AIR MOVEMENT & VENTILATION CONTROL WITHIN BUILDINGS

12th AIVC Conference, Ottawa, Canada
24-27 September, 1991

PAPER 4

SINGLE SIDED VENTILATION

Authors: Jacobus van der Maas
LESO-PB (Lab. d'Energie Solaire et de Physique du Bâtiment)
EPFL (Ecole Polytechnique Fédérale de Lausanne)
CH-1015 Lausanne, Switzerland

Dominique Bienfait
CSTB (Centre Scientifique et technique du Bâtiment)
F-77421 Marne-la-Vallée, France

Luk Vandaele
BBRI (Belgian Building Research Institute)
B-1342 Limelette, Belgium

Richard Walker
BRE (Building Research Establishment)
WD2 7JR Garston, United Kingdom

SYNOPSIS

Single sided ventilation was one of the topics of the research project "Air flows through large openings in buildings," which is part of subtask 2 of the IEA/ECB Annex XX (Optimization of Air Flow Patterns Within Buildings). The scope of this project was to test the range of validity of available algorithms to calculate heat and mass flow through large openings, and where possible to develop new ones.

We report on four new full scale experiments that were designed to measure the influence of wind on the ventilation and/or heat loss rates through single large openings: a) test-house with horizontal slit opening, set-up to measure internal pressures and the effect of air-compressibility (CSTB, France), b) attic with window ajar, set-up to measure long term ventilation rates with varying wind and temperatures (BBRI, Belgium), c) fully open window, set-up to measure ventilation rate and cooling as a function of time (BRE, UK) d) fully open window, set up to measure cooling as a function of time (EPFL, Switzerland).

The ventilation rates are measured with a tracer gaz technique. A new method is proposed to determine ventilation energy loss rates, by comparing the time variation of air and wall temperatures with a simplified dynamical thermal model.

New results include (i) the contribution of air compressibility to the single sided ventilation rate can be considerable in particular for relatively small openings to large volumes, (ii) wind induced two-way flow is not only caused by pressure fluctuations but a systematic variation of the pressure coefficient over the opening is observed (iii) long term observation of the ventilation rate scaled with the wind velocity (iv) ventilation heat loss rates after opening a window are described by a simple model allowing a better estimate of the energy consequences of inhabitant behaviour (v) an effect of (steady) wind on the airflow in a large opening is observed. Finally, uncertainties in single-sided ventilation appear to be dominated by uncertainties in the characterization of the local wind at the opening.

LIST OF SYMBOLS

ACH	Air change per hour (1/h)
ACR	Air change rate (m^3/s)
A	opening area (m^2)
b	wall thermal effusivity $b=\sqrt{\lambda\rho c}$
C_1	wind coefficient
C_2	stack coefficient
C_3	turbulent coefficient
C_d:	Discharge coefficient
Cp	heat capacity of air
Cs	area fraction for heat transfer
f	frequency (Hz)
F	non dimensional ventilation
g:	Acceleration of gravity (m/s^2)
H:	Height of the opening (m)
P,p:	Pressure (Pa)
Q:	Volume flow rate (m^3/s)
T:	average absolute air temperature (K)
T_{in}	inside air temperature (C)
T_{out}	inside air temperature (C)

v:	velocity (m/s)
V	Volume (m^3)
W:	Width of the opening (m)
ρ:	Air density (kg/m3)
Φ	Heat flow density (W/m^2)
δp,P	pressure variation (Pa)
ΔT	inside outside air temperature difference (K)

1. INTRODUCTION

The general scope of Subtask 2 of the the Annex XX is to help the development of multizone simulation programs. Part of the work concerned the development of new algorithms and one of the research topics chosen for this international cooperation was the study of flow patterns through large openings. In this paper an overview is given of the obtained results on external openings (i.e. single sided ventilation), and we refer to another paper in this conference for new results on internal openings [1]

The description of airflow through large external openings is basically the same as for internal openings as long as there is no wind. Therefore previous research on large external openings was mainly concentrated on wind effects [2], and a main goal of the new research has been to improve the knowledge of wind effects on ventilation.

A new topic for single sided ventilation is the evaluation of the energy consequences of inhabitant behavior. Inhabitants open windows and doors, and leave them open for some time before closing. The research project inhabitant behaviour for example [3], provides opening time intervals and therefore an algorithm was required for the calculation of both heat and mass flow as a function of time.

Literature reviews [2,4,5] formed a basis for the planning of the experiments. In addition to stack flow, air flows induced by *fluctuating wind pressures* and *eddy circulation* have been observed in single-sided ventilation. Two types of problem have then to be distinguished

(i) the prediction of fluctuating wind pressures at the position of the window from a knowledge of the geometry of the building, its surroundings and the wind characteristics some distance from the building (e.g. meteorological station).

(ii) the relation of these local fluctuating wind pressures to the total air exchange through a single opening.

The emphasis in the present studies is on the second type of problem.We report on four new full scale experiments involving four laboratories in Europe:

- BOUIN test-house with horizontal slit opening, set-up to measure internal pressures and the effect of air-compressibility (CSTB, France),
- GENT-attic with window ajar, set-up to measure long term ventilation rates with varying wind and stack effect (BBRI, Belgium),

- BRE-office with fully open window, set-up to study the effect of wind on ventilation and heat loss rate as a function of time after opening a window (BRE, UK)
- EPFL-offices with open window, set up to study the energy consequences of user behaviour by measuring ventilative cooling as a function of time and for rooms of different mass (LESO-PB, Switzerland).

In the next section, §2, we present the measurement set-ups, in §3 we discuss the models used for the interpretation of the data and in §4 the experimental results are presented and discussed. We conclude with a conclusion and recommendations for future research.

2. EXPERIMENTAL

2.1 SET-UP: CSTB (Marne-la-vallée, F)

The test house at Bouin (Figure 1) is a single zone building on an exposed site near the Atlantic coast. The volume of the test house is 93.6m3. The equivalent air leakage area of the house was measured and is less than 5cm2, which is small compared to the studied ventilation openings of 100 and 200cm^2. A key feature of this site is the mounting of the building on a turntable. This means that it can be rotated during an experiment, keeping the same side to the wind throughout a test.

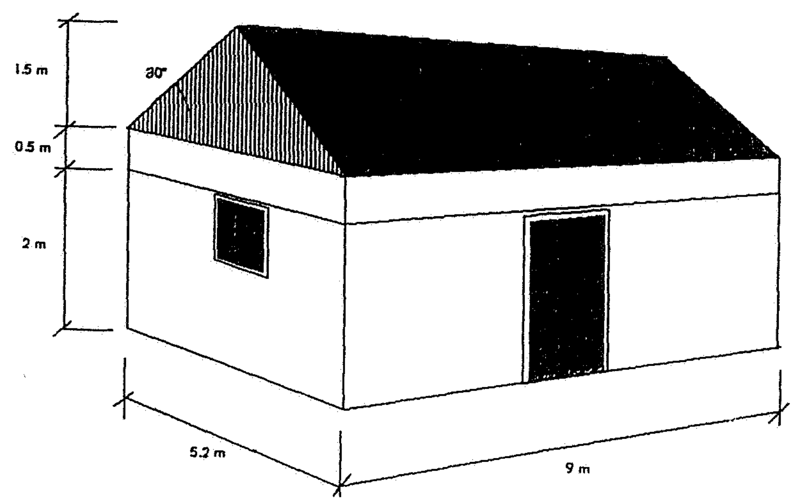


Figure 1. BOUIN test house.

A single opening was introduced into the building envelope and maintained either windward or leeward. Two sharp edged slots of 40cm width (2.5 and 5cm height, 1cm thick) were investigated. The ventilation rate is obtained from the tracer gas concentration decay measured in the room. The wind-induced external pressures, internal pressures, wind speed and direction and tracer gas concentration are all measured simultaneously, at a rate of 5 Hz. Each test consists of a 10 minute mixing period, with the opening sealed, and then after removing the seal, a 20 minute decay period. The tracer gas concentration is measured from five different sampling points in the room, to ensure the result is representative of the whole room. These points are 1.5m above the floor, and linked through a manifold to the gas analyser. During the mixing period, small fans are used to provide complete mixing of the tracer gas.

The wind pressure is measured close to the opening. This pressure is equal to the difference between the total pressure and the external static pressure. The internal pressure is also measured with respect to this same external static pressure. The pressure was measured at eight points within the opening (Figure 2), both inside and outside the building, allowing the direction of flow to be known locally. Full details of the site and the measuring equipment used can be found in [15].

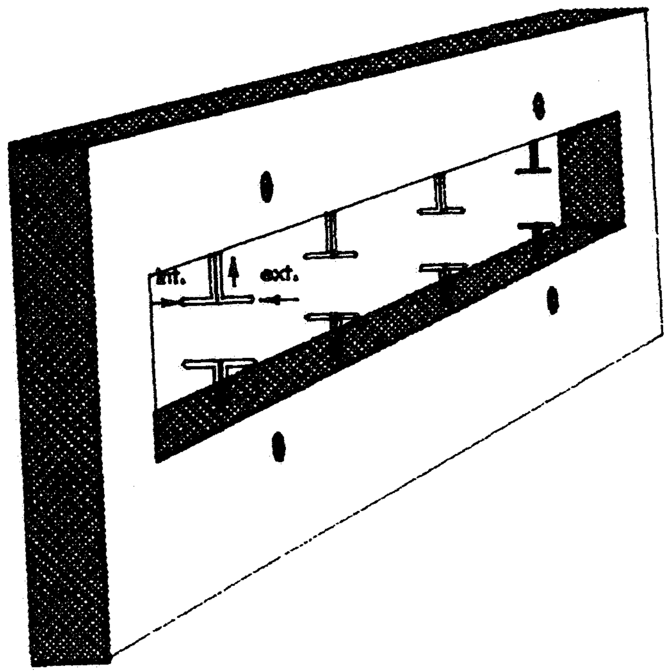


Figure 2. BOUIN: The four tapping points located in the frame are used for the determination of average wind pressure. The eight tapping points in the aperture are used for the investigation of two-way flow

2.2 SET-UP: BBRI (Limelette, B)

A single sided ventilation experiment was set up in an attic space of a 4-storey row house in the city of Gent (volume ca 28 m3). The highly insulated roof contains a 'Velux' roof window in both North and South slopes (width 1.25m. height 0.80m) as shown in Figures 3 and 4. A pressurisation test gave an airtightness level of 20 ACH at 50 Pa. Air change rates were measured with a constant injection tracer gas technique using N_2O as a tracer and an injection rate of 1 ml/s. Air samples were taken at 28 points. The room air temperature is measured at 12 points by means of thermo couples. The outdoor climate was measured through, the outdoor temperature, the windvelocity and the wind direction at ca. 2m above the roof top.

