A tracer gas method for the continuous monitoring of ventilation rates

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Summary

Ventilation rates in buildings having recirculating air distribution systems can be continuously monitored by injecting a tracer gas into the supply and measuring its concentration in the return air. This method has been successfully used in two houses. In one, which had a solid concrete ground floor, normal windows and air bricks to supply combustion air, ventilation rates were mainly dependent on windspeed. In the other, which had a suspended timber ground floor and weatherstripped windows, ventilation rates were much lower and mainly dependent on the internal to external temperature difference. There was also a seasonal difference in this house when ventilation rates measured in October were about one third less than those measured in July.

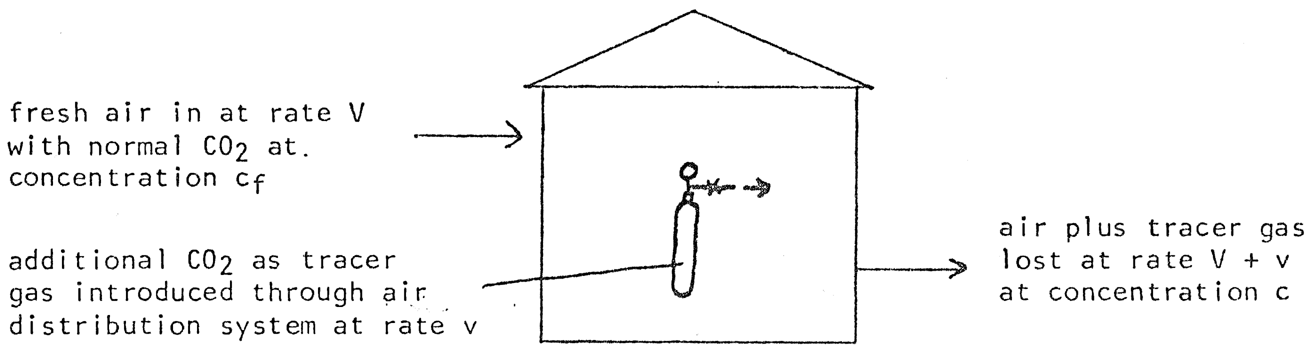
1. Introduction

Accurate measurements of ventilation rates using a tracer gas depend on good mixing of the gas into the air in the building. In buildings having full air distribution systems good mixing can be ensured by injecting the gas into the air in the building, preferably near the fan. Measuring the concentration of the gas in the return air means that it is measured for a representative sample of the air in the building.

Any air distribution system can be used, heating, ventilating or air conditioning. The proportion of air recirculating to fresh air entering the building either by infiltration or by ducts does not matter. Tests made in buildings when they are unoccupied can use carbon dioxide as the tracer gas.

2. Theory

The theory is relatively simple and based on the assumption that the tracer gas, carbon dioxide (CO_2) in this case, is uniformly mixed throughout the building as in the illustration.



Fresh air with a CO_2 concentration of c_f enters the building at a rate of V. The tracer gas is supplied at the rate v, and assuming perfect mixing its steady state concentration will be uniform throughout the building at c. Air therefore leaves the building at the rate V + v and concentration c.

Equating the input and output of carbon dioxide gives:

$$v + Vc_f = c(V + v)$$

$$\text{or} \quad V = v\left(\frac{1-c}{c-c_f}\right)$$

normally $c \ll 1$ and then

$$V \simeq \frac{v}{c-c_f}$$

Example

CO_2 flow rate $v = 0.05$ l/s

measured concentrations internally $c = 0.1\%$

in the fresh air $c_f = 0.03\%$

$$\text{Then } V = 0.05\left(\frac{1-0.001}{1-0.3}\right)1000 = 50\left(\frac{0.999}{0.7}\right) = 71.36 \text{ l/s or } 257 \text{ m}^3\text{/h}$$

$$\text{or } V \quad 0.05\left(\frac{1000}{1-0.3}\right) \qquad \approx 71.43 \text{ l/s or } 257 \text{ m}^3\text{/h}$$

Note. When a non-atmospheric tracer gas is used, such as nitrous oxide N_2O, then $c_f \approx 0$ and the expressions for V simplify to:

$$V \approx v\left(\frac{1}{c} - 1\right)$$

$$\text{or } V \simeq \frac{v}{c}$$

3. Houses tested, apparatus and procedure

The houses tested. The tests were carried out in the two houses shown in figure 1. Both are representative of present day construction and size, although the ECRC test house, in having weatherstripped windows, is rather well sealed. They were chosen because of their extensive ducted air distribution systems, nearly meeting the ideal of having air supplies into every room to ensure good mixing and test all sources of infiltration. In both houses air was not supplied to the bathrooms or WC, and in the private house the smallest bedroom was without a supply grille. It was important to keep doors to these rooms wide open during tests to obtain good air mixing. The position of the other internal doors was not so critical since the methods of returning the air to the heaters ensured adequate air passages between rooms.

