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Influence of Meteorological Conditions on Inhabitants' Behaviour in Dwellings with Mechanical Ventilation

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SUMMARY

Within the framework of the national research project "Ventilation in Housing Construction", studies on occupants' ventilation behaviour were conducted in a demonstration building in Duisburg-Neumühl (F.R.G.). Analyses were based on values measured during January 1 - December 31, 1984, in 24 flats with identical ground plans, all of which were equipped with mechanical ventilation systems. Data on all opening positions of all openable window sashes and door leaves were continuously recorded. All available data had to pass two plausibility tests.

In evaluating the occupants' behaviour with regard to the different types of rooms, natural ventilation was found to be most frequent in bedrooms, followed, in decreasing frequency, by children's rooms and living rooms. For all rooms, ventilation habits distinctly correlated with outdoor air temperature and wind velocity. A function suited to describe these relations was derived. It was found that in buildings with mechanical ventilation systems, window ventilation duration is reduced to a quarter of the corresponding values recorded for buildings with traditional ventilation.

1. INTRODUCTION

Within the framework of the national research project "Ventilation in Housing Construction", studies on occupants' window opening behaviour [1] were conducted in a demonstration building in Duisburg (W. Germany) which also formed part of the project. This demonstration building which was erected in 1983 is a terraced house comprising three blocks. In each block there are four floor levels with two flats each. Figure 1 shows the plan of a block floor with two apartments, each covering a flat floor space of 80 m^2. The storeys have an east/west orientation. All apartments are equipped with a central ventilation system. In the dining room, the parents' bedroom and the children's room, there is a double-sash window, with one side/bottom-sash fitting and one casement-hung, respectively. The sitting room window is a fixed window, the balcony door has side/bottom-sash fittings.

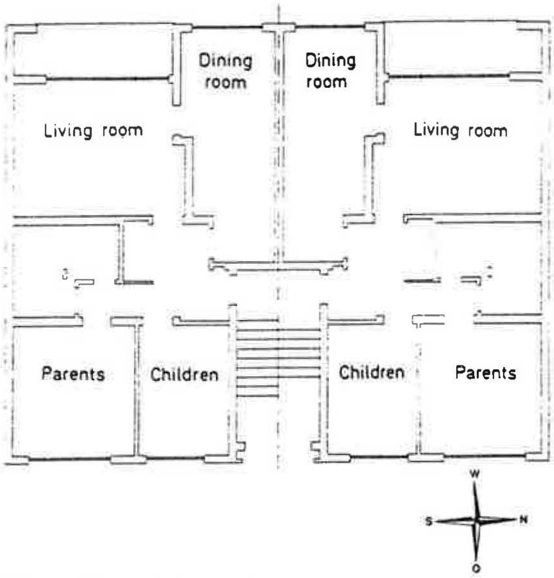

Fig. 1. Ground floor plan of a residential block with two flats on each floor. The floor plan and size of flat are the same for all of the 24 apartments included in the survey.

2. MEASURED VALUES AND PLAUSIBILITY TESTING

In order to allow the continuous recording of varying opening positions, every window sash and door leaf is furnished with contact sensors. Accordingly, 11 window contact sensors were installed in each flat. Every 30 minutes, the data provided by these contacts

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were recorded by the central data logger. The present analysis is based on data compiled between January 1 and December 31, 1984. No less than 4.6 million values out of the data recorded in this period are related to window opening. Additionally, all relevant weather data (such as air temperature, wind velocity, global irradiation, etc.), were continuously recorded as well as temperatures, humidity, and energy consumption for room heating and domestic appliances [2, 3].