Reported are the results of three single opening experiments: one with the South window (tophinged) opened over 7.5 cm, the second with the North window (midhinged) open over 5.5 cm (both on top and bottom), and a third experiment on a ventilation slit at the top of the North window (120 cm wide, 2 to 3cm high). In the latter slit configuration, pressure tubes were mounted outside and at the left and right part of the opening in order to test the validity of the assumption of a single pressure coefficient for the opening.

As illustrated in Figure 5, pressure differences were measured over both façades (N–S), inside-outside over both windows and outside left-right on both windows. The pressures, windvelocity and direction were measured about every 4 minutes, while the concentration and temperatures were measured every 40 minutes.

Air change rates and climatic parameters were monitored during a three week measuring period.

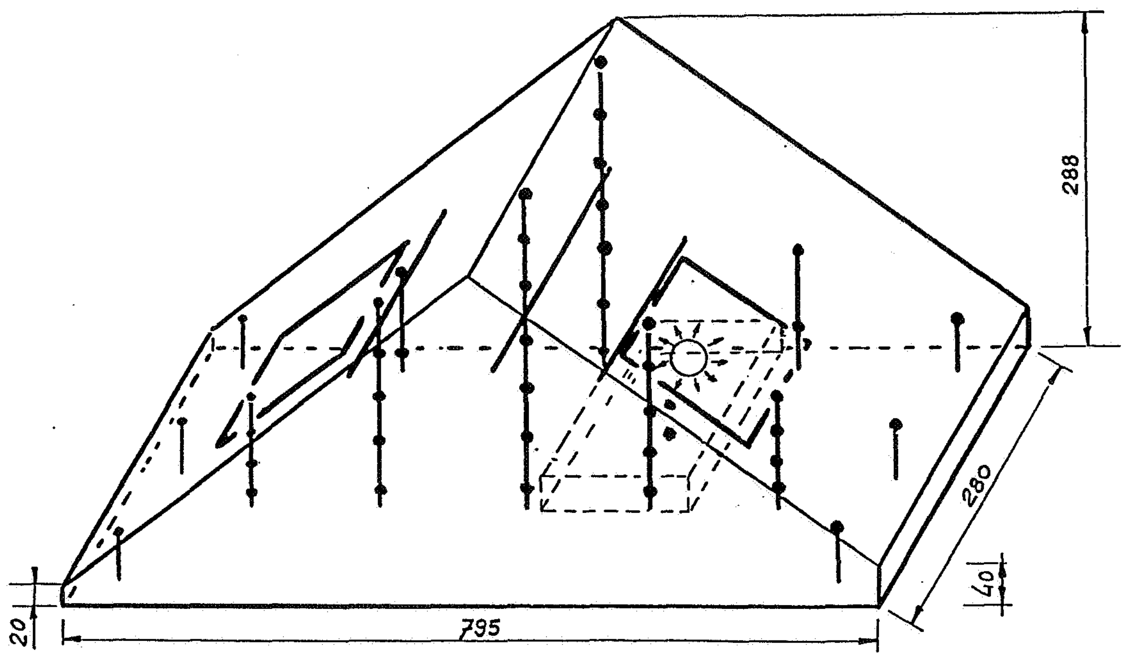


Figure 3. The attic in Gent.

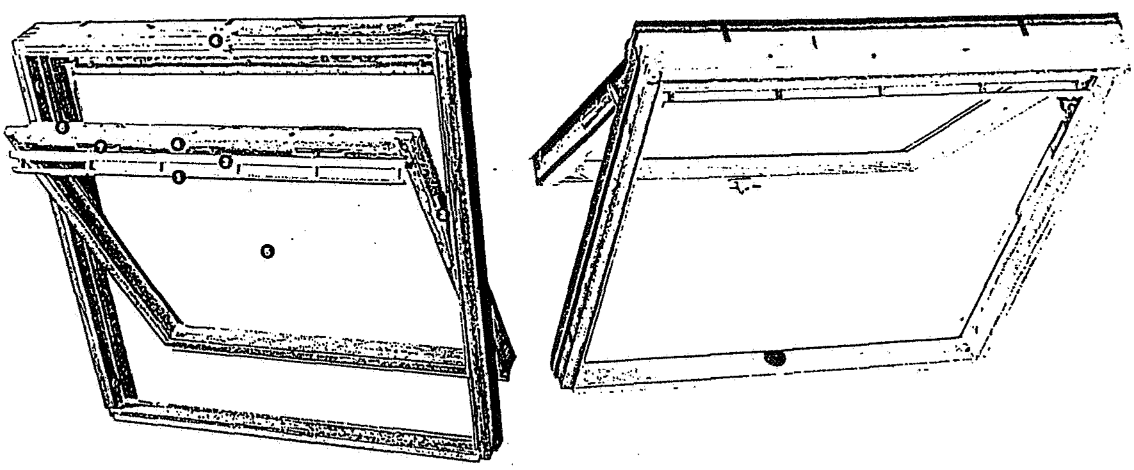


Figure 4. Roof window in north slope is midhinged (left) and the roof window in south slope is tophinged (right).

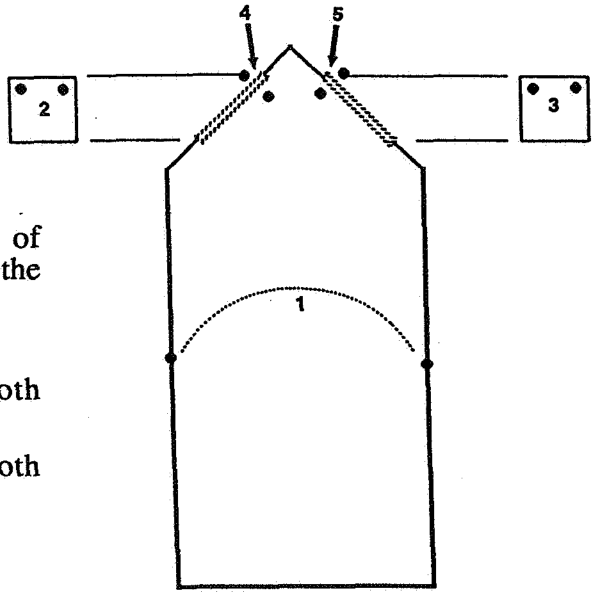


Figure 5. Measurement of the pressure differences in the attic in Gent:

- over both façades (N–S)

-.inside-outside over both windows

- outside left-right on both windows..

2.3 SET-UP: BRE (GARSTON, UK)

A series of experiments have been performed to measure the effect of wind on the time dependent ventilation rates and heat loss rates after the opening of a window. The data have been used to test a new single sided ventilation algorithm that includes both heat and mass transfer. When validated this algorithm would allow to make more realistic estimates of the energy consequences of user behaviour.

Measurements were carried out in an office room located at the corner on the top floor of a four-storey, naturally ventilated building (see Figure 6). The room comprised one internal wall and three external walls with glazing to their full height, and a false ceiling with poorly sealed roof vent above. Two adjacent glazed walls (east- and north-facing), and also the ceiling, were made airtight. This ensured single-sided ventilation via the remaining external wall (south facing) which incorporated five side-mounted casement windows evenly spaced along its width . The room volume is 242m^3 and the total wall surface area is 263m^2.

Ventilation rates were measured using the constant injection method using SF6 as a tracer gas. The precise concentration (parts by volume) is related to the ventilation rate Q m3/s as follows Q = s/C, where s is the injection rate.

Air samples were taken at eight measurement locations (Fig.6) within the room. Air temperature was recorded with thermistor probes at two locations at 1.1 m height, and surface temperatures were also measured using similar probes. Two ultrasonic anemometers were fixed into the aperture of the central window. The window measured 1.4 m high by 0.64 m wide, although the false ceiling partly obscured the upper 0.28 m (see Fig. 6). These anemometers measured three orthogonal velocity components at intervals of 12 ms, which are averaged over intervals of 0.25s and recorded. They were aligned to record one component perpendicular to the plane of the window aperture, and two within the plane.

A weather monitoring mast (ht 10m) located approximately 100m to the south-west provided data on external wind speed, direction and air temperature, averaged over 15 minute intervals. The height of the lower edge of the open window was 12.3 m.

Concerning the measurement procedure, two electric fan heaters (total 5.4 kW) were switched on to preheat the room for a minimum of approximately 24 hours before each test. Initially the windows were firmly closed and the test was immediately preceded by starting the mixing fan and tracer gas delivery and sampling system.

The test began by switching off the fan heaters and fully-opening (to 180°) the central window. Tests proceeded for approximately two hours duration in all cases. Tests were carried out over a variety of external conditions.

