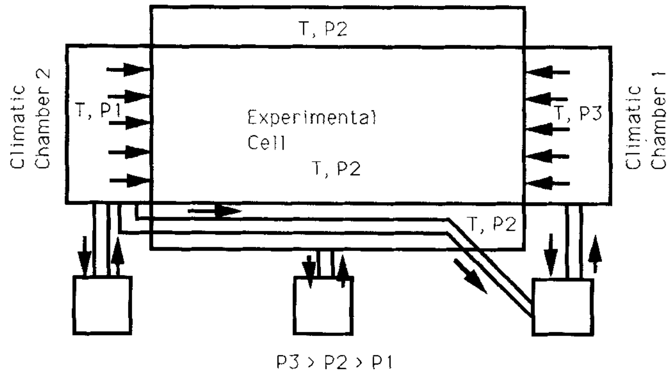

Fig. 2 Schematic representation of the OPTIBAT experimental facility.

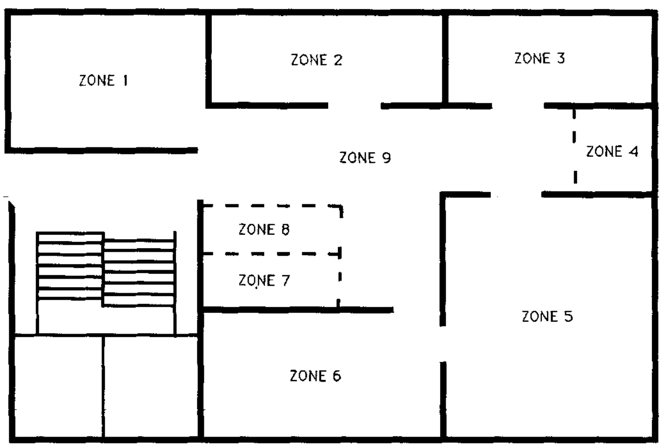

Fig. 3 The experimental building, OPTIBAT.

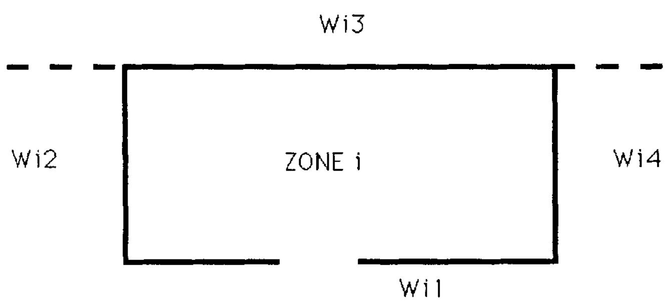

Fig. 4 Identification of the components in OPTIBAT: The components have been numbered clockwise starting from the door. Thus, Wi1 is wall number 1 of room number i.

apartment built in the laboratory hall of CETHIL in Lyon, France (Figure 3). This apartment is in fact a part of a building which was modified, and its facades were guarded with two climatic chambers. The climatic conditions in these two chambers could be varied: temperature between –10°C and 30°C, and relative humidity between 30% and 80%. The pressure difference between the two facades could reach up to 200 Pa, which is equivalent to a wind velocity of 70 km/h. The other facades were kept at the same conditions as the indoors.

The temperature and pressure drop were measured in the middle of the room at a 1.2 m height from the floor. During the experiment, the pressure difference between Climatic Chamber 1 and the indoors was 16 Pa (in winter configuration) or 1 Pa (in summer configuration), and between Climatic Chamber 2 and the indoors was maintained at –94 Pa (in winter configuration) or –41 Pa (in summer configuration). The pressure difference between the zone 4 and the thermal guard is –2.8 Pa (in winter configuration) and –1Pa (in summer configuration). The indoor air temperature was kept at 20°C throughout the apartment.

The fan pressurization test was used to measure the air leakage from the building envelope components such as windows, doors, and walls. In order to minimize the error due to measurement techniques, both the active (zone guarded method) and passive methods were used (Megri, 1993; Amara, 1993).

