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Ventilation Measurements in Houses and the Influence of Wall Ventilators

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A total of 390 measurements of ventilation rates has been made in seven closed rooms of six houses, using nitrous oxide as the tracer gas. The houses are located in outer suburbs of Melbourne. Half of the observations were taken when the wall ventilators were sealed, in order to explore the influence of the latter on room ventilation. Results for each room, grouped in ranges of wind direction and according to whether ventilators were open or closed, are shown as regression curves on plots of ventilation rate against wind speed. The ventilators are shown to have only a slight and not significantly useful effect on ventilation. Details are given of the apparatus and experimental techniques employed in the investigation.

INTRODUCTION

THIS paper describes an experimental determination of ventilation rates in houses of conventional construction in Melbourne. At the same time the opportunity was taken to explore the role of the ventilator, which is a mandatory provision for habitable rooms in at least five States and whose effectiveness was considered to be doubtful.

EXPERIMENTAL METHOD OF MEASURING VENTILATION

(a) Apparatus

Ventilation rates were determined using nitrous oxide as the tracer gas and a commercial infra-red gas analyser for measuring its concentration. The output of the gas analyser was amplified and recorded on a moving chart milliameter. The apparatus is a highly sensitive detector of nitrous oxide, enabling a maximum concentration of about 0·1 per cent by volume to be used in the rooms, which is a much lower concentration of tracer gas than can be measured using hydrogen and katharometers. Calibration of the gas analyser was carried out by connecting in a closed series circuit the sampling tube of the analyser with a blower and reservoir of several litres capacity. Nitrous oxide was injected in known quantities into the circulating air stream from a graduated hyperdermic syringe through a puncture made by the needle of the syringe in the walls of the rubber pressure tubing linking the pieces of equipment. Since the decay rates of nitrous oxide in rooms require a knowledge of only the relative changes in concentration of the gas with time, the total volumetric capacity of the calibrating system does not need to be measured accurately.

(b) Procedure

The ventilation rate in a room containing a tracer gas is given by

$$C = Co\,e^{-Rt}$$

where Co is the initial concentration of the tracer gas, C the concentration at time t h, and R the ventilation rate in room air changes per h. This relationship is valid only if there is good mixing between incoming fresh air and the air in the room.

To facilitate determination of decay rates without the repetition involved in making a fresh calculation for each test, the family of curves representing air changes at intervals of 0·1 changes per h was plotted on a short length of recording paper and photographically copied on to film to produce a transparent protractor for superimposing over the actual decay curves traced on the chart records during ventilation tests. For computing the points of the curves for the protractor the results of the calibration tests were used in conjunction with the most generally suitable paper speed. To allow for any other paper speed it is necessary to multiply the ventilation rate obtained with the protractor by the ratio of the new to the aforementioned paper speed.

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The duration of room tests was usually between 10 and 25 min, depending on the ventilation rate. While tracer gas was being injected into the room and for several minutes thereafter, two oscillating electric fans were run to thoroughly mix the nitrous oxide with the air. Room air was drawn mechanically into the analyser through rubber tubing, the inlet end of which was fastened to a stand placed at the centre of the room at a height half way between floor and ceiling. For ease of handling the gas analyser and all auxiliary equipment were mounted on a trolley.

The doors and windows of rooms under test were kept closed and openings in wall ventilators sealed, when required, with strips of foamed plastic. Two of the rooms tested have brick fireplaces and chimneys which could be sealed airtight at the top. For taking wind measurements a small, portable, cup anemometer and recording weather vane were mounted on a pipe-work stand placed near the centre of the yard behind the house. The height of the anemometer above ground level was about 10 ft and that of the weather vane 2 ft lower; these heights are about 4·5 and 2·5 ft respectively greater than that of the paling dividing fences between houses.

(c) Sampling technique

The theory used in the measurement of ventilation rates by the tracer-gas method assumes that there is good mixing of infiltrating air with that already in the room. Appreciable temperature differences between the room air and surfaces within the room assist in this regard, as also does good distribution of the openings into the room. In measuring ventilation rates in heated rooms with hydrogen katharometers Dick[1] found that air circulation was adequate in rooms of square or rectangular floor plan to allow representative sampling to be made from a central point without the need to stir the room air. The objection to running fans during the test period is that infiltration could be affected.