Prior to processing this complex data material, it was considered necessary to have all measured values checked for their plausibility. When checked, some measurement contacts were found to be faulty (both temporarily and throughout the entire measuring period). In a further plausibility test, both opening periods and opening positions of any side/bottom-hung sash were checked in detail. Due to design and positioning of the measurement contacts, the side/bottom-hung sash window will be registered to be open in the side-hung position by both the side and the bottom contact. If the same window is open in the bottom-hung position, however, this is recorded *only* by the bottom contact. Consequently, faulty recording must be assumed, whenever the opening times recorded (for one and the same sash) by the bottom contact are shorter than those recorded by the side contact. In the final analysis, only those rooms with 100% reliable measurement contacts were considered, i.e., all of a room's eleven window contacts had to pass both plausibility tests in order to be eligibile for evaluation. The respective plausibility test results are compiled in Table 1. While approx. 70% out of the living rooms, parents' bedrooms, and children's rooms have passed the plausibility tests, there is only one dining room providing correct data. Since this one dining room is not representative for statistical evaluations, it was excluded from the analysis.

3. FREQUENCY AND DURATION OF OPEN WINDOWS AND METEOROLOGICAL CONDITIONS DURING OBSERVATION

For the rooms included in the evaluation, the mean monthly opening time is investigated for all rooms as a whole and with respect to the various types of rooms. However, the results presented in this context are

TABLE 1

Plausibility test results for window contacts in the rooms under observation. Measurement period: January 1 - December 31, 1984

Room		Living room			Dining room			Parents			Children		
Flat	Position	A1	A2	A3	A1	A2	A3	A1	A2	A3	A1	A2	A3
Ground floor	left	×	▽	▽	●	●	●	×	×	▽	▽	●	▽
	right	▽	×	×	●	●	●	●	×	●	● ▽	×	●
1st floor	left	×	×	×	●	●	▽	×	×	×	×	×	×
	right	×	×	×	●	●	●	×	×	×	×	●	×
2nd floor	left	×	▽	×	●	▽	●	● ▽	▽	×	▽	▽	×
	right	●	●	×	●	●	▽	▽	×	×	▽	×	●
3rd floor	left	×	×	×	▽	●	●	×	×	×	×	▽	×
	right	×	▽	▽	●	×	▽	×	●	●	×	×	×

▽ measurement contact temporarily faulty (no values measured) [first plausibility test].
● measured values partially unaccounted for (total opening time recorded in bottom-hung position < total opening time recorded in side-hung position) [second plausibility test].
× all window contacts functioning correctly over the whole measurement period [data included in analysis].

not the absolute duration of opening. Rather, the opening time recorded is related to the maximum possible duration of opening (hours per month) and thus normalized. The results are presented in Fig. 2. Here, a distinction is made between side-hung and bottom-hung position; analysis covers the entire window (i.e., both window sashes). With a result of approx. 10% in side-hung positions, this implies that all sashes were opened on average for six minutes per hour in the side-hung position.

As may be gathered from Fig. 2, windows are open longest in summer and shortest in winter. While in August the overall opening time for all windows amounts to about 25% on average — i.e., 15 minutes per hour — it

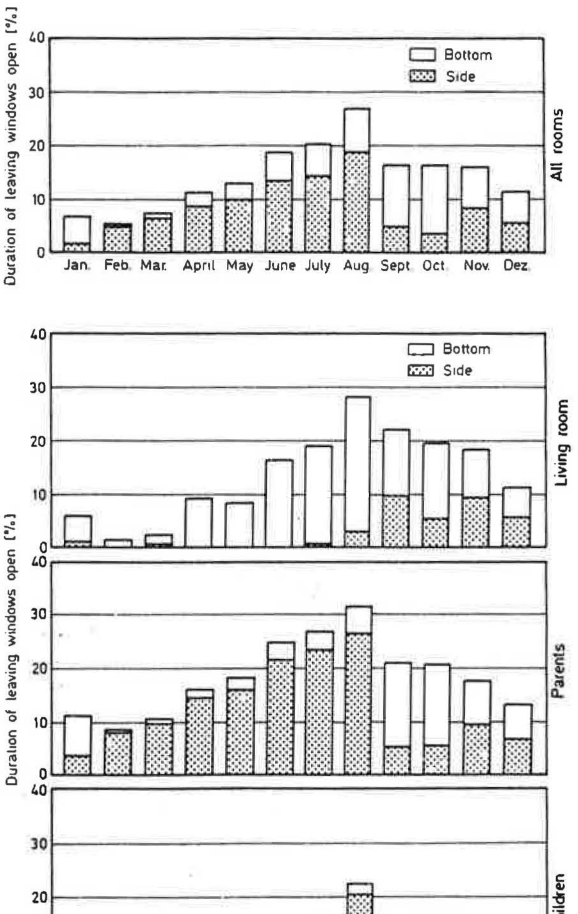

Fig. 2. Mean monthly duration of window ventilation. Values for all rooms and for different types of rooms (expressed in percentages). Analysis covers the entire window, i.e., both window sashes.

