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The ventilation of buildings.

Investigation of the consequences of opening one window on the internal climate of a room.

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THE VENTILATION OF BUILDINGS

INVESTIGATION OF THE CONSEQUENCES OF OPENING ONE WINDOW ON THE INTERNAL CLIMATE OF A ROOM (SEG PROJECT NO. 1.9)

1. INTRODUCTION

In December 1978 the Steering Group on Energy and Buildings (SEG) gave to the Sound, Light and Internal Climate Division (GLB) of the TNO Institute for Environmental Hygiene and Health Technology (IMG) the task of setting up an investigation on the consequences of opening windows on the internal climate and the ventilation process in rooms in dwellings (SEG Project No. 1.9). The interest, in this topic arises from the energy loss that is associated with leaving windows open under winter conditions.

People introduce outside air into their dwellings for various reasons; they do this in different ways.

There will always be some (and sometimes fairly strong) air currents in dwellings in consequence of leaks in the outside walls. This type of 'continuous change' is sensible.

A number of constructional measures have been devised for producing continuous changes of this type ('set-out' windows, ventilation gratings, vertical (suction) ducts). Investigations of these phenomena have been conducted (successfully) for a long time.

Similarly, it is fairly common to introduce much larger quantities of outside air over shorter or longer periods. One or more movable parts of windows are kept fully or nearly fully open; the rooms are 'aired' or 'ventilated'.

This is done very commonly. Investigations conducted in this country and abroad indicate that windows are left open for a long time (ie for several hours at a stretch every day) by more than 40% of the population. It will be clear that in relation to the saving of energy it is desirable to examine the relation between the usefulness of this practice and the energy losses associated with it.

Accordingly, the present investigation comprises:

(a) a series of measurements of the ventilating effect of keeping open a window in a room, and also the effect on the internal climate;

(b) an examination of the results in order to discover whether they can be explained on a theoretical basis, even as regards the order of magnitude; if this is found to be the case, then they can be used for making predictions even in cases where there are no direct measurements;

(c) an estimate of the energy consumption associated with the leaving open of a window with an area <u>eg 0.5 m^2</u> in a room, <u>for 3 hours</u>;

(d) an estimate of how the same air-change effect can be obtained with lower energy consumption by keeping the window open for a shorter time.

These problems have received very little investigation. Accordingly, this investigation deals with the situation in which one window in a room of a dwelling is kept open, while the inside doors are closed (see Fig. 1).

<u>Fig. 1</u>: What will the ventilation (air-change rate) be with one window kept open?

Because it was not known at the beginning how the GLB's usual measuring equipment would behave in the presence of the temperature drop after the opening of the window, preliminary test measurements were made in January 1979 in a single-family dwelling at Schipluiden (1). From these it appeared possible to achieve our objective with the existing equipments.

For the measurements it was necessary to make use of one of GLB's Data Acquisition Systems (DAS). It was envisaged that in the initial period of this investigation regular use ought to be made of DAS for, purposes of programme development and the 'running in' of the measurement process. Accordingly it was decided to make a number of measurements within the IMG-TNO building. The office was made comparable to a room in a dwelling by turning off the air-conditioning system. After this, measurements were made in a flat at Delft, with different types of window (casement and sash/slide types) being simulated. In January 1980 a last measurement was made in the IMG-TNO building office, at a low external temperature.

2. OBJECT OF THE INVESTIGATION

The object of this investigation is to measure the determining factor with air flowing through one single open window:

- influence of wind;
- influence of internal/external temperature difference;
- influence of type of window

The inside door of the room under investigation was kept closed and sealed during the measurements.

The next thing to be ascertained was the extent to which the internal climate was disturbed. Measurements were made of:

- air speed;
- temperature

at different points in the room under investigation.

Lastly, and most important, the air-change effect had to be determined. This is investigated by direct measurement of the so-called 'air-change rate' ('ventilatievoud') using the so-called 'tracer-gas method'.

The results as regards the ventilation are interpreted in terms of energy consumption. Of particular importance here is the saving in energy consumption which is possible by avoiding keeping (large) windows open for an unnecessarily long time.

To summarise:- how does air come through an open window towards the interior, and how is it at the same time removed through the same window when the inside doors are closed;

- what quantities are involved in the process;
- how does this air exchange affect the internal climate;
- what degree of freshening is achieved;
- what energy losses are involved in the process.

3. THEORY

For the description of the ventilation process with opening of one window, several publications are known, including references (2,3). The driving 'forces' for the air exchanges through the open window are;

1 : temperature differences (internal/external);

2 : wind.

Point 1

In consequence of temperature differences, density differences arise in the air. These cause pressure differences and/or air movements. These are generally designated as:

- thermal (with rising air);
- thermal draught or chimney affect (this refers to the reduced pressure underneath in a hot chimney stack);
- free convection (heat exchange of eg a hot object with its (colder) surroundings, associated with vertical air movements).

The thermal pressure difference can be calculated by means of the formula

$$\Delta P_{th} = g \cdot \rho_o \cdot T_o \left[\frac{T_1 - T_2}{T_1 \cdot T_2}\right] \Delta h \qquad (1)$$

At temperature of about 300 K, eqn. (1) becomes

$$\Delta P_{th} = 0.04 . \Delta T . \Delta h \qquad (2)$$

Point 2

Wind gives rise to air-pressure differences around buildings; these may be broken down into a pressure averaged overtime and a superposed fluctuating pressure signals. This fluctuating signal results from eddies which are produced in the so-called boundary layer of the air-stream along the surface of the ground. The average pressure differences are given approximately by

$$\Delta P = [illegible] . \frac{1}{2} [illegible] \qquad (3)$$

Where K is a dimensionless factor ralated to the braking of the bottom air layers of the boundary layer (in which the building-up occurs), as well as to the shape of the building or facade under consideration, and to the wind direction.

The ratio between the instantaneous value of the wind speed and the average wind speed gives the intensity of the eddies and is called the 'turbulence factor'

$$K = \sqrt{V^2}/V_w \qquad (4)$$

In this investigation, however, the turbulence is left out of consideration, on account of the complex measuring equipment which would otherwise be required. The instantaneous value of the air speed in the windows opening is measured at four places (4).

The fluctuations in these speed values gives an idea of the extent to which the air-change rate is influenced by the turbulence.

Another driving 'force' which is caused by the wind is the eddying which occurs in the opening of a casement/pivoted window, as a result of the wind, blowing parallel with the facade, pushing against the window-pane (see Fig. 2).

Fig. 2. Eddying in the opening of a casement window.

The literature does not provide any formulae (see Annex 2) which represent the simultaneous influence of temperature and wind on the ventilation process due to an open window.

In our opinion, however, it may be expected that in principle a notional mean airspeed in the half-effective-window-opening may be taken as the combined effect of wind and temperature difference.

$$U_{eff} = \sqrt{C_1 V_w^2 + C_2 . H . \Delta T + C_3} \qquad (5)$$

Where C_1 depends on the braking of the wind around the dwelling under consideration

C_2 may be estimated to be about 0.0052. See Annex. 2.