It appeared from the work of Van Straaten[2] that a fairly good approximation to the average ventilation rate in an ordinary unheated room could be obtained by sampling at a single central point without air stirring. To confirm this, three experiments were conducted in an L-shaped room covering three-quarters of the floor area of a weatherboard hut, which has four external walls 20 ft in length and stands in the grounds of the Division of Building Research. The room has six external windows and an external door. Decay rates were measured simultaneously at four points in the room, including the central point, by means of a manifold fitted with valves for switching the air intake to the gas analyser from one sampling point to another. In each of the experiments undertaken identical decay rates were obtained at each point. As a further check, on six occasions when ventilation rates were low the fans were switched on at the end of tests in three houses without any sudden change in the ventilation rate.

INDEPENDENT CHECKS OF MEASURING TECHNIQUES

(a) Methods

As a check on the performance of the method used to measure decay rates by the tracer-gas method with nitrous oxide and an infra-red gas analyser, room tests were carried out — (i) with hydrogen as tracer gas and a katharometer built to the design of Coblenz and Achenbach[3]; (ii) by injecting large quantities of bottled oxygen and measuring its content in the room with an Orsat apparatus by absorption in aqueous chromous chloride. The hydrogen katharometer was calibrated inside a large desiccator into which measured amounts of the gas were injected from a hyperdermic syringe through the rubber stopper. Inside the desiccator an acoustic air pump, simply adapted from a small loudspeaker, served to mix the hydrogen and air evenly before taking a calibrating reading. As it was found that the zero setting of the hydrogen katharometer was strongly affected by changes in the oxygen content of the room air, simultaneous measurements of room decay rates could be made only with firstly, nitrous oxide and oxygen and, secondly, nitrous oxide and hydrogen. The maximum concentration of hydrogen used was about 1 per cent by volume and that of oxygen about 35 per cent, compared with the 21 per cent occurring naturally in air.

(b) Results

In the first instance testing was carried out in the smaller room of the weatherboard hut used to check the tracer-gas sampling technique. The ceiling and the linings of the internal and external walls of the room were either unpainted fibrous plaster, a sheet material consisting of gypsum plaster reinforced with embedded strands of sisal, or gypsum plasterboard faced with heavy paper. The room surfaces were later painted. The floor of the hut is a concrete slab on the ground. Room decay rates using nitrous oxide and oxygen together were in close agreement over a wide range of wind conditions. In a further series of tests made, decay rates for hydrogen proved to be substantially higher than those for nitrous oxide, the proportionate differences tending to fall with rising ventilation rate as can be seen from the graph in figure 1. The slope of the full line of best fit does not significantly depart from that of the dashed line which represents the theoretical case in which decay rates of each gas are equal. Within the limits of experimental error there is, therefore, a constant difference between the decay rates of hydrogen and oxygen. Because this difference is constant it is not dependent on wind strength, which means that infiltration as such is not involved.

The available evidence at this stage suggested that appreciable diffusion of hydrogen was occurring through the fabric of the gypsum plaster linings, which being unsealed by paint and having a porous structure could be expected to be subject to this effect. If this explanation were correct the decay rates obtained jointly with hydrogen and nitrous oxide would be the same in rooms with impermeable walls. Two further series of experiments, the results of which corroborated the latter requirement, were undertaken using those tracer gases together in a laboratory with a concrete floor and ceiling and masonry walls, and then in the smaller room of the timber hut after two coats of latex water-based paint had been applied to the walls and ceiling. Decay rates of each tracer gas for the six tests held in the masonry room were identical within the limits of experimental error over a range of ventilation rates of 0·75–2·3 room air changes per h. A similar measure of agreement was obtained in ten tests in the timber hut using hydrogen and nitrous oxide together, and in several other tests using nitrous oxide and oxygen together.

The gross decay rate indicated by the hydrogen katharometer in the unpainted gypsum plaster-lined room is the sum of the decay rate for transfer of hydrogen through the lining and the decay rate for infiltration of air. The only previous reference noted is that of Bahnfleth, Moseley and Harris [4] in regard to houses with inner linings of plywood and asbestos cement, using helium as tracer gas.