decreases to about 5% in winter. In the first six months of the year, windows are preferably opened in the side-hung position, while in the last six months of the year the proportion of windows being kept open in the bottom-hung position is at about 50%. This phenomenon may possibly be accounted for by the higher degree of trapped moisture (sweating), which necessitates an increased air change at the beginning of first occupation.

Comparing the results for the different types of rooms with the overall figures, bedrooms are found to be the rooms most frequently ventilated. Here, too, at the beginning of occupation the side-hung position is preferred, while at the end of the measuring period the bottom-hung position prevails. Even in extreme winter weather, bedrooms are ventilated distinctly more frequently than all of the rooms on average. During the entire measuring period, the window opening time recorded for bedrooms exceeds the average for all rooms by some 50%.

Values measured for living rooms are comparable to the average of all rooms. In living room ventilation, the bottom-hung window opening position is predominant. This may be explained by the balcony door providing the only openable unit. It has a side/bottom-sash fitting, with the bottom-hinged position obviously being preferred by users.

In children's rooms, windows are open least of all rooms. Here, too, in the first six months of the year the side-hung position is preferred, while in the last six months the bottom-hinged position is more frequent. In terms of ventilation habits, the children's rooms are among all rooms those which are ventilated most regularly. Here, it is only in extreme seasons, that the average overall opening times distinctly deviate from the mean value of approx. 10%. As illustrated by Fig. 2, the window opening behaviour strongly correlates with seasonal influences. Due to this correlation, the most important weather parameters were investigated in addition to the users' opening habits.

In Fig. 3 annual mean daily outdoor air temperatures are presented. They range from −2 °C to 28 °C. Until mid-April, relatively low temperatures clearly below the heating line were recorded, and even in June mean daily temperatures were seldom recorded to exceed

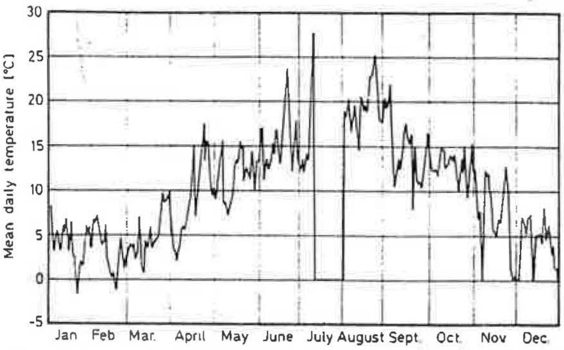

Fig. 3. Mean daily outdoor air temperatures recorded from January 1 to December 31, 1984. (The July gap is due to a black-out in the data recording system.)

15 °C. In autumn, the mild weather with mean daily temperatures around 15 °C lasted until the end of October, before temperatures dropped below the heating line.

The annual curve of the daily totals of global irradiation incident on a horizontal surface is plotted in Fig. 4. Ideal conditions (cloudless skies) would produce a bell-shaped curve with its maximum on June 21 (sun at highest point) and its minimum on December 21 (sun at lowest point). Due to cloud cover or overcasting, deviations from the bell-shaped function occur. At the beginning of April, in May, and in September, pronounced radiation minima are to be observed.

In Fig. 5, the annual curve of the mean wind velocity is plotted. Maximum and minimum values range between 0 and 7.5 m/s. On average, wind velocities fluctuate around 2 - 4 m/s; in the cold days of January and February, wind speeds were, however, slightly higher than in the other months.