C_3 is a measure of the speeds in the window opening resulting eg from air currents in the room resulting from temperature differences in the room.

The values of C_1, C_2 and C_3 actually depend on the pattern of currents in the window.

Fig. 3 indicates that the wind effect (C_1) and the temperature effect (C_2) will not reinforce one another at any point in the window. Since moreover the pattern of currents in the window is changing vigorously, an exact determination of C_1, C_2 and C_3 will provide no better prediction of the effective speed in the half-effective-window-opening. C_1, C_2 and C_3 will therefore be deduced from the measurement results.

Fig. 3 Current profiles (flow patterns) in an open window, averaged over time.

(a) Temperature effect; (b) Wind effect; (c) Combined effect.

4. MEASUREMENT ARRANGEMENTS

Fig. 4. Schematic picture of the measurement arrangement (in the room).

T = Temperature measurement point

S = Air speed measurement point

C = Tracer-gas-concentration measurement point

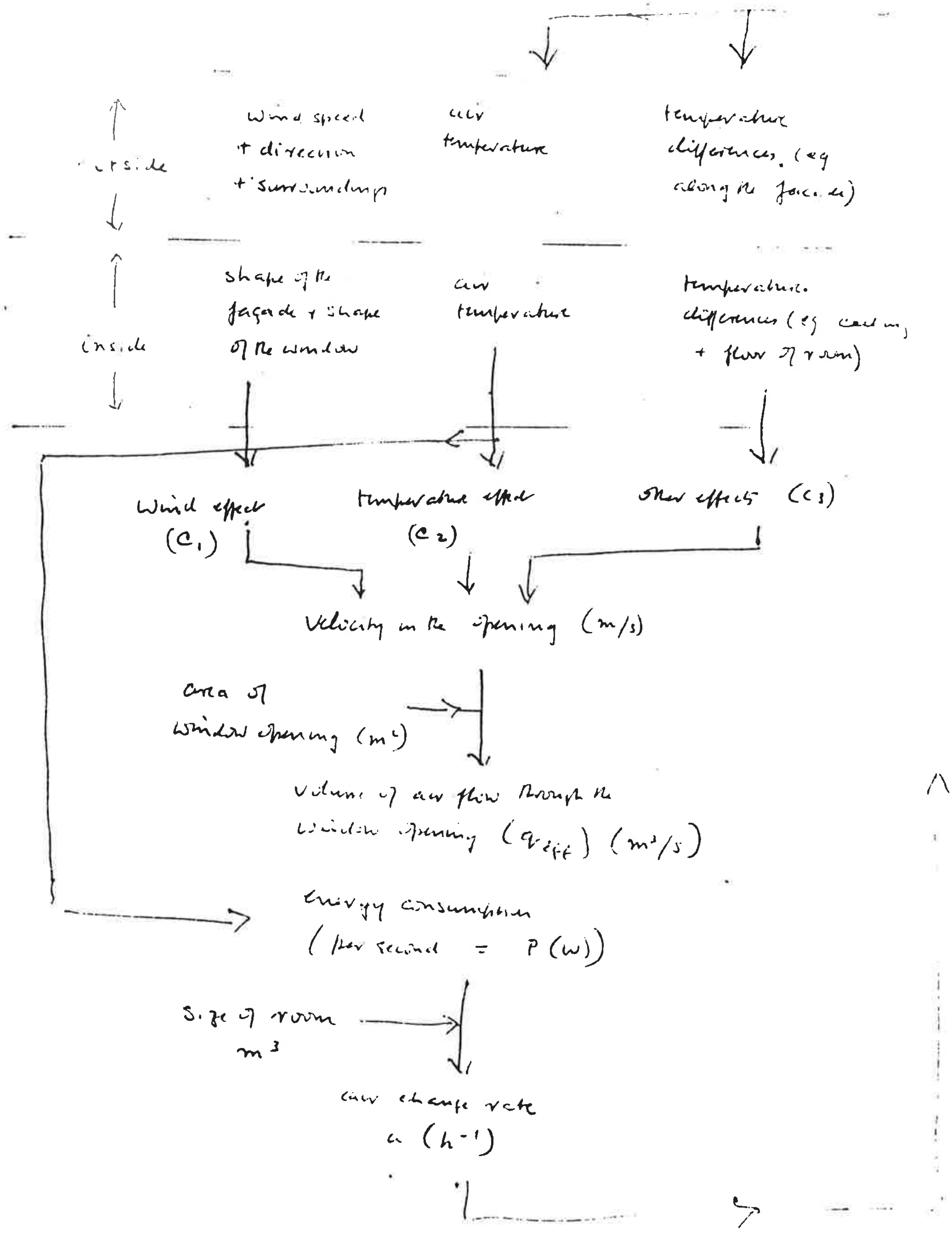

Fig. 5. Schematic representation of the relations between external conditions, wind speeds in the windows and internal conditions.

In the window opening there are 6 temperature measurement points, 4 speed measuring points where the air speed is measured independently of the flow direction (so-called RMS air speed) and 4 speed measuring points where the air speed perpendicular to the plane of the window is measured, depending on its direction. The speed in the window opening are important when evaluating the coupling.

On the three supports within the room there are altogether 9 temperature measurement points and 9 air-speed measurement points. From these it is possible to obtain a picture of the internal climate in the room. Each support is provided with a concentration measuring point, at which a measurement is made of the concentration of the tracer gas which is blown into the room before opening the window. From the observations of these concentrations the air-change rate in the room is derived (see Annex 3). The air-change rate (divided by 3600 (s)) multiplied by the room volume (m^3) gives the ventilation volume flow. We represent this by q_{eff}. This volume flow on average comes in through one half of the window and goes out through the other half. In such a half-window there then exists a mean speed, the equivalent speed, which thus has a direct relation with the measured air-change rate.

A speed measuring point and a temperature measuring point are arranged outside, at about 2 m from the facade. This is in order to be able to ascertain whether there is a better relation between the speed and temperature measured here and the measured internal conditions than between the meteo data and the measured internal conditions (see Fig. 6).

Fig. 6. Relation between the meteo conditions along the facade and the resulting internal conditions.

Photos of the measurement set-up are shown in Figs. 7, 8 and 9.

A schematic representation of the method of connecting up the equipment is shown in Annex 10.

Fig. 7. The measuring set-up in the bedroom in the flat at Delft. In the background is the window under consideration. The white blocks at the left of the window contain the pressure transducers, for example, the speed-pressure disks, in the window opening. One of the katharometers can be seen on the support in the foreground. This photo gives an idea of the inconvenience caused to the occupants of these measurements.

Fig. 8. Facade with investigated open window of the flat at Delft. The measurement points for observing the air speed along the facade and the external air temperature are arranged on the balcony railings.

Fig. 9. Close-up of the open window of Fig. 8. The four light-coloured disks in the winds opening are the speed-pressure disks. At the left along the window-frame two of the four anemometers (with the two small spheres ('bolletjes') are clearly visible.

