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MEASUREMENT OF AIR CHANGE RATE IN AN INHABITED BUILDING WITH A CONSTANT TRACER GAS CONCENTRATION TECHNIQUE

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ABSTRACT

An apparatus measuring the air change rate by the tracer gas method was built at the Solar Energy Research Group of the Ecole Polytechnique Fédérale, Lausanne. Up to 10 locations can be measured simultaneously either by the decay method or the constant flow or the constant concentration method. This equipment was used to measure the air infiltration in various buildings. One of them was a three-storey one-family house, which was inhabited during the 12-day survey.

The measurements show that in such buildings, the air infiltration varies strongly from time to time, even when all windows and doors are closed. Moreover, strong exchanges between rooms are observed.

It is shown that, in multiroom inhabited buildings, the constant concentration method used during a lengthy survey allows one to obtain the total air infiltration flow rate. With only one tracer gas, the infiltration rates into each room are measured, but the exchanges between rooms can only be estimated qualitatively. Some effects of the inhabitants' behavior are quantified.

INTRODUCTION

Improvement in the thermal performance of low-energy buildings requires precise knowledge about air change. In particular, substantial effort is now dedicated to quantification of occupant influence on air change. To measure this influence, measuring techniques must have the following characteristics:

- Allow continuous measurement over extended periods of time (several days or weeks) under varying air change conditions.
- Avoid any health risks to living beings over prolonged measurement periods.

It is now known that a good way to monitor the air change rate in an inhabited dwelling during a long time period is the constant concentration tracer gas method. A Compact Equipment for Survey of Air Renewal (CESAR) was developed at the Ecole Polytechnique Federale de Lausanne in Switzerland (Roulet and Scartezzini 1984, 1985). This apparatus was designed for simultaneous analysis of up to ten inhabited rooms over extended periods of time. By use of an appropriate tracer gas technique with a nontoxic gas (N_2O) at a 100 ppm constant concentration, a level found acceptable in Europe (Sharer 1983), the two criteria mentionned above can be attained.

Several air change surveys were carried out on various inhabited buildings (Scartezzini et al. 1985) during the 1983/1984 and 1984/1985 heating seasons. One of them was a three-storey single-family Swiss dwelling, which contained 10 interconnected rooms. Results of this survey as well as a short description of the apparatus developped are reported below.

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DESCRIPTION OF THE APPARATUS

CESAR is a compact and mobile installation for on-site measurements. This apparatus was designed for simultaneous analysis of up to ten inhabited rooms over extended periods of time. Three operating modes with different tracer gas techniques can be used: the "decay" and "continuous flow" methods and above all the "constant concentration" method. This last approach shows marked advantages when compared to the others; measurement of infiltration can be carried out even in inhabited buildings with varying air change rates. Four main components constitute the overall apparatus and are described below:

The monitoring microcomputer maintains the constant concentration, using a quadratic criterion control described below and acquires the data (tracer gas flow rates, wind speed and direction, and recently indoor and outdoor temperatures). Acquired data is recorded on a magnetic support (floppy disc). Analysis of monitored data is done automatically by the computer at the end of the survey. Air infiltration rates and airflow rates as well as statistical parameters are displayed after each analysis.

The two-channel infrared spectroanalyzer measures the nitrogen protoxyde (N_2O) and water vapor concentration levels. Since absorption bands slightly ovelap, measurement of the water content of air is made simultaneously for automatic correction by the microcomputer. A high precision N_2O/N_2 gas mixture is used for periodical calibration.

A ten-channel gas-sampling unit performs the sampling of small amounts of air in up to ten different rooms. The scanning interval can be set between 10 and 1000 seconds. The typical scanning interval between two rooms is 50 seconds.

The programmable ten-channel injection unit injects, under microcomputer control, known quantities of tracer gas in up to ten different rooms. Injection flow rate is stabilized by use of a highly accurate double-stage pressure valve or a constant pressure buffer tank. Gas exhaust pressure is 200 kPa (2 Bar). Small fans disperse the tracer gas in the test rooms. The overall injection device was calibrated by use of a high precision (2% accuracy) volumetric flowmeter.

Three computer programs are used with this system: CESAR is the BASIC controlling program for the constant concentration method. It controls the programmable injector and data logging onto the floppy discs. It can also, as an option, run the decay method. The control principle is the following (Foulard et al., 1982):

At regular time intervals, Δt, the effective concentration, C_i, is measured in each room. The quantities $u_i(j\,\Delta t)$ of tracer gas injected in room number i at time $j\,\Delta t$ is then computed by minimizing the quadratic form:

$$J = \sum_{j=0}^{\infty} \underline{e}^T(j\,\Delta t)\,\underline{\underline{Q}}_e\,\underline{e}(j\,\Delta t) + \underline{v}^T(j\,\Delta t)\,\underline{\underline{Q}}_v\,\underline{v}(j\,\Delta t) + \underline{u}^T(j\,\Delta t)\,\underline{\underline{R}}\,\underline{u}(j\,\Delta t) \qquad (1)$$

where

$\underline{e}$ = the error vector, the components of which are the differences between the effective concentration in room i, $C_i(j\,\Delta t)$ and the target concentration $C_{i,o}$:

$$e_i(j\,\Delta t) = C_i(j\,\Delta t) - C_{io}$$

$\underline{v}$ = the time integral of $\underline{e}$: $v_i(j\,\Delta t) = v_i((j-1)\,\Delta t) + \Delta t\, e_i$

$\underline{\underline{Q}}_e$, $\underline{\underline{Q}}_v$ and $\underline{\underline{R}}$ are weighting matrixes, properly chosen to ensure a quick but stable control.