All annual curves show a gap between July 11 and 31, 1984, which is obviously due to a

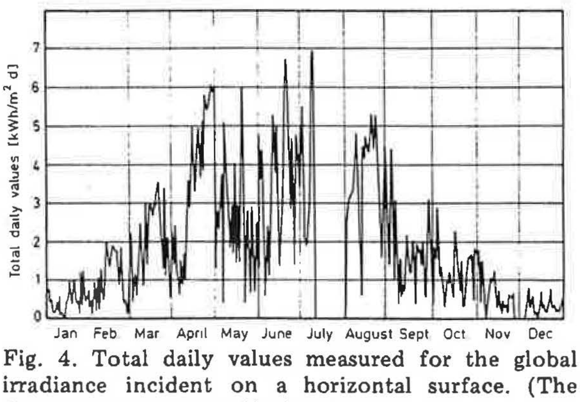

Fig. 4. Total daily values measured for the global irradiance incident on a horizontal surface. (The July gap is due to a black-out in the data recording system.)

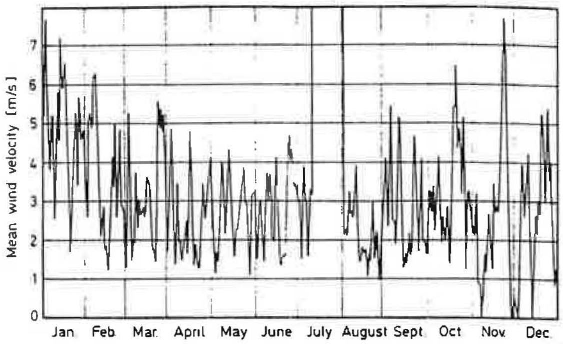

Fig. 5. Mean daily wind velocities measured between January 1 and December 31, 1984. (The July gap is due to a black-out in the data recording system.)

black-out in the data recording system. This data gap has however no influence on the determination of the mean monthly values, because July data were used only during days 1 - 10.

4. VARIATIONS IN USERS' BEHAVIOUR

In order to demonstrate to what extent users may vary in their window opening habits, one occupant with extremely long ventilation periods and one with extraordinarily short ventilation periods were compared to the average value of all occupants, classified according to the different types of rooms. The deviations are illustrated by mean monthly values in Fig. 6. As for the living room, there are hardly any significant deviations from average. They range within a margin of ±10%. In bedrooms and children's rooms, however, deviations are much more marked, with a variance of up to ±20%. If — instead of viewing all of the values — only 90% are taken into account, discarding the extremely untypical users' values, the margin of deviation is reduced to less than ±5%. Accordingly, the elaborated relations describe a representative part of the whole complex under investigation.

5. USERS' BEHAVIOUR IN CORRELATION WITH METEOROLOGICAL CONDITIONS

It was investigated whether there is a relevant correlation between duration of

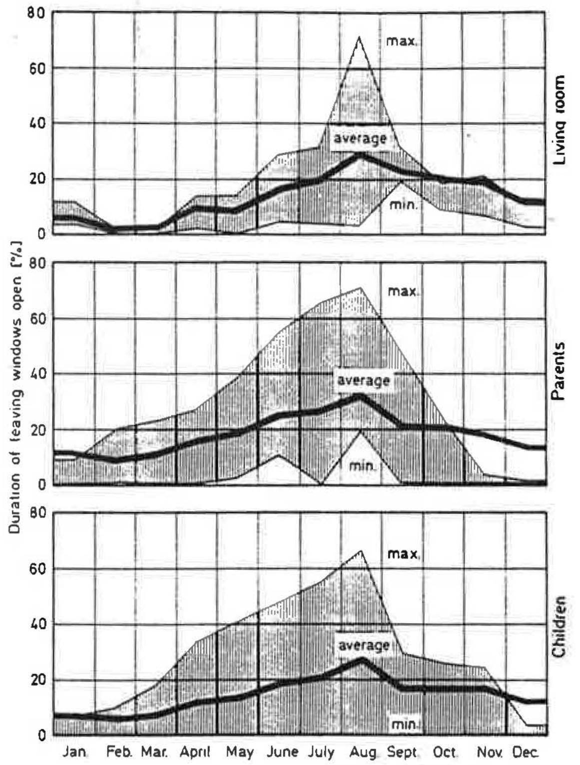

Fig. 6. Variations in occupants' ventilation behaviour in different rooms given as mean monthly duration of leaving windows open (mean monthly overall occupants' values as compared with values measured for a single occupant with untypically short ventilation periods).

window opening and weather parameters. Accordingly, window opening times were correlated with meteorological data. Since these analyses are based on 1.5 million twin values, it is impossible to give an adequate and clear diagrammatic presentation. Instead, the respective mean values are superimposed on the weather parameters. Diagrams are given for overall values (all rooms) and values differentiated between living rooms, parents' rooms, and children's rooms.