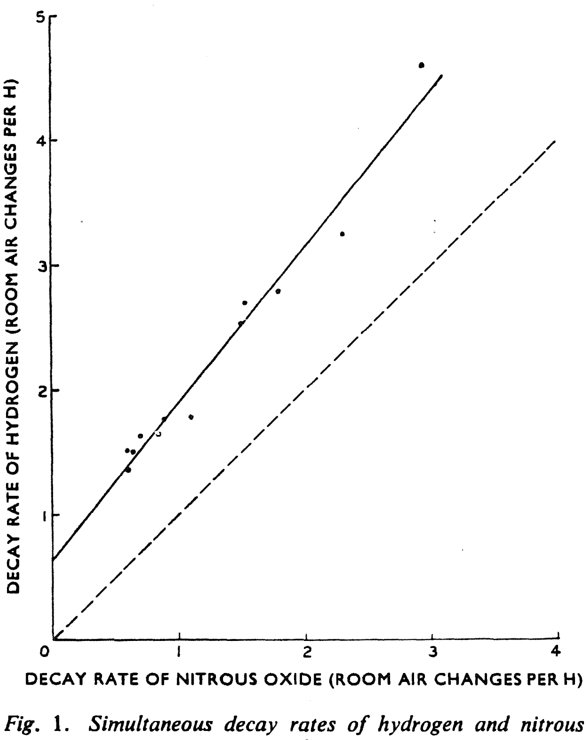

Fig. 1. Simultaneous decay rates of hydrogen and nitrous oxide.

The broken line is for the hypothetical case in which the decay rates of the two tracer gases are the same.

VENTILATION TESTS IN ROOMS OF HOUSES

(a) Description of houses and sites

Ventilation tests were carried out in six single-storey detached houses comprising a group of three situated side by side, and three others in separate localities. All the houses are in outer suburbs of Melbourne. The houses are of timber frame construction clad with weatherboards or 4½-in. brick, internally lined with fibrous plaster or plaster board. Floors consist of tongued and grooved timber boards and were uncovered in three of the rooms. Windows are wooden top-hung types in houses I and II, steel casements in houses III and V, and wooden double-hung types in houses IV and VI. To reduce inconvenience to the occupants of the houses tests were with one exception confined to one room in each house. No control was possible over settings of windows and doors of the occupied portions of the houses.

The group of three houses (I–III) lies on the outskirts of an isolated housing area located on a moderately defined ridge and surrounded by belts of trees. Houses IV, V and VI are located in housing areas of flat terrain. Small trees and shrubs are plentiful in the gardens of all the houses and surrounding neighbourhoods generally, except in the case of house IV. On the whole the amount of shelter of the houses and their sites from wind gave the impression of being fairly typical of suburban Melbourne.

The ratios of wind speeds measured at the house sites during the ventilation experiments to values recorded for the same times at the Central Weather Office of the Bureau of Meteorology ranged from 0·32 to 0·57. These periods necessarily cover only a limited number of different wind directions. The wind speed readings of the Bureau of Meteorology are measured with a Dines pressure tube anemometer at an exposed position on the top of a building in the central urban area of Melbourne. In contrast with those for the house sites, ratios of close to unity applied to measurements of wind speed made with the portable anemometer in the middle of a large, open, treeless suburban park of flat terrain.

(b) Details of rooms

Details of the rooms in which the ventilation tests were carried out are given in Table 1.

Each of the living rooms in houses I and III has external doors which for brevity are included in Table 1 as though they were windows. Crack lengths refer to the perimeters of moveable window sashes and door frames. There are large differences in measured window fits from house to house and this obscures the relevance of the quantitative information on crack lengths.

(c) Results

(i) *Temperature differences* — The effect on the ventilation rate of wind speed and air temperature gradient between indoors and outdoors was examined by multiple regression for all observations made in houses I and III with ventilators open and closed. With a few exceptions, air temperatures inside the three rooms concerned differed from corresponding shade air temperatures by amounts of not more than 10 deg F. No significant correlation could be detected between ventilation rate and

Table 1. *Details of rooms.*

House and type of room	Volume of room (ft^3)	Aspect of external walls: With window(s)	With ventilator(s)	With window(s) and ventilator(s)	No openings	Unobstructed area of each ventilator (in^2)	Total crack length of window(s) (ft)
I(a) Living room	1800	W		N		7·5	66
(b) Bedroom	790			S		7·5	24
II Bedroom	2250	N		E	S	7·6	17
III Living room	3115	E, W		N		6·5	96
IV Dining room	880	S	E			5·2	16
V Bedroom	1170			N	E, W	5·5	23
VI Bedroom	1420		E	N, S		8·5	70

temperature difference or its square root. The cases include those in which the chimney of the living room of house I was open. Stack effect was not large enough to show up, being apparently overridden by wind-induced suction at the chimney outlet. Absence of temperature dependency for ventilation in unheated rooms even when flues are open has been noted by Warner[5].