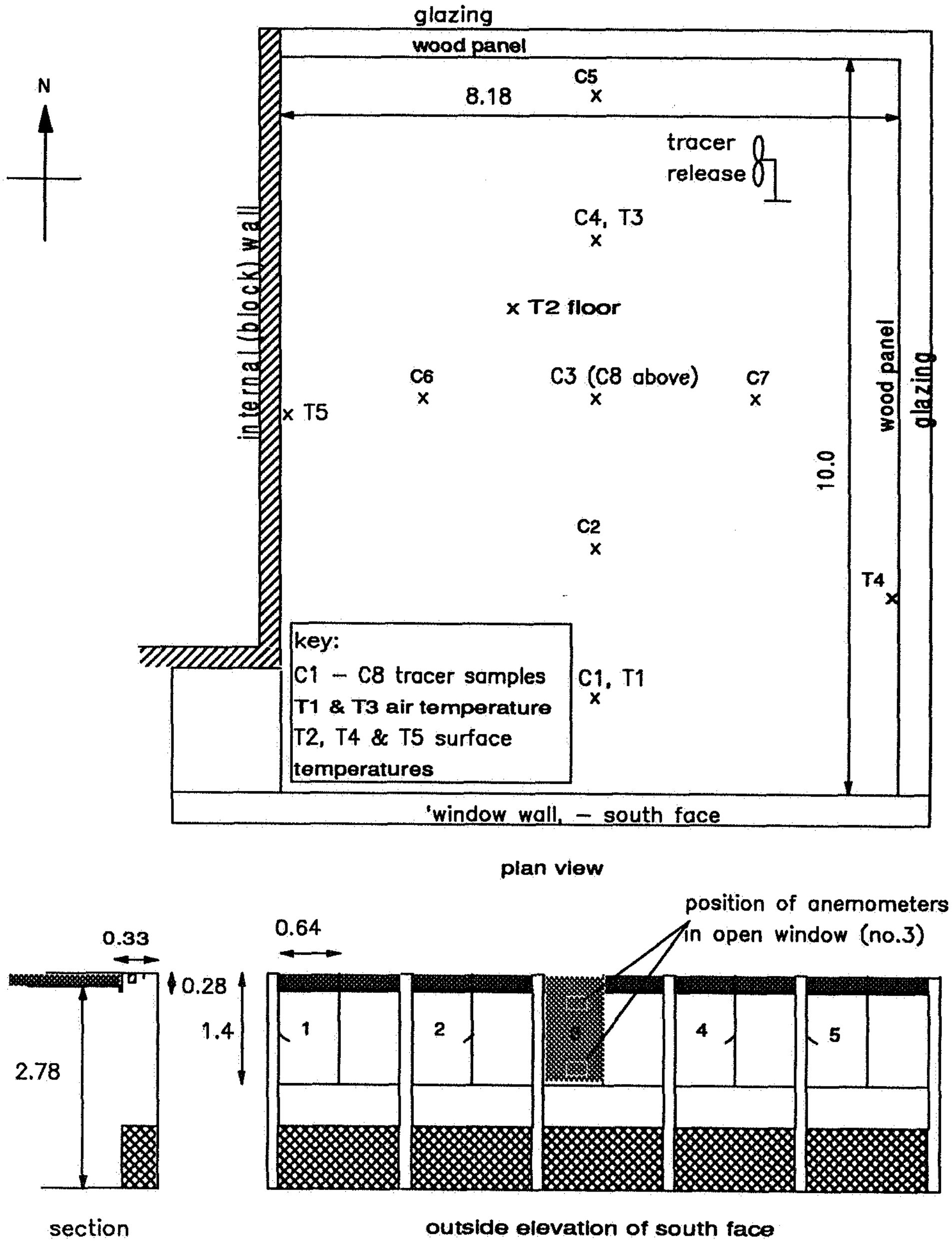


Figure 6. BRE testroom and measurement locations. The average thermal effusivity of the walls b=850 [J/ (m^2 K.$s^{0.5}$)]

2.4 SET-UP: LESO-PB (LAUSANNE, CH)

In a series of experiments performed at the LESO-PB, a newly developed algorithm coupling heat and mass transfer during single sided ventilation is tested on different rooms. The thermal characteristics of each room are determined in a separate heater test with the window closed.

The air velocity is measured with an omni-directional DISA anemometer, with a time constant <0.1s. Wall temperatures variations were detected by scanning the walls with a radiation infrared thermometer and the temperatures were measured with thermocouples. Velocity and temperature profiles were analogue recorded by mounting the probes on a motor-driven trolley moving in the opening.The inflowing cold air temperature was measured at the bottom of the window opening. The heat loss tests were performed at night to avoid solar heat gains through the south window.

Three rooms with vastly different thermal characteristics have been studied. We will consider here only the a room of the LESO building 40m^3 volume and 70m^2 wall surface (see Figure 7). The room is characterized by an average thermal effusivity of the walls of b=1000 [J/ (m^2 K.s$^{0.5}$)] with a 20% uncertainty, determined in a separate heater test with the window closed.

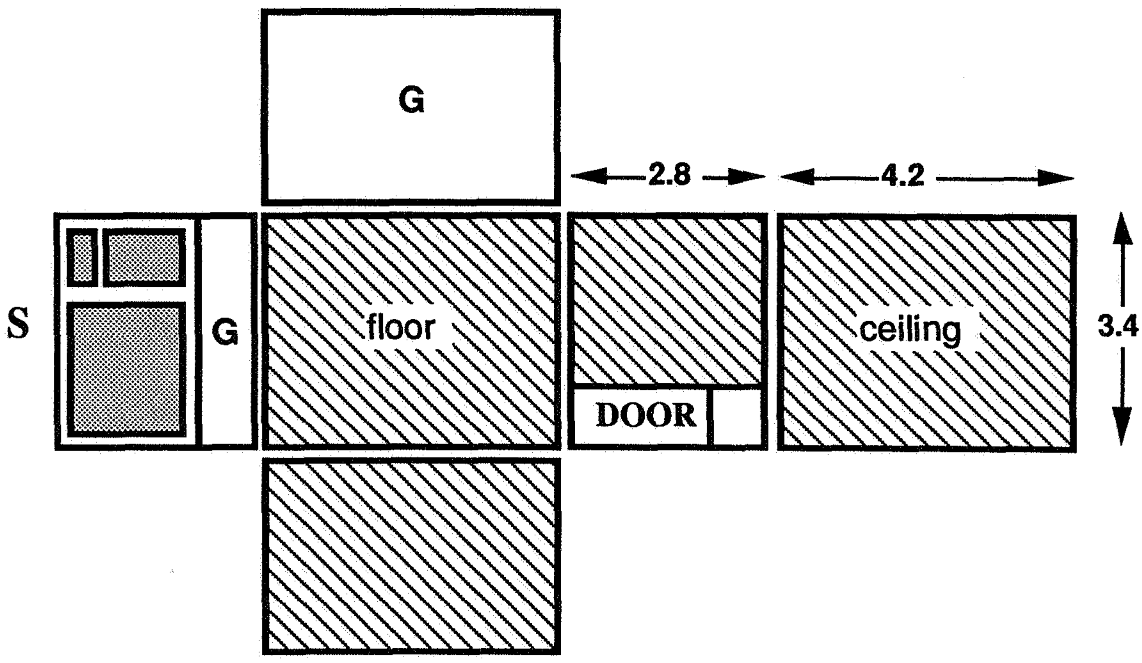


Figure 7. Floorplan of the LESO test room. The walls, floor and ceiling have 10cm glasswool insulation as a second layer. The first layer is 10cm concreet (dashed) and 1cm gypsum (G). The door is of wood. The windows have an U-value of 1.5W/m2-K. The maximum window opening is 0.85 by 1.05m^2 and the distance between the top of the opening and the ceiling is 0.7m. The width of the window could be reduced to 27cm by placing a wood board in the opening.

3. MODELING SINGLE SIDED VENTILATION

3.1 General

The ventilation rate (Q m^3/s) can be measured independently either with a tracer gas decay method or with a constant injection method.

The latter method is more suitable to measure high ventilation rates that vary in time. (Assuming complete mixing and slow variations in the ventilation rate the constant supply rate (s m^3/s) and the measured concentration (parts per volume) are related to the ventilation rate by Q=s/C).

In the case of single sided ventilation through a rectangular opening of area A, the air flowing in through one half of the opening must flow out through the other half at least when assuming mass conservation (no compressibility). This leads to the definition of an effective velocity in the opening v_{eff}

$$v_{eff} = \frac{Q}{(A/2)} \qquad (1)$$

3.2 Stack effect

The steady ventilation resulting from natural convection flow caused by air density differences (the stack effect) can be calculated with a simple model based on the Bernoulli theorem [1]. If the two interconnected zones can be considered uniform in temperature (the zone temperature variation over the opening height is relatively small), the stack flow is calculated for an opening (height H and width W) with

$$Q = \frac{1}{3} C_d WH \sqrt{\frac{g}{T} H \Delta T} = \frac{A}{2} v_{eff} \approx \frac{A}{2} \sqrt{0.0052\, H\, \Delta T} \qquad (2)$$

where ΔT is the interzone temperature difference. To obtain the numerical value a discharge coefficient C_d=0.6 is used.

It is interesting to note that this discharge coefficient takes two different effects into account :

(i) streamline contraction, which means that the effective opening area is smaller than A=WH

(ii) viscous pressure loss, which means that for a given pressure difference the velocity is lower than would be expected from the Bernoulli equation.

In the interzone experiments of reference (1) it was found that the C_d of equation (2) varies between 0.3 and 0.5. The measured velocities did not follow a parabolic profile, and the velocity calculated from the Bernoulli equation was systematically much larger than measured. For simplicity and for comparison with the existing literature we will yet use the overall discharge value C_d = 0.6 in expression (2).

3.3 Empirical description

Because ventilation increases nearly proportionally to the wind velocity and the opening area it is easy, in practice, to define a dimensionless ventilation parameter

$$F = \frac{Q}{A\, v_w} \tag{3}$$

Comparison with expression (1) makes clear that the maximum value of F is 0.5.

From windtunnel experiments of the single sided ventilation induced by turbulent wind, it is concluded that the pressure fluctuations in the plane of the window have a dominant influence [8] and in particular the eddies of the size of the window are important because they can completely penetrate into the space. Reference [8] concludes that for airflow parallel to the façade of the model F can be considered constant having a value of about 0.03, which is close to the windtunnel result found by Warren [9]. For other inflow directions Crommelin and Vrins [8] have found decreased ventilation, with a minimum value for an opening at the leeside.

De Gids and Phaff [6,7] investigating the consequences of opening one window on the internal climate of a number of apartment rooms, proposed an empirical formula

$$Q = \frac{A}{2}\sqrt{C_1\, v_w^2 + C_2\, \Delta T\, H + C_3} \tag{4}$$

and obtained by a least mean square fit the following values for the coefficients $C_1 = 0.001$, $C_2 = 0.0035$, $C_3 = 0.01$. The window heights were about 1m.