5.1. Outdoor air temperature

When investigating outdoor air temperature influences on users' window opening behaviour, a distinction is made between daytime and night-time ventilating. Daytime ventilating is further subdivided into days with high and low solar radiation intensities. Figure 7 illustrates outdoor air temperature influences. Evidently, the influence of global irradiation is only a relatively weak one. Daytime values vary by a moderate margin. In general, night-

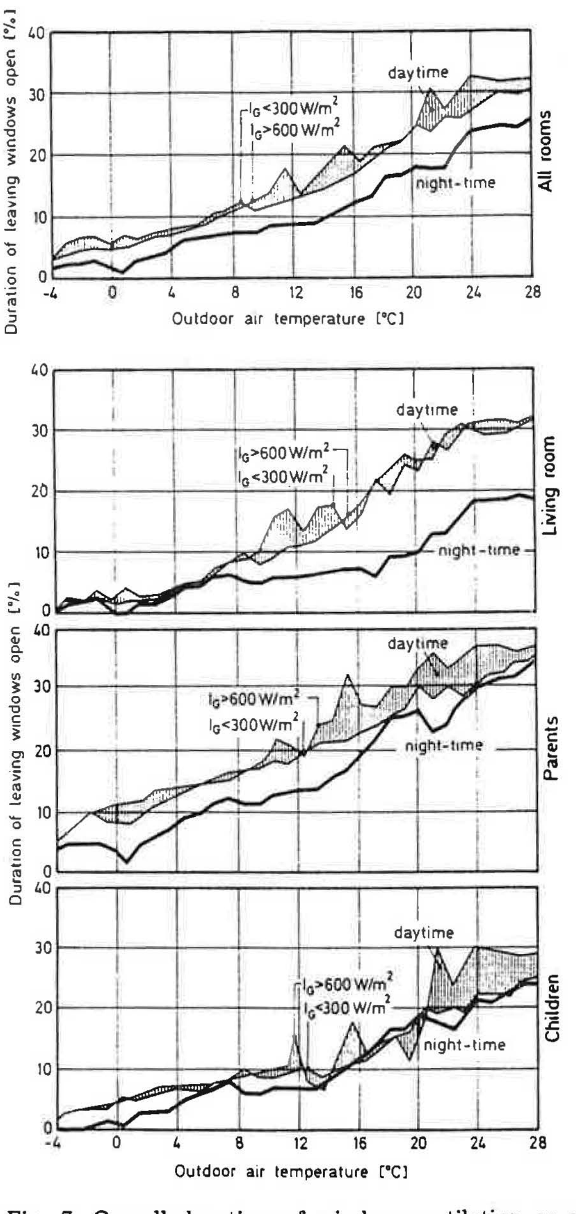

Fig. 7. Overall duration of window ventilation as a function of daytime/night-time outdoor air temperatures, for all rooms and for various types of rooms (expressed as percentages).

time ventilation occurs less frequently than daytime ventilation. The correlation between ventilation habits and outdoor air temperature may be approximately described by two straight lines. Below 12 °C, daytime ventilation increases by some 0.75% per degree temperature difference; above 12 °C by some 1.1% per K; in terms of ventilating frequency, this represents an increase of about 50%. At night temperatures below 12 °C, ventilation duration is raised by about 0.5% per K, and at night temperatures exceeding 12 °C by

TABLE 2

Correlation between duration of window ventilation and outdoor air temperature (analysis results)

