A Comparison of Computed Infiltration Rates with Results Obtained from a set of full - scale Measurements

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SUMMARY

This paper presents the results obtained from a digital analogue method of calculating infiltration rates in buildings. The results are compared with a set of full scale observations carried out by G.T. Tamura and A.G. Wilson.

NOMENCLATURE used in the main report

V Volume flow rate, m^3/hr

C A coefficient, dependent on the orifice geometry, $m^3/hr./m./mm.wg.^{1/n}$

L Window crackage length, m.

dP Pressure difference across orifice, mm.w.g.

n An exponent, dependent on the orifice geometry.

W Wind speed, m/s.

I Total infiltration rate in building, air changes/hr.

NOMENCLATURE used in Appendix I

C Helium gas concentration, proportion by volume

Co Initial internal helium gas concentration

Ca Helium gas concentration at position a

y Window crack width

l Cross sectional length of window crackage

z Total length of window crackage

λ Mean free path length of helium at N.T.P.

Vm Molecular velocity of helium at N.T.P.

V Building volume

INTRODUCTION

1.1. To the best knowledge of the author there have been no published comparisons of predicted infiltration rates, using methods such as that in the 1971 I.H.V.E. Guide, with either full scale or model results. The method of Jackman and den Ouden (6), and other digital analogue methods, rely on balancing flow rates through a number of openings using an equation of the form

$$V = C.L.\ (dP)^{1/n} \qquad \ldots 1.1.$$

to compute the volume flow rate through each opening. They assume that the pressures on building faces are time-invariant. No indication is given of the dependence of these methods on such factors as building porosity or meteorological data, which are subject to considerable uncertainty. This paper sets out to investigate the accuracy of the analogue technique.

1.2. An important part in the development of any analogue system is the testing of the model to determine the limits of its accuracy by comparing the analogue results with full scale observations. The relatively small number of full scale studies carried out to date serve as an indication of their difficulty. However it is because of the paucity of these results that the importance of testing the analogue technique becomes greater if it is to be used as the basis for a design technique.

1.3. Tamura and Wilson carried out a series of full scale tests on a small building, (1), the results of which have been used here in the comparison with the analogue technique. It is significant to note that very few of the papers giving full scale results give sufficient information for any valid comparative calculations to be carried out. In particular sufficient data about the external climate of the building is often lacking.

1.4. The results from this comparison are necessarily limited. The building studied is a small single-storey domestic dwelling with basement. In the paper the effect on ventilation rate of wind speed and direction, stack effect and wind and stack effect acting together are studied. It has only been possible to compare results for the situations with no stack effect taking place. Stack effect taking place on one floor through sash windows is not modelled by the programme, as it is designed mainly to study multi-storey buildings. These comparisons give some indications of the accuracy of the analogue technique.

2. DESCRIPTION OF THE FULL SCALE STUDY

2.1. A full description of the test house, house number 1, is given in Tamura and Wilson's paper. A plan of the building is given in figure 1. It is a single storey, timber framed building, with basement. Internal wall surfaces are plasterboard. The plan area is 77.1 m^2 and the net volume, including basement, and allowing 10% for furnishings is given as 336 m^3. Figures for window crackage are given as an equivalent length to that of average fit, double-hung, wood sash, weatherstripped windows. The figures being based on data from the A.S.H.R.A.E. Guide and Data Book. These figures are given in Table 1.

2.2. Ventilation rates were determined from measurements with a katharometer of the rate of change of concentration of helium gas discharged in the house. All internal doors were open during the periods of measurement. A circulating blower was also operated continuously during each test. It was assumed that a fairly uniform concentration of helium was achieved under test conditions. Wind speeds were recorded by a cup anemometer mounted next to the house and at a height of 7.6 m. The house was situated on the edge of a housing area, with its south wall facing a wooded region.

2.3. The results of the full scale leakage tests are given in Table 2 and are also shown in Figure 2. The air change rates given are net rates including the basement area. The line of best fit, computed assuming a linear relationship between wind speed and air change rate, is drawn. The increase in air change rate for each metre per second increase in wind speed is 0.037. No significant effect of wind direction can be noted from the records. An apparent ventilation rate of 0.037 air changes per hour was obtained with no wind speed and only small temperature differences.

3. DESCRIPTION OF THE ANALOGUE CALCULATIONS

3.1. In order to carry out the comparative calculations it was necessary to make a further set of assumptions. The height of the building was taken to be 4 m. This allowed sufficient height for one storey and sufficient basement above ground level to let in windows. The recorded average wind speed was corrected to four metres height using a power law relationship, with an exponent of 0.3. This seems a typical exponent for a suburban situation, as discussed by Harris (3). Values of crackage length were assigned to each window. These had to be estimated as relative amounts of the crackage on each elevation from the verbal description of the windows. Finally values of pressure coefficient had to be assumed. These were based on the figures given in Building Research Station Digest 119(2) and the assumed figures may be seen in figure 3. Also in the calculations the effect of the basement windows was not included due to uncertainty about the relevant pressure coefficients. Consequently the house volume was reduced by a factor equivalent to the reduction in window area, to 300 m^3, to compensate for this.