From the relatively high value of the turbulence term $C_3 = 0.01$, this fit suggests that for windvelocities smaller than 3m/s, or for a 1m high window temperature differences less than 3K, there is a lowest value for the ventilation parameter $F = 0.05$, caused by turbulent fluctuations.

Without the C_3 term, the value $C_1 = 0.001$, would correspond to a ventilation parameter $F = 0.015$, which is low, also comparing $C_2 = 0.0035$ with expression (2), the fit predicts a relatively weak stack effect.

While the spread in the data around the fit to equation (4) is considerable [6,7], this result is a very useful reference for new ventilation studies.

3.4 Fluctuating wind pressures

Cockroft and Robertson [10] studied ventilation with normal wind incidence, and proposed a theory to take pressure fluctuations into account and more recently, Haghighat [11] proposed a new model approach.

To understand the interpretation of the measurements presented in the next section the models will be qualitatively discussed.

A quick estimate can be made of the air change rate resulting from a fluctuating pressure at a single large opening of a volume V. We assume that the pressure variations are instantaneous, this means that the size of the opening does not limit the flow. For a change in pressure of δp (Pa), the air density changes by $\delta\rho = \rho\, \delta p/p$ and this causes an air flow of $\delta V \cong V\, \delta p/p$. Therefore fluctuations of frequency f(Hz) and amplitude δp would induce an in and outflow of air of

$$Q(\text{fluctuating}) = f\, V\, 2\, \delta p\, /\, p \tag{5}$$

This is the maximum value one can expect for a single frequency component of the external wind. As an example, taking a room of $100m^3$ and windpressure fluctuations at 1Hz and 20Pa amplitude, then $0.04m^3/s$ of air flows in and out. Assuming complete mixing this fluctuating windpressure would cause a total influx of fresh air of 1.4ACH.

In general there is a pressure drop over the opening, and for rapid fluctuations the inertial mass of the air will limit the acceleration of the air.

In Figure 8, we show the analogous electrical elements included in the air flow model proposed by Haghighat [11]. The effect of the non-zero air-mass is represented by an impedance L, whose impedance value increases with frequency. R is the non-linear air flow resistance of the opening which increases with the air flow rate, and the amount of air stored in the volume is represented by a capacitance.

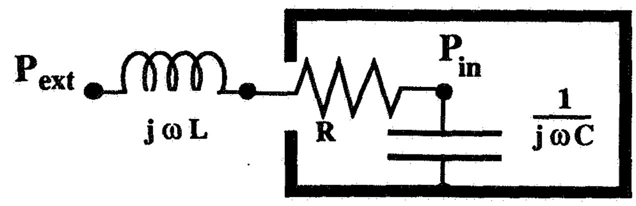


Figure 8. The equivalent circuit for the modelling of ventilation induced by pressure fluctuations

For particular forms of the external pressure, the 2nd order non-linear differential equation corresponding to this model has to be solved numerically to find the internal pressure and the airflow, which both can be compared with experiments.

For a given situation the problem can be simplified by estimating the relative magnitude of the three circuit elements in Figure 1. The non-linear flow resistance and the capacity are forming a low pass filter, and an estimate of the cut-off frequency f_c, will show whether the flow impedance $2\pi f_c L$ can be neglected. The calculation of the internal pressure is now reduced to the solution of a first order non-linear differential equation.

This is the approximation used for the interpretation of the BOUIN measurements. Defining the non-linear flow resistance R by the flow equation

$$Q = C_d A \sqrt{\frac{2 \Delta P}{\rho}} \tag{6}$$

and measuting the external pressure directly, the equation to be solved for the internal pressure is of the form

$$\frac{dP_{in}}{dt} = \pm \frac{A}{V} \frac{\gamma R T_{in} C_d}{\sqrt{\rho}} \sqrt{|P_{ext} - P_{in}|} \tag{7}$$

We note that the model presented schematically in Figure 8 does not include two-way flow, neither does it take into account effects related to the finite velocity of pressure (sound) waves.

3.5 Ventilation rate and heat tranfer

The heat loss rate Φ, resulting from a ventilation rate Q is proportional to the temperature difference between the in and out flowing air, and the calculation of the heat loss rate reduces to the problem of calculating the outflowing air temperature.

As a first approximation a single zone thermal model was proposed [12,13] where the inside air temperature is taken uniform, T_{in}. This is reasonable in practice when the outside temperature, T_{out}, is relatively low. The heat loss rate is then written as

$$\Phi = Q \rho C_p (T_{in} - T_{out}) \qquad (8)$$

Due to the heat transfer resistance between the air and the walls, T_{in} is situated in between the inside wall surface temperature and the outside air temperature. This is illustrated in Figure 9 where the heat current source 1, represents the ventilation heat loss rate given by equation (8).

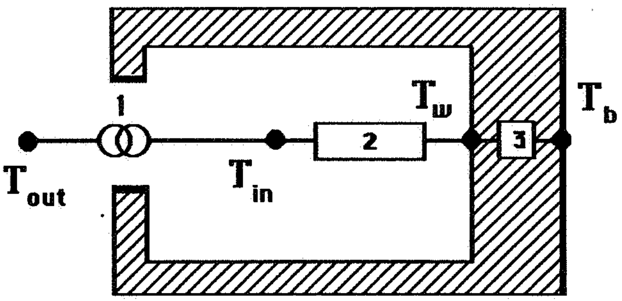


Figure 9. The equivalent circuit for the modelling of ventilation heat loss rate. The ventilation heat loss rate (1), the heat transfer resistance (2) the dynamic wall resistance (3). T_{in} is the inside air temperature and T_w is the wall surface temperature.

As discussed in references [12,13] the wall surface temperature T_w is changing slowly and can be calculated from a solution of the heat equation for a half-infinite homogeneous wall. The difference between the wall surface temperature and the nearby air temperature, $T_w - T_{in}$, is easily measured and is given by

$$T_w - T_{in} = \frac{\Phi}{Cs\, h_c\, S_i} = \frac{Q \rho C_p (T_{in} - T_{out})}{C_2\, h_c\, S_i} \qquad (9)$$

The new parameters in equation (9) are the total inside surface area S_i, the convective heat transfer coefficent h_c and the coefficient Cs, the fraction of S_i actif in convective heat transfer. It was found that a constant value of $h_c = 6W/m^2K$ is consistent with the data (the value is typical for low velocity forced convection). The concept of Cs is illustrated in Figure 10.

From (9) it follows that we can *calculate the ventilation rate indirectly from $T_w - T_{in}$*. Even if Cs is initially unknown variations in $T_w - T_{in}$ with time (or from measurement to measurement) are related to variations in the ventilation rate.

Ventilation rates determined from such heat transfer measurements allow an independent comparison with tracer ventilation rates.

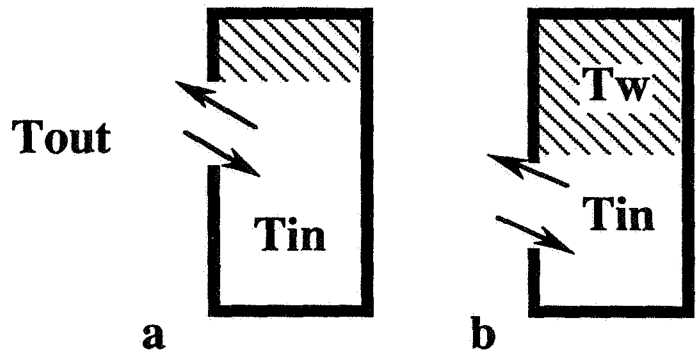


Figure 10. Above the upper level of the window the trapped warm (dashed) is at the same temperature as the wall, the ceiling and wall surface above the top of the window do not cool by convection. The coefficient Cs is about 0.8 in (a) and 0.4 in (b).

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 CSTB (BOUIN test house)

Table 1 summarizes the ventilation configurations studied with the test house in BOUIN. Are given the average windvelocity, the wind direction (from normal incidence to the opening) and the ventilation rates calculated from the measured decay of tracer gas concentrations. The standard deviation of the windvelocities and the wind direction is given between parentheses. Test cases 1, 2 and 4 are therefore with the opening to windward and cases 3 and 5 with the opening on the lee side. We note that the stack effect is calculated to be less than 0.01ACH and therfore neglected.

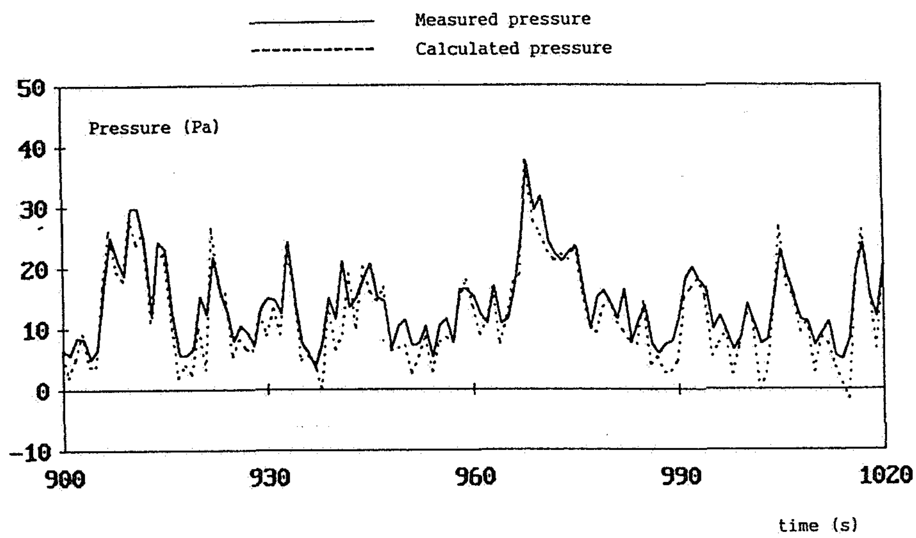
The external windpressure is measured at the orifice and can then be used directly as input for a simulation programme to calculate the internal pressure and the air change rate.