Room			Outdoor air temperature	
			$\theta_{La} < 12$ °C	$\theta_{La} \geqq 12$ °C
Living room	daytime	%	$4 + 0.71\theta_{La}$	$12.5 + 1.4(\theta_{La} - 12)$
	night-time	%	$2 + 0.33\theta_{La}$	$6 + 0.83(\theta_{La} - 12)$
Parents	daytime	%	$9 + \theta_{La}$	$21 + (\theta_{La} - 12)$
	night-time	%	$5 + 0.63\theta_{La}$	$12.5 + 1.2(\theta_{La} - 12)$
Children	daytime	%	$4 + 0.5\theta_{La}$	$10 + (\theta_{La} - 12)$
	night-time	%	$2 + 0.5\theta_{La}$	$8 + (\theta_{La} - 12)$
All rooms	daytime	%	$6 + 0.75\theta_{La}$	$15 + 1.1(\theta_{La} - 12)$
	night-time	%	$3 + 0.5\theta_{La}$	$9 + 1.1(\theta_{La} - 12)$

some 1.1% per K, which corresponds to a 100% increase in ventilation frequency. These results allow the mean overall ventilation behaviour to be described as a function of outdoor air temperature. In Table 2 the individual functions for temperatures <12 °C and $\geqslant 12$ °C are compiled.

The temperature dependence was partially found to vary from the overall room values according to the type of room. In living rooms, a change in ventilation behaviour is to be stated at temperatures above 12 °C. This shows good agreement with the average value for all rooms. Here, increases in ventilation frequency amount to some 0.71% per K for temperatures below 12 °C and to some 1.4% per K for temperatures above 12 °C, which again indicates a doubling of ventilation frequency. In spite of the night-time ventilation curve deviating from the daytime curve, here, too, two different sectors (below and above 12 °C) are to be observed. For temperatures below 12 °C, increases amount to some 0.33% per K, and for temperatures exceeding 12 °C to some 0.83% per K. In Table 2, the average living-room ventilation behaviour is presented as a function of outdoor air temperatures.

Daytime ventilation behaviour in parents' bedrooms is not characterized by the significant change of habits recorded for temperatures above 12 °C. Rather, it can be approximately described by a straight curve with a gradient of 1% per K over the entire temperature scale. The corresponding night-time curve, however, again records a comparatively distinct change in ventilation behaviour at 12 °C outdoor air temperature. For temperatures below 12 °C the gradients amount to approx. 0.63% per K, for temperatures above 12 °C to approx. 1.2% per K, which signifies once more a 100% increase in ventilation frequency. Hence, the average ventilation behaviour in parents' bedrooms may accordingly be described as a function of outdoor temperatures as compiled in Table 2.

Though ventilation behaviour in children's rooms is quite similar to the average ventilation habits recorded for all rooms, gradients are slightly lower here. For temperatures below 12 °C, the gradient is about 5% per K, for temperatures above 12 °C it is about 1% per K. Night-time values range below daytime values by about 2% of opening times. This difference is almost independent of temperature influences. The average temperature dependent ventilation behaviour in children's bedrooms is also outlined in Table 2.

5.2. Horizontal global irradiance

Another meteorological parameter to be investigated is the solar irradiance. In Fig. 8, durations of leaving windows open are plotted for summer and winter months as a function of the horizontal global irradiance. Although a strong influence appears to develop, a distinct dependence on solar irradiance cannot be confirmed, as the influences of outdoor air temperature and global irradiance are superimposed in Fig. 7. As clearly shown in Fig. 6, the global irradiance varies only by a narrow and hence negligible margin.