T indicates the transposed vectors.

Minimizing J gives the control matrix $\underline{\underline{L}}$, $\underline{\underline{M}}$, and $\underline{\underline{N}}$, which depends on the volumes V_i of the rooms, the target concentrations, the weighting matrix, and a set of estimated air change rates for each room. The vector $\underline{u}(j\,\Delta t)$ containing the tracer gas quantities to be injected is then:

$$\underline{u}(j\,\Delta t) = -\,\underline{\underline{L}}\,\underline{C}(j\,\Delta t) - \underline{\underline{M}}\,\underline{v}(j\,\Delta t) + \underline{\underline{N}}\,\underline{C}_o \qquad (2)$$

This algorithm is close to a proportional-integral control method, which is known to give a good regulation quality (Bohac et al. 1985) It takes into account the interaction between rooms, but this capability was not used in this work, the control matrix L, M, and N being computed as if the rooms were independant.

CESARVAX is the FORTRAN code used to compute the control matrices. Air change rates (estimated or obtained in a first "decay" experiment) as well as room volumes are used as input parameters to that code. Finally, AUBE interprets the data files created by CESAR and gives graphical and numerical results.

AIR CHANGE SURVEY IN A ONE FAMILY HOME AT APPLES

Purpose of the Survey and Description of the Building

A 12-day survey was conducted in a three-storey, single-family home located in Apples, Switzerland. The main purpose of this survey was to investigate the air infiltration in a home having many interconnected rooms on several storeys as well as to test CESAR in the field. This home is built on six half levels (Figure 1). It has a heated volume of 530 cubic meters (19'000 ft^3) and 10 heated rooms that are interconnected with respect to air change. Airflows occur between the 10 rooms since they all open to the staircase through open or loose-fitting doors.

The building has masonry walls with an external 4 cm (R 7) fiberglass insulation. Some exposed walls were retrofitted with an additional 4 cm internal insulation (total R 13). The windows are double glazed with weatherstripped wood frames, and the roof is frame wood including 14 cm fiberglass insulation (R 20). The toilets have a vent stack, and a manually controlled fan is used in the kitchen. As usual in Europe, there are traps on any plumbing fixtures. In the other rooms, natural ventilation occurs through leaks and open windows. The kitchen and the living room have wood stoves, which are occasionally used. Usually, heat is provided by a central heating system through warm water radiators.

The building is occupied by two to four adults and their habits did not change during the survey. They recorded the important events (closing and opening windows, number of occupants, etc.) in a diary. The structure of the building (high spaces, interconnected rooms) as well as the inhabitant behavior (opening doors and windows) brought to this experiment some difficulties which were interesting for testing the apparatus and the monitoring software.

Measurements

The 10 measuring channels of CESAR were used for the heated rooms. Five other nonheated rooms, such as the cellars, were not measured. Hence the air change between the heated space and the outdoor <u>or</u> unheated space was monitored.

Measurements were made using the "constant concentration" method between October 24 and November 7, 1984, and the data were recorded in eight-hour files on a floppy disk. During this period, the wind velocity (taken 1 m over the top of the roof) was very low, always less than 5 m/s (2.5 knots) with an average of 1 m/s (0.5 knot).

Interpretation Method

Because of the large air change rate variations that occur in inhabited dwellings, it is fairly difficult to maintain a constant tracer gas concentration level. Even with the sophisticated control system of the CESAR apparatus, small variations cannot be avoided. The measurements were interpreted with Equation 8, giving the volume W of indoor air lost from time t_1 to t_2. This equation is obtained the following way: in a room i of an N-room building, the room volume being V_i, in which a flow of tracer gas $q_i(t)$ is injected, the conservation of tracer gas gives a first set of N equations (Perera 1982):

$$V_i \frac{dC_i}{dt} = q_i + \sum_{j=1}^{N} (C_j Q_{ji} - C_i Q_{ij})(1 - \delta_{ij}) - C_i Q_{io} + C_o Q_{oi} \qquad (3)$$

<u>where</u>

C_j = the tracer gas concentration of room j (C_i for room i)

Q_{ji} = the air flows from room j to room i. Indice j is for the rooms connected to the room i and o for the outdoor air.