The guarded zone method employs two blower doors. The pressure difference across the outer walls of the primary zone is kept constant (i.e at zero Pa) while the pressure in the secondary zone is varied between –200 and +200 Pa. The flow rates required to maintain the constant pressure difference across the external walls of the primary zone were recorded for different pressure levels in the secondary zone (Figure 4).

Table 5 Value of C and n for the internal and external components

Component	Active method		Passive method	
	C [m^3/(h.Pa^n)]	n	C [m^3/(h.Pa^n)]	n
W11=W22	0.01±0.02	0.95±0.05	0.14±0.001	0.90±0.001
W21	19.30±0.38	0.71±0.01	20.22±1.03	0.78±0.05
W22	0.01±0.02	0.95±0.05	0.14±0.001	0.90±0.001
W24	0.08±0.02	0.99±0.01	0.17±0.01	0.87±0.01
W31	14.17±0.03	0.66±0.001	14.94±1.26	0.59±0.004
W32=W24	0.08±0.02	0.99±0.01	0.17±0.01	0.87±0.01
W41	2.54±0.22	0.92±0.03	2.49±0.16	0.84±0.02
W42	2.89±0.21	0.66±0.01	2.97±0.08	0.65±0.01
W44	5.48±0.04	0.51±0.002	5.64±0.02	0.51±0.01
W51	14.67±1.54	0.71±0.03	15.03±0.64	0.76±0.01
W54=W62	6.47±0.02	0.64±0.01	6.29±0.02	0.64±0.001
W61=W72	1.76±0.26	0.74±0.05	1.24±0.21	0.81±0.02
W64	1.64±0.06	0.77±0.02	1.99±0.27	0.69±0.06
W71	4.59±0.99	0.89±0.04	4.83±0.31	0.80±0.02
W72	1.76±0.26	0.74±0.05	1.24±0.21	0.81±0.02
W74	0.34±0.01	0.97±0.01	0.34±0.01	0.97±0.01
W82=W74	0.34±0.01	0.97±0.01	0.34±0.01	0.97±0.01
W12	Impermeable component		Impermeable component	
W13	Impermeable component		Impermeable component	
W14	12.62±1.04	0.59±0.03	13.43±0.91	0.58±0.02
W23	13.93±0.84	0.57±0.02	11.82±1.4	0.60±0.04
W33	9.37±1.15	0.61±0.03	10.02±1.08	0.55±0.04
W34	Impermeable component		Impermeable component	
W43	Impermeable component		Impermeable component	
W52	Impermeable component		Impermeable component	
W53	13.52±1.6	0.55±0.03	13.34±0.21	0.57±0.01
W63	6.79±1.15	0.52±0.05	5.86±0.02	0.56±0.005
W73	Impermeable component		Impermeable component	
W83	3.34±0.59	0.65±0.05	3.94±0.54	0.59±0.04