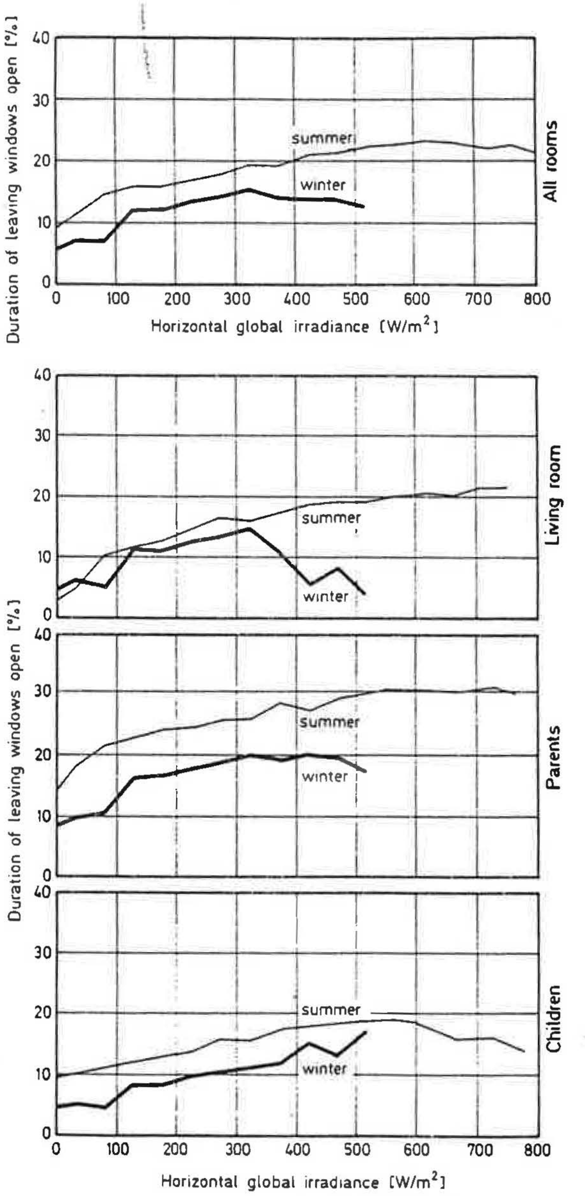

Fig. 8. Overall duration of window ventilation as a function of the horizontal global irradiance in summer and winter months (for all rooms and for various types of rooms; expressed as percentages).

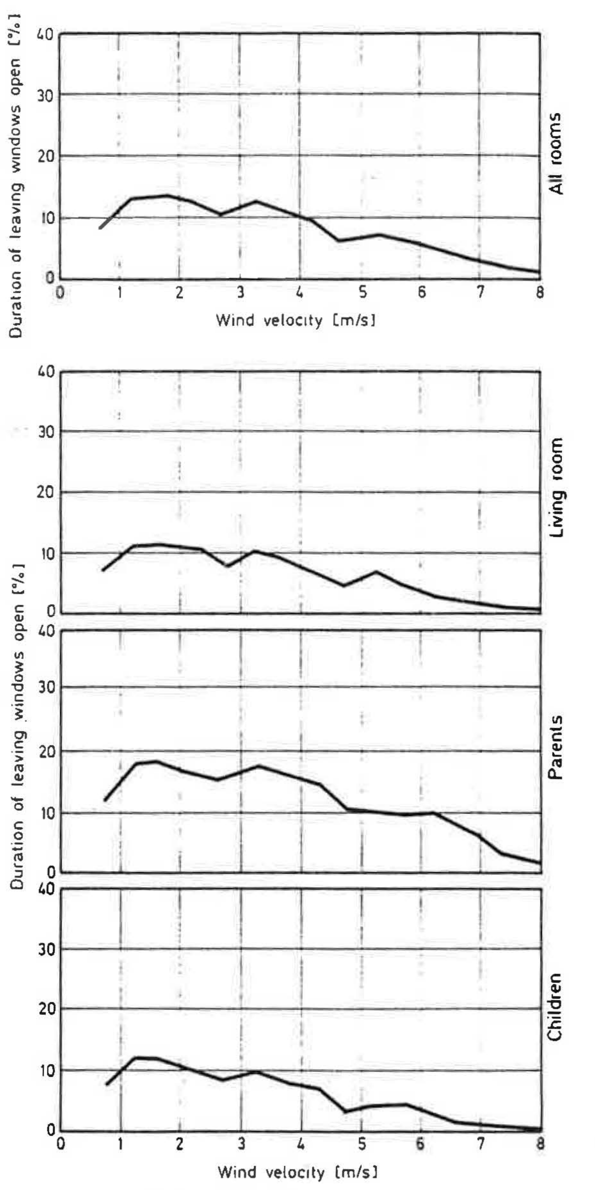

Fig. 9. Overall duration of window ventilation as a function of wind velocity, given for all rooms and for various types of rooms; expressed as percentages.