4.1.1 Internal pressures

For the simulations with the air infiltration program SIREN of the CSTB, it was assumed that the only mechanism for air exchange is the compressibility of the air. Therefore the external pressures measured at the opening are averaged, and the internal pressure is calculated by solving the first order differential equation (Equation 7) numerically. In Figure 11a are plotted the measured and calculated internal pressure for the windward test 1. It is seen that the algorithm reproduces the main features of the internal pressure variations. Figure 11b concerns the same plot for leeward test 3, but this time there is a systematic difference between the observed and calculated pressure. This could be due to the simplifying assumption

Test	opening area (cm2)	wind velocity (m/s)	wind incidence angle ϕ	tracer measured (ACH)	compressibility calculated (ACH)	F (Eq.3)
1	100	7.7 (1.2)	18 (7)	0.21	-	0.07
2	100	5.1 (0.9)	0 (?)	0.20	0.09	0.10
3	100	10.2 (1.5)	229 (8)	0.58	-	0.15
4	200	5.8 (1.15)	10 (10)	0.35	0.24	0.07
5	200	5.8 (1.1)	191 (10)	0.20	-	0.045
Ref7	230	5	0	0.02	0.06	$<10^{-3}$

Table I



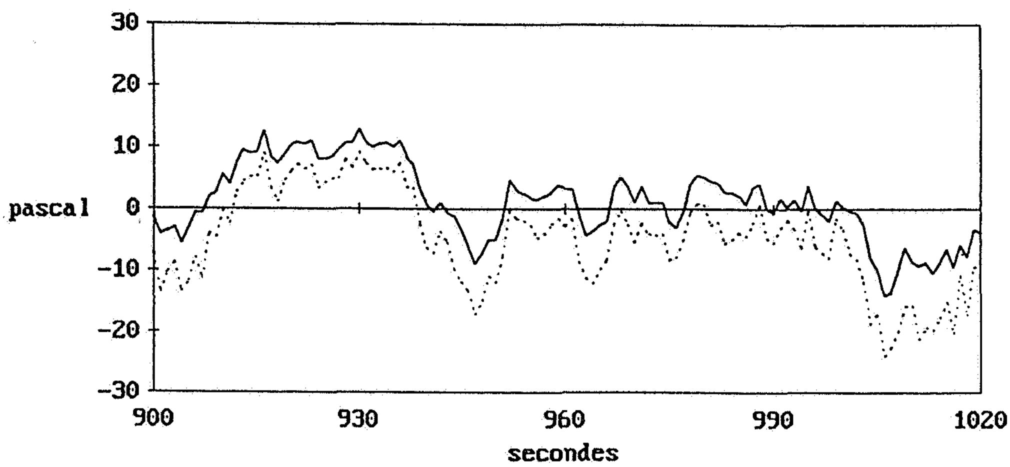


Figure 11. The measured and calculated internal pressure of the BOUIN house for $100cm^2$: windward test 1 (a) and leeward test 3 (b).

that there is no two-way flow. In particular in test 3, the incidence of the wind is not normal but almost at an angle of 45° so that eddy flow can be expected.

The solution of Equation 7, with experimental data points every 0.2sec as input, can become unstable. Indeed there appeared to be a numerical problem with the solution for the larger 200cm^2 opening.

The French group has made his measured data available to other groups in Subtask 2 and the wind pressure and velocity data of test 4 have been received at the LESO-PB in Lausanne. Analysis with a computer code specially written to solve Equation 1 (code TURBUL), the numerical instability and aliasing problems were immediately apparent. Using a NAG FORTRAN library routine, the internal pressure could be correctly calculated from the external pressure data as shown in Figure 12.

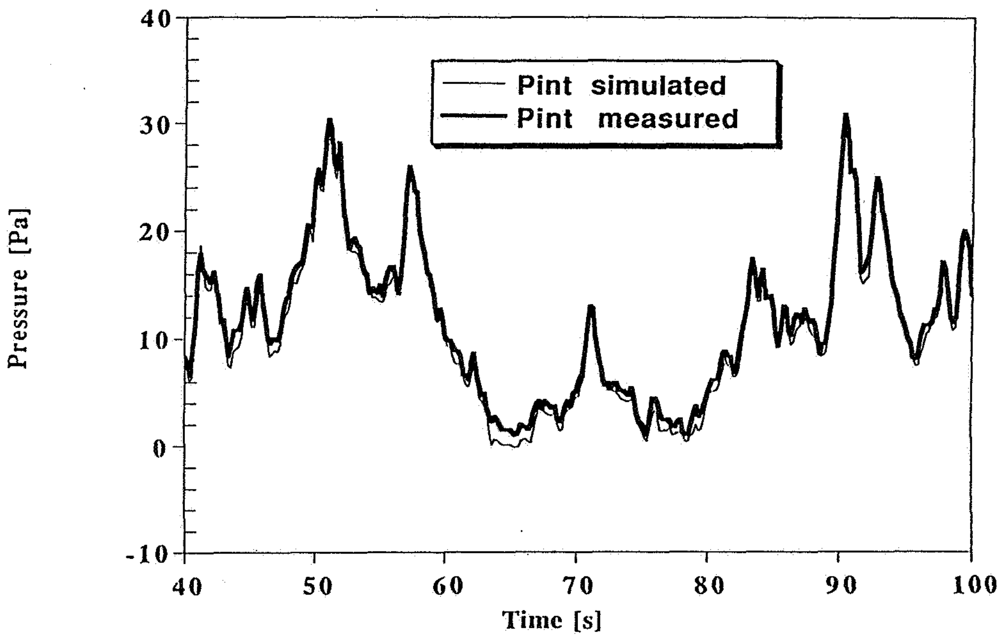


Figure 12. The measured and calculated internal pressure of the BOUIN house for 200cm^2 windward test 4.

4.1.2 Air change rates.

As discussed in §3, to calculate the air change rate resulting from fluctuating pressures one has to know which part of the inflowing fresh air flows out without mixing with the air.

Assuming that the inflowing air mixes completely, the air change rate was calculated with the code SIREN giving 0.09ACH for test 2, about half the measured ACR. Using the same assumption, the code TURBUL gives 0.24 ACH for test 4, which is 70%.of the measured ACR.

This result contrasts with the findings of Cockroft and Robertson [10] who found that only one-third of the fluctuating air flow into the enclosure was finally mixed with the bulk of air in the enclosure. Their set-up was very different though, using a 225 cm^2 opening in a 3.5m^3 isothermal model, and wind simulated with a variable speed fan. The result is included for comparison in Table 1.

With a comparable opening size but with a 30 times larger volume, the BOUIN data do not show evidence for incomplete mixing. A factor that may be important is the 5-10K inside-outside temperature difference in the BOUIN experiments (zero in Ref.7). Indeed the colder air entering the enclosure is likely to fall immediately being automatically replaced by inside air during the backflow. Systematic experiments are necessary to study this mechanism.

For test 2 the importance of two way flow was examined. Instead of just taking the pressure spatially averaged over the whole opening, the pressure was measured at eight points within the opening (see Figure 2). The pressure was measured both inside and outside the building, allowing the direction of flow through each part to be measured. A new estimate of the ventilation rate taking two-way flow into account gave 0.15 ACH, which is still smaller than the observed rate, and detailed further analysis of the data is necessary.

Finally the fact that the measured internal pressure can be simulated in detail means that Equation (7) applies to these particular cases, but it is not known yet what the limits of this model are in particular with respect to ventilation.

Indeed, with increasing opening to volume ratio the time constant (RC in Figure 8) decreases and a much higher measurement frequency is necessary.

Finally for comparison with the empirical models presented in §3, in the last column of Table I are given the ventilation coefficients F (see expression (3)). They appear to be unexpectedly high compared with the scale model measurements showing that for a correct prediction of ventilation rates a detailed knowledge of the ventilation mechanisms is necessary.

4.2. BBRI (attic in Gent)

4.2.1. Ventilation rates

The results of ten days monitoring of the attic in Gent with the south window slightly opened (1500cm^2) are given in Figures 13a,b and c. As seen from Figure 13a the outside temperature peaked around 15°C in the afternoon and reached a minimum of around 8°C in the early morning hours. The well insulated attic was not heated and stayed systematically warmer than the outside air by 6 to 11K. The air change rate due to the stack effect alone is then expected to be less than 0.1ACH.

The wind direction was between south and east as shown by the upper trace in Figure 13b (south is 180°). The lower trace is the wind speed, typically 2m/s but peaking above 4m/s during days 265, 266, 267-268 etc., with a maximum at 6.5m/s in the morning of day 268.

The measured air change rates have been correlated to the windvelocity and the stack effect by a multiple linear regression using equation (4) The best fit gave the values C_1=0.003 and C_2= 0.005 and C_3=0; this expression is plotted with the measured ACR in Figure 13c.

The factor C_1= 0.003 corresponds to a ventilation parameter F=0.027 (expression (3)), in excellent agreement with the results of Crommelin and Vrins [8]. The fitted factor C_2= 0.005 agrees with expression (2) for the stack effect. Putting in the values for ΔT and H it is seen that the stack effect is contributing less than 0.1[1/h] which is insignificant compared to the wind effect. Neglecting then the stack effect, expression (4) reduces for this particular case to $Q \approx 0.5\, v_w$ [1/h]. Indeed the simulated trace in Figure 13c is nearly proportional to the windvelocities in Figure 13b.

