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INFLUENCE OF OPEN WINDOWS ON THE INTERZONE AIR MOVEMENT WITHIN A SEMI-DETACHED DWELLING

M D A E S Perera and P R Warren

Building Research Establishment
Garston
Watford, WD2 7JR
United Kingdom

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1. INTRODUCTION

Although most buildings in a temperate climate such as the United Kingdom rely on natural ventilation, its prediction is one of the most difficult aspects of building design. When this is further clouded by occupant behaviour, eg. by opening windows, prediction becomes even more difficult.

Studies by Dick and Thomas[1] and Brundrett[2], amongst others, have shown that occupants of dwellings often open windows even in the winter. Brundrett showed that they do so in a systematic manner which is strongly correlated with the outside air temperature and modified by wind speed. It was also found that bedroom windows were those most frequently opened.

In this paper, a multicell airflow computer program called BREEZE is used to determine the influence of open windows on the ventilation rates of a semidetached house for a variety of weather conditions. For a limited number of cases, the predicted values are compared with field measurements to indicate the degree of confidence which can be placed in the computer simulation. The effect of closing internal doors on ventilation rates and interzonal airflows is also considered.

2. COMPUTER PROGRAM

For this work, the BREEZE program was used to determine the interzonal airflows as well as the ventilation rates. This program is a modified version of the SMOKE program[3]. BREEZE is written in FORTRAN-4 and, for the computer modelling reported here, was mounted on a DEC VAX mainframe computer. It requires about 84 kb of memory and takes about 20 seconds for a typical computer run.

In the program, the building is considered as a network with zones, in this instance rooms, represented by nodes and the air flow path by branches connecting the nodes. Pressure differentials are set up between nodes due to a combination of stack and wind effect. The relationship between applied pressure difference and the flow between nodes is defined for each flow path. The program allows for a number of different types of flow path, the most commonly used being of the general form

$$Q = K \Delta p^n$$

where Q is the volume flow rate, Δp the applied pressure difference and K and n characteristics of the opening.

Wind pressures are obtained from wind tunnel data, generally expressed in the form of pressure coefficients, C_p. Then the surface pressure at any external opening is given by,

$$p = (\rho/2) U^2 C_p + p_o$$

where U is wind speed, ρ air density and p_o the freestream static pressure in the wind.

The set of equations which derives from the network is solved by conventional network theory, analogous to that used for the solution of complex electrical circuits. The difficulty created by the nonlinear pressure-flow relationship is overcome by successive linear approximations. The linear approximations at each iteration are based upon the solution to the previous iteration.

In addition, the program contains a facility for taking into account 'single-sided' ventilation. This occurs when the openings connecting outside air to a space are much larger than the openings which connects it to other parts of the building. This form of air exchange may result from local stack effect or that due to the wind. The equations governing the magnitude of these interchanges are discussed in Reference 4. Having proceeded through the general solution to determine pressure driven flows, the program identifies spaces in which single-sided ventilation may be important and computes the flows due to wind and stack. These are compared with the result from the solution for pressure driven flows and the largest of these three taken as the solution.

3. VALIDATION OF COMPUTER MODEL

To investigate the validity of the computer simulation, a comparison has been carried out for a semidetached test house at Capenhurst, England belonging to the Electricity Council Research Centre (ECRC). Predicted whole house infiltration rates and room ventilation rates were compared with field measurements carried out by the Building Research Establishment (BRE).

3.1. Building

The test building is a two-storey, small, semidetached house with a brick gable wall and timber-framed front and back walls. This house lies (Figure 1) at the south-west end of row of three pairs of semidetached houses located in rural terrain. The predominant winds from the south-west blow over open ground onto the brick-built gable end-wall.

Figure 2 shows a plan of the test house. All windows are metal-framed, single-glazed windows horizontally pivoted at the midpoints of the vertical sides. All external doors are wooden framed with single glazing. The test house is 5.6 m wide and 7.2 m deep. Each floor is 2.3 m high and the roof pitch is about 22°.

3.2. Leakage characteristics

Component pressurisation tests were carried out on all windows and doors to determine their leakage characteristics. The results were expressed in the form,

$$Q = Q_{50} \; (.p/50)^{n} \; m^{3}h^{-1}$$

where Q is the flow rate for an applied pressure differential .p (Pascals) between inside and outside, n is an exponent and Q_{50} is the flow rate at 50 Pascals. Measurements showed that the overall flow through closed windows and external doors could be represented by the above expression.

Whole house pressurisation tests were also carried out. Large differences between the whole house leakage and the summed component leakages showed that there was substantial background leakage. These can be summarised as follows:

	Q_{50}	n
Whole house leakage	2325	0.570
Total leakage through components	858	0.706
Resulting background leakage	1468	0.501

This large background leakage must be taken into account in any modelling procedure[5]. In this instance, this was carried out by apportioning part of the leakage to each purpose-built component and the other part to leakage through cracks into the attic and into the crawl-space.

The apportionment was carried out by area-weighting the permeable area appropriate to that leakage path as a proportion of the total permeable area of the building. For this purpose, the latter is defined[6] as the sum of the areas of the external walls of the house together with the area of the ground floor (which was permeable to air flow) and the area of the surface between the house and roof space. The leakage characteristics thus calculated for the ECRC house are tabulated in Table 1. The Table also gives the equivalent areas[7] corresponding to the main bedroom window when they could be opened to three 'notch' settings.

3.3. Wind pressure coefficients

Wind pressure coefficients (Table 1) for winds from the south-west and north-west striking the gable end-wall and the rear wall respectively were obtained from a series of wind-tunnel model studies. The airflow for these tests was modelled[8] to simulate the boundary layer flow over flat, open countryside with few obstacles. The pressure coefficients are defined with reference to an unobstructed wind speed measured at a height of 10 m in full scale.

3.4. Comparison between measured and predicted rates

In Figure 3 the predicted whole house infiltration rates are plotted against various wind speeds for three temperature differentials between inside and outside air. In the computer runs, all internal doors were kept open and the wind was taken to blow from the south west towards the gable end-wall. Superimposed are field measurements of whole building infiltration rates measured using the conventional tracer decay technique.

These field measurements were also carried out with all windows and outside doors closed and with all internal doors open. During the measurements, the temperature differential between inside and outside was about 5°C. On average, the wind was also blowing onto the gable end-wall of the house in a manner similar to the computer simulations. Figure 3 shows the good comparison between measured and predicted whole house infiltration rates. The predicted curves also show the influence of temperature differential and the regions over which buoyancy effects dominate.

Figure 4 shows similar comparison between measured and predicted room ventilation rates in Bedroom 1 (Figure 2) with and without the window in that room kept open to Notch 3 (Table 1). During this set of field measurements, all internal doors were kept closed. The wind, as before, was blowing from the south west and the temperature differential was about 10°C.