3.2. The standard leakage coefficients given in the paper are assumed to be 60 cu.ft/hr/ft at a pressure difference of 0.3 inches w.g. This leakage coefficient was assumed in the calculations. The equation relating volume flow rate through a crack to the pressure difference across the crack is represented as

$$V = C.L. (dP)^{1/n} \qquad \ldots 3.1.$$

where V is the volume flow rate m^3/hr

L is the craok length, m

dP is the pressure difference, mm.w.g.

n is an exponent.

Typical values of the exponent n for windows of the type described have been abstracted from the work of Dick and Thomas (4). The assumed value is 1.6.

Then as the assumed values of C is

C = 60 cu.ft./hr./ft at 0.3 in.w.g.

This is equivalent to

$5.61\ m^3/hr./m.$ at 7.6 mm.w.g.

$= 5.61\ (1/7.6)^{1/1.6}\ m^3/hr./m.$ at 1 mm.w.g.

$= 2.02\ m^3/h/m/mm.w.g.^{0.6}$

Consequently the assumed figures of leakage coefficients may be seen in Fig. 1. The assumed values of leakage coefficients for all internal doors were taken to be $10,000\ m^3/h/mm.w.g.^{0.6}$. This represents a typical figure for an open doorway. In fact the resistance to air flow of the doorways is so small as to have virtually no control on the average air change rate.

3.3. Using these figures calculations were carried out under each set of average external conditions noted in the paper, where the mean wind was from a primary cardinal direction. Calculations were not carried out to simulate the three conditions where the mean wind direction was from a secondary direction due to lack of certainty of the appropriate pressure coefficient values. In this way nine of the twelve sets of test conditions were simulated.

3.4. The results of the calculations are given in Table 3, and in Figure 4. A line of best fit was found in the same way as for the full scale results, that is assuming a linear relationship between wind speed and air change rate. The increase in air change rate for each metre per second increase in wind speed is 0.033. No significant spread of results due to wind direction can be seen. An apparent ventilation rate of -0.008 air changes per hour was found from the line of best fit with no wind speed or temperature difference.

3.5. A further analysis of the computed and full scale observations was made by computing lines of best fit assuming that the infiltration rate varied in proportion to the wind speed to the power 1.25. This was the exponent assumed in the analogue tests. From these analyses the line of best fit for the observed results was found to be

$$I = 0.023\ W^{1.25} + 0.050 \qquad \ldots 3.2.$$

and the line of best fit for the computed results was found to be

$$I = 0.023\ W^{1.25} + 0.002 \qquad \ldots 3.3.$$

These lines of best fit are shown in Figure 5. For each of these four lines of best fit the root mean square deviations from the lines were calculated. The R.M.S. deviations assuming a linear relationship are = 0.010 for the observed results and = 0.009 for the computed results. The R.M.S. deviations assuming an exponent of 1.25 are = 0.007 for the observed results and = 0.011 for the computed results. A summary of the results obtained is given in Table 4.

4. DISCUSSION OF RESULTS

4.1. The results of the full scale tests show generally a higher ventilation rate for any given wind speed than the computed results. The rates of increase of ventilation rate for standard increase of wind speed are very similar. They are 0.037 air changes/metre per second for the full scale results and 0.033 air changes/metre per second for the model situation. The difference in apparent ventilation rates between the two sets of results at zero wind speed is 0.045 air changes per hour. This means that over the range of wind speeds used the relative error between the two sets of results is virtually constant.

4.2. In order to assess the significance of these results it is necessary to consider the errors involved in obtaining them. In particular, for both sets of results, there is an apparent ventilation rate occurring at zero wind speed. In the case of the computed results the reason for this may be explained fairly simply. The assumed opening characteristics used in the calculations, as noted earlier, are of the form

$$V = C.L.\ (dP)^{1/1.6} \qquad \ldots 4.1.$$

$$\text{or} \quad V \propto (dP)^{0.62}$$

Now as the pressure differences produced across the building are proportional to the square of the wind speed, w

$$\text{then } dP \propto (W)^2$$

$$\text{or} \quad V \propto (W)^{1.25} \qquad \ldots 4.2.$$

Initially the results from the computer study were analysed in the same way as the full scale results, in order to form a valid comparison. The line of best fit was computed assuming a linear relationship between wind speed and volume flow rate. As this is not the actual case (eqn. 4.2.) the line of best fit will depend on the values of wind speed chosen for analysis. The line may also have some apparent ventilation rate at zero wind speed.