On the ECRC test house the ducting in the loft and under the floor was sealed to minimize air leakage and therefore heat losses. The system was not used for heating during the ventilation tests so the fan was run at a low speed to reduce the air leakage even further. In the private house the internal stub-duct system did not need such treatment.

Apparatus. The tracer gas injection and sampling apparatus is shown in figure 2 and was used to determine the ventilation rate in the two houses. The tracer gas flow rate needed depends upon the ventilation rate and the tracer concentration levels which can be measured with the apparatus. The rate of 0.05 l/s used in the above example is suitable for unoccupied houses, and corresponds to a consumption of about 0.3 kg/h of carbon dioxide.

The valve arrangement shown in figure 2 enables the carbon dioxide concentration to be measured in turn in the atmosphere and in the return air from the house. In addition the zero of the analyser is easily checked by drawing air through the CO_2 absorber. The calibration can also be checked using a mixture of an accurately known concentration of CO_2 in air, here in the range 0.055% to 0.065%.

People could not remain in the houses when measurements were in progress since they exhale CO_2. They therefore remained outside with the apparatus, and sampled the house air remotely through tubes.

An average internal house temperature was obtained by measuring the temperature of the return air using a thermocouple. External temperatures were measured in a Stevenson screen at the ECRC test house, and locally using a thermocouple at the private house. Windspeeds were measured only at the ECRC site and these speeds, averaged over the house immediately preceding the test and taken to be the same at the private house 8 km away.

Injection and sampling tube positions. The carbon dioxide was injected just upstream of the fan so that it was thoroughly mixed with the recirculating air. The sampling point for measuring the concentration in the return air was upstream of the injection point, but downstream of the last return air grille. The supply and sampling tubes were about 10mm outside diameter, and convenient positions for their entry into the houses from the garages were found. In the case of the private house this was through the air brick (a) in figure 2.

The atmospheric sampling tube was mounted in a convenient position above the ground and a few metres from the house on the windward side. It was therefore moved about according to the direction of the wind.

Procedure. On starting a series of tests the carbon dioxide was supplied at the maximum rate through the flow meter for about twenty minutes to build up the concentration quickly. Then the flow was set back and two hours or more allowed for the flows and concentrations to settle before taking measurements.

Measurements were generally made at hourly or half-hourly intervals. The zero and calibration of the analyser was checked each time before measuring the concentrations in the house and atmosphere. Internal and external temperatures were measured at the same time, or more frequently if they were changing. This was seldom needed because internally there was either no heating, or it was controlled by thermostat. External temperatures did not often change much over the preceding hour, so the average was taken. Average windspeeds were recorded at the ECRC test house.

4. Results and discussion

The results are given in table 1 and figures 3a and 3b. Internal doors were open during these tests, but external doors and windows were in their normal closed positions.

The first significant finding is that the ventilation rate (V) is dependent mainly on windspeed (W) in the private house, but in the ECRC test house it is dependent mainly on the internal to external temperature difference (ΔT). The following results of regression analyses show this:

Private house	Correlation coefficient
$V = 76.1 + 23.4W$	0.91
$V = -30.9 + 20.4\,\Delta T$	0.69
ECRC test house - July	
$V = 58.4 + 3.43\,\Delta T$	0.94
$V = 99.4 - 7.6W$	0.56
ECRC test house - October	
$V = 34.3 + 2.78\,\Delta T$	0.93
$V = 39.8 + 4.0W$	0.32

Units are V m^3/h, W m/s and ΔT K.

The correlation coefficient using the better variable exceeds 0.9. Inclusion of the second variable gives negligible improvement:

Private house	Correlation coefficient
$V = 44.7 + 20.9W + 4.3\,\Delta T$	0.92
ECRC test house - July	
$V = 57.6 + 3.46\,\Delta T + 0.2\,W$	0.94
ECRC test house - October	
$V = 30.0 + 2.5\,\Delta T + 1.5\,W$	0.94

The second significant finding is the lower ventilation rate in the ECRC test house in October, by about 1/3, compared with the results in July, see figure 3b.