5. MEASUREMENT OBJECTS (See Annex 5)

5.1 Single-family dwellings at Schipluiden

Measurements were made in the first-floor bedroom at the east facade of a single-family dwelling. The dwelling is situated in a row of five houses at the outer edge of the built-up area of the village of Schipluiden (ZH = South Holland province). The bedroom has a pivot casement window 1.2 m high and 0.7 m wide, a floor area of 3.9 m x 3.7 m (14.5 m^2) and a height of 2.6 m (room volume = 37.5 m^3). The floor and ceiling are of wood, covered respectively with carpet and gypsum sheets. The walls are papered. There is a cupboard along the whole of one of the long walls.

5.2 IMG-TNO building

Measurements were made in Room 1-29 of the four-floor IMG building of the 'Zuidpolder' TND complex. The room investigated is on the first floor at the south facade, has a small pivot casement window 0.9 m high by 0.4 m wide, a floor area of 5.07 x 2.90 m (14.7 m^2) and a height of 3.61 m. The room volume is 53.1 m^3. Walls, floor and ceiling are of concrete or a stone-type material. The floor is covered with linoleum and the ceiling is almost entirely covered with 'soft-board'. On the facade outside the window, about 1 m from the opening, there is a concrete pillar forming part of the bearing structure of the building. The foot-bridges to the other parts of the TNO building run from the first to the fourth floor inclusive.

5.3 Flat at Delft

Measurements were made on the first floor at the S.W. facade of a four-storey block. The investigated bedroom has a pivot casemen window 1.07 m high by 0.7 m wide, a floor area of 4.1 m x 2.2 m (9 m^2) and a height of 2.6 m (room volume = 23.5 m^3). Above the pivot casement window there is also a small flap (? hopper) window 0.28 m high and 0.7 m wide. The walls are concrete and all papered. The floor is laid-carpeted and the ceiling is plasterwork. On the facade outside there is a narrow balcony. Between the surrounding blocks of flats there are trees and shrubs. The trees reach up to the fourth floor.

6. MEASUREMENT PROGRAMME

For sampling the (approx.) 38 measurement point as frequently as possible, a programme was written for the DAS computer. The measurement points are divided into three groups, namely:

1 : a measurement every 5 seconds of the signal from the:

4 speed-pressure disks in the window opening

4 thermo-anemometers in the window opening

6 thermocouples in the window opening

3 katharometers in the room.

2 : a measurement every 30 seconds ... :

3 x 3 thermo-anemometers in the room

3 x 3 thermocouples in the room

3 : a measurement every 120 seconds (2 minutes) ...:

1 cup anemometer (only for the TNO building) outside

1 thermo-anomometer (only for the flat at Delft) outside

1 thermocouple

The measurement itself proceeds broadly as follows:

1 : start of measurement

2 : determining the zero point of the speed-pressure disks (this was done by shielding the disks from the wind by covering them with a hood)

3 : blowing in the tracer gas with the window closed and the door sealed(1).

4 : open the window.

At the end of the measurements, point 2 was carried out again.

7. RESULTS

The findings of the measurements which are to be interpreted directly are given in the present Section, and are subdivided into results regarding:

ventilation (7.1)

internal climate (7.2)

Footnote (1): During the measurement no more tracer gas is blown in. The drop in the concentration is a measure of the air-change rate (see Annex 3) and thus of the volume flow through the window.

In the present Section the significance of the measurement results is examined: the results themselves are tabulated in Annex 4 as output of the minicomputer used. In these Tables in Annex 4 some of the columns are not used particularly in cases where part of the working-out (evaluation) had already been done without the machine.

In order to make the measurement results more easily comparable with one another, the measurement conditions are subjected to detailed standardisation in the next Section.

7.1 Ventilation

On account of the differences between the three rooms where measurements were conducted (size of window and of room), the measured values of the air-change rate are not comparable with one another.

The values of the most important magnitudes lie within the following ranges:

- air-change rate 0.2 (window closed) to 25 (window open) (h^{-1});
- internal/external temperature difference 2 to 17°C;
- wind speed (metres) 1.5 to 11 (m/s).

An example of the variation of tracer-gas concentration in the room during a measurement is illustrated in Annex 6 and Fig. 10a. It is seen that the most rapid drop in the concentration is observed close to the floor, next comes the measurement point high up in the room, and last, with the slowest variation, the one in the middle of the room. The air-flow pattern in the room is apparently as illustrated in Fig. 10b. Smoke tests and temperature measurements support this view.

Fig. 10a. Graph showing time variation of concentration at the different katharometers.

Fig. 10b. Air-flow pattern in the room, consistent with the concentration variation shown in Fig. 10a.

7.2 Internal climate

Annex 9 and Fig. 11 illustrate an example of the temperature variation at different points in the room and in the window. Only in the window opening are temperatures observed which are nearly the same as the outside temperature. The temperature drop inside the room, particularly at higher levels, is remarkably small. The incoming air, which is colder and hence spreads over the floor, is apparently warmed before it reaches the higher levels inside the room.

Fig. 11. Temperature variation inside the room and in the plane of the window.

The variation of the (air-)speed inside the room is evaluated in Annex 8. Only at the measurement points under the window or close behind, and to a lesser extent also at the points close to the floor, is a small increase in the speed observed, with values up to about 0.5 m/s. Inside the room, at some distance from the window, the air speeds remain below 0.2 m/s.

8. PROCESSING THE MEASUREMENT RESULTS

8.1 Ventilation

Starting from the measured air-change rates, it is possible to calculate a so-called 'effective volume flow'. This is the quantity of air (in m^3/s) which enters through the window (eg through the 'lower half') and which also emerges through the window ('upper half').

$$\text{effective volume flow } \dot{V}_{eff} = \frac{n \cdot V}{3600} = \frac{V}{t}$$

(Where n is the air-change rate, and V is the room volume.)

The window opening can be described more precisely in the form of an 'effective area' as follows.

To be able to speak of a definite effecitve area when the window is not fully open is simple with a sliding (sash) window, where it is defined as the open area in the particular state. With a casement (pivot) window this is not so simple since in this case if the window is partly open there are effectively two surfaces one after the other:

A1 width x height of the window;

A2 area between the runway ('spanning') of the window and the window frame (see Fig. 12a, 12b).

Fig. 12a.
Calculation of effective window opening.

Fig. 12b.

From the theory of currents, these areas can be regarded as series-connected resistances, and can be accordingly added together. In consequence of the interaction between the two areas (they are not infinitely distance from one another), the calculated value will be somewhat on the high side, particularly for small angles of opening.

Comparison with P Warren's measurement results (2) with a pivot/casement window indicates that the differences lie within the margin of error of the measurements in this investigation.

The value of A for the window in this investigation is calculated in Annex II.

The equivalent speed can be derived by dividing the effective volume flow by half the effective window opening:

equivalent speed in the half-effective-window opening

$$S_{eq.} = \frac{q_{eff}}{\frac{1}{2} A_{eff}} \quad \left(\frac{m^3/s}{m^2} = m/s\right)$$

This must now be brought into relation with S_{eff} as defined in formula (5).