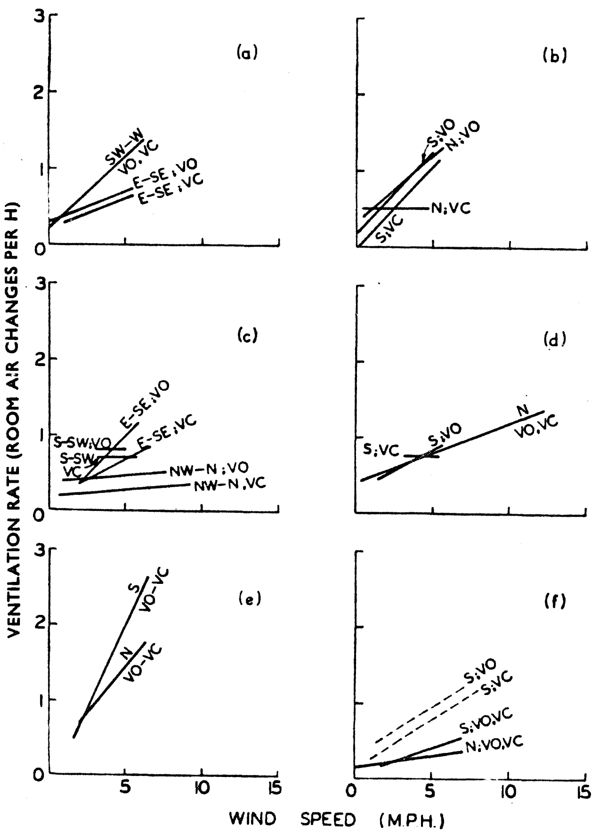

Fig. 2. *Ventilation of rooms in relation to wind speeds.*

(*a*)—House I, living room, flue sealed
(*b*)—House I, bedroom
(*c*)—House II
(*d*)—House III, flue sealed
(*e*)—House IV
(*f*)—House V (solid lines); house VI (broken lines)

Wind directions shown; VO = ventilators open; VC = ventilators closed.

(ii) *Effect of wind*— Correlations were examined between ventilation rate and wind speed for each room, the observations being grouped according to wind direction and whether ventilators were open or closed. Twenty-six of a total of 30 different sets of results showed a significant correlation between ventilation rate and wind speed, and for three of the remaining sets the range of wind speeds was too small to expect significant correlation. The regression coefficients for corresponding pairs of observations obtained with ventilators open and closed were compared, and if shown to be significantly the same covariance analysis was applied for equal wind speeds. The resultant plots of ventilation rate against wind speed are shown in figures 2 and 3. For the four sets of observations in which there was no significant correlation, the results are represented by lines drawn parallel to the horizontal axis through points denoting the mean ventilation rate of each set.

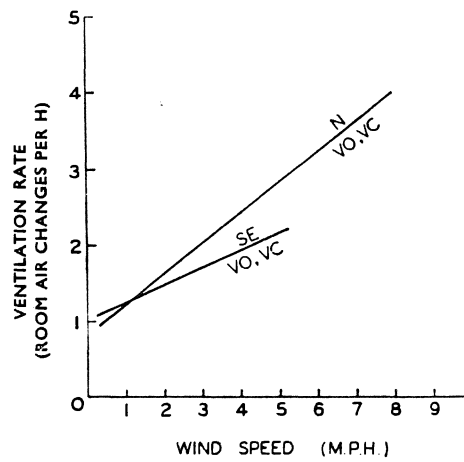

Fig. 3. *Ventilation of living room of House I, flue open.*
VO = ventilators open; VC = ventilators closed.

Further information on the graphed regressions is given in Table 2, which includes the number of observations together with the values of the regression coefficients and their significance levels.

The standard deviation of individual points for

Table 2. Summary of statistical analysis.