4.3. In order to illustrate this effect both sets of results were analysed assuming that the relationship between wind speed and volume flow rate was as given in equation 4.2. The rates of increase of ventilation rate for standard increase of wind speed are again very similar. The difference in apparent ventilation rates between the two sets of results, 0.048 air changes per hour is also very similar. However the computed results show a reduction in the apparent ventilation rate at zero wind speed to less than 0.002 air changes per hour (Figure 5). Thus the error is reduced to one fifth of the previous error. The apparent ventilation rate at zero wind speed of the full scale results is increased to 0.050 air changes. This is probably a more accurate estimate of the zero error than the previous 0.037 air changes per hour.

4.4. This apparent ventilation rate at zero wind speed shown in the full scale results is relatively large. The major factors causing errors in the observed ventilation rates given by Tamura and Wilson are the diffusion of the tracer gas through the building fabric, and the fact that the stack and wind effects could not be entirely independently investigated, that is there was some ventilation due to small changes in external temperature during the tests. There are other factors which could lead to significant errors in the observations. Non-uniform distribution of the helium gas, because of imperfect mixing, would produce erroneous readings. The accuracies of the readings from the katharometers, at the low flow rates observed, is likely to be lower than at more usual ventilation rates. The omission of any estimation of the adventitious ventilation occurring will lead to the computed ventilation rates being too low. The assumptions made in the data used in the calculation, noted in section 3, will also act as possible sources of error in the computed ventilation rates.

4.5. Of the factors which may affect the accuracy of the full-scale observations two could produce effects leading to systematic overestimates of the ventilation rate due to wind alone. These are diffusion and the simultaneous action of small stack effects. Loss of helium through the building will lead to a faster rate of decay and an apparent error in the infiltration rate. The theoretical estimation of diffusion rate is complex.

A simplified analysis, in which diffusion is assumed to take place through the window crackage only, suggests an apparent error in the ventilation rate in the order of +0.01 air changes/hour, (Appendix 1). This calculation underestimates the magnitude of this effect as it does not take into account diffusion through the solid surfaces. Model tests by Malinowski (5) show that diffusion of a nitrogen tracer is only affected to a small extent by external air velocity. As helium, which has a higher diffusion rate, is used as the tracer in Tamura's experiments the effect of external wind speed will probably be less. The error in the full scale ventilation rate due to this effect is taken to be positive, relatively constant with wind speed and having a value greater than 0.01 air changes/hour. Field measurements by Howard (7), of ventilation rates calculated from the rate of decay of a hydrogen tracer, show a similar constant positive error with wind speed due to diffusion of the gas.

4.6. The second factor which may affect the accuracy of the full scale results is the possibility of non-uniform mixing of the tracer gas. This would lead to unrepresentative sampling of the tracer gas and a possible overestimate of the ventilation rate. The use of the internal air mixing system during the tests was designed to minimise this factor. Because of the high air movement rates internally, due to the fans, the quality of the mixing, and thus the errors in the apparent ventilation rate are unlikely to be affected greatly by the infiltration rate, and any error is likely to be relatively constant with wind speed. The loss in accuracy of the katharometers at the very low air change rates observed is likely to be significant; the observing period being quite long to establish a significant amount of loss of tracer gas. Although this will affect individual readings, it should not necessarily produce any systematic error in the ventilation rates.

4.7. The small temperature differences acting during the tests will lead to overestimates of the ventilation rate caused by wind acting alone. The magnitude of this effect is extremely difficult to isolate in the full scale observations. It may be seen from the relationship between wind speeds and temperature differences causing the same ventilation rates ((1), Figure 6) given in Tamura and Wilson's paper that all the tests, except tests 12 and 19, took place with temperature differences acting significantly less than those which would cause an effect equal to that caused by the wind. The ventilation rates which would be caused by these temperature effects acting alone can be estimated generally as 50-60% of those caused by the wind alone. The combined effect of wind and temperature difference, as observed, may then be expected to be in the order of 10% greater than may have been expected from the wind alone. The errors would be greater in tests 12 and 19 where the temperature differences are realtively larger. The errors then may be of the order of 0.01 to 0.02 air changes/hour.

4.8. The last possible source of error to be considered is ventilation through other cracks in the building fabric. Non-consideration of this effect will lead to computed ventilation rates which are lower than those actually occurring. Figures of leakage coefficients for plastered wood frame construction obtained from the A.S.H.R.A.E. Handbook of Fundamentals are of the order of 0.025 m^3/hr./m^2/mm $wg^{0.6}$. The equivalent coefficient for all the wall surfaces in the test building will be of the order of 10 m^3/hr./mm $wg^{0.6}$. In comparison the total leakage coefficient for the building openings is approximately 200 m^3/hr./mm $wg^{0.6}$. Inclusion of this factor in the calculation will lead to an increase of the computed ventilation rates by approximately 5%.

4.9. It can be seen that the estimation of the errors in the observed ventilation rates is extremely general. Loss of tracer gas by diffusion and higher ventilation rates due to the stack effect acting simultaneously are probably the more important mechanisms causing error. Non-uniform mixing of the tracer gas and the adventitious ventilation will also produce errors which would help to explain the discrepancy between the full scale results and the computed results.