From the values of $S_{eq.}$ and the associated wind speeds and temperature differences, an attempt can now be made to derive values for the coefficients C_1, C_2 and C_3 appearing in formula (5).

The temperature difference in formula (5) can be calculated starting from the measured internal temperature (averaged over the whole measurement) and the measured external temperature or the meteo external temperature. The meteo air temperature is chosen here.

For the wind speed in formula (5) also, the meteo value or the measured value along the facade can be taken. The wind speed measured along the facade of the TNO building was seldom more than 1 m/s and that lies in the neighbourhood of the starting speed of the cup anemometer used here, hence these measured speeds are not exact. For the measurements in the flat at Delft a thermo-anemometer was used. These results look more reliable. In connection with the comparison of the different measurement locations, however, the meteo windspeed was taken as the variable. The values of C_1, C_2 and C_3 are determined by 'trial and error', such that S_{eff} and $S_{eq.}$ correlate with one another as far as possible. The values of C_1, C_2 and C_3 lie within the probability interval determined by a multiple-regression calculation.

In Annex 13 the following magnitudes are plotted against one another:

- the equivalent air speed (determined from the measured air-change rate);

- the effective speed (determined from the meteo wind speed and the internal/external temperature difference).

In Annex 13 the effective air speed is calculated from the following formula:

$$S_{eff} = \sqrt{0.001 \cdot V_w^2 + 0.0035 \cdot H.(\Delta T + 1.5) + 0.01} \qquad (6)$$

The constants C_1, C_2 and C_3 are determined by iteration so as to obtain the best possible agreement between the equivalent and the effective air speeds, and between the values of the constants and the theoretical values. The boundaries of the probability interval found from the multiple-regression calculation are:

$$C_1 = -0.0018 \text{ to } 0.015$$
$$C_2 = -0.018 \text{ to } 0.014 \qquad (7)$$
$$C_3 = -0.04 \text{ to } 0.24$$

(The term 1.5 added to ΔT in formula (6) is a correction for the density difference of the air in the room as a resul of the mean concentration of the helium trace gas.)

In Annex 13 some difference can be seen between the points determined from the measurements on the sliding/sash window and the pivot/casement windows in the flat at Delft. This may possibly be explained by the effect of the window-wing of the pivot/casement window, which gives rise to an increase of the speed in the window opening as a result of wind along the facade. There were too few measurements on the flap/hopper window to enable separate conclusions to be drawn in this case.

There is a clear correlation between the two magnitudes S_{eq} and S_{eff}. The residual dispersion could possibly be explained in terms of the wind direction (resolved into components perpendicular and parallel to the facade).

This means that, from these measurements, we are in a position to be able to predict the air-change rate and the associated energy loss, as regards order of magnitude (for the rooms where the measurements were made).

8.2 Air speeds in the window opening

Annex 7 illustrates an example of the evaluated signal from a speed-pressure-disk. This signal is corrected as far as possible for the zero-point drift of the pressure transducer. The times at which the disk was shielded are indicated in Annex 7. At these times the indicated speed should have been zero. The mean value of the air speeds in the window ($\overline{S}_\perp$) perpendicular to the window opening is determined from the indication of the speed-pressure-disk. The speed determined from the thermo-anemometers ($\overline{S}_a$) may be regarded as the RMS value of the speed.

From $\overline{S}_{\perp}$ and $\overline{S}_{a}$ something may be said about the fluctuating portion of the speeds in the window opening. A defect in this respect is that the speed component parallel to the plane of the window cannot be elimincated from $\overline{S}_{a}$.

An estimate of the fluctuating portion of the air speeds in the window ($\overline{S}$) is thus:

$$\overline{S} = \overline{S}_{a} - \overline{S}_{\perp} \qquad (8)$$

8.3 Energy consumption

Multiplying the calculated effective speed by the half-effective-window area gives the effective ventilation volume flow q_{eff}.

The energy loss (P) associated with this ventilation volume flow is then:

$$P = \tfrac{1}{2} A_{eff} \cdot S_{eff} \cdot \rho \cdot (E_{internal} - E_{external}) \qquad (9)$$

where ($E_{int} - E_{ext}$) is the difference between the heat capacity (enthalpy) of the internal and the external air. The difference between the absolute humidity of the external and the internal air is generally small, certainly when there is a window open. Formula (9) is then approximately:

$$P = \qquad (10)$$

or $$P = \qquad (11)$$

Example:

inside					outside		
T	=	20°C	to	17°C	T	=	5°C
RG	=	40%	to	32°O	RH	=	70%
E	=	33	to	27 (kJ/kg)	E	=	14.8 (kJ/kg)
window: A_{eff}	=	0.5 (m^2)			V_{wind}	=	6 (m/s)
H	=	1 (m)					

Equation (6) gives for S_{eff} (without the 1.5 correction term):

$$S_{eff} = \qquad (11a)$$

Eqn. (9) → P = (11b)

or, with equal absolute air humidity (which occurs after some time);

Eqn, (10) → P = (11c)

If we assume that the 'airing' of a room is intended to reduce the concentration of smelly substances and pollution in the internal air to eg 1% of the concentration before opening a window, then it should be sufficient to leave the window open for 4.6/a (h). In the above example we have

$$a = \frac{\frac{1}{2} A_{eff} \times S_{eff} \times 3600}{V} = \frac{\frac{1}{2} \times 0.5 \times 0.31 \times 3600}{25} = 11 \ (h^{-1})$$

Hence the window has to be left open for 4.6/11 (h) = about 25 minutes.

This reasoning takes no account of smelly substances or pollution which would pass out of the room for example by evaporation (eg wet washing, or damp bedclothes). In cases of this type it may indeed be useful to leave a small window (flat window/hopper light) open for a long time, but not a large window. According to these measurements, the air-change rate with an open flat window/hopper light was of the order of $a = 1 \ (h^{-1})$.

The following rough examination of the reduction of energy consumption is based on the following conditions in a dwelling in which, in two rooms, during a heating season:

1 : the windows are kept closed;

2 : the windows are kept open for 3 hours per day;

3 : the windows are kept open for 25 min. per day.

Further, assuming the conditions from the foregoing example, then $a = 11 \ (h^{-1})$ and $P = 1200$ per room with the window open. With windows and inside doors closed, the value of $\underline{a}$ will probably lie between 0.1 and 0.5, and the energy loss per second $P = 10$ to 60 (W) per room.

The energy consumption per heating season attributable to the ventilation of the two rooms is then, in these three cases:

Case No.	Windows	$\overline{P}$ (W)	Gas consumption (m^3)
1	Closed	20 to 120	18 to 108
2	Open 3 hrs per day.	320 to 400	285 to 365
3	Open 25 min. per day.	60 x 160	55 to 143

$\overline{P}$ here is the mean power lost in the ventilation air during a heating season.

$\overline{P}$ = fraction-time window open. (2.1200) + fraction time window closed (20..120)(W

In determining the gas consumption, the heating season is taken as 200 days, the boiler efficiency as 0.6 and the combustion heat of natural gas as 32 MJ/m^3. By not allowing windows to remain open for an unnecessarily long time (3 hours), about 225 m^3 of natural gas per heating season can be saved (225 = 285 - 55 or = 365 - 143), according to this investigation.