δ_{ij} = the Cronecker symbol, equal to 1 if i=j and 0 otherwise.

Another set of N equations is given by the conservation of air mass:

$$Q_{oi} - Q_{io} + \sum_{j=1}^{N} (Q_{ji} - Q_{ij})(1 - \delta_{ij}) = 0 \qquad (4)$$

Equations 3 and 4 can be combined:

$$V_i \frac{dC_i}{dt} - q_i = Q_{oi}(C_o - C_i) + \sum_{j=1}^{N} (C_j - C_i) Q_{ij}(1 - \delta_{ij}) \qquad (5)$$

and give a set of N equations. If, by measurements, all the concentrations C_i, their time derivatives and the volumes V_i are known, N^2 unknowns remain, which are the air-flows Q_{ji} ($i \neq j$), and Q_{oi}. As Sherman et al. (1980) pointed out, the best way to obtain N sets of N equations is to use N different tracer gases.

That is not the case here, but the target concentrations in the various rooms being the same, the effective concentrations can be assumed to be all equal.

Hence, assuming also $C_o = 0$, Equation 5 gives:

$$V_i \frac{dC_i}{dt} = q_i - C_i Q_{oi} \qquad (6)$$

Each Equation 6 can be solved by itself. Dropping the indices for clarity and rewriting Equation 6, we get, for each room:

$$Q = \frac{q}{C} - \frac{V}{C}\frac{dC}{dt} \qquad (7)$$

If the concentration is exactly constant, the solution is very simple. In practice and in inhabited rooms, it is however not the case and the time derivative may not be negligible.

Equation can be integrated between the times t_1 and t_2, giving the volume of air comimg from the outside into the room during that time interval :

$$W = \int_{t_1}^{t_2} \frac{q(t)}{C(t)}\, dt - V\,(\ln C(t_2) - \ln C(t_1)) \qquad (8)$$

The integral is evaluated on the discrete measurements by the trapeze method. Such an equation was applied to each room as if these rooms were independant and the total amount of fresh air coming into the entire dwelling is obtained by summation. From this quantity, the average air flow and air change rates can be easily evaluated.

<u>Results</u>

Figure 2 shows the mean air change rate for the entire dwelling averaged over eight-hour intervals. It is obvious that the behavior of inhabitants can lead to very strong variations of the air change, but no obvious correlation appears between the airflow rate and the window openings.

Separate sums of the airflow rates can be made for two different configurations: one when all the windows are closed, and another when only one or two windows, located in the bedrooms on the upper level are open (inhabitants sleep there with open windows). Histograms of the air change rate in these two configurations are shown on Figure 3.

The total mean air change rate, for the entire heated space during the whole survey, is 0.49 /h. This air change rate decreases to 0.37 /h for the time periods when all the windows are closed and increases to 0.55 /h if one or two bedroom windows are open. It is, of course, larger when more windows are open.

Figure 4 shows the air infiltration flowrates for each room. The main infiltration occurs in the kitchen, which is on the lower level and has large glazed sliding doors. It is obvious that, when all the windows are closed, the fresh air comes into the house mainly in this room. If one or two bedroom windows located at the top of the building are open, additional fresh air comes into these rooms, as well as into the living room and the staircase (entrance), located at a lower level and interconnected by a large aperture without any door.

The infiltration in the bathroom, having only a skylight opening, looks very low, since a large quantity of indoor air, already containing the target concentration level of tracer gas, comes from the staircase through a loose-fitting door that is often open and goes out through leaks in the skylight. It must be said that no condensation damages or mold growth are observed in this bathroom, so its air change rate must be sufficient; but this air comes mainly from the building.

The total rising airflow caused by stack effect is more obvious when looking at particular records, as in Figure 5. When the window of the parents' bedroom is closed, effects can be seen in five other rooms located either at the same level as the bathroom (channel 3), at the lower level of the kitchen (channel 7), and in between as in the staircase (4), the living room (9), and knitting room (6). Qualitatively, it is clear that the fresh air enters the dwelling through the kitchen and the living room and goes out through the upper rooms. In the absence of wind, the stack effect is clearly dominant.

Figures 6 and 7 show the wind speed and outdoor temperature during the survey. No significant correlation can be found between these parameters and the total airflow rate, even if the data are separated in two classes: closed and open windows. This is because the wind and stack effects are combined and a model more sophisticated that a simple correlation coefficient has to be used. Secondly, the behavior of the inhabitants was not completely measured, and some door or window openings, changing the airflow rates, were not noted in the diary. Finally, temperatures were unfortunately not recorded near the monitored home but taken at the nearest meteorological center, which is the LESO building located 12 km away. In the new version of the apparatus, the temperatures are now recorded.

CONCLUSIONS

It is shown that, in multi-room inhabited buildings, the constant concentration method used during a lengthy survey makes it possible to obtain the total air infiltration, despite strong variations of the airflow rate. With only one tracer gas, the infiltration rates for each room can be measured, but the exchanges between rooms can only be estimated qualitatively.