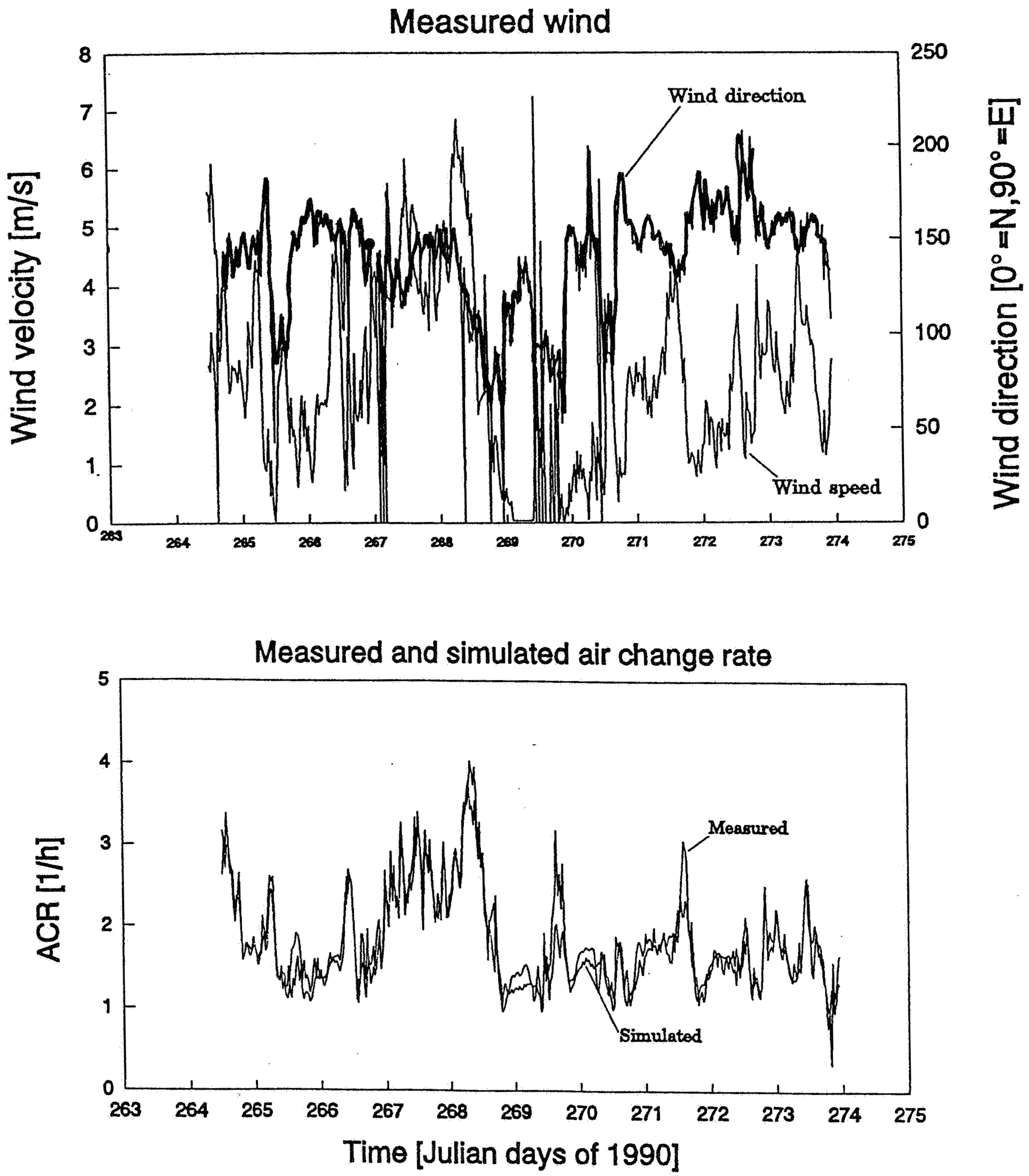


Figure 13. Attic in Gent, south window opened over 7.5cm (A=0.15m^2). (a) measured temperatures; (b) wind velocitiy (lower trace) and wind direction (upper trace); (c) measured and calculated air change rate.

The overall agreement between the simulated and measured ACR is good, showing that for a particular situation the ventilation rate can be characterized by one such a coefficient C_1. The peak ventilation rates are underestimated however and the analysis of the data should be pushed further. By looking closely at the differences it can be found out how the value of C_1 is correlatedwith the measured pressure coefficients and what the relative importance is of two-way flow and compressibility effects.

The same type of measurements and analysis has been performed for the North window that was then on the *lee-side*. It was noted that there was a negative correlation between the wind velocity and the stack effect. For a given wind, an increased inside-outside temperature difference corresponded to a reduced ACR. This is reflected by the correlation coefficients C_1=0.038 and C_2= –0.041. We note that these coefficients are an order of magnitude higher than before for similar ventilation rates. This means that the interpretation of the fit is difficult and uncertain: in calculating Q with expression (4) one subtracts two large numbers.

Unfortunately after the measurements, a pressurization test revealed a leakage in the South wall-roof junction. This means that with the north window open, cross-ventilation may have contributed significantly to the ventilation rate, complicating the interpretation of the data

4.2.2. Pressure coefficients

In general for the modelling of ventilation through openings of small height the airflow is calculated from the pressure difference between the inside and the outside and one single pressure coefficient is assumed for the outside.

A series of measurements have been made on the ventilation slit at the top of the window shown in Figure 4, which is 2-3cm high and 120 cm wide, in order to test the hypothesis that the pressure coefficient does not vary over the opening.

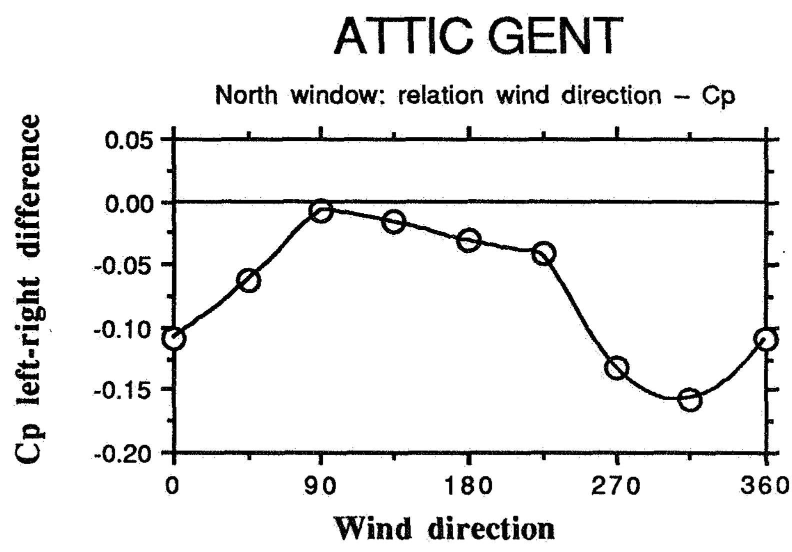


Figure 14. Attic in Gent, ventilation slit. The difference in pressure coefficients measured left and right of the opening as a function of the winddirection (0=North, 90=East). Wind velocities >2m/s. The standard deviation in each plotted value is about 0.03.

Two pressure tubes are mounted one at each side of the opening and connected to a differential manometer. The difference in left-right pressures was recorded and converted in a difference in pressure coefficient by dividing by the dynamic pressure $1/\rho v_w^2$ .Only data corresponding with wind velocities larger than 2m/s have been taken into account..

In Figure 14 we have condensed the results by plotting average values of the difference in left-right pressure coefficents as a function of the wind orientation. It is seen that the variation is sytematic and that differences in Cp of 0.15 are possible. Surprisingly the situation is not symmetric with respect to normal wind incidence: the pressure coefficient at the right side is always larger than the left side. It is believed that this the influence of the surrounding houses, rather than a problem with the manometer readings.

The result indicates that the assumption of a homogeneous pressure coefficient for the whole width of the ventilation opening is not correct. The assumption may be acceptable when the air flow through the opening is in a single direction, but not when two way flow is taking place as in single sided ventilation.

The two-way flow mechanism could explain the magnitude of the observed air change rates in Figure 13c. Indeed, for the data in Figure 13c to be understood in terms of two-way flow, one can estimate that a difference in pressure coefficient left-right of about 0.05 would be sufficient.

Future measurement campaigns should therefore measure both ventilation rate and pressure distribution over the opening.

4.3 BRE

4.3.1 Heater experiments

Before starting the ventilation experiments, the thermal behaviour of the room was extensively investigated with a number of heater tests. The procedure is explained in references [12,14], and these tests give confidence in the interpretation of changes in wall temperatures in terms of heat flow rates.

In Figure 15b is shown the measured and calculated variation of both air and floor temperature for a thermal effusivity $b=\sqrt{(\lambda\rho c)} = 850$ [J/ (m^2 K.$s^{0.5}$)], and a time constant of 20minutes. The uncertainty in the average b-value of the room is about 20% mainly due to uncertainty in the background drift of the room. It is surprising that such a complex room (see §2.3) can still be described reasonably well by the simplified dynamic thermal model (see ref 12).

4.3.2 Ventilation

We report on eleven ventilation experiments with an identical procedure so that they can be intercompared. As discussed in §2.3, at time t=0, the background heating is put off and the window is opened completely. The air temperature which was much higher than the floor temperature before t=0, drops with a time constant of about 10 minutes. In Figure 16 compares the observed air and floor temperature with the model calculation. The ventilation rate is calculated with expression (2) for the stack expression. There are no free parameters in the model and the agreement is rather good. The calculated curves are slightly above the measured data points.

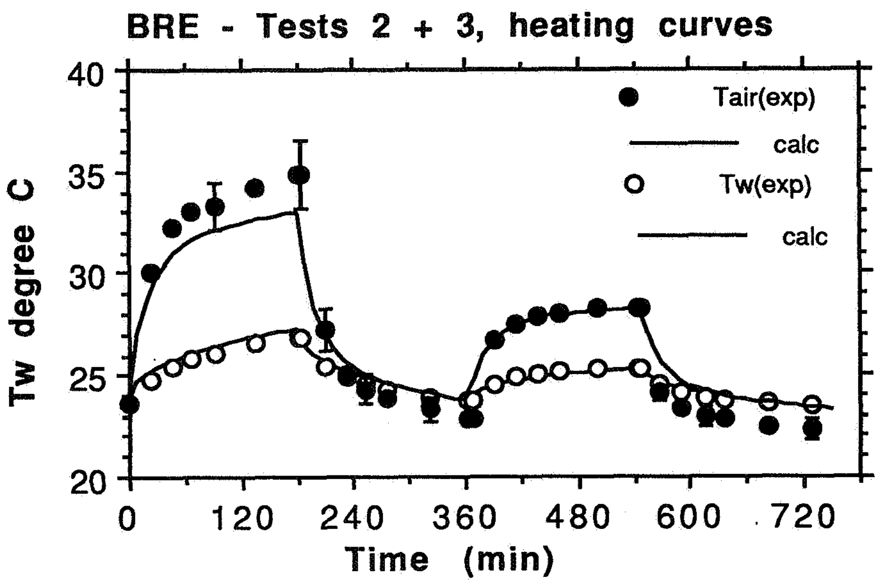


Figure 15. Heater test of the BRE room. A 9kW electrical fan heater is switched on (t=0) and off (t=180min); 5kW is switched on (t=360min) and off (t=540min). The floor surface temperature is used as a reference for the wall temperature. The air (filled symbol) and the floor temperature variation compared with the model calculation (see ref 12) using a thermal effusivity $b=\sqrt{(\lambda\rho c)}$ = 890 SI units, characteristic for the room. Compensation for background drift has been made.