The exact comparison between measured and predicted room airchange rates is not good. This was to be expected since the background leakage was distributed on an area-weighted basis. Etheridge and Alexander[9] have shown that this problem can be solved in an iterative manner by choosing several different distribution patterns which satisfy the whole-house leakage characteristic and then applying other conditions (such as comparing predicted rates with measured ventilation rates) to obtain the best possible distribution. Alexander et al[10], however, describe an experimental pressurisation technique whereby the distribution of background leakage areas may be determined for use with these prediction methods.

Figure 4 shows that the predictions overestimate the measured room rates when the room window is closed but underestimate when the window is opened. Both predictions and measurements, however, show the expected increase in the room ventilation rate with increasing wind speed and with the opening of the window.

The results were considered to be sufficiently good to proceed to a series of calculations of whole house and zone ventilation rates for a standardised house. The zones were large, i.e. either the whole upstairs or downstairs space, and were expected to be less sensitive to background leakage than individual rooms.

4. PREDICTIONS USING 'STANDARD' HOUSE CONFIGURATION

If the total permeable area of the building is A_p, then it has been shown[6] that Q_T/A_p is a good indicator of the overall permeability to airflow of the building envelope. For the ECRC house, this index works out as 11.8 m^3h^{-1}/m^2. This is much tighter than the average index of 22.1 m^3h^{-1}/m^2 found[6] in a small sample of UK housing.

It was decided that further computer predictions should be carried out in a 'standard' house with leakage characteristics more representative of existing UK dwellings. Using the same house and room configuration as the ECRC house, a 'standard' house model was set up using values[6] of 200 m^3 (compared to 197 m^3 for the ECRC house) for the house volume together with Q_T = 2740 m^3h^{-1} and n = 0.60. The component and crack leakages were determined as before using area-weighting and are tabulated in Table 1. Calculations show that this distribution results in 62% of the leakage at 50 Pa being background crackage. This compares with the average 60% as found by Warren and Webb[6].

Various computer simulations are now considered based on the standard house. Unless otherwise stated, all simulations were carried out with the following configuration:

- Wind blowing onto the rear of the house.
- Temperature differential of 5°C.
- Internal doors open.

4.1. Effect of wind direction

Simulations were carried out for winds blowing towards the front, rear and end walls of the test house. Figure 5 shows the whole house infiltration rates obtained. At low windspeeds, buoyancy effects dominate and wind direction has only a small influence on the airchange rates. At higher wind speeds, and as expected, the infiltration rates are much greater for winds blowing onto either the front or rear of the building than for winds blowing onto the end wall. The leakage distribution is such that there is no discernible difference in the rates for winds blowing either towards the front or the rear of the house.

4.2. Effect of opening an upstairs bedroom window

The influence of opening an upstairs window on the ventilation airflows was determined by a series of simulations carried out with the window in the leeward Bedroom 1 open to various notches on the window catch.

Figure 6.a. shows the increase in the whole house ventilation rate when the window is opened to Notch 3 (Table 1). Figure 6.b. shows that this is brought about by an increase in the fresh air inflow into both storeys of the house. It should be noted that more fresh air flows into the downstairs region than the upstairs and that there is a net flow upwards within the house. In all these and subsequent figures, the flow rates relating to each floor have been normalised by the floor volumes of 100 m^3 each.

The effect of gradually opening the window was also examined. At a windspeed of 4 ms^{-1}, representative for the locality in which the test house is situated, the resulting whole-house ventilation rates were as follows:

Window opening pattern	Ventilation rate (ach)
Window closed	0.69
Window open to first notch (#1)	0.75
Window open with catch resting on frame (#2)	0.84
Window open to main stop (#3)	1.21
Windows in Bedrooms 1 and 2 (windward) both open to Notch #3	2.09

4.3. Effect of opening banks of upstair windows

The effect that opening all windward or leeward upstairs windows (i.e. 'banks' of windows) has on the ventilation airflows within the building was examined. Simulations were carried out with various combinations of open leeward and windward banks of windows.

Figure 7.a. shows the increase in the whole house ventilation rate when the windows were opened. At a wind speed of 4 ms^{-1}, the ventilation rates from

these simulations were;

Windows		Ventilation rate
Windward	Leeward	(air changes per hour)
closed	closed	0.69
closed	open	1.57
open	closed	1.82
open	open	4.33

The total airchange rate in each floor for each of the window opening patterns is also shown in Figure 7.a. in a manner similar to that given by Dickson[7]. It shows that the most significant increases occur upstairs. For a 4 ms^{-1} wind speed, the airchange rate upstairs triples in value when either the windward or leeward windows are opened. This increase is eightfold when all upstair windows are opened. Qualitatively, these effects are similar to those observed by Dickson[7] from field measurements on a detached house.

The ventilation rate downstairs is seen to decrease when all upstairs windows are opened. This can be traced (Figure 7.b.) to a reduction, in this instance, of the inflow of fresh air into that region. It is also interesting to note that, in the simulations when the upstair windward windows were opened, there is a flow reversal with air flowing down the stairwell.

4.4. Influence of internal doors

A series of simulations were carried out to determine the effect, if any, of closing internal doors on the ventilation flows. Simulations were carried out with the window in either the upstair leeward Bedroom 1 open to Notch 3 or with the downstairs kitchen window open by the same amount. Since it has been shown previously that there is no discernible difference in the airchange rates for winds blowing either onto the front or rear of the house, the wind was taken to blow towards the front of the house when the kitchen window was opened.

Figures 8.a. and 8.b. show clearly that the whole house ventilation rate is reduced only when internal doors are shut in the floor in which the window is open. At 4 ms^{-1}, this reduction was 25% when the upstair window was open and 18% when the downstair window was open.

5. DISCUSSION

Predicted whole house infiltration rates have been shown to compare very well with field measurements. The comparison was, however, poor when individual room rates were determined. It was suggested that this was possibly due to an incorrect distribution of the background leakage amongst the rooms when input as data into the computer model.

For this study, it was shown that opening upstairs windows strongly influences the ventilation flow. Opening a leeward window was shown to double the whole house infiltration rate whilst opening a window in each of the two main bedrooms, one on the windward and the other on the leeward side of the house, trebled the rate. This increase was magnified when banks of windows were opened upstairs.

Finally, for the particular conditions considered, the simulations showed that closing internal doors reduces the whole building ventilation rate but only if the doors are shut in the floor in which a window is open.

6. CONCLUSIONS

The computer program BREEZE has been used to evaluate the importance of

- window opening patterns,
- open or closed internal doors,
- wind speed, wind direction and difference in internal and external temperatures,

on the ventilation airflows in a typical semidetached house.