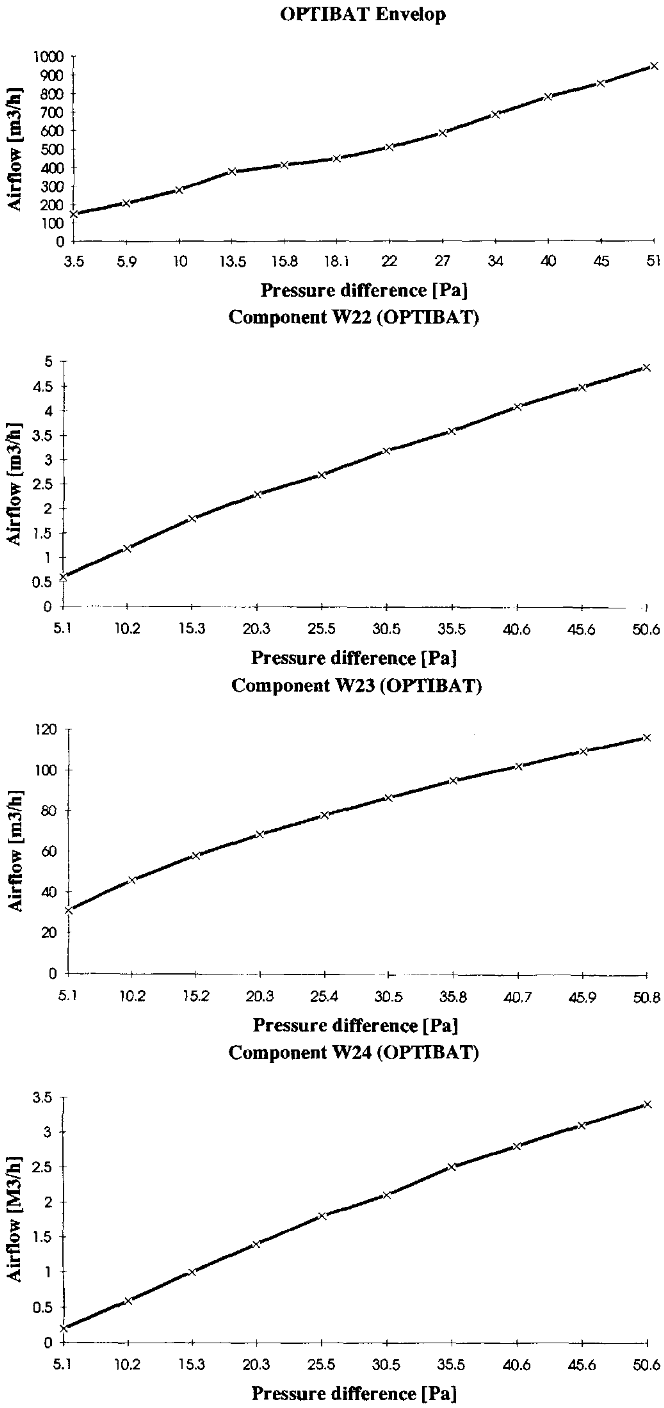

Fig. 5 OPTIBAT Fan Pressurization data.

In the passive method, one blower door is employed with the interior and exterior openings kept either closed or opened. The blower door is installed in the door of the room containing the element to be measured. The advantages of this method are that it is cheaper than the active method and easy to use. However, it requires more time than the active method and the estimation of the flow coefficients is more difficult because it requires the solution of a set of nonlinear equations coupled with statistical treatment (Megri, 1993).

A least square regression technique was used to estimate the flow coefficients, C and flow exponents, n. Table 5 gives the values of these parameters for each component. In order to identify the components, they have been numbered clockwise starting from the door. Thus, Wi1 is wall number 1 of room number i (Figures 5a, 5b, 5c, 5d).

The values of C and n obtained using active and passive techniques are not the same in all cases. The statistical error treatment however shows that, in most of the cases, the confidence intervals calculated using the two methods overlap with each other (Megri, 1993). This good agreement between the results indicates that the possible error between the actual values (C and n) and those used as input in the models has been minimized.

The air leakage from the inside doors is not determined by the fan pressurization method, but estimated by C=0.83*S, where S is the area of the crack [m^2], and n=0.5.

A smoke test was also performed to find accurately the location of these cracks. They were mainly located above the windows near the shutters, where the electric cables crossed (Amara, 1993).

The multi-tracer gas technique was used to measure the interzonal airflows in OPTIBAT (Figure 6). The concentration of every tracer gas was measured in the zones. The airflows out of the zones were obtained by the solution of the set of equations for each zone (Amara, 1993).