House	Ventilators open or closed	Wind direction	Mean wind speed (mile/h)	Mean ventilation rate (room air changes/h)	Number of observations	Regression coefficient	Standard deviation of individual points (wind speed constant)
I, Living room	Open	E/SE	3·15	0·54	14	0·077†	0·13
	Closed	E/SE	2·98	0·45	14	0·077†	0·13
	Open, closed	W/SW	4·09	1·00	18	0·192‡	0·16
	Open, closed	N	3·25	2·13	25a	0·41‡	0·55
	Open, closed	SE	2·90	1·69	19a	0·23†	0·38
I, Bedroom	Open	S	3·49	0·93	17	0·215‡	0·22
	Closed	S	3·39	0·70	21	0·215‡	0·22
	Open	N	2·91	0·84	13	0·17†	0·24
	Closed	N	2·72	0·51	15	Not sig.	0·20
II	Open	S/SW	4·53	0·83	6	Not sig.	0·30
	Closed	S/SW	4·47	0·71	11	Not sig.	0·21
	Open	E/SE	3·93	0·74	8	0·211†	0·13
	Closed	E/SE	3·62	0·60	6	0·123†	0·13
	Open	N/NW	3·59	0·45	11	0·019†	0·06
	Closed	N/NW	3·84	0·27	15	0·019*	0·06
III	Open, closed	N	5·35	0·83	24	0·083‡	0·16
	Open	S	4·17	0·73	10	0·107*	0·17
	Closed	S	4·16	0·74	13	Not sig.	0·17
IV	Open, closed	S	4·28	1·59	12	0·493‡	0·33
	Open, closed	N	4·78	1·38	14	0·247†	0·34
V	Open	NW	3·66	0·30	26	0·069†	0·09
	Closed	NW	2·93	0·24	20	0·029†	0·09
VI	Open	S	4·79	0·91	30	0·136‡	0·16
	Closed	S	4·83	0·83	28	0·136‡	0·16

a Observations made when chimney was open.
* Significant at 5 per cent level.
† Significant at 1 per cent level.
‡ Significant at 0·1 per cent level.

constant wind speed compared with the mean ventilation rate indicates the average degree of scatter of the observations about the particular regression line. It can be seen from the graphed results that ventilation rates in the rooms generally did not rise much above one air change per h, except for house IV in which rates of more than two air changes were reached. In house V the maximum rate was only 0·5 air change per h. The average annual wind speed recorded in Melbourne is about 8 mile/h and the corresponding speed at the house sites would be a fraction of this, probably in the region of 50 per cent. This means that the higher rates measured apply to comparatively windy weather. In relatively calm weather ventilation rates were characteristically below 0·5 room air change per h, ranging down to about 0·2 change. The prevalence of such ventilation conditions in the rooms is fairly common, as can be seen from the fact that the mean annual frequency of wind speeds at Melbourne airport in the range 0–5 mile/h is about 25 per cent, the highest monthly frequency of 36 per cent falling in March and the lowest of about 21 per cent from August to November.

(iii) *Effect of chimney*—The presence of the open chimney in the living room of house I had a marked effect on infiltration, as can be seen from a comparison of figures 2(a) and 3. When winds were south-easterly ventilation rates were more than three times those obtained with the chimney closed. The maximum ventilation rate reached was 4 air changes per h when the wind was blowing from the north at about 8 mile/h. The minimum rate was about 1 room air change per h in still weather. Ventilation rates were independent of whether wall ventilators were open or closed. The large size of the chimney flue (9 × 9 in.) undoubtedly is an important factor in its effectiveness in boosting ventilation. Upon exposure to wind a suction pressure is normally developed at the outlet of a flue and this pressure may approach the magnitude of the velocity head of the wind under favourable circumstances[1]. Heating of flues leads to still higher ventilation rates in rooms.

VENTILATORS

(a) Details of ventilators

The wall ventilators of the houses are gypsum plaster castings, typically $10 \times 6 \times \frac{3}{8}$ in. outside dimensions, let into the fibrous plaster lining of external walls about 1 ft below the ceiling; each ventilator has several rows of horizontal slots, usually $\frac{1}{4}$ in. wide, which in some designs are broken by vertical ribs for decoration. Flywire mesh is fitted to the backs of the ventilators to keep out insects. In walls externally clad with weatherboards, openings are present in the cladding opposite the ventilators and these openings are capped with slotted or perforated metal cowls to prevent entrance of rain. In brick veneer construction the ventilators open into the wall cavity which in turn opens without obstruction into the roof and underfloor spaces, both of which are ventilated.