Both these findings can be explained by considering the air infiltration routes. First the private house has an impervious concrete floor, but unweatherstripped windows and air bricks presenting openings to the wind. The ECRC house has weatherstripped windows and no air bricks and so is relatively well sealed against the wind, but it has a suspended wooden floor which makes it relatively leaky to buoyancy forces and hence temperature difference ΔT.

The explanation of the second finding is the change of gap size through which air infiltrates, from July to October. In July timber is drier than in October and therefore gaps are larger between window and door frames and walls, and around joists resting on walls.

In all cases there are significant intercepts in the graphs and residuals in the equations even when both variables are included. This could mean that there are more factors than average windspeed (W) and average temperature difference (ΔT) promoting ventilation, and also errors in the measurements.

Overall the ECRC test house is significantly better sealed than the private one. For example on a winter day with W = 4 m/s and ΔT = 14K, then the ventilation rates are:

Private house

using W and ΔT	$44.7 + 20.9 \times 4 + 4.3 \times 14$	= 189 m^3/h
" W only		= 165 m^3/h

ECRC house 14 (October correlation)

using W and ΔT	$30 + 2.7 \times 14 + 1.5 \times 4$	= 74 m^3/h
" ΔT only		= 73 m^3/h

The private house has under these typical conditions, with all windows closed, a ventilation rate that is quite high, at about one air change per hour, and nearly three times the ECRC house.

5. Conclusions

1. A method of achieving good mixing of the tracer gas for ventilation measurements is to introduce the gas into an air distribution system. Analysing in the return ensures representative bulk sampling.

2. The method has been used in unoccupied houses using carbon dioxide as the tracer gas and has shown:

(a) In a house having a solid concrete ground floor, normal windows and air bricks, ventilation rates are mainly dependent on windspeed.

(b) In a house with suspended wooden floor and weatherstripped windows ventilation rates are mainly dependent on internal to external temperature difference.

(c) A seasonal difference has been found for the house in (b) with the natural ventilation rate 50% higher in July than in October. The explanation is the larger gaps between timber and brick when the timber is drier in July than in October.

(d) Under a typical winter heating condition the natural ventilation rate for the house in (b) is about 75 m^3/h compared with 180 m^3/h for the house in (a).

Acknowledgements

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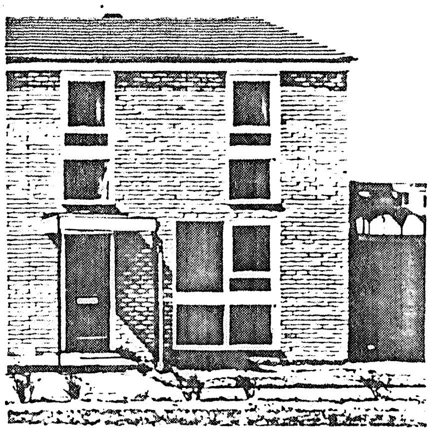
Table 1 Measured results for the three series of tests

Internal doors were open, but all external doors and windows were in their normal closed positions.

House and period		Test No.	Ventilation rate V m^3/h	Average windspeed W m/s	Internal-external temperature difference ΔT K
Private house	18 February 1975	1	135	1.5	8.0
		2	130	1.3	5.7
		3	133	1.75	6.5
		4	137	1.65	10.0
		5	130	1.15	10.0
	3 February 1975	6	134	2.6	10.0
		7	131	2.5	10.5
		8	126	2.65	9.0
		9	113	2.9	8.5
		10	112	3.0	8.0
		11	95	2.9	8.5
		12	117	2.75	8.5
	9 April 1975	13	228	6.35	11.0
		14	243	6.6	13.0
		15	245	6.5	12.0
		16	243	6.5	12.0
		17	239	6.7	10.0
		18	221	6.6	9.0
means			162	3.7	9.5
ECRC Test House 14 in July, 1975		19	65	2.8	0.1
		20	60	3.6	0.5
		21	56	4.0	0.25
		22	59	4.4	0.1
		23	66	4.6	2.9
		24	64	4.6	2.8
		25	63	4.8	0.4
		26	63	5.0	0.6
		27	63	5.2	1.2
		28	77	4.9	4.9
		29	75	3.7	5.2
		30	72	3.5	5.3
		31	78	3.0	4.0
		32	74	3.4	3.4
		33	69	3.5	3.8
		34	71	3.6	3.9
		35	77	1.7	4.3
		36	49	2.2	3.6
		37	77	0.7	5.0
		38	85	3.0	4.2
		39	65	1.1	4.3
		40	113	1.1	13.4
		41	113	1.3	14.2
		42	110	1.7	16.1
		43	116	2.1	18.3
means			75	3.2	4.9