Evaluation of the COMIS and CONTAM94 Models with Experimental Results

The COMIS and CONTAM models were used to predict the inter-zonal airflow in OPTIBAT using the estimated values of C and n as input data. Since zones 4, 7, 8 and 9 are at the same pressure, in simulation they

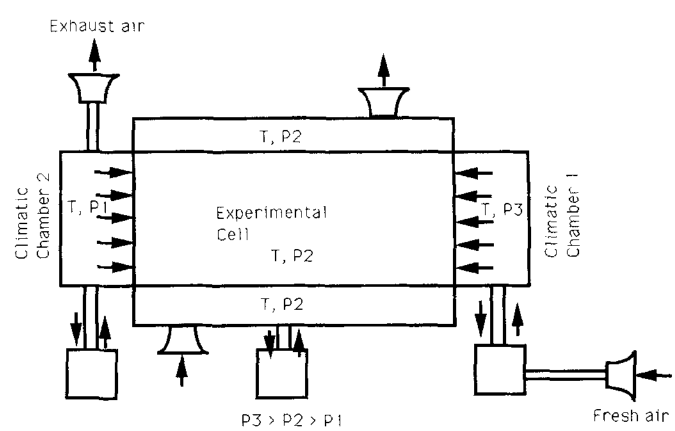

Fig. 6 Modifications made to the OPTIBAT experimental facility to perform the tracer gas technique.

Table 6 Comparison between experimental results and prediction made by COMIS and CONTAM94 (m^3/h) (winter configuration)

		out	zone 1	zone 2	zone 3	zone 4*	zone 5	zone 6
Measurement	out	199±11	48.5±1.6	41.4±1.8	83.9±2.3	0.0±6	21.2±2	0.0±2.2
COMIS		166.2	52.2	44.6	68.4	0.0	0.0	1.0
CONTAM94		166.79	52.35	44.64	68.82	0.0	0.0	1.0
Measurement	Zone 1	0.0±4.2	48.8±1.7	0.3±0.5	0.0	57.1±3.8	0.0	0.0
COMIS		0.0	51.6	0.0	0.0	52.2	0.0	0.0
CONTAM94		0.0	52.35	0.01	0.0	52.34	0.0	0.0
Measurement	Zone 2	1.6±3.9	0.2±0.5	42.0±2	0.3±0.9	39.9±3.2	0.0	0.0
COMIS		0.0	0.0	41.1	0.1	44.6	0.0	0.0
CONTAM94		0.0	0.01	44.64	0.08	44.56	0.0	0.0
Measurement	Zone 3	0.5±6.4	0.0	0.3±0.5	84.8±2.6	84.0±6	0.0	0.0
COMIS		0.0	0.0	0.0	67.4	68.5	0.0	0.0
CONTAM94		0.0	0.0	0.08	68.9	68.89	0.0	0.0
Measurement	Zone 4*	94.5±1.1	0.2±0.5	0.3±0.4	0.5±0.8	181±10.4	30.0±2	55.5±3
COMIS		36.0	0.0	0.0	0.0	163.00	66.6	61.9
CONTAM94		37.44	0.0	0.0	0.0	165.79	66.36	62.0
Measurement	Zone 5	67.4±4.3	0.0	0.0	0.0	0.0±3	70.1±2.7	2.3±1.3
COMIS		78.1	0.0	0.0	0.0	0.0	77.0	0.0
CONTAM94		77.18	0.0	0.0	0.0	0.0	77.18	0.0
Measurement	Zone 6	39.4±4.8	0.0	0.0	0.0	0.0±2.4	18.9±1.1	57.8±4
COMIS		52.2	0.0	0.0	0.0	0.0	11.5	62.9
CONTAM94		53.15	0.0	0.0	0.0	0.0	10.82	62.98

Table 7 Comparison between experimental results and COMIS and CONTAM94 predictions (m^3/h) (summer configuration)