In houses I–V the rooms tested are fitted with only two wall ventilators spaced well apart in the same external walls, with an additional ventilator in the ceiling in house III. The room of house VI has one ventilator in each of the three external walls. Inspection of the flywire mesh backing the ventilators of the rooms in which tests were carried out revealed that there were slight traces of deposited dust on the flywire. In house I, however, which was four years old at the time of the tests, several ventilators in the kitchen and an adjoining living room (neither tested for ventilation) were noticed to have heavy deposits of dust on the flywire, although dust accumulation in ventilators elsewhere in the house was only very slight. It seems a reasonable conjecture that over a period of time heavy choking or complete blocking of the mesh of ventilators by dust may not be uncommon.

The unobstructed areas of individual ventilators, as obtained by measurement and allowing for 25 per cent blockage by flywire mesh, are stated in Table 1. Only three of the seven rooms, viz. the bedroom of house I and the rooms of houses IV and VI, comply with the Victorian Uniform Building Regulations in respect of the total minimum area of ventilation openings stipulated per hundred ft^2 (or part thereof) of floor area for habitable rooms.

(b) Experimental results

Inspection of the 15 pairs of linear regression equations for open and closed ventilators reveals that open ventilators had no effect in six instances, increased ventilation rates in eight instances over almost the entire common range of wind speeds of each pair, and produced conflicting results dependent on wind speed in the remaining instance. In the second case the relative differences increased with rising wind speed in about half of the results and were constant for the balance.

(c) Effectiveness of wall ventilators

Wall ventilators are clearly intended to maintain natural ventilation in rooms at times when windows and doors are shut. Safeguarding the health of the occupants is doubtless the primary historical reason for their use, but concepts of comfort are also inextricably involved. The matter of what constitutes the minimum standard of ventilation in occupied rooms, below which it is potentially unhealthy or undesirable on other grounds to fall, is beyond the scope of the study. An informed answer can be provided, however, to the question of whether or not ventilators make a worthwhile addition to ventilation in closed rooms of houses, mainly at the critical periods when slight winds or near-still conditions depress room ventilation rates. On the whole the effect of ventilators is judged to be quite small and of insignificant usefulness in modifying the atmospheres of occupied rooms. Much of this ineffectiveness must arise from the fact that the area of opening of a ventilator to the outside air is small by comparison with that of an open window, which produces an increase of many times in the ventilation rate. The small relative differences in ventilation caused by opening or closing the ventilators is evidently linked with the fact that the area of opening of the ventilator is typically comparable with the area of cracks around individual windows. In a similar way the openings formed by cracks and gaps at the structural joints of rooms act to suppress further the relative effectiveness of any one opening such as the wall ventilator. To increase the effectiveness of a wall ventilator by enlarging the area of fixed opening has the serious objection that this would cause uncomfortable draughty conditions in cool windy weather.

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390 mesures de ventilation ont été effectuées dans 7 chambres fermées appartenant à six maisons différentes, et l'acide nitreux a été utilisé comme gaz révélateur. Ces maisons se trouvent dans des banlieues à l'extérieur de Melbourne. La moitié des observations furent effectuées avec les ventilateurs muraux scellés afin d'investiguer l'influence de ces derniers sur la ventilation de la chambre. Les résultats obtenus pour chaque chambre ont été groupés selon les diverses directions du vent et selon que les ventilateurs étaient ouverts ou fermés et ont été indiqués sur des courbes à rebroussement sur des graphiques représentant la ventilation et la vitesse du vent. Ceci a prouvé que les ventilateurs n'ont qu'un effet restreint et pas du tout significatif sur la ventilation. Des détails sont donnés sur l'appareil et les techniques expérimentales adoptées durant ces recherches.

Insgesamt 390 Messungen von Belüftungsgeschwindigkeiten wurden in sieben geschlossenen Räumen in sechs Häusern ausgeführt und Salpetergas wurde als Indikatorgas verwendet. Die Häuser befinden sich in den äusseren Vororten von Melbourne. Die Hälfte der Beobachtungen wurde an verschlossenen Wandlüftungs Klappen vorgenommen, um den Einfluss der Lüftungsklappen auf die Raumbelüftung zu untersuchen. Ergebnisse für jeden Raum, gruppiert in Windrichtungsbereichen und je nachdem, ob die Lüftungsklappen offen oder geschlossen waren, sind als Rückartungskurven von Belüftungsgeschwindigkeit Auftragungen gegen Windgeschwindigkeit gezeigt. Es wird ferner gezeigt das die Lüftungsklappen nur eine geringe und keine bedeutungsvolle nützliche Wirkung auf die Belüftung haben. Einzelheiten über den Apparat und die Versuchstechnik welche in der Untersuchung verwendet wurden, sind gegeben.