It is shown that BREEZE can provide a useful design tool with which to assess the influence of changes of building fabric, of form or location on the ventilation of that building. It is equally applicable to larger buildings such as offices and to smaller buildings such as the dwellings discussed in this paper. To make this program more widely available, BREEZE has now being developed and implemented as an interactive user-friendly package on an IBM personal computer.

ACKNOWLEDGEMENTS

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Leakage path	ECRC TEST HOUSE				STANDARD HOUSE*			Pressure coefficents, C_p for winds blowing towards	
	Leakage Coeff. (metric units)	Cracks length (m)	Cracks Coefficient K	Exponent	Leakage Coeff. (metric units)	Cracks length (m)	Cracks Coefficient K	end-wall	rear-wall
Hall door	2.744			0.818	1.761			0.09	-0.19
Kitchen window	2.284			0.518	2.935			0.09	0.22
Diner window	2.134			0.600	2.348			-0.01	0.15
Porch door	1.599			0.775	0.587			0.15	-0.07
Living room window	3.094			0.518	3.522			-0.01	-0.15
Hall floor		13.36	3.01	0.501		13.36	4.12	0.04	0.01
Kitchen floor		11.90	3.38	0.501		11.90	4.63	0.04	0.01
Diner floor		12.00	3.35	0.501		12.00	4.59	0.04	0.01
Living room floor		14.64	4.32	0.501		14.64	5.91	0.04	0.01
Bathroom window	4.328			0.500	1.761			0.09	0.22
W/C window	5.218			0.475	0.587			0.09	0.19
Bed #2 window	2.389			0.579	2.935			-0.01	0.15
Bed #1 window	2.809			0.579	3.522			-0.01	-0.15
Bed #3 window	2.354			0.531	2.348			0.09	-0.19
Landing ceiling		11.32	3.04	0.501		11.32	4.17	0.00	-0.06
Bathroom ceiling		6.70	1.71	0.501		6.70	2.35	0.00	-0.06
W/C ceiling		4.90	1.17	0.501		4.90	1.61	0.00	-0.06
Bed #2 ceiling		13.40	3.43	0.501		13.40	4.70	0.00	-0.06
Bed #1 ceiling		13.88	3.72	0.501		13.88	5.10	0.00	-0.06
Bed #3 ceiling		9.16	2.51	0.501		9.16	3.43	0.00	-0.06
Internal doors									
- open	84.24			0.500					
- closed	16.38			0.500					
Open window									
- Notch #1	13.00			0.500					
- Notch #2	26.00			0.500					
- Notch #3	110.00			0.500					

*Note: Exponent = 0.600 in all instances

Table 1 Leakage characteristics and pressure coefficients for the ECRC and 'Standard' house models