4.10. The results of the two sets of tests were also compared in terms of the degree of spread of points from the line of best fit. Assuming a linear relationship between wind speed and ventilation rate the R.M.S.

deviation in the full scale observations is 0.010 air changes. In the computed results the R.M.S. deviation is 0.009 air changes. Assuming an exponential relationship the R.M.S. deviation in the full scale results is 0.007 while in the computed results the error is 0.011 air changes per hour. Here there is reasonably good agreement between the observed and computed sets of results.

5. CONCLUSIONS

5.1. Comparisons of the variation of full scale infiltration rates with wind speed were made between full scale observations on a small domestic dwelling and calculations using a digital model. The calculated results are in good agreement with the full scale results in terms of the rate of change of infiltration rate with wind speed. Analysis assuming an exponential, rather than a linear, relationship between ventilation rate and wind speed gives a better explanation of the zero error. The computed results agree with the full scale results in showing that the total infiltration rate is more sensitive to wind speed than to wind direction. The full scale results show consistently higher ventilation rates than the computed results. This difference is caused by several factors leading to overestimates of the full scale ventilation rate; diffusion effects and the temperature differences acting being probably the more significant ones. Any estimate of the magnitude of the error is extremely difficult but it may be of the same order of magnitude as the difference between the observed and the computed results.

5.2. Although the agreement between the observed and computed rates of increase of ventilation rate with wind speed are good, it must be emphasised that this is probably largely fortuitious. The assumptions made in the data used for the calculation and the possible errors in the full scale observations are of such magnitude that only general conclusions may be drawn. The study emphasises that further, closely controlled comparative tests need to be carried out before the limits of accuracy of the current computational techniques can be established in practice.

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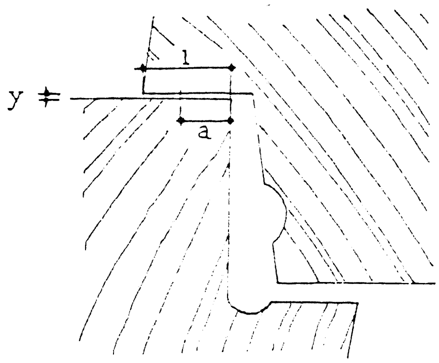
Appendix 1

An estimation of the rate of loss of helium through the building openings by diffusion

If it is assumed that all diffusion of tracer gas in the full scale building takes place through the window openings then it is possible to make an estimate of the order of magnitude of this effect.

Considering the crackage through which the helium will diffuse a simplified analysis may be made by considering only that part of the crackage where major resistance to flow occurs. This will be that part of the crack where the width is smallest. One may consider this as a channel of uniform width Y, length l, and total channel length of z.



The helium gas concentration at one end of the crack will be approximately equal to the mean internal concentration, Co while the outer end may be assumed to have a concentration near to zero.

At any point in the crack, a distant, a, from the outer end, considering a thin element, under steady state conditions, and over a time scale which is short in comparison to the rate of decrease in the mean internal level in concentration of the tracer gas.

the net flow into the element = net flow out of the element

or $\quad dc/dt = 0$

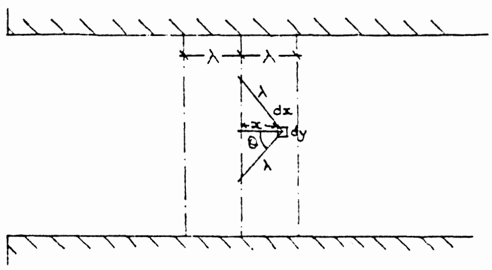
but by Fick's law $\quad dc/dt = d^2C/da^2$

then $\quad c \propto ka$

or $\quad Ca = \frac{a}{l} Co$

where Ca is the concentration of helium at a.

Now if two adjacent elements are taken, of width λ and distances a and $a-\lambda$ from the outer edge where λ is the mean free path length of helium at N.T.P.



One can consider a small volume in the inner element of dimensions, dx, dy, dz and a distance x from the interface. The solid angle subtended at the interface by molecules travelling over their mean free path lengths can be computed as

$$= \frac{\int_0^{\cos^{-1} x/\lambda} 2\pi\lambda . \sin\theta . d\lambda}{\lambda^2}$$

$$= \frac{\int_0^{\cos^{-1} x/\lambda} 2\pi\lambda . \sin\theta . \lambda d\theta}{\lambda^2}$$