From investigations conducted in this country and abroad, it appears that in 40% to 50% of dwellings windows are kept open for several hours a day; thus by influencing the occupiers behaviour in this respect it is possible to make a real contribution to energy-saving policy.

9. COMPARISON OF THE FINDINGS WITH THE LITERATURE

We assume the same conditions as for the example discussed in the preceding Section.

These conditions are:

window area	A	=	0.5 (m^2)
window height	H	=	1 (m)
fully open	0	=	1
wind speed	V_w	=	6 (m/s)
temperature difference	ΔT	=	10°C

From formulae (14) and (15) taken from Warren (2) (see Annex 2) it follows that:

$$(14) \rightarrow q_v \; = \qquad\qquad \text{(W14)}$$

$$(15) \rightarrow q_v \; = \qquad\qquad \text{(W15)}$$

From formula (6) (without the 1.5 correction term) it follows that:

$$S_{eff} = \sqrt{0.001 \times 6^2 + 0.0035 \times 1 \times 10 + 0.01} = 0.28 \text{ (m/s)}$$

Combining the speed-pressures of the speeds calculated from (W14) and (W15) yields

$$\tfrac{1}{2}\rho(0.224)^2 + \tfrac{1}{2}\rho(0.147)^2 = 0.046 \; (Pa)$$

thus a speed of $S = \sqrt{\frac{2 \times 0.046}{\rho}} = \underline{\underline{0.27}}$ (m/s) may be expected.

The agreement is good, particularly bearing in mind that this calculation is a very rough one.

In his publication, Cockroft gives some measurement results in which only wind influence is included. The conditions are results are:

window area	A	=	0.2 (m^2)
wind speed	V_w	=	2.5; 5; 7.5 (m/s)
	ΔT	=	0
volume	V	=	48 m^3

V_w (m/s)	2.5	5	7
a (h^{-1}) S (m/s)	0.13 0.017	0.35 0.047	0.58 0.077

At the same time, (6) gives the following values for wind influence alone:

s_{eff} (m/s)	0.08	0.16	0.22

Equation (W14), taken from Warren, gives for the same conditions:

s_{eff} (m/s)	0.06	0.12	0.18

From this it is seen that Cockroft's results yield lower air-change rates than the value found here or those given by Warren.

10. CONCLUSION

10.1 Ventilation

On the basis of these measurements, we are in a position to make rough predictions regarding the air-change rate in the rooms where the measurements were made. Comparisón of the predictions made here with those of Warren (2) and Cockroft (3) indicate good agreement with the former; Cockroft's measurements, on the other hand yield lower air-change rates (a factor of 3 to 4) than found here. From the results found here, the differences between the various types of window appear to be small. The number of measurements in relation to the number of variables is still small for obtaining a more precise determination of this possible difference.

The air-change rate in the rooms dealt with in this investigation may be estimated as

$$a = \frac{3600 \times \frac{1}{2} A_{eff} \times \sqrt{0.001 \times V_w^2 + 0.0035 \times H \times \Delta T + 0.01}}{V} \quad (h^{-1})$$

10.2 Energy consumption

The ventilation energy loss per second resulting from keeping open a window of about 0.5 m^2 with an internal/external temperature difference of about 15°C and a wind speed of about 6 m/s is of the order of 1 kW.

Considering two similar dwellings where in the one dwelling a windiw is kept while in the other dwelling the windows in the two bedrooms are kept open in each of two bedrooms for 3 hours per day while in the other dwelling the windows in the two bedrooms are kept open for about 25 minutes per day, the difference between the gas consumption in the two dwellings is of the order of 225 m^3 per heating season.

10.3 Internal climate

The disturbance of the internal climate resulting from keeping a window open is less than was initially supposed. The mean drop in the internal temperature during the measurements was about 3°C. This temperature drop occurs mainly in the first minutes after opening the window. After about 10 to 20 minutes the temperature continues to fall only slowly.

Close to the window and in the window opening, air speeds of the order of 0.5 m/s are observed. Along the floor and under the window a slight increase of the mean air speed is observed. Within the room, at some distance from the window, however, the air speeds remain eblow 0.2 (m/s).

11. SYMBOLS

A	=	window area (B x H)	(m^2)
A_1	=	window area for calculating A_{eff}	
A_2	=	area between runway/groove and window frame with part-open window	(m^2)
A_{eff}	=	effective window opening	(m^2)
a	=	air-change rate (number of air changes per hour)	(h^{-1})
B	=	width of window	(m)
C_o	=	initial concentration of tracer gas	(vol %)
$C_{(t)}$	=	concentration of tracer gas, at instant t	(vol %)
C_1	=	constant relating to wind influence $\sqrt{K \times \frac{1}{2}\rho}$ or S_{eff}	($kg\ m^{-3}$)
C_2	=	constant relating to temperature influence	($m\ K^{-1}\ s^{-2}$)
C_3	=	constant relating to air speeds caused by eddies due eg to temperature differences in the investigated room	($m^2\ s^{-2}$)

E	=	enthalpy of (humid) air	(kJ/kg)
f	=	factor effecting the connection between the fluctuating air-volume-flow in the window opening and the effective volume flow	(-)
g	=	gravity constant	(N/kg)
H	=	height of window	(m)
h	=	height	(m)
K	=	factor effecting the connection between a wind pressure (on a facade) and the speed-pressure of the wind	(-)
O	=	relation between and expressed as %	(%)
P	=	power (ventilation-energy loss per second	(W)
p	=	air pressure (speed pressure or thermal pressure, not barometric pressure)	(Pa)
Δp_{th}	=	thermal pressure difference	(Pa)
q	=	air-volume-flow	(m^3/s)
q_{eff}	=	air-volume-flow just sufficient to obtain the measured air-change rate	(m^3/s)
rv	=	relative humidity of the air (RH)	(%)
R	=	wind direction: 0, 360° = North; 90° = East, etc.	(°)
$\overline{S}$	=	mean speed ⊥ to window opening ('d.c. component')	(m/s)
S_{eff}	=	calculated value of the mean air speed in the half-effective-window-opening, from ΔT and V_w	(m/s)
s	=	air speed in the window opening ('a.c. component') determined from $S_a - \overline{S}$	(m/s)
S_a	=	air speed measured by thermo-anem.	(m/s)
T_i	=	internal air temperature	(°C)
T_o, T_{meteo}	=	external temperature, meteo temperature	(°C)

ΔT	=	$T_i - T_o$ = internal/external temperature difference	(^oC)
t	=	time	(s)
V	=	room volume	(m^3)
V_w	=	meteo wind speed	(m/s)
v	=	wind speed ('a.c. component')	(m/s)
W	=	degree of turbulence	(-)
α	=	angle of opening of a casement/pivot window; 0 = closed, 90 = fully open	(^{o})
ρ_o	=	density of air at 0^oC = 1.293	(kg/m^3)
$\rho_{(T)}$	=	density of air at T ^oC = $\rho_o \frac{273}{T + 273}$	
K	=	ratio C_p/C_v for air = 1.4	(-)
τ	=	time constant $1/\tau = \alpha/3600$	(s)
μ	=	contraction coefficient	(-)

12. LITERATURE REFERENCES

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ANNEX 1 - EXPLANATION OF SOME OF THE TERMS USED

Cup anemometer = wind speed meter. This type is widely used in met stations. Starting speed about 1 (m/s).