Table 1 continued

House and period	Test No.	Ventilation rate V m³/h	Average windspeed W m/s	Internal-external temperature difference T K
ECRC Test House 14 in October, 1975	44	38	2.2	1.4
	45	37	1.9	1.9
	46	38	1.8	2.2
	47	38	1.3	2.4
	48	80	3.3	16.5
	49	77	2.7	16.5
	50	83	3.8	16.5
	51	83	3.4	16.5
	52	44	4.0	4.5
	53	46	4.7	4.5
	54	47	4.5	4.5
	55	46	4.9	4.5
	56	55	2.1	3.6
	57	50	2.4	3.7
	58	44	2.5	3.7
	59	45	2.5	3.8
	60	77	4.5	10.6
	61	73	4.5	10.6
	62	63	3.5	12.3
	63	65	3.8	12.7
	64	67	3.8	13.0
	65	70	5.4	13.4
	66	65	0.0	8.1
	67	42	2.5	6.1
	68	42	2.2	5.5
	69	41	2.2	5.1
	70	39	2.3	4.8
	71	27	2.0	0.0
	72	29	2.0	0.0
	73	43	5.3	0.0
	74	46	5.3	0.0
	75	38	3.3	0.0
mean		52	3.1	6.5



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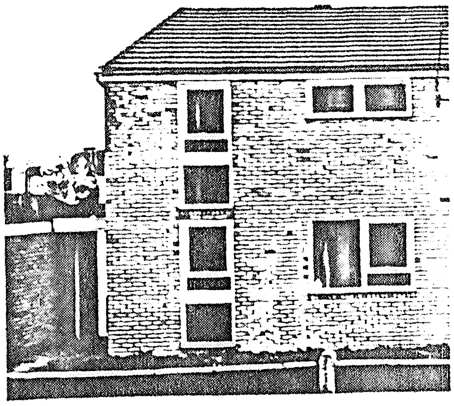
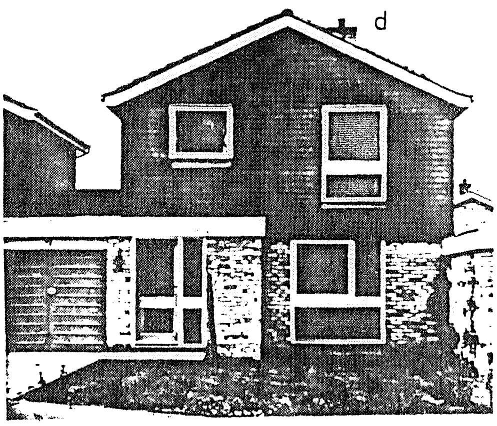


Back

ECRC Test House 14 — Semi-detached, $85m^2$ floor area, 5 person, 3 bedroomed.

Heating system:	ducted warm air, running in loft to a ceiling diffuser in each bedroom upstairs, and under the floor to a perimeter grille downstairs, in the hall, lounge and kitchen/dinette. Stub duct return from two of the bedrooms, landing, hall, lounge and dinette.
House construction:	brick/cavity/block external walls, wet plastered, suspended wooden ground floor with plastic floor tiles in the kitchen and fitted carpets elsewhere.
Ventilation openings:	no specific ventilators, air bricks or extract fans (the ridge ventilator is for the soil vent pipe).
Windows:	metal framed in timber subframes, all opening lights weatherstripped.
Doors:	wooden in wood frames, not weatherstripped.



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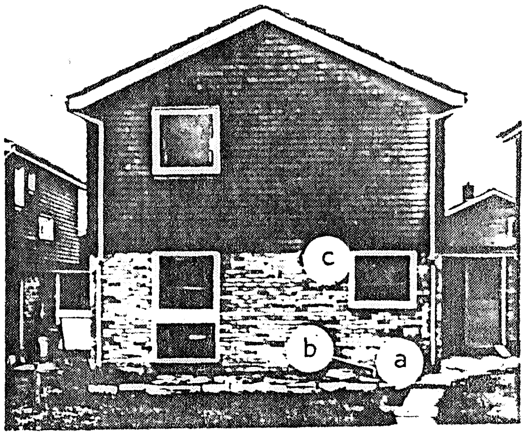

Back

Private House — Detached, $80m^2$ floor area, 5 person, 3 bedroomed.