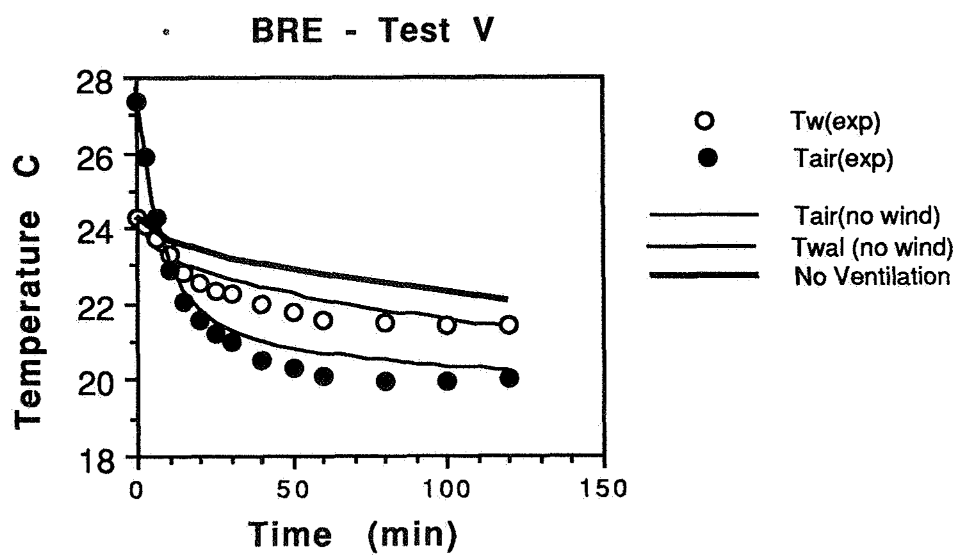


Figure 16. At t = 0 the background heating is switched off and the window is opened. In the calculation only stack ventilation is assumed. The temperature difference, Twall-Tair, measured after one hour (t=60min) depends on the ventilation rate.

After about one hour, the temperature difference between the floor and the air is quite constant and equal to about 1.5K for both the model and the experiment. This is the parameter we will compare in the following for the different ventilation experiments

In Figure 17, we have plotted as a function of meteo wind speed, both the calculated stack velocity (open symbol) and the effective ventilation velocity. The latter has been calculated from the tracer air change rate and expression (1). The inside outside temperature difference is not very different for the various experiments so that the average stack velocity is for all the experiments about 30cm/s.

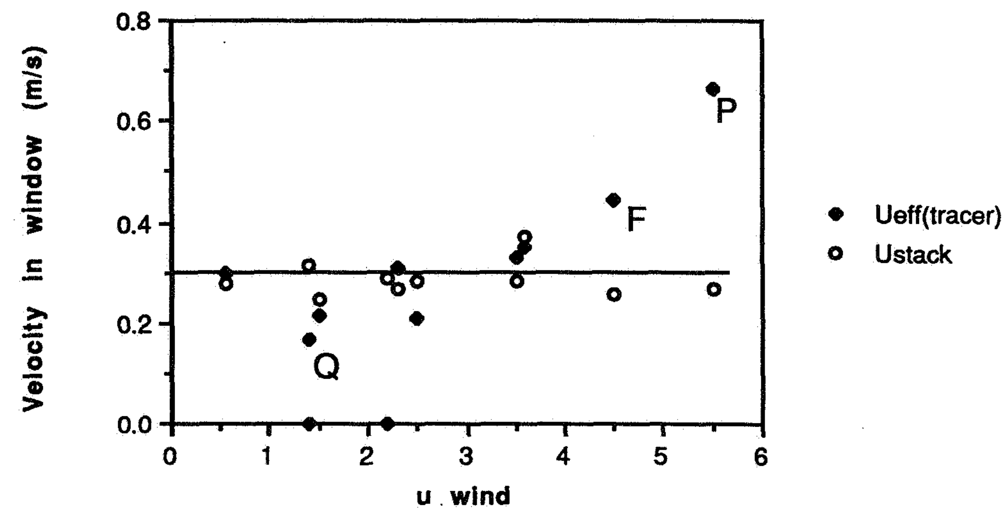


Figure 17. BRE test room. Stack velocity and effective velocity as a function of the windvelocity.

The available data have not yet been analysed in all detail but no clear corelation with wind direction is apparent.

The data point indicated by Q corresponds to the leeside and surprisingly the air change rate is reduced by nearly 50% with respect to the stack effect.

The only measurements where the ventilation rate is significantly increased by the wind are F and P. For the P-case, with normal incident wind, the effective velocity has more than doubled. The ventilation parameter is then F=0.06, not a very exceptional value and it is rather the absence of strong wind effects that is surprising.

For $T_{in}-T_{out}$ nearly the same in all tests, Equation 9 predicts a linear relationship between Q and T_w-T_{in}. Therefore we compare in Figure 18, T_w-T_{in} (at t=60min) with the air change rate. With the exception of the P test, there is apparently a good correlation, and it should be possible to compare systematically ventilation rates with heat loss measurements. This will be found out when all the data have been analysed.

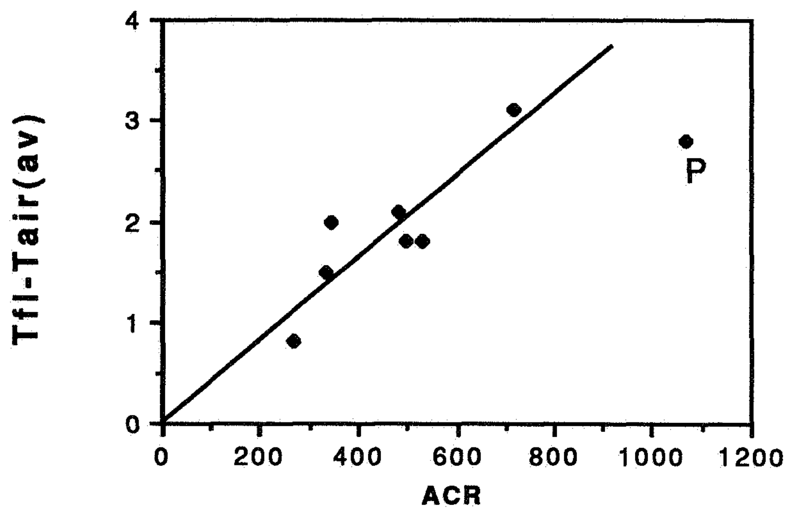


Figure 18. BRE test room. The air change rate in m^3/hr is well correlated with the floor-air temperature difference as predicted by equation 9. The P measurement corresponds to a wind increased ACR.

4.4 LESO-PB

The single sided ventilation algorithm predicting the ventilation energy loss caused by an inhabitant who leaves a window open for a certain period of time (see §3), has already been tested for various cases where the stack effect was dominating (12-14). We present here an experimental result where the ventilation and heat loss rate were increased by wind. The case without wind is used as a reference.

For the test without wind (<1m/s) the 0.85m wide window was left open for 10 hours during a windless night (outside temperature near 5.5°C). The unfurnished office room was initially at 21.5°C for 24 hrs, and the time dependent decrease in air and wall temperature are reasonably well explained by the model illustrated in Figure 9, and calculating the ventilation rate with the stackflow equation (equation (2).

A test with a strong southern wind was conducted for 7 hours at night and with the window opening reduced to one third of the width (W=0.26m; outside temperature near 4.5°C). The room was initially at 19°C for 24 hrs in thermal equilibrium with the building, and the effect of the wind was to increase the average air velocity in the window to 0.6m/s, about two times the expected stackvelocity.

In Figure 19, we compare the cooling rate from stack flow (well known from other experiments see ref 12) with the observed cooling.

The picture is consistent.

(i) There is strongly increased cooling of the walls.

(ii) The temperature drop T_w–T_{in} is more than two times larger than expected from the stack effect (see equation 9).

(iii) The velocity in the window is more than two times higher than the stack velocity.

Comparison with the model (Figure 9) shows that taking not the stack velocity but a window air velocity of 0.65 m/s, the observed cooling can virtually be explained.

We have no data to corelate the external wind velocity and the air flow in the window. The wind at the LESO building is strongly attenuated by surrounding buildings and difficult to characterize from meteo values.