Data acquisition system = A system capable of successively sampling the measurement points and recording the measurement values, whether or not pre-processed, on a cassette tape.

Katharometer = A measurement pick-up/transducer giving an output of about 4.2 mV per vol. % the concentration.

RMS value = Root Mean Square value, also known as 'effective value'. If V is the speed, $V_{RMS} = \frac{1}{t} \int_0^t \sqrt{V^2\, dt}$; this defines a mean value over a definite period (over the time t).

Speed-pressure disk = A measurement pick-up/transducer giving an output $\Delta p = V^2 \cos \alpha$, where α is the angle of incidence with respect to the normal to the disk. The principle of this disk is similar to that of the pitot tube.

Thermo-anemometer = A measurement pick-p/transducer which yields an approximation to the RMS value of the air speed, via a non-linear calibration formula. This anemometer is independent of direction.

Thermocouple = Here: Copper-constantan couple. A pick-up for temperature measurements.
Signal = 40 $\mu V/^{o}C$.

Time constant = $\tau(s)$. In this paper represents the ventilation time constant, ie the period over which the total volume of the ventilation air which has flowed through is equal to the volume of the investigated room. $\tau = 3600/a$ or $a = 3600/\tau$.
τ is an SI magnitude (s).

Tracer gas = In this paper, the gas used for making the measurements of the air-change rate, see Annex 3. The gas used here is helium.

Annex 2. DERIVATIONS

The value of C_2 in formula (5) can be approximated theoretically (see Fig. 13).

The speed, as a function of height and temperature difference (see Fig. 13) is given by:

$$S_{(h,\Delta T)} = \pm\sqrt{\frac{2 \cdot \Delta p_{th}}{\rho}} \pm\sqrt{\frac{2 \cdot 0{,}04 \cdot \Delta T \cdot h}{c}} \qquad (12)$$

By integrating over the theight and multiplying by the contraction coefficient $\mu = 0.61$ we obtain the effective speed in the half-window-opening.

$$S_{eff} = \pm \mu \cdot 0{,}254 \cdot \frac{1}{\frac{1}{2}H}\sqrt{\Delta T} \int_0^{\frac{1}{2}H} \sqrt{h} \cdot dh$$

$$= \pm 0{,}072\sqrt{\Delta T \cdot h} = \sqrt{0{,}0052 \cdot \Delta T \cdot H} \qquad (13)$$

$$C_2 = 0{,}0052$$

The factor μ, which has the value 0.61 here, is strictly applicable for high air speeds in the window. It is not impossible that, at the low speeds occurring here, the value of μ is closer to 1.

Fig. 13 Speed in the window opening resulting from the temperature difference ΔT.

In literature references (2) and (3) the following formulae are presented:

$$q_v = 1/3 . A . 0,61 . 0\sqrt{\frac{g . \Delta T . H}{T}} \qquad (14)$$

with temperature difference as causative 'force',

$$q_v = 0,02 . A . 0,61 . 0 . V_w \qquad (15)$$

with the wind as causative 'force'.

Using a hot-wire anomometer, Cockroft (3) measured the RMS value of the air speeds in the open window and hence obtained, via the compressibility of the air in the room, a volume flow in the window of

$$q_v = \pm A . 0,61 . \sqrt{\left|S_{\perp}^2 - \frac{2\kappa p}{\rho}\right|} \qquad (16)$$

with wind as the causative 'force'.

Since the rapid fluctuations of the air speed and the associated fluctuations of the air flow are not able to exchange their concentration completely with the air in the room, Cockroft introduces an effective air flow in the window, defined as:

$$q_{eff} = \tfrac{1}{2} . f . |q_{i_{\perp}}| \qquad (17)$$

In this formula, the factor $\frac{1}{2}$ is introduced because on average the effective air flow through half of the window area may be inwards and through the other half may be outwards. f is a factor which depends on the frequency of the air-flow fluctuations in the window and takes account of the effect of the air exchange with the room air. (For low frequencies f = 1; for very high frequencies, in the neighbourhood of 100 Hz or more, f approaches 0.) The formulae (14) and (16) do not include any term representing the air exchange resulting from diffusion, since this mechanism has a negligibly small effect here.

ANNEX 3. CALCULATION OF THE AIR-CHANGE RATE

When the air in the room is completely mixed (ie same concentration everywhere), the concentration will decrease exponentially after the window is opened:

$$- V \cdot \frac{dC}{dt} = a \cdot V.C. \qquad (18)$$

With t expressed in (h), the solution is:

$$C_{(t)} = C_o \cdot e^{-a.t} \qquad (19)$$

It is now possible to calculate a by inserting C_o and an arbitrary value $C_{(t_1)}$ in the formula for the concentration, whereupon:

$$a = \frac{1}{t_1 - t_o} \quad ln \frac{C_o}{C_{t_1}} \qquad t \text{ in } (h)^{*} \qquad (20)$$

In formula (20), t_o is the initial constant and t_1 the final instant.

When the curve of the variation is not exactly exponential (imperfect mixing), a may be calculated for a number of instants and then averaged. However, the concentrations of He used here, about 1% (C_o), by themselves produce a driving force. He is ofcourse much lighter than air. 1% He corresponds roughly with the effect of an internal/external temperature difference of 3^oC. The concentration variation is now no longer truly exponential, but can still be treated as such, as an approximation.

In the evaluation, a correction is made for the effect of the He concentration by adding 1.5^oC to ΔT in the calculation of C_{eff}, formulae (6) and (7).

Footnote: * After the introduction of the SI system, the calculation should strictly be made using τ (time constant):

$$\tau = \frac{t_1 - t_o}{ln (C_o/C_{t_1})}$$

ANNEX 4. TABLES SHOWING MEASUREMENT CONDITIONS AND RESULTS

Measurement conditions (windows)

The descriptions of the conditions are preceded by the measurement number.