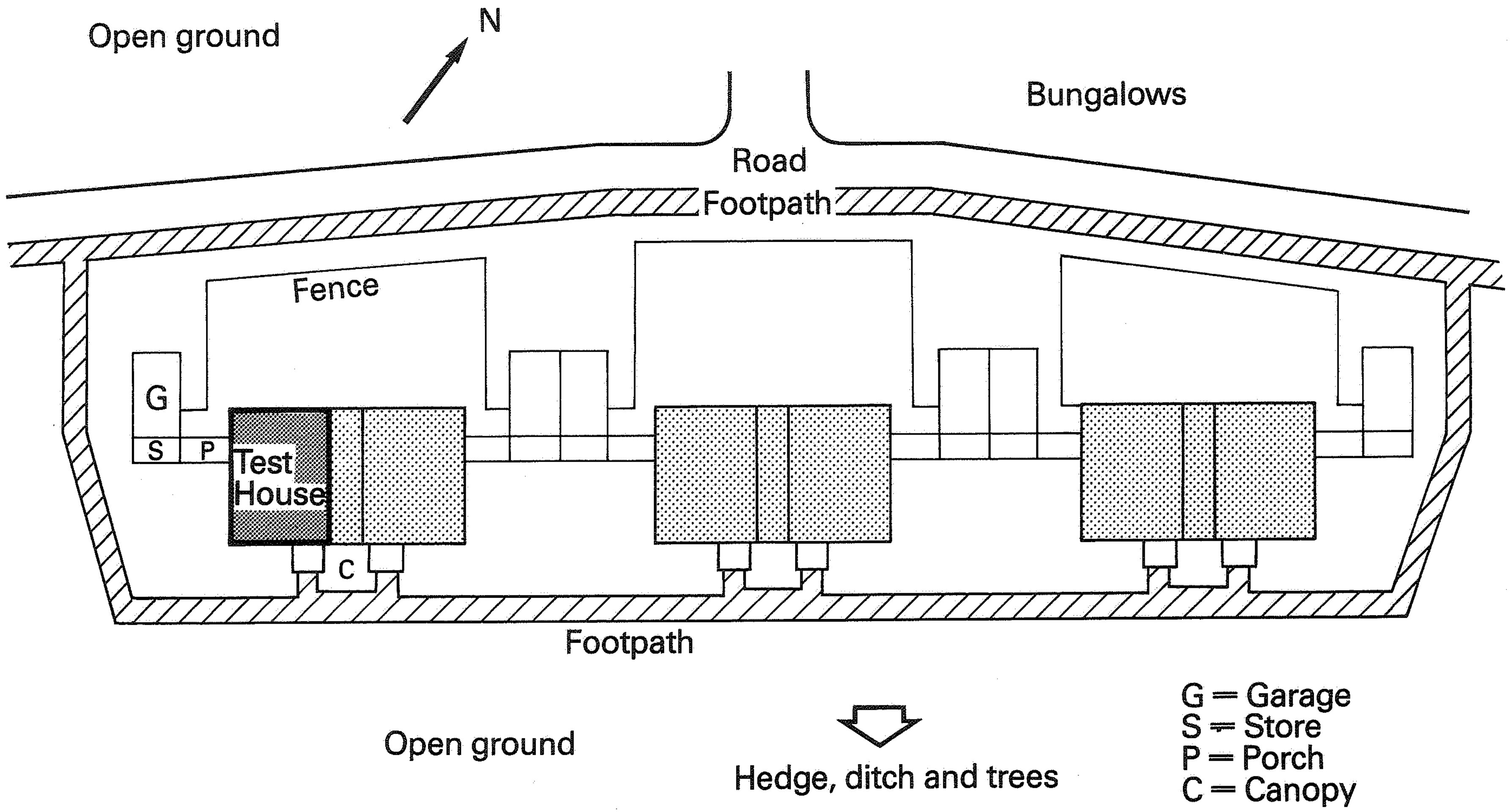

Figure 1 - Site plan of houses

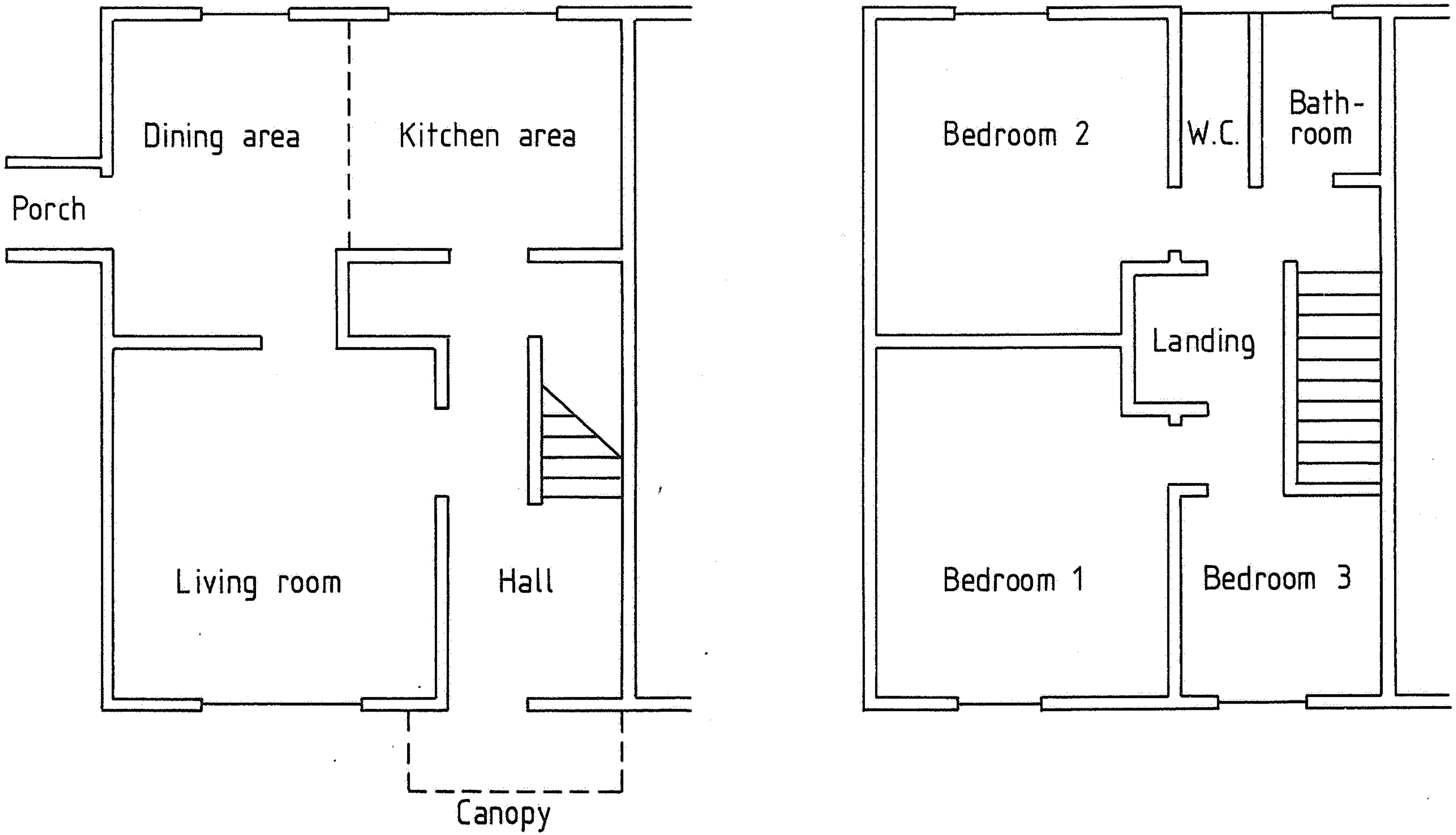

Figure 2 - Plan of test house

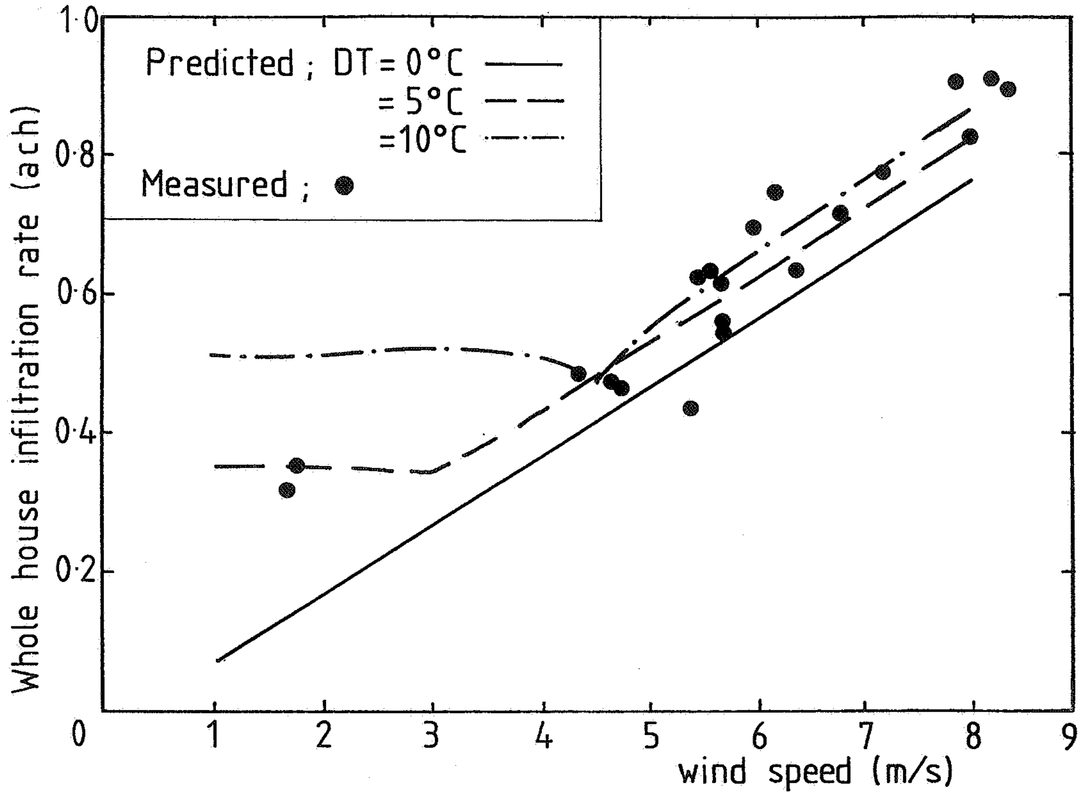

Figure 3 - Comparison of measured versus predicted infiltration rate for ECRC house