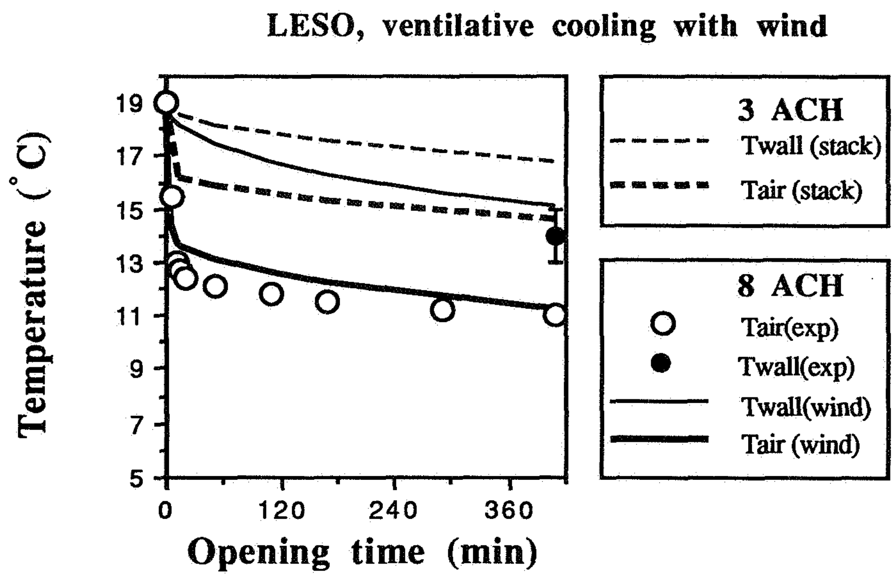


Figure 19 The window width is 0.27cm and the wind increases the ventilation rate and therefore the cooling. The windy case is calculated with an effective velocity of 0.65m/s in the window instead of the stack velocity of 0.21m/s.

The velocity profile suggests that it is possible in single sided ventilation that the stack flow in the opening is continuously accelerated by wind. Usually one assumes that the wind has only a perturbing action creating turbulence and fluctuating flows. The apparent steady outflow of air is remarquable because it is not documented as far as we know.

The velocity profile was continuously measured in the window with a probe mounted on a trolley 1cm in front of the inner window frame (1.1m high) traveling up/down in 30min.

In Figure 20 we show an original analog recorder trace. There are the following interesting features

(i) a neutral level can be distinguished near the center of the opening.

(ii) the top trace is rather smooth and is close to a parabolic profile, while the lower trace is very much effected by the turbulence of the wind.

(iii) the profile is asymmetric

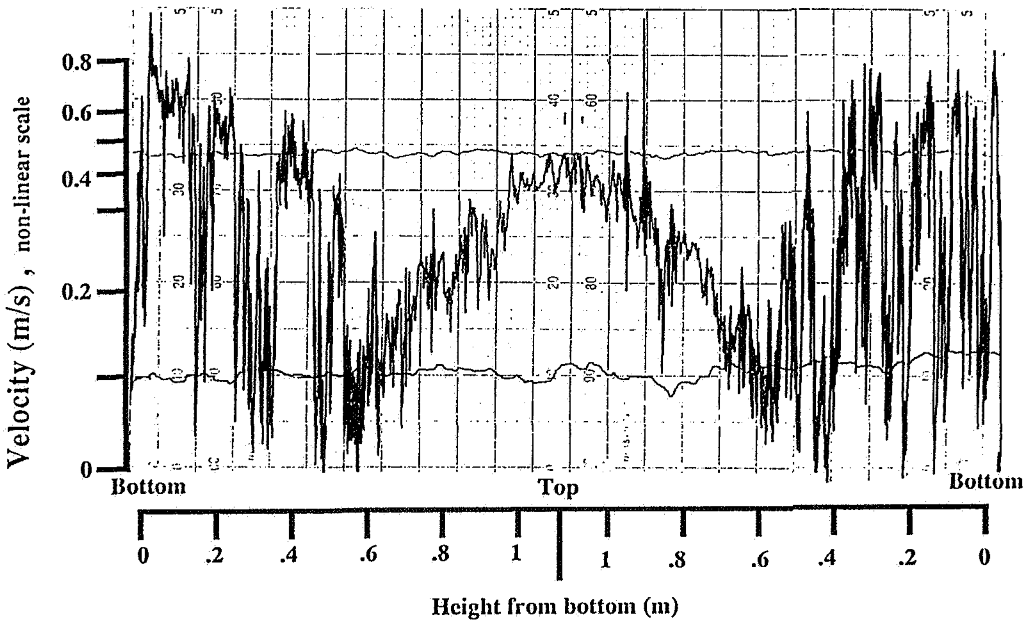


Figure 20. Part of continuous recorder trace of an omni-directional anemometer traveling in the centre line of the window. The window height is 1.1m and the probe velocity is about 3cm per minute. The velocity scale is not linear. The calculated average stack velocity is 21cm/s. A neutral level can be distinguished at the middle of the opening. Below the neutral level the turbulence is systematically much higher than above.

5 CONCLUSIONS

Single sided ventilation experiments have been conducted in the frame work of the Annex 20, and allowed fruitful cooperation between four laboratories in four countries. Experiments have been coordinated, data and types of analysis have been critically discussed. The results include new insights on ventilation caused by wind pressure fluctuations, two-way flow and ventilation energy loss. It has become clear that while the greatest uncertainty resides in lack of knowledge of the local wind, even when the local wind is measured the results on ventilation is not well known

6 ACKNOWLEDGEMENTS

The authors acknowledge research support from the AFME (France), OFEN (Switzerland), BRE (United Kingdom) and BBRI (Belgium). Many people contributed to the measurements and data analysis, thanks to all of them.

REFERENCES

[1] Pelletret R., Allard F., Haghighat F., Liebecq G., and Van der Maas J., 'Modelling of large openings' 12th AIVC Conference 24-27, Ottawa, September 1991.

[2] Warren P R, "Flow through external openings, Draft Extract", Annex 20: Second Expert Meeting in Warwick, UK, Nov. 7-10 1988.

[3] Roulet C. and Scartezzini J, 'Stochastic model of inhabitant behaviour in regard to ventilation' 12th AIVC Conference 24-27, Ottawa, September 1991.

[4] Vandaele L, Wouters P, "Air flows through large openings; an overview of existing approaches", Third Expert Meeting in Aalborg, Denmark, May 30-June 2, 1989

[5] Van der Maas, J., 'Airflow through large internal and external openings' Status Report subtask 2, task 2.1, Fourth Annex 20 Expert Meeting in Lommel, Belgium, November 13-16,1989

[6] Phaff J C , de Gids W F, Ton J A et al Ventilatie van gebouwen. Onderzoek naar de gevolgen van het openen van een raam op het binnenklimaat van een kamer (Investigation of the consequences of opening one window on the internal climate of a room) Delft IMG-TNO rapport C448, March 1980. Airbase #2201 (Data tables and Figures only available in the Dutch version).

[7] De Gids, W., and Phaff, H., 1982. "Ventilation Rates and Energy Consumption due to Open Windows", Air Infiltration Review. Vol. 4 N° 1, pp. 4 - 5.

[8] Crommelin R.D., Vrins E.M.H., "Ventilation through a single opening in a scale model", Publication P 87/048, TNO Delft, 1987-09-01.

[9] Warren, P.R., 1986. The Analysis of Single-Sided Ventilation Measurements, Air Infiltration Review, Vol. 7 N° 2, pp. 3 - 5.

[10] Cockroft J.P. and Robertson P. "Ventilation of an enclosure through a single opening", Building and Environment Vol 11,pp29–35, 1976

[11] Haghighat F., Rao J. and Fazio P. 1991, "The influence of turbulent wind on air change rates–a modelling approach", Building and environment Vol 26, pp. 95-109

[12] Van der Maas J, Roulet C -A, Hertig J -A, "Some aspects of gravity driven airflow through large openings in buildings" ASHRAE Transactions 1989, Vol.95, Part 2, pp. 573-583

[13] Van der Maas J., Roulet C.-A. "Ventilation and Energy loss rates after opening a window", Air infiltration review, Vol 11, No 4,1990, pp 12–15

[14] Van der Maas J., Roulet C.-A.and Hertig J.-A., "Transient single sided ventilation trough large openings in buildings", ROOMVENT '90, Oslo, June 1990, C48

[15] Riberon J., Villain J., 'Etude en vraie grandeur des débits effectifs de renouvellement d'air', CSTB GEC/DAC-90.101R, Champs-Sur-Marne, July 1990

12th AIVC Conference, Ottawa, Canada, 24-27 September, 1991

SINGLE SIDED VENTILATION
by Van der Maas et al

ERRATA

page 11 eq. (5)	drop factor 2 in
page 12 line 3:	$0.02m^3/s$ (not 0.04)
page 12 line 5:	0.7 ACH (not 1.4)
page 12 eq. (7):	multiply by $\sqrt{(2\rho)}$, (not divide by $\sqrt{\rho}$)
page 17 §4.2.1, line 6	"..expected to be about 1.5ACH"
page 17 5th line from bottom	"..is contributing 1.5[1/h] which is significant"
page 17 bottom	drop last two sentences

§5. Conclusions

Single sided ventilation experiments have been conducted in the frame work of the Annex 20, and allowed fruitful cooperation between four laboratories in four countries. Experiments have been coordinated, data and types of analysis have been critically discussed. This paper is an overview of the obtained results that will be published in an Annex 20 report [16].

It has been shown in separate experiments that

(i) the contribution of air compressibility to the single sided ventilation rate can be considerable in particular for relatively small openings to large volumes.

(ii) a systematic variation of the pressure coefficient over the opening has been observed and appears to vary with wind direction; the resulting two-way flow significantly contributes to the airchange rate under conditions of single sided ventilation

(iii) the ventilation rate of the attic in Gent (long term observation under varying conditions of wind speed and direction) is well described by a simple model with a single free parameter.

(iv) ventilation heat loss rates after opening a window are described by a simple model allowing a better estimate of the energy consequences of inhabitant behaviour

(v) an effect of steady wind on the airflow in a single large opening can be measured.

The validation process of more detailed single sided ventilation models has only started. One difficulty in future research will be the simultaneous presence of pressure fluctuations, two way flow and stack effect. To reduce the complexity, one should learn to know the relative importance of each ventilation mechanism under various circumstances.

On the other hand the uncertainty in predicting ventilation is in many cases dominated by a lack of knowledge of the local wind. New research on the transfer of meteo data to local wind values is therefore mandatory if we want to make use of the more detailed models developed for single sided ventilation.

[16] Van der Maas J., Allard F., Haghighat F., Pelletret R., Riberon J., Vandaele L. and Walker R. , "Airflow through large openings in buildings", a Technical Report of subtask 2 of the Annex 20: Optimization of air flow patterns within buildings. To be published: autumn 1991.