		out	zone 1	zone 2	zone 3	zone 4*	zone 5	zone 6
Measurement	out	67.4±4	10.9±0.5	6.7±0.2	13.3±0.4	33.5±1.6	1.7±0.8	0.0±1.8
COMIS		82.9	12.28	8.4	13.8	47.19	0.0	1.23
CONTAM94		83.47	12.48	8.51	14.10	47.09	0.0	1.28
Measurement	Zone 1	0±1.1	11.1±0.5	0±0.1	0	13.2±1	0.0	0.0
COMIS		0	12.29	0	0	12.29	0.0	0.0
CONTAM94		0	12.46	0	0.01	12.46	0.0	0.0
Measurement	Zone 2	0±0.7	0.1±0.1	6.9±0.2	0.4±0.1	6.7±0.6	0.0	0.0
COMIS		0	0	8.4	0	8.39	0.0	0.0
CONTAM94		0	0	8.5	0.01	8.49	0.0	0.0
Measurement	Zone 3	0.9±0.9	0	0±0.1	13.9±0.4	12.9±0.7	0.0	0.0
COMIS		0	0	0	13.81	13.81	0.0	0.0
CONTAM94		0	0	0	14.11	14.12	0.0	0.0
Measurement	Zone 4*	2.4±3.6	0.1±0.1	0.1±0.1	0.2±0.1	66.9±2.4	28±1.4	36.2±2.2
COMIS		0.0	0	0	0	81.68	41.65	40.04
CONTAM94		0.0	0	0	0	82.16	42.27	39.91
Measurement	Zone 5	39±1.9	0	0	0	0.3±0.6	39.9±1.8	0.7±0.5
COMIS		50.3	0	0	0	0	50.3	0.0
CONTAM94		50.46	0	0	0	0	50.46	0.0
Measurement	Zone 6	26.4±3	0	0	0.0	0.2±0.6	10.2±0.7	36.9±2.8
COMIS		32.61	0	0	0.0	0.0	8.67	41.275
CONTAM94		33.02	0	0	0.0	0.0	8.18	41.19

were considered as one zone, 4*. Table 6 (winter configuration) and Table 7 (summer configuration) show the predictions made by COMIS and CONTAM94, as well as measured values.

– *Winter configuration*: The differences between the experimental airflow results in zones 1 and 2 are 7.6% and 7.8% respectively. For zone 3, COMIS and CONTAM94 underpredict the flow rate by almost 18% compared with the measured value. This may be due to the fact that this zone is near the air-conditioning system fan. The pressure on the facade of zone 3 is larger than that of the other facades of the building (zones 1 and 2 for example which are far from the fan). Zone 4* is the central zone and is connected to the other zones. The difference between the experimental and COMIS results observed in zone 3, due to its higher pressure, influences zone 4* by the flow $Q_{4^*\text{-->}3}$.

– *Summer configuration*: The results obtained for the summer configuration are better than those of the winter configuration (lower wind speed). This is because

Table 8 Comparison of pressure predicted by COMIS and CONTAM 94 (winter configuration)

	COMIS	CONTAM94
Zone 1	−1.5	−1.5
Zone 2	−1.5	−1.5
Zone 3	−2.0	−2.0
Zone 4*	−2.59	−2.6
Zone 5	−3.29	−3.3
Zone 6	−3.26	−3.3

the fan has little influence on the flow in zone 3, thus the pressures are more homogeneous.

The pressures predicted by COMIS and CONTAM94 for the winter configuration are shown in Table 8. In general, there is excellent agreement between the predictions made by COMIS and CONTAM94.

Field Measurement Test - Canadian Bungalow

Field measurements were carried out in a single family bungalow-type dwelling, with attached garage, made up of brick, wood and aluminium, as shown in Figure 7. It is located in a suburb of Montreal and is surrounded by single-storey houses. The house is a one-storey building, naturally ventilated, with three bedrooms, one living room, one family room and a basement. Windows are well insulated and double glazed.

Fan pressurization and depressurization tests were conducted to characterize the permeability of the bedrooms, garage, basement and the house as a whole. The results indicated that it is an air-tight house. For every test, the indoor and outdoor pressure difference was varied from −60 Pa to +60 Pa, with a step of 5 Pa (Figures 8a, 8b, 8c, 8d). The outdoor and indoor temperatures were identical, near 20°C, and the wind velocity was negligible. The results of the measurement and regression methods for the residential building are given in Table 9. A Thermography Test was also carried out to locate the possible position of cracks around windows, doors or in the envelope itself. None were observed.