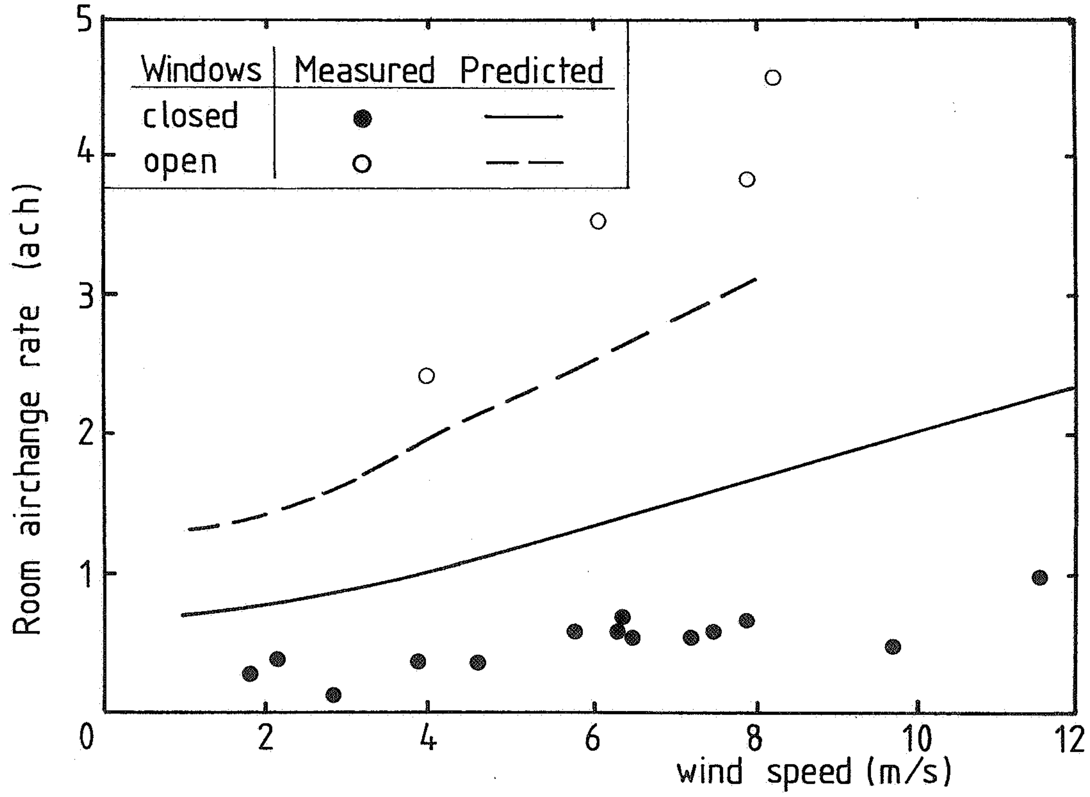

Figure 4 - Airchange rate in Bedroom # 1 for ECRC house

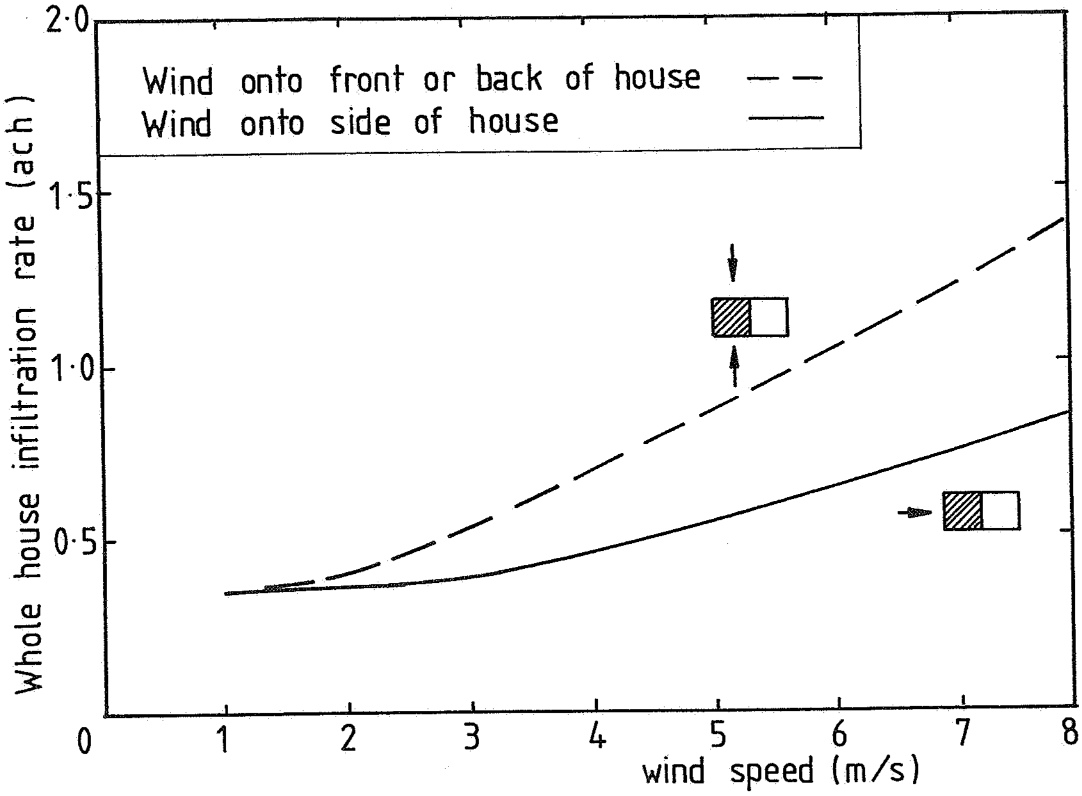

Figure 5 - Effect of wind direction for standard house