Single-family dwelling at Schipluiden

1. Casement/pivot window completely open
   (window = 0.7 m wide, 1.20 m high)

2. Casement/pivot window about 0.07 m open
   (5 to 6 degrees).

TNO Building

1. Casement/pivot window closed (window 0.4 m wide 0.9 m high)
2. Casement/pivot window completely open
3. Casement/pivot window completely open
4. Casement/pivot window completely open
5. Casement/pivot window completely open
6. Casement/pivot window and door completely open (continuation of No. 5)
7. Casement/pivot window 45 degrees open
8. Casement/pivot window 14 degrees open
9. Casement/pivot window completely open
10. Casement/pivot window completely open
11. Casement/pivot window completely open
12. Casement/pivot window completely open
13. Casement/pivot window 45 degrees open
14. Casement/pivot window and door open (continuation of No. 12)
15. Casement/pivot window completely closed
16. Casement/pivot window completely open

ANNEX 4 (Continued)

Flat at Delft

1. Casement/pivot window closed window 0.7 m wide, 1.07 m high)
2. Casement/pivot window completely open
3. Casement/pivot window completely open
4. Sash/sliding window completely open (0.7 m wide, 1.07 m high)
5. Casement/pivot window 45 degrees open
6. Casement/pivot window completely open
7. Casement/pivot window 45 degrees open
8. Data lost
9. Casement/pivot window completely open
10. Casement/pivot window completely open (no tracer gas blown in)
11. Flat/hopper light 0.1 m open (0.7 m wide, 0.28 m high)
12. Casement/pivot window 45 degrees open
13. Casement/pivot window completely open
14. Sash/sliding window completely open
15. Sash/sliding window 0.33 m open (0.33 m wide, 1.07 m high)
16. Sash/sliding window 0.33 m open
17. Sash/sliding window 0.33 m open
18. Sash/sliding window completely open
19. Sash/sliding window completely open
20. Sash/sliding window completely open
21. Casement/pivot window completely open
22. Sash/sliding window 0.22 m open
23. Sash/sliding window 0.22 m open
24. Sash/sliding window 0.13 m open
25. Flap/hopper light: data lost
26. Flat/hopper light: 0.1 m open

For casement/pivot windows, 'Completely open' means 90°.

ANNEX 4 (Continued)

Dutch p. 35, lower half.

TNO Building

Column 1 0 No. of measurement

Column 2 = not used

Column 3 = not used

Column 4 = not used

Column 5 = not used

Column 6 = not used

Column 7 = not used

Column 8 = measured external air temperature (°C, start of test)

Column 9 = measured external air temperature (°C, end of test)

Column 10 = measured wind speed, maximum, in front of the facade (m/s)

Column 11 = measured wind speed, minimum, in front of the facade (m/s)

Column 12 = internal temperature at height of 2.2 m (start of test)

Column 13 = internal temperature at height of 2.2 m (end of test)

Column 14 = internal temperature at height of 1.5 m (start of test)

Column 15 = internal temperature at height of 0.2 m (end of test)

Column 16 = internal temperature at height of 0.2 m (start of test)

Column 17 = internal temperature at height of 0.2 m (end of test)

Column 18 = air temperature (met., Rotterdam)

Column 19 = wind speed (met., Rotterdam)

Column 20 = wind direction (met., Rotterdam)

Column 21 = air-change rate (mean of three Ratharometers)

Column 22 = not used

Column 23 = temperature drop in the middle of the room (during the test)

Column 24 = measured external temperature - met. air temperature

Column 25 = (mean) measured wind speed / met. wind speed

ANNEX 4 (Continued)

Dutch p. 36, lower half

Flat at Delft

Column 1 = No. of measurement

Column 2 = Helium concentration, initial, at window (katharometer mV)

Column 3 = Helium concentration, final, at window (karthorometer, mV)

Column 4 = Helium concentration, initial, middle of room (karthorometer, mV)

Column 5 = Helium concentration, final, middle of room (kartharometer mV)

Column 6 = time (s) corresponding to the intial concentration

Column 7 = time (s) corresponding to the final concentration

Column 8 = measured external air temp., start of test (°C)

Column 9 = measured external air temp., end of test (°C)

Column 10 = measured wind speed in front of the facade, min. (m/s)

Column 11 = measured wind speed in front of the facade, max. (m/s)

Column 12 = internal temperature at height of 2.2 m (start of test)

Column 13 = internal temperature at height of 2.2 m (end of test)

Column 14 = internal temperature at height of 1.5 m (start of test)

Column 15 = internal temperature at height of 1.5 m (end of test)

Column 16 = internal temperature at height of 0.2 m (start of test)

Column 17 = internal temperature at height of 0.2 m (end of test)

Column 18 = air temperature (met., Rotterdam)

Column 19 = wind speed (met., Rotterdam)

Column 20 = wind direction (met., Rotterdam)

Column 21 = air-change rate at the window

Column 22 = air-change rate in the middle of the room

Column 23 = temperature drop in the middle of the room (during the test)

Column 24 = measured external air temperature - met. air temperature

Column 25 = (mean) measured wind speed/met. wind speed

ANNEX 5. DIAGRAMMATIC SKETCHES OF MEASURED OBJECTS

ANNEX 6. TIME VARIATION OF TRACER-GAS CONCENTRATION

ANNEX 7. TIME VARIATION OF SPEED IN THE WINDOW OPENING

ANNEX 8. TIME VARIATION OF SPEED IN THE ROOM

ANNEX 9. TEMPERATURE IN THE ROOM

ANNEX 10. SCHEMATIC ARRANGEMENT OF MEASUREMENT SET-UP AND CONNECTIONS

Magnitude	Sensor	Number	Supply/conditioner	DAS
Air speed S	Speed-pressure disk	(4)	Pressure transducer and conditioner	
Air speed RMS value S_e	Thermo-anemometer	(4+9+1)	175 mA supply	
Air Temperature T	Thermocouple $Cu - Co$	(6+9)	Reference junction	Scanner; Digital Volt-meter
Variation of concentration °C	Kathorometer	(3)	350 mA supply	Computer with cassette tape
Wind speed V_w	Cup anemometer	(1)	Integrator	

Pressure transducer: Converts air-pressure differences into electrical voltages $1 P_a \rightarrow 0.1$ V

Thermo-anemometer: Converts air speeds into electrical voltages independently of the direction of flow.

Thermo-couple: All couples are connected to the same reference junction.

Katharometer: Converts tracer-gas concentrations into electrical voltages. 1% He → about 4.2 m V.

Cup anemometer: At speeds over 1 m/s delivers a voltage proportional to the mean wind speed in the plane in which the cups are spinning.

ANNEX 11. CALCULATION OF EFFECTIVE WINDOW AREA

	Schipluiden	TNO Building	Flat at Delft
angle			

Column 1 = angle = angle of opening of window, degrees

OO = effective window opening as % of window opening at 180°

FF = ratio: effective window opening m^2 room volume m^3

In the above, the following formulae are used:

$$O = \left\{ \frac{100}{A_{eff(180^\circ)}} \qquad \frac{1}{(A_1)^2} \right\}^{-\frac{1}{2}} \quad (\%)$$

$$F = A_1 . O/V \quad m^2/m^3 \quad (1/m)$$

Explanation of letter-symbols used:

A_1 = $B^* H$ = window area

A_2 = $2B \sin (\alpha/2)$ $(B \cos (\alpha/2)$ = area between runway and frame

B = width of window

H = height of window

V = volume of room

α = angle of opening of window (0° = closed; 90° = completely open)

For small angles, the values calculated here lie somewhat above the values found experimentally by P Warren (2).