$$= -[2\pi . \cos\theta]_0^{\cos^{-1} x/\lambda}$$

$$= 2\pi[1 - x/\lambda]$$

Then the probability of molecules crossing the interface from this volume

$$= \frac{2\pi\,[1 - x/\lambda]}{4\pi}$$

and the number of molecules escaping will be

$$= \tfrac{1}{2}\ \left[1 - x/\lambda\right]\ Ca.dV$$

where dV is the element volume

$$= \tfrac{1}{2}\ \left[1 - x/\lambda\right]\ Ca.dx.dy.dz$$

and the total number escaping from the element throughout the building crackage

$$= \int_0^\lambda \int_0^y \int_0^z \tfrac{1}{2}\left[1 - x/\lambda\right] Ca.dx.dy.dz$$

$$= \tfrac{1}{2}\left[x - x^2/2\right]\ y.z.Ca$$

$$= \tfrac{1}{4}.\lambda.y.z.Ca$$

then this number of molecules is equivalent to

$$= \tfrac{1}{4}.\ y.z.\frac{a}{l}.Co$$

but the number of molecules moving from the second element back to the first will be

$$\tfrac{1}{4}.\lambda.y.z.\ \frac{[a - \lambda]}{l}\ Co$$

and the net loss of molecules will be

$$\tfrac{1}{4}.\lambda.y.z.\ \frac{\lambda}{l}\ Co$$

but these will move at a speed Vm where Vm is the mean molecular velocity. Thus the rate of loss of molecules will be

$$\tfrac{1}{4}.\lambda.y.z.\frac{\lambda}{l}.\ Co.\ \frac{Vm}{\lambda}$$

and as the initial number of molecules of helium in the building

$$= V.\ Co$$

where V is the building volume

then the rate of loss of concentration

$$= \tfrac{1}{4}.\lambda.y.z.\ \frac{\lambda}{l}.\frac{Vm}{\lambda}.Co.\frac{1}{V.Co}$$

$$= \frac{\lambda.y.z.Vm}{4.l.\ V}$$

In particular when the units of λ,y,z,l are in cm., V in cm^3., and Vm in cm/s., then the rate of loss of helium/hr

$$= \frac{900.\lambda.y.z.Vm.}{l.V}$$

In the full scale building

$$z = 10^4 \text{ cm}$$

$$y \simeq 0.04 \text{ cm}$$

$$l \simeq 0.25 \text{ cm (assumed)}$$

$$V = 3.4 \times 10^8 \text{ cm}^3$$

$$Vm \text{ helium} = 12 \times 10^4 \text{ cm/sec}$$

$$\lambda \text{ NTP helium} = 17 \times 10^{-6} \text{ cm/sec}$$

and the rate of loss of concentration/hr $\simeq$ 0.009

if this is assumed to be an apparent air change rate, n/hr

$$\text{then } \log_e n = \frac{Co}{C_{1hr}}$$

$$= {}^1/_{0.991}$$

$$= 1.009$$

then n $\simeq$ 0.009 air changes/hr.

the apparent ventilation rate at zero wind speed due to diffusion of helium through the building crackage will of the order of

<u>0.01 air changes/hr</u>

TABLE 1

Equivalent window crackage lengths in test house No. 1 (Tamura and Wilson)

	Equivalent length of crackage, ft.			
Elevation	N	S	E	W
First Floor	38.7	0.0	126.0	155.9
Basement			32.6	
	38.7	0.0	158.6	155.9

The assumed leakage coefficient for this standard equivalent crackage is given as 60 cuft./hr/ft/0.3 in.w.g.

TABLE 2

Infiltration test results, house No. 1, (Tamura and Wilson)

Test No.	Date	Temp. difference °C	Average Wind Velocity m/s	Wind Direction	Infiltration Rate/hr.
9	1.8.61	1.7	1.36	N	0.07
10	2.8.61	-2.5	1.88	E	0.10
11	3.8.61	-1.1	2.69	NW	0.16
12	4.8.61	-1.1	0.45	E	0.07
13	10.8.61	-3.3	3.18	SW	0.17
14	14.8.61	1.1	1.53	W	0.09
15	16.8.61	3.3	3.62	N	0.17
16	17.8.61	-1.1	1.22	W	0.08
17	18.8.61	-1.7	1.62	SW	0.11
18	21.8.61	3.3	3.22	E	0.14
19	22.8.61	1.7	0.45	S	0.06
20	23.8.61	1.7	2.59	E	0.13

TABLE 3

Computed infiltration figures, house No. 1.