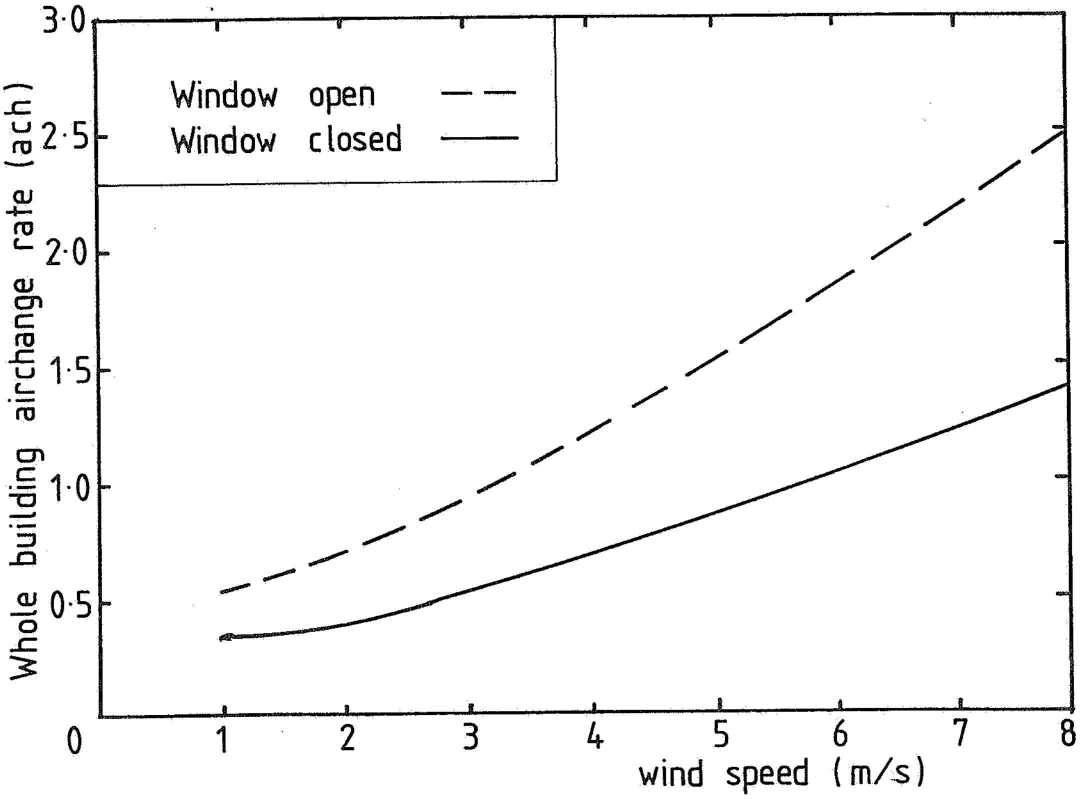

Figure 6.a - Effect of opening bedroom window

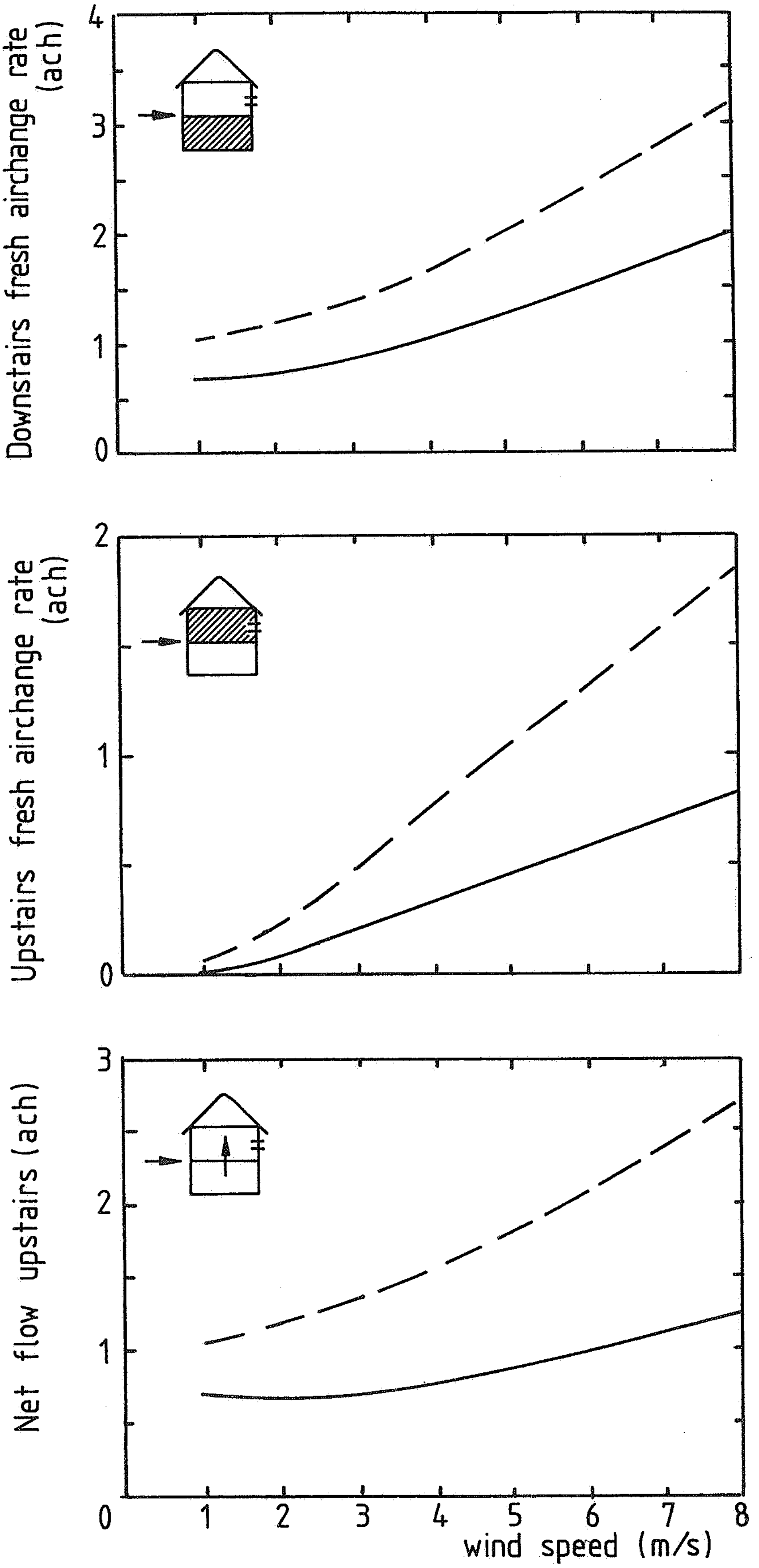

Figure 6.b - Effect of opening bedroom window (key as in Figure 6.a)