The air infiltration is not directly correlated with either the wind speed or with the outside temperature, but a stack effect can nevertheless clearly be seen. One window opening may have an effect through the whole building, and a significant change in infiltration is caused by inhabitant behavior.

This experiment has shown that some improvements should be made on the apparatus. More development of the tracer gas concentration control system will be undertaken, taking into account the exchanges between rooms and the stack effect, to avoid the overshoots such as those seen on channels 2 and 7 in Figure 7. Moreover, it was clear, after that experiment, that more parameters have to be automatically recorded (e.g., window and door openings, fan and stove operation, etc.) to explain the observed airflows with a theoretical model (e.g., Sherman and Modera 1984).

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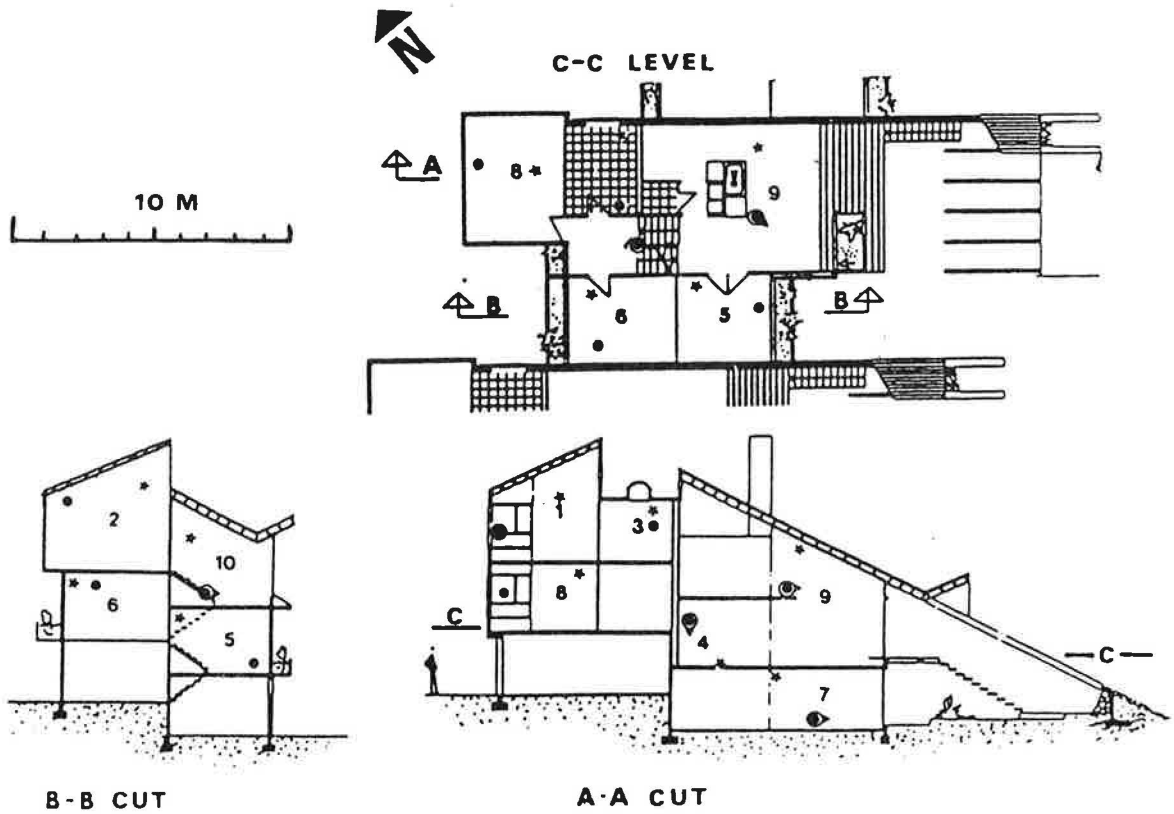

Figure 1. Sketch of the middle level Apples family home and vertical cuts showing the interconnected half levels. (1) Yve's bedroom, (2) parents' bedroom, (3) bathroom, (4) entrance and stairs, (5) "fumoir;" (6) knitting room, (7) friend's room, (8) kitchen, (9) living room, (10) Guy's bedroom. Circles mark the tracer injection points; arrows show the direction of airflow from the mixing fans. Sampling points are marked by stars