Heating system:	stub duct entirely internal, gas fired, supply grilles in two of the bedrooms and landing upstairs and in the lounge, dining room and kitchen. Return through the house.
House construction:	brick/cavity/block and tiles/cavity/block walls wet plastered, solid concrete floor, plastic floor tiles in kitchen, fitted carpets elsewhere.
Ventilation openings:	air brick to kitchen cupboard (a), airbrick for combustion air (b), kitchen extract fan (c), flue (d).
Windows and doors:	wooden, not weatherstripped.

Figure 1 The two houses subjected to the ventilation tests

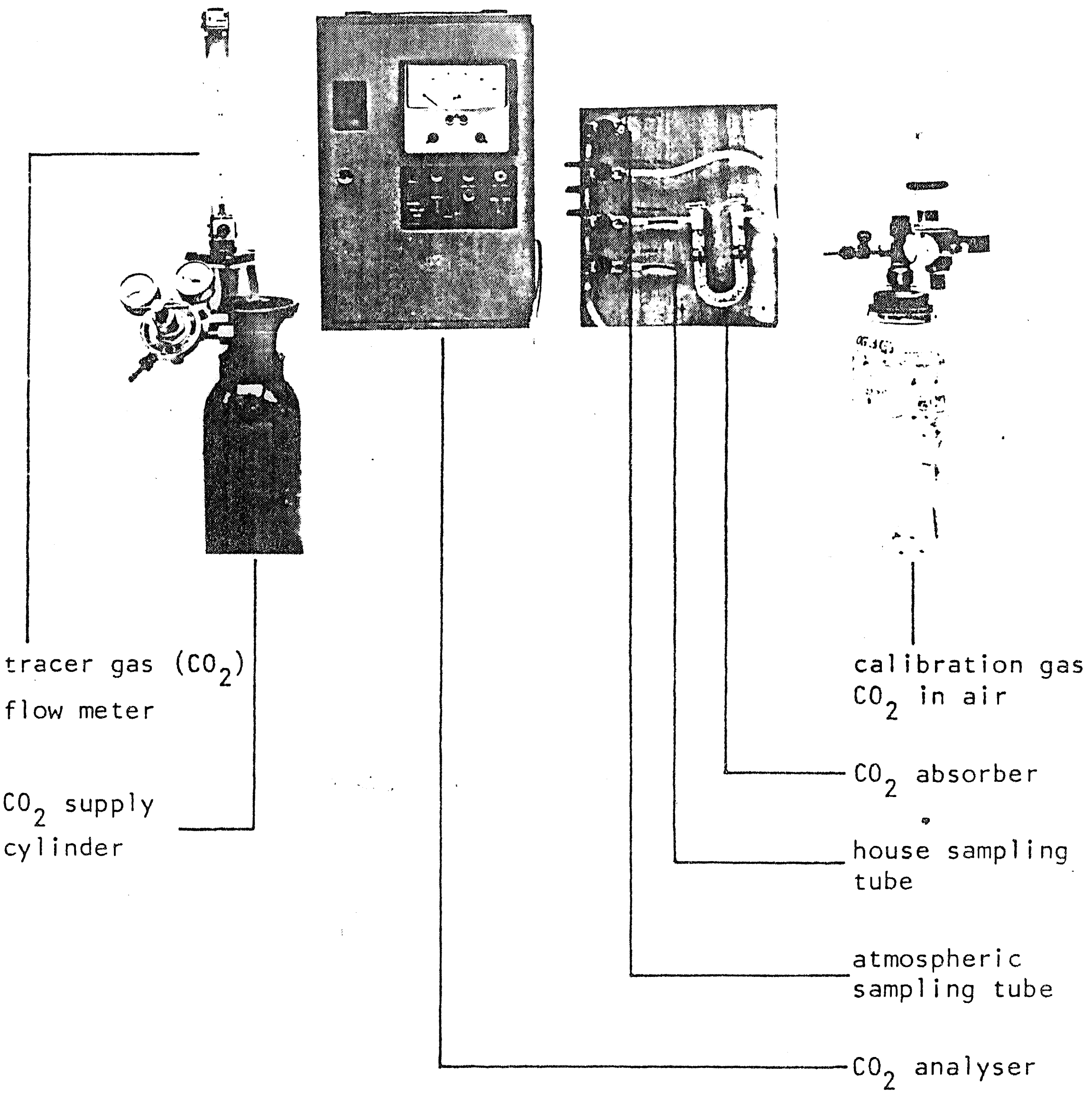

Figure 2 Tracer gas injection and sampling apparatus

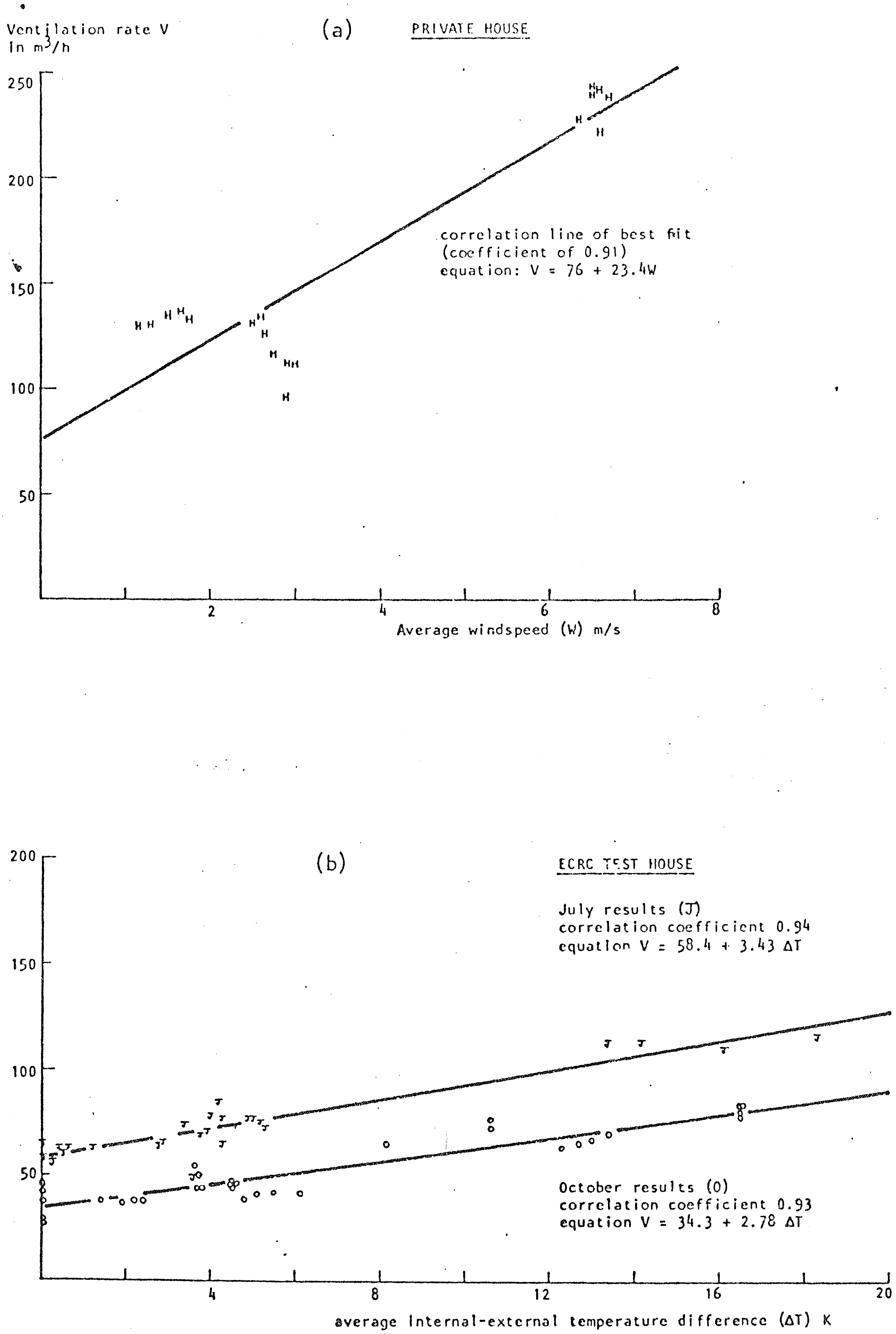

Figure 3. Measured results and the results from the regression analysis