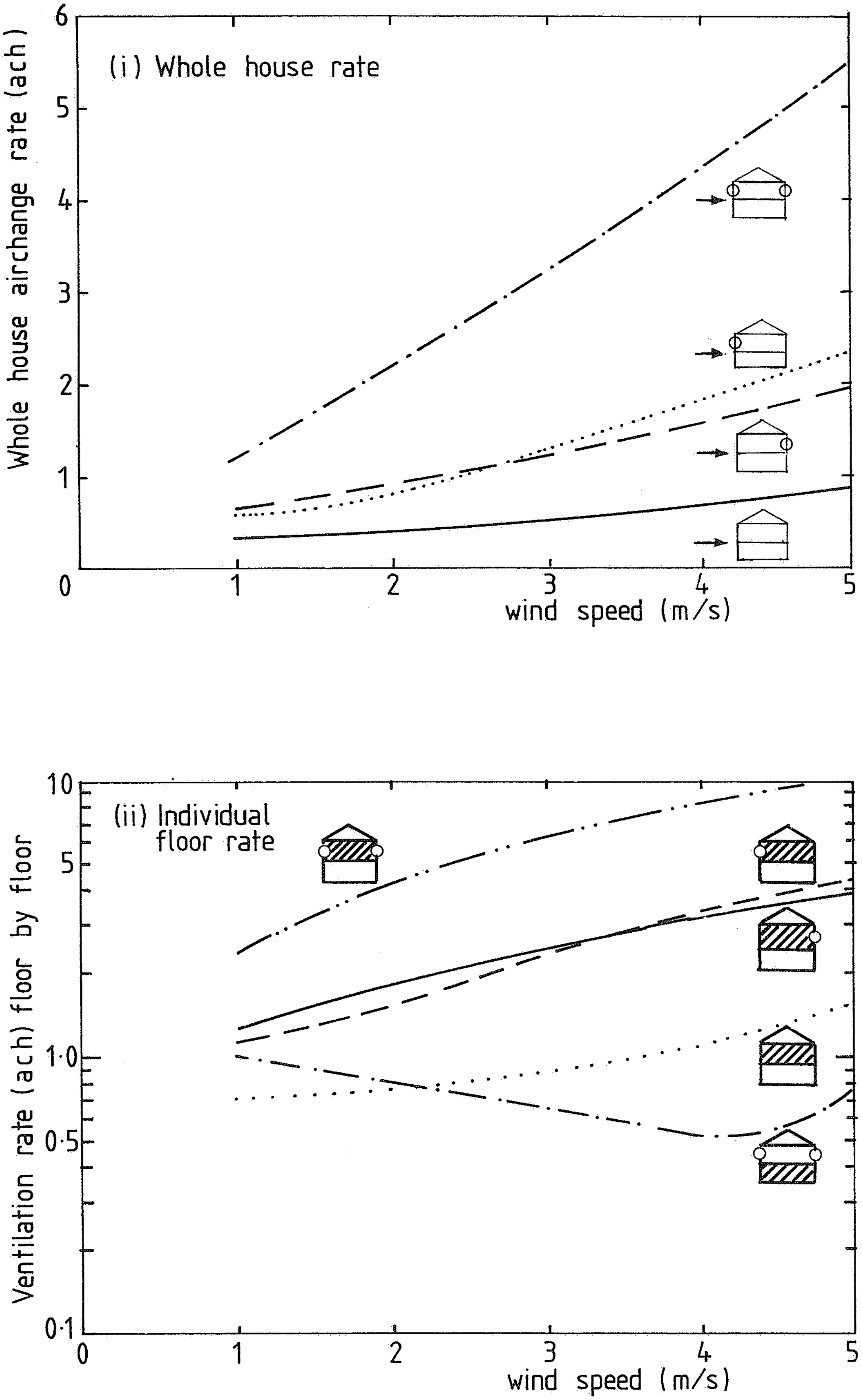

Figure 7.a – Effect of opening banks of upstairs windows

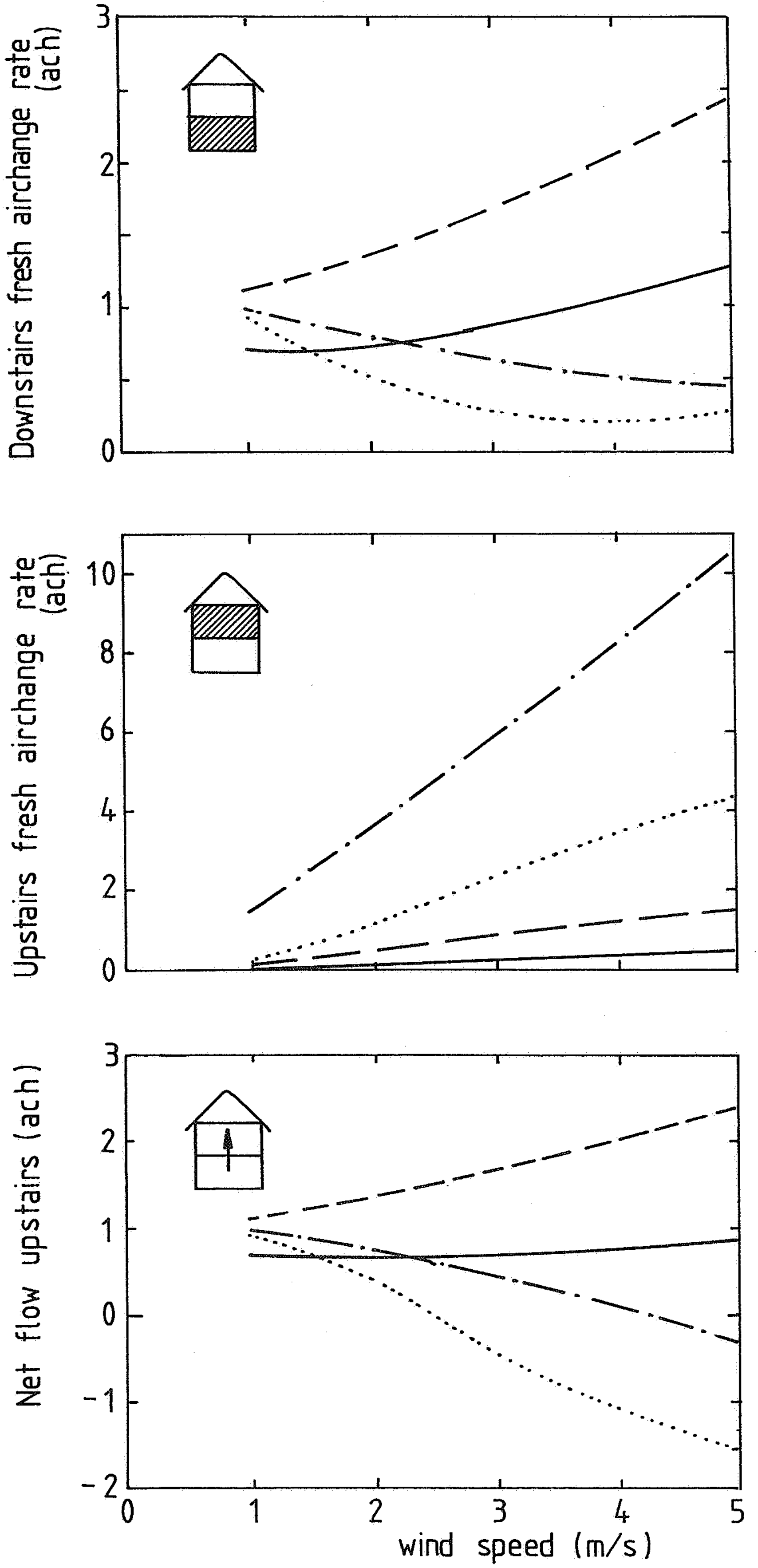

Figure 7.b - Effect of opening banks of upstairs windows (key as in 7a(i))