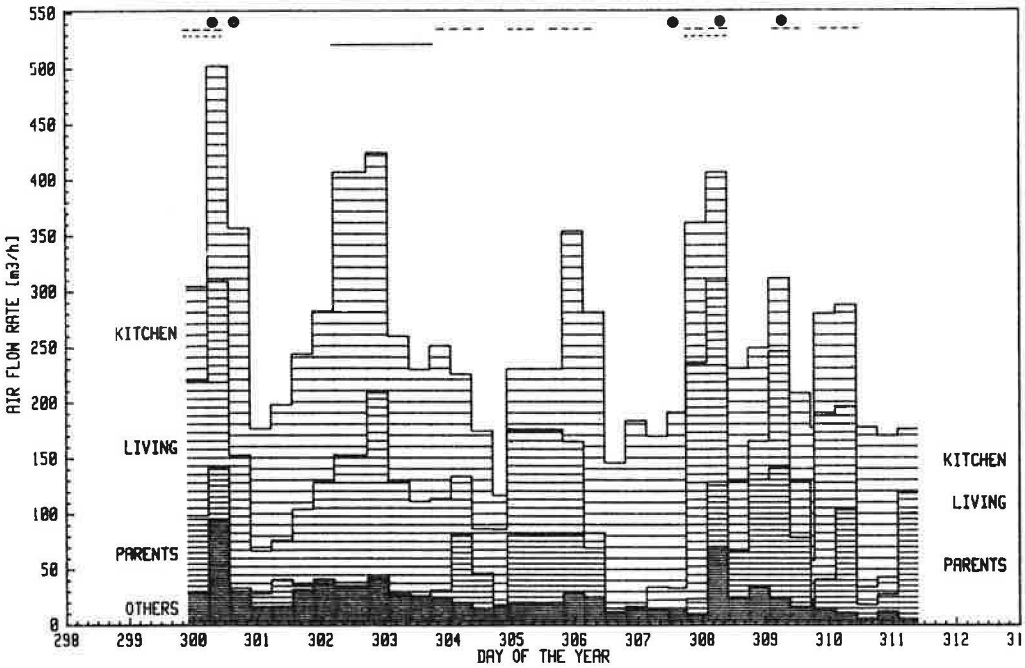

Figure 2. Airflow rate for the rooms experiencing the highest air infiltration rate as measured by the constant concentration method and averaged over every 8-hour interval. ●: large ventilation of the dwelling by opening glazed doors for 15 minutes; ···: window open in Yve's room; ——: open sky window in the bathroom; ---: window of parents' bedroom open during the night

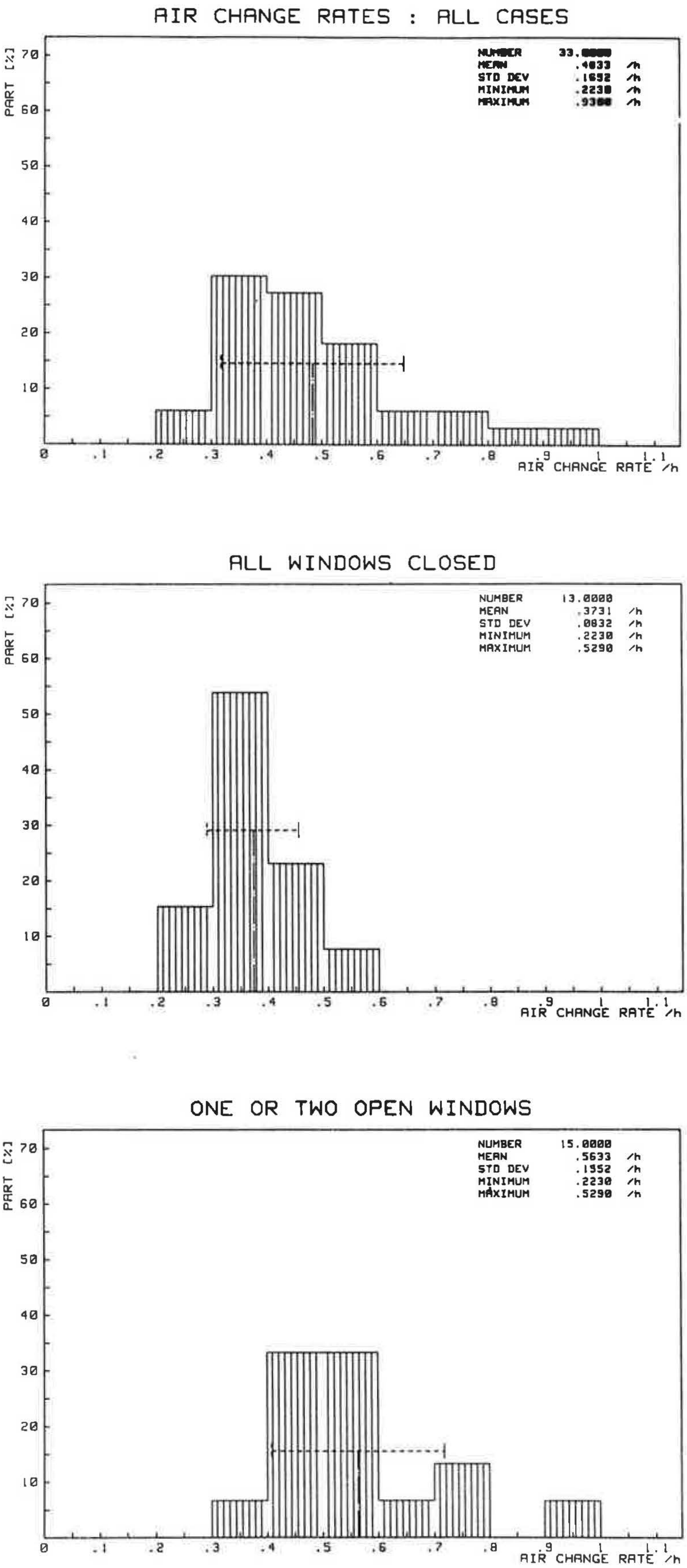

Figure 3. Histograms of the average air change rates for the whole building. Top: all values; middle: values measured with all windows closed; bottom: values measured with one or two windows open