5.3. Wind velocity

It may be supposed that ventilation periods are also affected by wind velocities. In Fig. 9, influences of wind velocities are illustrated. The relationship may be expressed almost linearly, while the ventilation behaviour is found to be almost independent of any type of room. Based on an average wind velocity of 3 m/s, wind influences can be introduced as a correction term for temperature-related window ventilation periods by way of:

$$t_{\text{open (w)}} = \frac{10 - W}{7} \times t_{\text{open (3 m/s)}} \quad (\%)$$

5.4. Comparison with previous studies

To evaluate the results obtained in this study, they are compared to findings presented in previous investigations. In an extensive series of studies conducted by Austrian researchers [4] and in earlier British observations [5], values recorded during heating

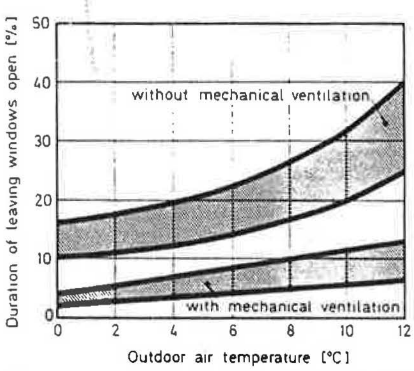

Fig. 10. Comparison of duration of window ventilation in flats with natural ventilation (according to refs. 4 and 5) and flats with mechanical ventilation as a function of outdoor air temperature (based on an indoor air temperature of 20 °C).

periods in solely window-ventilated flats with various heating systems are presented, resulting in the following functional relations for mean window ventilation duration:

Panzhauser *et al.* [4]

$t_{open} = 100 \times (2.6 \pm 0.6\ K)/(\theta_{Li} - \theta_{La})(\%)$

Brundrett [5]

$t_{open} = 100 \times 2.6/(\theta_{Li} - \theta_{La})(\%)$

In Fig. 10 the above-mentioned relations established for window-ventilated flats are compared with the results obtained in the present study (in accordance with Table 2). It is found that in flats without mechanical ventilation systems, windows are open about four times as long as in mechanically ventilated flats. Accordingly, energy losses due to 'uncontrolled' ventilation are drastically reduced, but not — as frequently assumed — prevented.

6. SYNOPSIS AND OUTLOOK

Within the framework of the national research project "Ventilation in Housing Construction", studies on occupants' ventilation behaviour were conducted in a demonstration building in Duisburg–Neumühl (F.R.G.) which also formed part of the project. Analyses were based on values measured from January 1 - December 31, 1984, in 24 flats with identical ground plans, all of which were equipped with mechanical ventilation systems. Data on all opening positions of all openable window sashes and door leaves were continuously recorded, thus providing exact time data for all opening positions to be stored on data carriers. All available data had to pass two plausibility tests, which resulted in 70% of the main room data being considered eligible for analysis.

In evaluating the occupants' behaviour with regard to the different types of rooms, natural ventilation was found to be most frequent in bedrooms, followed, in decreasing frequency, by children's rooms and living rooms. For all rooms, ventilation habits distinctly correlated with outdoor air temperature and wind velocity. A function suited to describe these relations was derived. An alteration in occupants' behaviour recorded during the period of measurements is probably accounted for by the initially higher content of trapped moisture (sweating) at the beginning of first occupation. When finally comparing the present results with studies on users' ventilation behaviour in flats with conventional window ventilation, it was found that in buildings with mechanical ventilation systems, window ventilation duration is reduced to a quarter of the corresponding values recorded for buildings with traditional ventilation.

ACKNOWLEDGEMENT

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LIST OF SYMBOLS

θ_{La}	exterior air temperature (°C)
θ_{Li}	indoor air temperature (°C)
W	exterior air velocity (m/s)
$t_{open\ (w)}$	temperature-selected window ventilation periods (%)

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