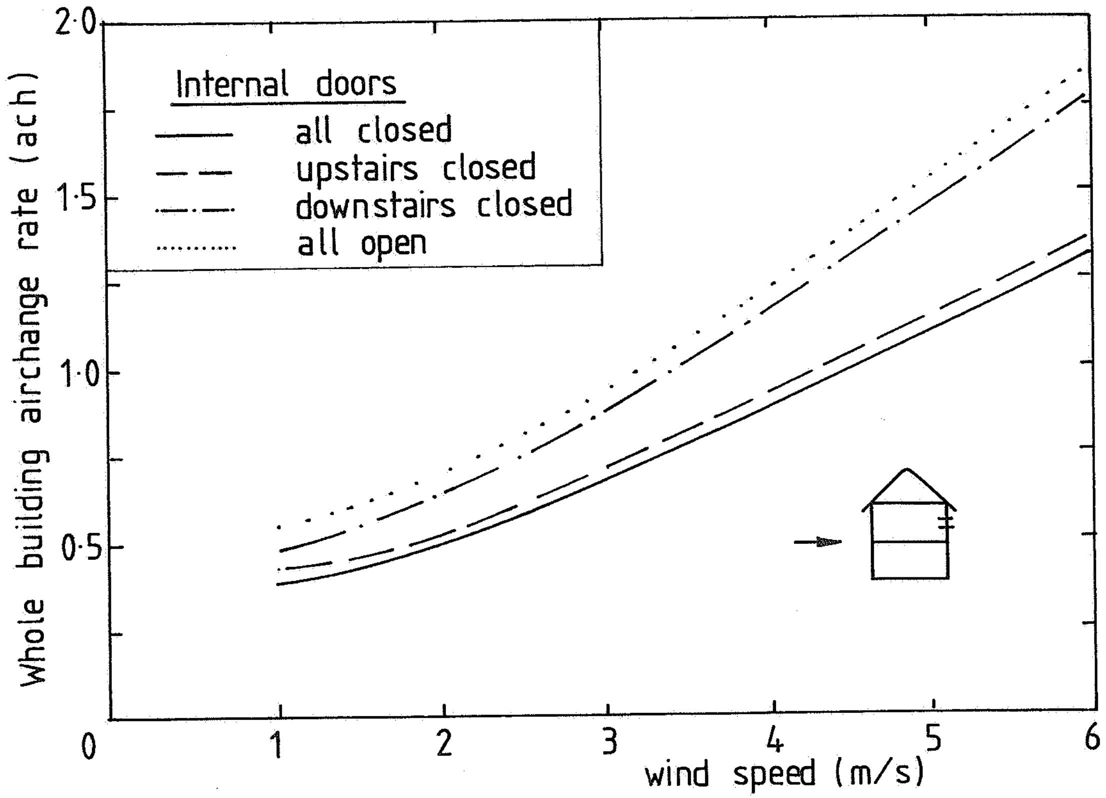

Figure 8.a-Effect of closing internal doors with bedroom window open

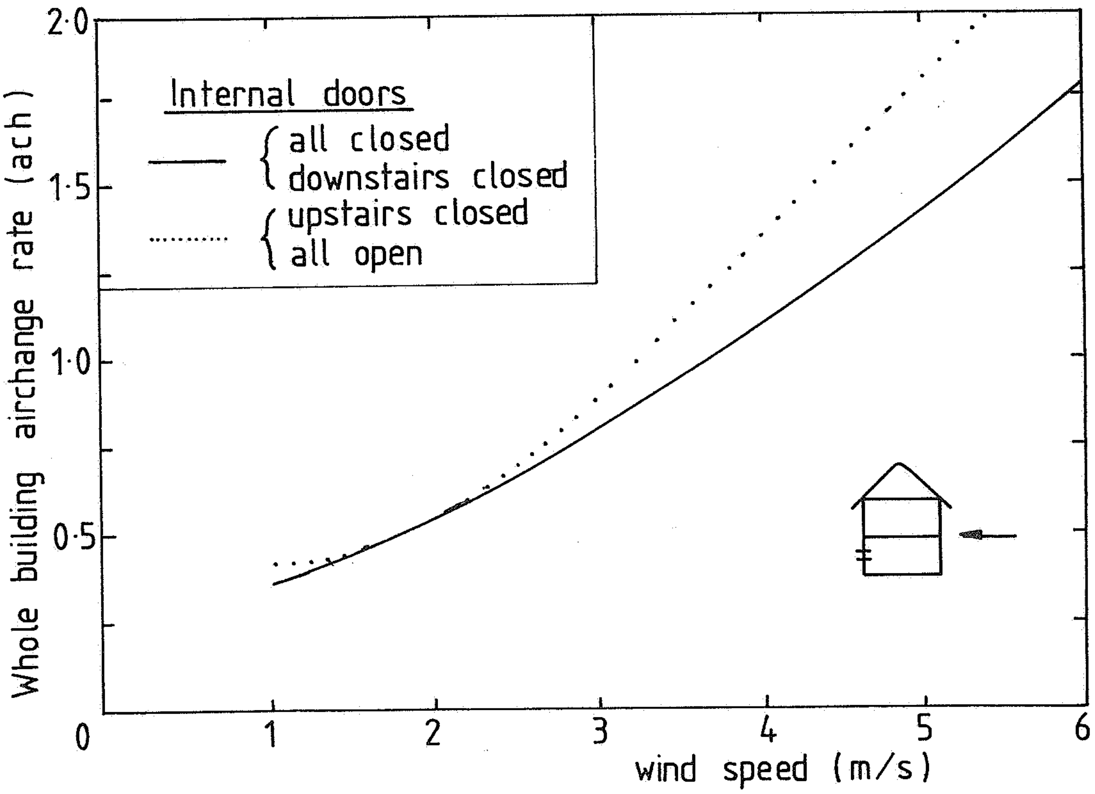

Figure 8.b-Effect of closing internal doors with kitchen window open