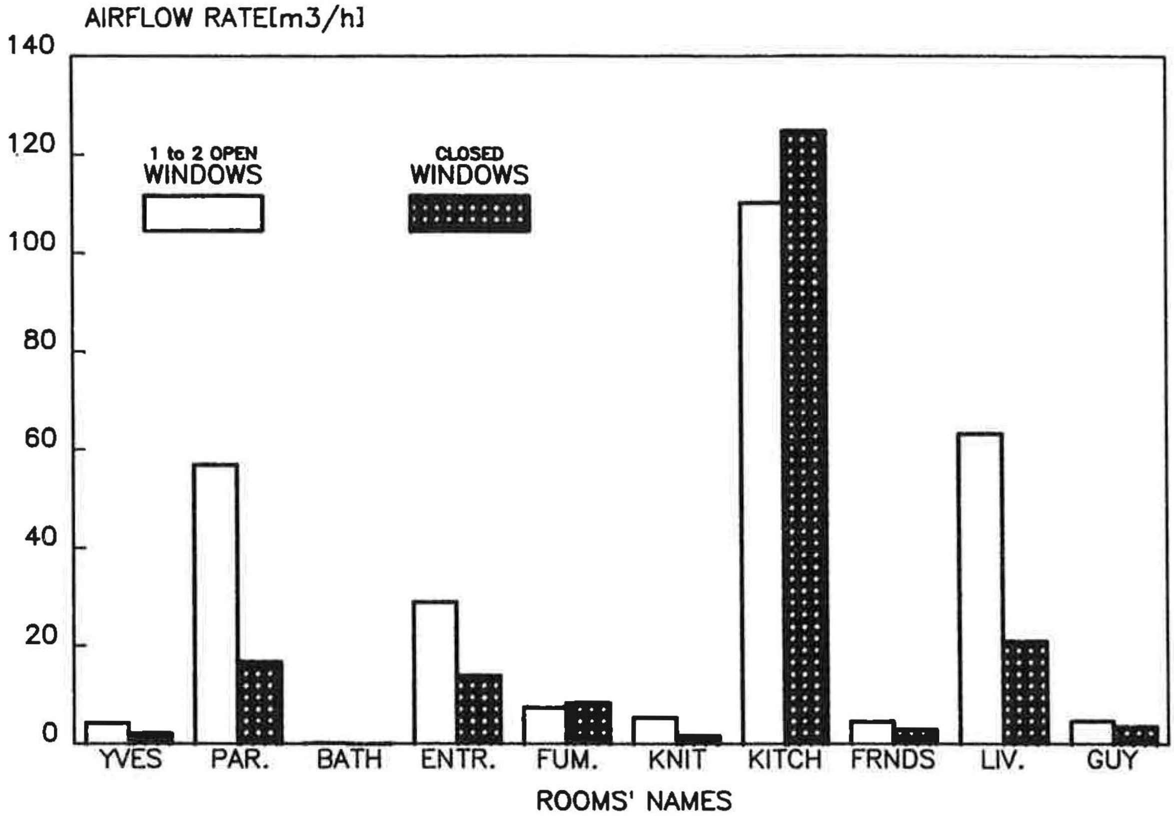

Figure 4. Comparison of the total airflows of each room, averaged over the whole survey. The open windows are upper-level bedroom windows