Simulation of Test No.	Average wind speed m/s	Wind Direction	Calculated Infiltration Rate/hr.
9	1.36	N	0.028
10	1.88	E	0.058
12	0.45	E	0.009
14	1.53	W	0.047
15	3.62	N	0.096
16	1.22	W	0.035
18	3.22	E	0.114
19	0.45	S	0.005
20	2.59	E	0.087

TABLE 4

Summary of results given in paper

Lines of best fit

Linear relationship, full scale observations from Tamura and Wilson

$I = 0.037\ W + 0.037$ R.M.S. error $\pm$ 0.010

Linear relationship, computed results

$I = 0.033\ W - 0.008$ R.M.S. error $\pm$ 0.009

Exponential relationship full scale observations from Tamura and Wilson

$I = 0.023\ W^{1.25} + 0.050$ R.M.S. error $\pm$ 0.007

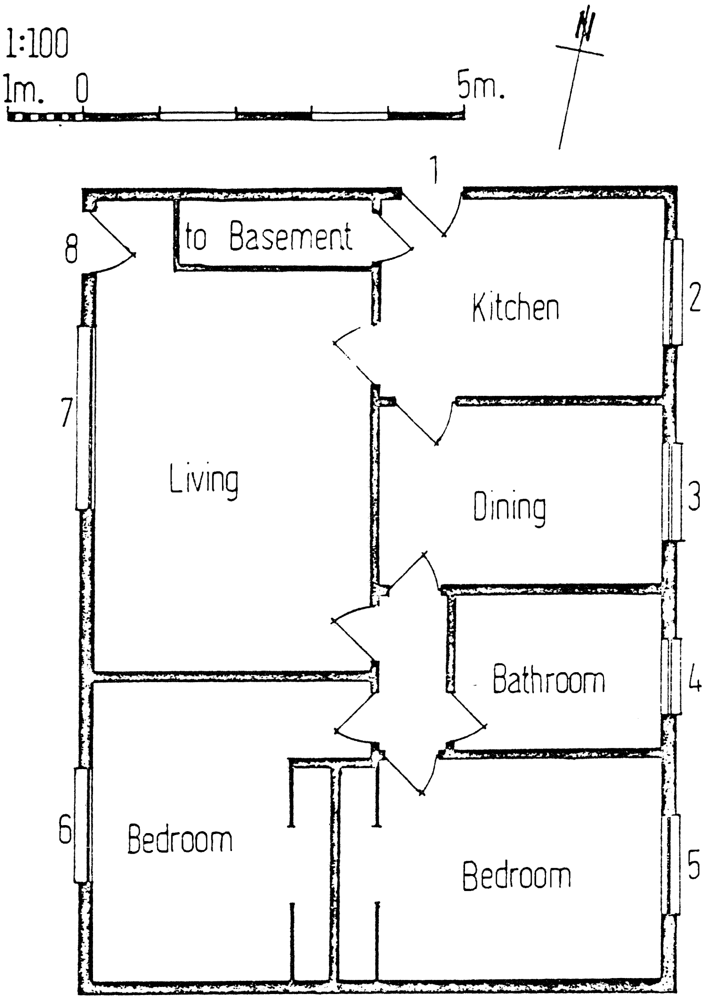
Exponential relationship, computed results

$I = 0.023\ W^{1.25} + 0.002$ R.M.S. error $\pm$ 0.011

I is infiltration rate, air changes/hr.

W is wind speed, m/s.

Figure 1 Plan of house no. 1, after Tamura and Wilson.



Assumed leakage coefficients.

Opening	Elevation	Crackage Length, m.	Coefficient, c.m.h./mm.wg.$^{0.6}$
Door, 1	N	11.800	23.7
Window, 2	E	10.600	21.3
Window, 3	E	10.600	21.3
Window, 4	E	6.100	12.3
Window, 5	E	10.600	21.3
Window, 6	W	10.600	21.3
Window, 7	W	24.300	49.8
Door, 8	W	11.800	23.7

Figure 2 Comparison of observed ventilation rate with wind speed, after Tamura and Wilson.