A single tracer gas experiment was also performed to determine the interzonal contaminant movement. SF_6 tracer gas was injected in the living room and samples were taken at four locations: in the basement and three bedrooms. The samples were collected at different time

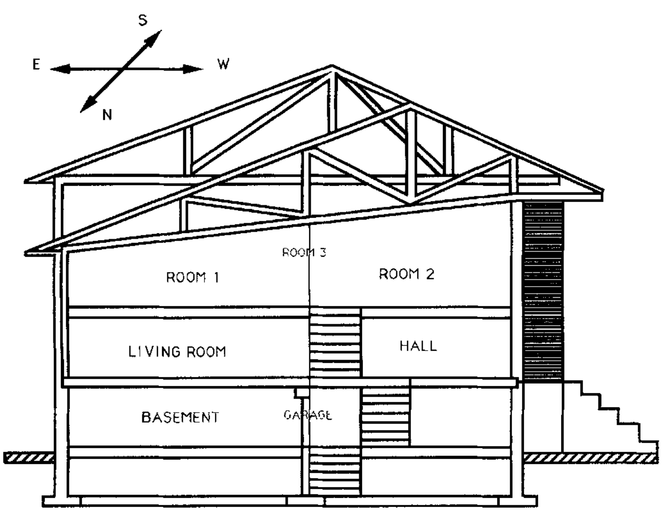

Fig. 7 The experimental residential building (vertical section).

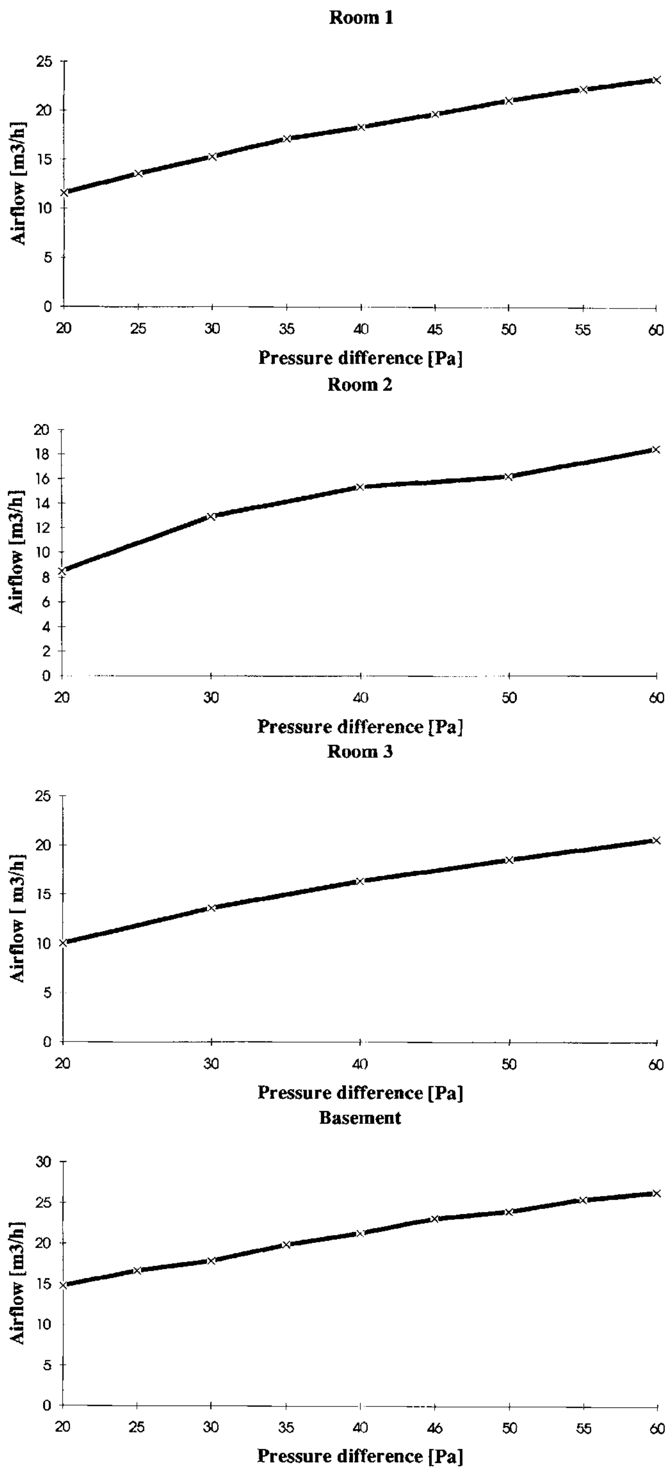

Fig. 8 Bungalow Fan Pressurization data.