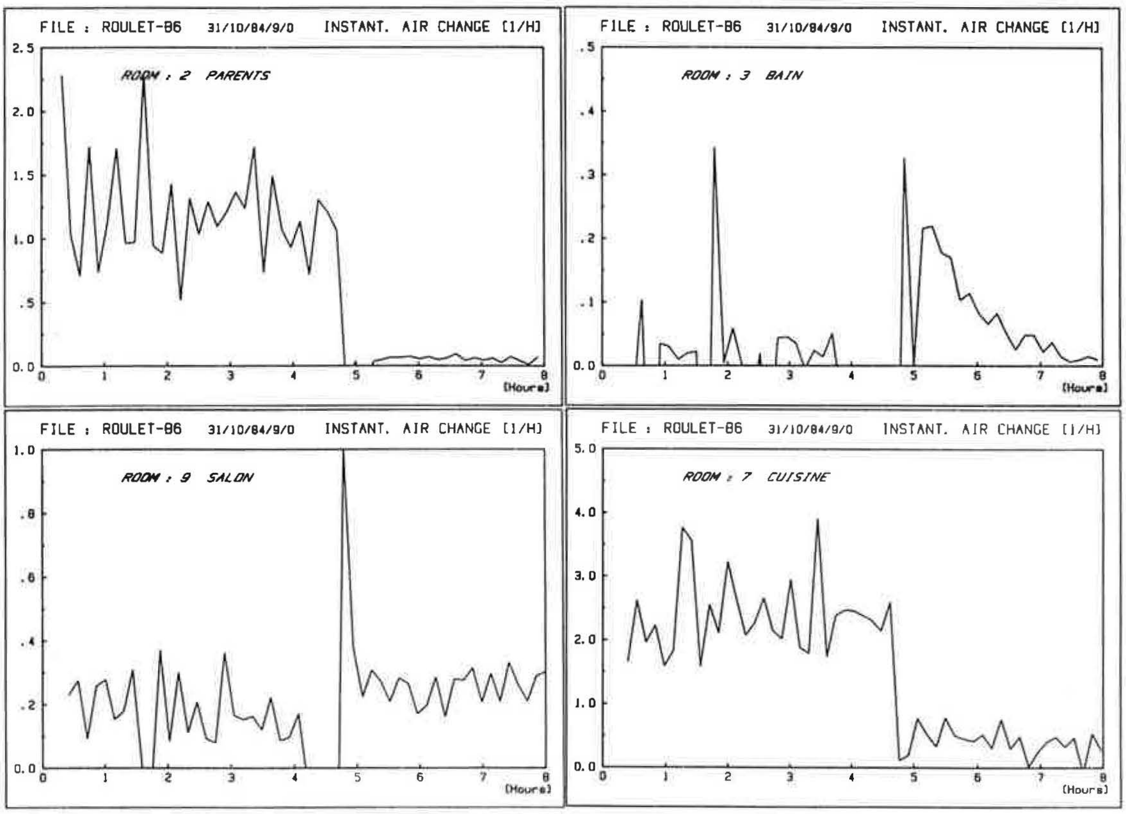

Figure 5. Air change rate vs. time for four interconnected rooms. This record shows the effect of closing the window of the parents' room (top story) 4.7 hours after the beginning of that measurement on the air change in the bath (BAIN) at the same story, in the living room,(SALON), and in the kitchen (CUISINE)