ANNEX 12. TABLE SHOWING SPEEDS IN THE WINDOW OPENING

Column 1 = Number of measurement

Column 2 = Mean speed in the window (d.c. component) $\overline{S}$

Column 3 = Mean speed in the window (a.c. component) $\overline{s}$

Column 4 = Equivalent speed in the window

Column 5 = (Mean) measured wind speed along the facade m/s

Column 6 = Met. wind speed (Rotterdam) (m/s)

Column 7 = Mean interval temperature - measured external temperature

Column 8 = (mean internal temperautre) - (met. temperature)

Column 9 = Met. wind direction

Column 10 = Effective speed (formula (6))

Since the Schipluiden measurements were made only for guidance, they are not processed in this Annex.

ANNEX 13. RELATION BETWEEN THE (INDIRECTLY) MEASURED AND THE CALCULATED SPEED IN THE WINDOW OPENING

S_{eq} = equivalent speed in the half (*eff.*) window opening

S_{eff} = effective speed in the half (*eff.*) window opening (formula (6)).

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SUMMARY

Introduction

A few years ago, the (Netherlands) Ministry of Housing and Environment set up a Steering Group on Energy and Buildings, which initiated an investigation of the possibilities for the efficient use of energy with particular reference to residential and working premises.

As one of its activities this Steering Group initiated an investigation into the possibilities for saving energy by closing (large) windows in good time after the so-called 'airing' of bedrooms, for example.

The investigation was conducted by the TNO Institute for Environmental Hygiene and Health Technology at Delft, and three different rooms were examined.

The object

The purpose of the investigation was to obtain data on the amount of the ventilation, the ventilation energy-loss and the resulting internal climate in a room after a window has been left open.

Starting points

The investigation examined bedrooms having a large openable window (sash-type and casement type), for one or two persons. A total of about 40 measurements were made (in three rooms) with internal/external temperature differences of about 5-15^{o}C and (meteo) wind speeds of about 1.5 - 10 in/s. During the measurements, the heating in the investigated room was switched off and the inside door was closed.

Results

During the measurements, the values of the most important parameters lay within the following ranges:

air speed in the window opening: 0.1 - 0.5 m/s;
ventilation energy-loss per second: 200 - 3000 W.

The air-change rate ('ventilatievoud') is the magnitude used for representing the ventilation. The air-change rate is the ratio between the volume of ventilating air in one hour and the room volume. For example, if the air-change rate is 10, then the volume of ventilating air which has passed through the room per hour is ten times as great as the room volume.

The measurements results are expressed approximately by some simple formula. This means that it is possible to make approximate predictions for the air-change rate, the ventilation energy-loss and the possible saving in energy consumption by closing windows in good time (without thereby spoiling the freshness of the air).

Only slight differences were observed between the measurements results for the different types of window.

Ventilation

The ventilation resulting from opening a window in a room is greater than was initially assumed. The air-change rate is around 10 with:

mean meteo conditions (wind 5 m/s,
internal/external temperature difference 10^{o}C);
a room volume of 25 m^3.

This means that for 'airing' a room by leaving a window open, a period of less than half an hour is mostly sufficient. This does not apply when smells or pollution, for example, have to be removed from the room (eg wet washing, damp bed-cothes). In such cases it may well be desirable to leave a small window open for a long time. According to the measurements, the air-change rate with an open hopper light was about 1(h^{-1}).

The air-change rate for a room of volume 25 m^3 and a window of area 0.5 m^2 (this is a relatively small window) is tabulated below (using an approximate formula from the measurements in this investigation):

AIR-CHANGE RATE (PER HOUR)

Wind speed (m/s)	Temperature difference ΔT (^{o}C)			
	0	55	10	15
0	3.5	6	7.5	9
2	4.5	6.5	8	9.5
5	6.5	8	9.5	10.5
8	10	11	12	13

With windspeed and temperature difference both equal to 0 there is still an air-change rate of 3.5 due to eddies along the facade.

In practice, upward and downward deviations from the numbers in the above Table are to be expected, up to a factor of 1.5.

Energy Saving

In the following rough survey of the possible energy saving, the assume the following conditions in a dwelling in which, during one heating season, two rooms have the windows:

1 : kept closed;
2 : kept open 3 hours per day;
3 : kept open 25 min per day.

We again assume a room volume of 25 m^3, a window area of 0.5 m^2, a wind speed of 5 m/s and an internal/external temperature difference ΔT of 12-15 ^oC. Then the energy consumption due to the ventilation in the two rooms together is:

Conditions	Windows	Gas consumption for the heating season (· days), m^3 1 m^3 gas 32 MJ
1	Closed	18 - 110
2	Open 3 hours/day	285 - 365 = open too long
3	Open 25 min/day	55 - 145 = closed on time

Recent investigations in this country and abroad indicate that leaving bedroom windows open for more than one hour per day occurs in about 40 to 50% of dwellings. In the above example, closing the windows in good time yields a saving of about 225 m^3 of natural gas for one dwelling per heating season.

The ventilation energy-loss per second due to an open window can be expressed in Watts. It can then be compared, for example, with the electric power of lamps. In the following Table, the ventilation energy-loss for second (Watts) is given for an open window of area 0.5 m^2 for different wind speeds and internal/external temperature differences.

Wind speed (m/s)	Temperature difference ΔT (^oC)			
	0			
0	-	260 W	660 W	1165 W
2	-	275	690	1200
5	-	355	820	1375
8	-	470	1025	1655

The above figures are based on measurements made with the room heating switched off. With the radiator on, the energy loss will be somewhat higher.

Internal climate

The temperature drop and the air speeds in the room after opening a window are smaller than was initially supposed. Only in and directly under the window opening were the observed temperatures in the neighbourhood of the external temperature. Inside the room, at 1.5 m above the floor, the temperature drop during the measurements (duration of measurements = 1/2 hour) was seldom greater than 4^{o}C, with an internal/external temperature difference of about 15^{o}C.

In the plane of the window and under the window air speeds of about 0.5 m/s were observed during the measurements. Further inside the room the speeds remain below about 0.2 m/s.

Conclusion

In general, keeping a (large) window open for a 1/2 hour is sufficient for 'airing' a bedroom.

Keeping a (large) window open for a long time (more than 1 1/2 hour) makes no further improvement in the freshness of the air inside a bedroom, but does increase the consumption of energy (even with the heating switched off).

It is estimated that 225 m^3 of natural gas can be saved, per heating season per dwelling, by airing bedrooms for shorter periods.

The air-change effect produced by opening a window can be predicted from the measurement results of this investigation.

Recommendation

The results given here regarding ventilation by open windows are derived from measurements at three locations and on two types of window. In view of the spread in the measurement results, it must be accepted that these results cannot be used without reservations for predictions relating to ventilation by open window for all the dwellings in the Netherlands.

Hence we consider that supplementary check measurements are required in about 20 dwellings. These supplementary measurements should include in particular the determination of the air-change rate as a function of meteo conditions, and details of window position and dimensions. With these check measurements it will be possible to adapt and improve the approximate functions (formulaes) established by this investigation.

CONTENTS

ANNEXES

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