Table 9 C and n coefficients for the external components

	C $m^3/(h.Pa^n)$	n	correlation coefficient r
Outdoor wall garage	1.73	0.96	1.00
Outdoor basement	1.75	0.99	0.99
Outdoor room 1	1.83	0.66	1.00
Outdoor room 2	1.92	0.5	1.00
Outdoor room 3	1.84	0.5	0.99
House	103.98	0.77	0.99

Table 10 Climatic conditions for the tracer gas measurements

Time	Wind velocity (m/s)	Wind direction (deg)	Outside temperature (°C)
05:00	4.112	51	15
06:00	3.598	51	14
07:00	0.514	52	13
08:00	4.626	51	12
09:00	3.598	51	15
10:00	0.0	42	13
11:00	3.598	41	11
12:00	2.57	51	10
13:00	3.084	51	08
14:00	2.57	51	09
15:00	1.028	51	09
16:00	1.542	41	10
17:00	2.57	41	15
18:00	2.056	31	20
19:00	3.084	41	21
20:00	2.056	51	16
21:00	3.084	41	11
22:00	4.626	41	11
23:00	2.57	51	04

intervals for a period of three hours, using a syringe and vacuum tubes. The samples were analyzed using a gas analyzer. SF_6 tracer gas was also used to measure the infiltration rate. The meteorological data from Dorval airport, which is located 10 km from the house, was used in the simulation program (see Table 10).

The comparisons between the COMIS and CONTAM94 predictions and the experimental results are plotted in Figures 9 through 12. The difference, in general, is less than 15%. The reasons for the differences may be due to the fact that approximate average input data were used for simulation, especially the wind pressure coefficients and the differences between measured and calculated air exchange rates. Also, the complex geometry of the building may not have ensured a perfect mixing of the gas with the indoor air.

Conclusion

A comprehensive validation of two airflow models, CONTAM and COMIS, was carried out at three levels. For the first level, an inter-program comparison was made, where the airflow rates and pressures predicted by these models for a four-zone paper building were

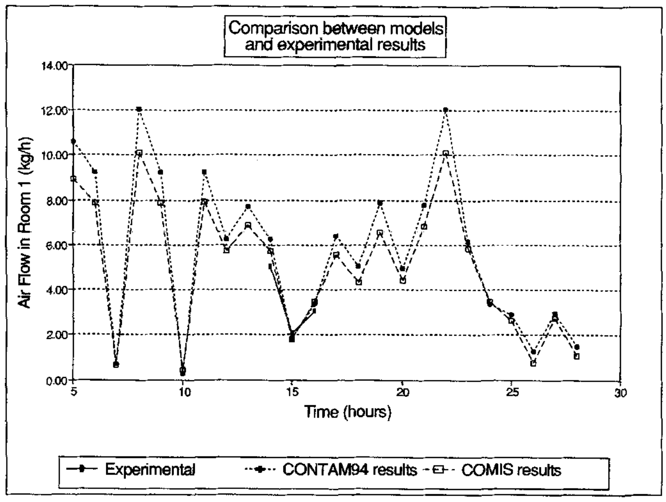

Fig. 9 Comparison between airflow predicted by COMIS and CONTAM94 and measurement data given by the tracer gas technique (Room1).