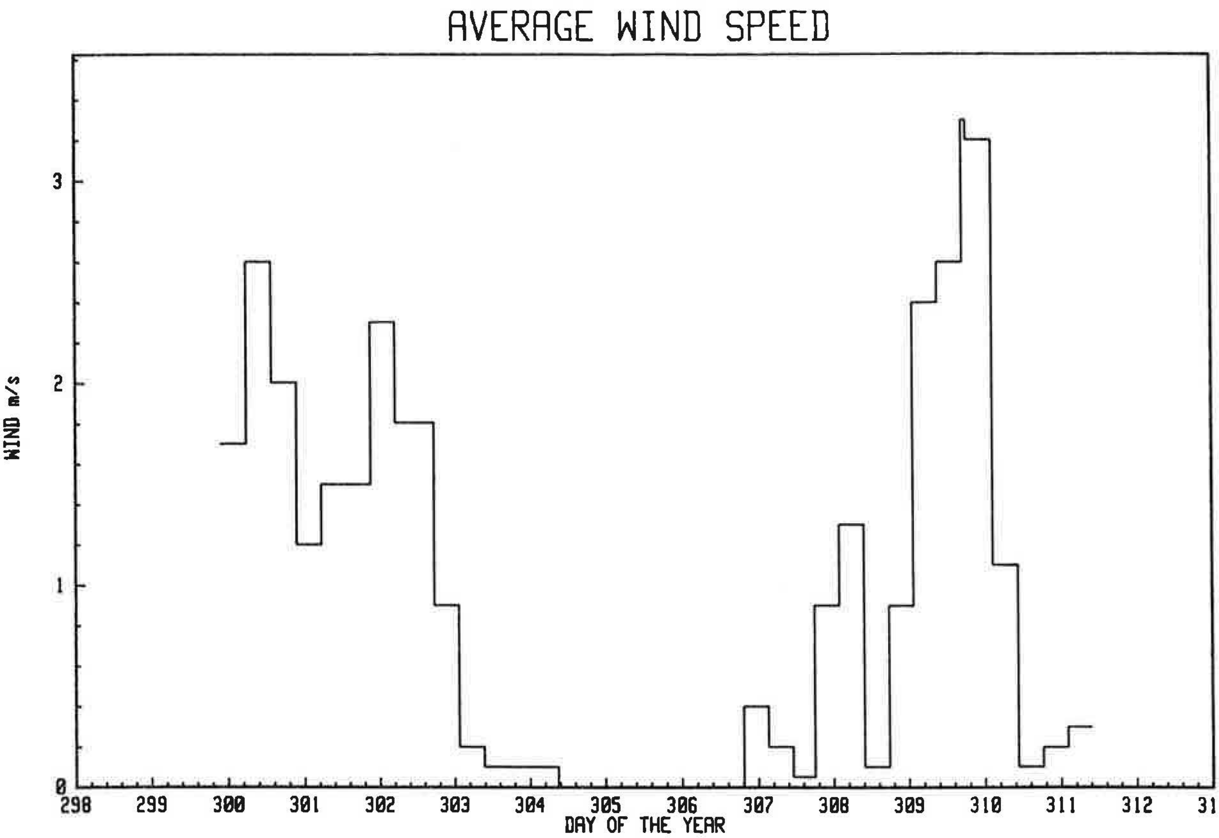

Figure 6. *Average wind speed, taken 1 m over the top of the roof, during the survey*

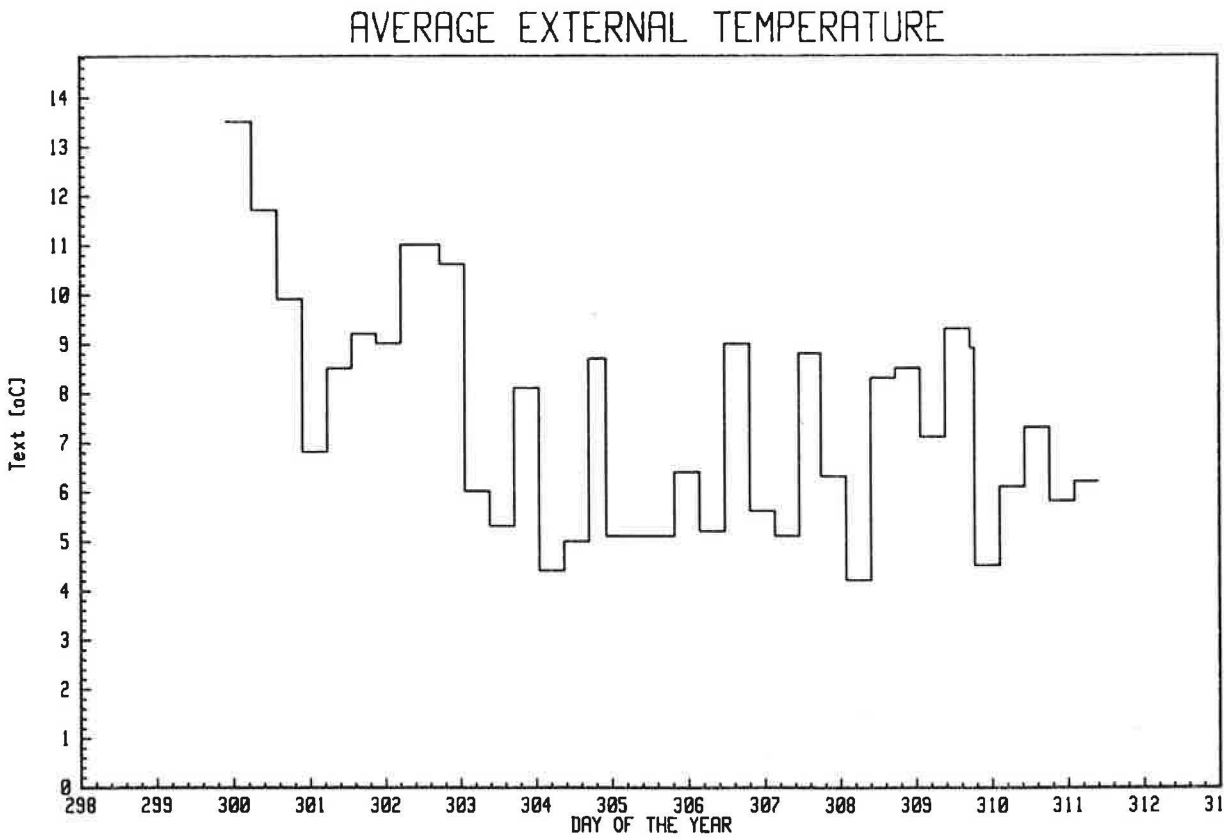

Figure 7. *Average outdoor air temperature at the LESO building during the survey*

Discussion

M.V. JOKL, Technical University of Prague, CZECHOSLAVAKIA: What kind of tracing gas was used and why?

C. ROULET: Nitrous oxide (N_2O) was used as a tracer gas for the reason mentioned in the paper. Moreover, this gas is easily measured continuously by infrared absorption. This condition is necessary to achieve a constant concentration.

JOKL: What is the quantity of fresh air related to one person (number of members of the family)?

ROULET: The quantity of fresh air related to one person can be calculated from the indications given in the paper. The average air change rate is 0.49/h and the volume of the house is 530 m^3, yielding about 260 m^3/h of fresh air for two to four people (say two people on the average), or 130 m^3/h person.