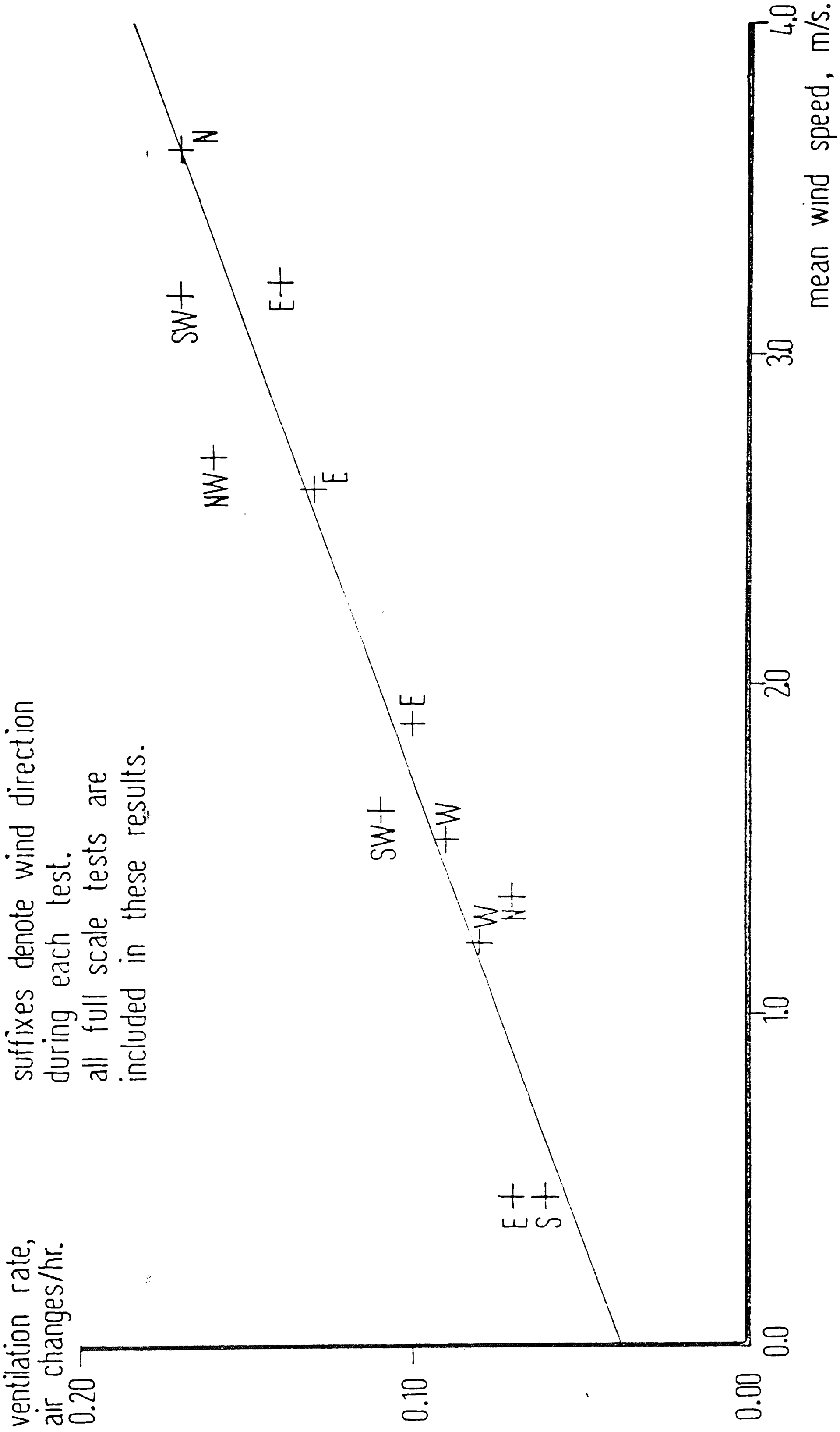
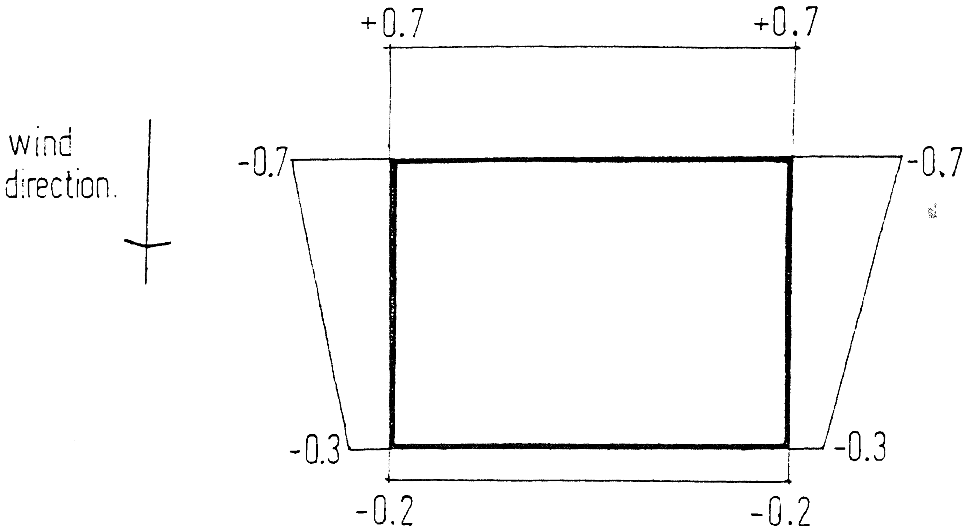


Figure 3 Assumed pressure coefficients based on B R S Digest 119.