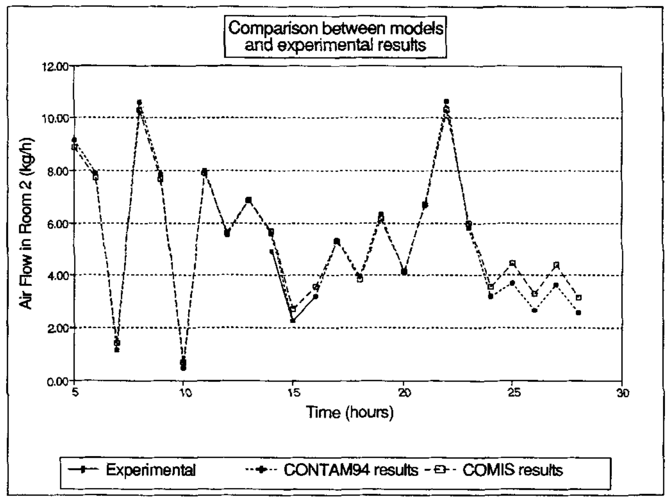

Fig. 10 Comparison between airflow predicted by COMIS and CONTAM94 and measurement data given by the tracer gas technique (Room 2).

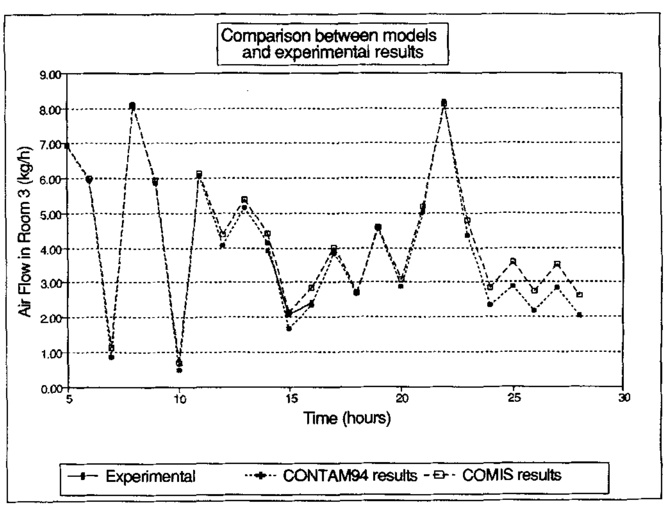

Fig. 11 Comparison between airflow predicted by COMIS and CONTAM94 and measurement data given by the tracer gas technique (Room 3).

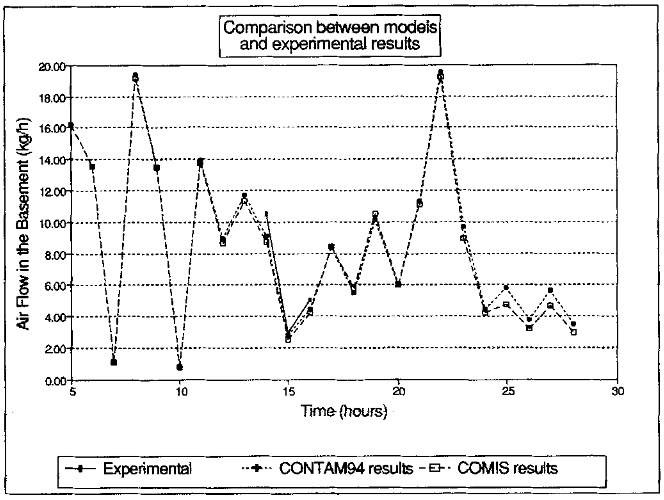

Fig. 12 Comparison between airflow predicted by COMIS and CONTAM94 and measurement data given by the tracer gas technique (Basement).

compared with the predictions made by AIRNET, CBSAIR and BUS. The results were in good agreement.

At the next level, the models' predictions were compared with the measured data from a controlled environment test for both summer and winter conditions. The results under summer conditions were better than those in winter. The relative error in air change rates when comparing the measurement and simulation results is mostly within ±20%. In most of the cases, the airflow measured is less than the airflow predicted by the simulation programs. However, in general, there was excellent agreement between the predictions made by these models.

At the third level, these models were used to predict the contaminant concentration in a multi-zone single-family house. The results indicated that the predicted and measured values were in good agreement.

This work provides also a platform for comparison of the other new airflow models with those discussed here.

Acknowledgements

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