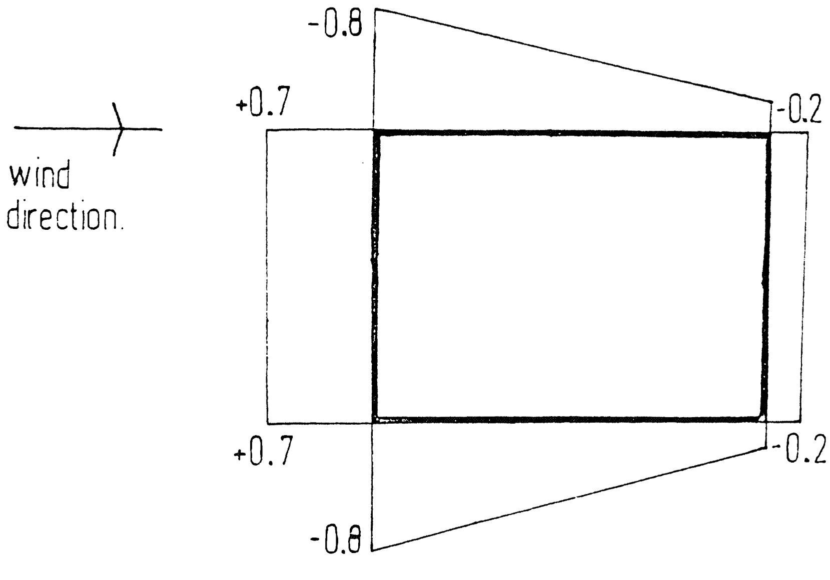


Figure 4. Comparison of computed ventilation rate with wind speed.

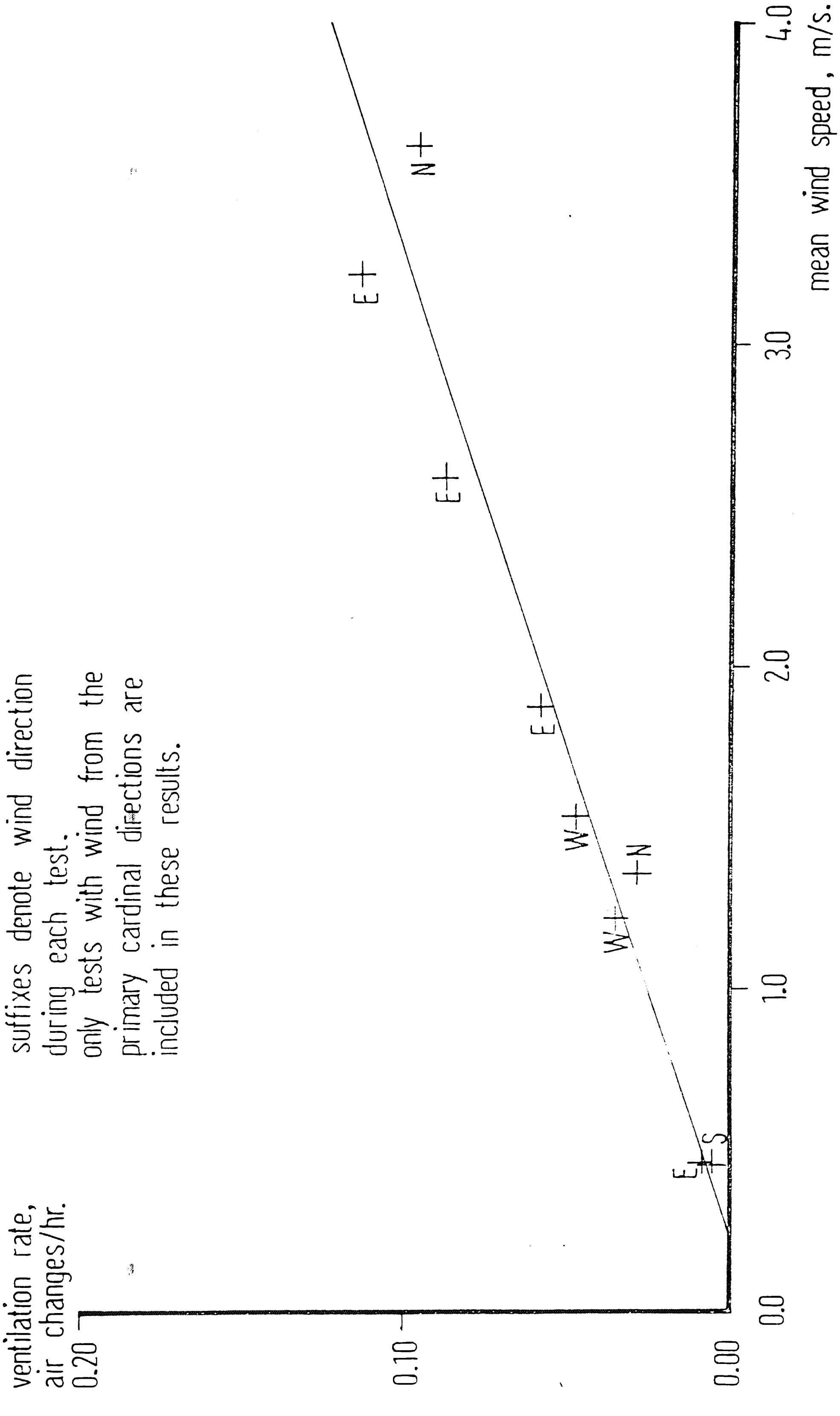


Figure 5. Comparisons of lines of best fit for observed and computed results, assuming an exponential relationship between wind speed and ventilation rate.