3733

C S A E
S C G R

Canadian Society of Agricultural Engineering

Paper No. 89-4065
AN ASAE/CSAE MEETING PRESENTATION

EFFECT OF DIFFERENT RIDGE OPENING WIDTHS ON THE THERMAL PERFORMANCE AND VENTILATION RATE OF A NATURALLY VENTILATED SWINE BUILDING DURING WARM SUMMER CONDITIONS.

by

Y. Choinière[1], J.A. Munroe[2], G. Desmarais[1], H. Dubois[1], Y. Renson[3]

1. Alfred College of Agriculture and Food, Alfred, Ont. K0B 1A0;
2. Engineering and Statistical Research Centre, Research Branch, Agriculture Canada, Ottawa, Ont. K1A 0C6;
3. Institut d'enseignement agricolè et technique du Hainaut, Ath. Belgium.

Written for presentation at the 1989 International Summer Meeting jointly sponsored by the AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS and the CANADIAN SOCIETY OF AGRICULTURAL ENGINEERING

Quebec Municipal Convention Centre
Quebec, PQ, Canada
June 25-28, 1989

SUMMARY:
Ridge opening widths (0, 25, and 125 mm) were tested during the summer of 1988. Results showed minor differences in interior thermal performances among the ridge widths. Based on calculated ventilation rates, a minimum ridge opening could be advantageous. On this basis, side wall openings can be designed for wind effects only.

KEYWORDS: ventilation, natural ventilation, summer, ridge width

American Society of Agricultural Engineers

St. Joseph, MI 49085-9659 USA

INTRODUCTION

Current popular designs for warm naturally ventilated swine finishing buildings generally include large sidewall openings and a continuous ridge opening. But there is a controversy among designers regarding the effect of the ridge opening area on the thermal performance and the ventilation rate, particularly under summer conditions.

It was therefore decided to initiate a study to determine the influence of the ridge opening area on temperature distribution within a warm naturally ventilated swine finishing barn, and on ventilation rate. The study would be restricted to warm summer conditions.

LITERATURE REVIEW

Thermal Performance of Naturally Ventilated Buildings

For insulated, naturally ventilated dairy barns, Kammel et al. (1982) showed that interior temperatures were similar to exterior temperatures during the hot season (above 25°C). They also stated that "when large sidewall doors are provided for warm weather conditions, the ridge opening should not be oversized". For naturally ventilated swine finishing barns, Choinière et al. (1987) reported isothermal conditions (the same temperature inside as outside) for exterior temperatures above 20°C.

For a modified open front style swine finishing barn,Boyd (1985) reported that inside temperatures were often below exterior temperatures during the daytime. There were no vertical or horizontal gradients of temperature across or along the building during the daytime. He noted that inside-outside temperature differences occurred during the night period when: 1) lower wind speeds were recorded; and 2) the automatic sidewall door controllers were causing the doors to close in order to maintain the desired internal temperature.

Barrie et al. (1985) studied a naturally ventilated building for finishing hogs with large sidewall openings but no ridge opening. Minimum interior temperature increases, even during periods of low wind speed, indicated no adverse effect due to the absence of a ridge opening. On the other hand, Meyer and Goetsch (1984) recommended the use of a large ridge opening (600 mm wide) in order to obtain better temperature control during the warm season.

Contribution No. C-100, from Engineering and Statistical Research Centre, Research Branch, Agriculture Canada, Ottawa, Ont. K1A0C6.

Choinière et al. (1988c) proposed the use of a minimum ridge opening during cold weather. They also recommended that further studies be made on the effectiveness of different size ridge openings in relation to desired ventilation rate and temperature control.

Measurement of Ventilation Rates Based on CO_2 Levels

Hitchin and Wilson (1967) discussed two basic methods to measure ventilation rates with a tracer gas which are: 1) the rate of decay method; and 2) the equilibrium concentration method. The rate of decay method consists of introducing a high concentration of tracer gas into a ventilated airspace and, after stopping the supply, measuring the rate of decay. Moulsley and Fryer (1985) used this rate of decay technique to investigate air leakage in broiler barns. The same technique has also been widely used for other ventilation rate experiments.

The equilibrium concentration method supposes that the tracer gas is emitted continuously at a uniform rate and that an equilibrium tracer gas concentration directly related to ventilation rate can be obtained in the airspace. Hitchin and Wilson (1967) discussed the difficulty in obtaining an equilibrium due to non-static weather conditions and non-uniformity of the tracer gas supply.

For warm weather, Owen (1982) recommended that the control of ventilation rates for livestock should be based on the CO2 concentration inside the building and the upper critical temperature of the livestock instead of only on interior temperature. Since the hogs were a source of CO_2, he emphasized the fact that the concentration of CO_2 inside the barn could be used as an indicator of the ventilation rate.

Based on the equilibrium method, Feddes and DeShazer (1988) proposed a simple way to predict the ventilation rate based on the difference in CO_2 concentration inside and outside and an assumed CO_2 production by the animals.

For a naturally ventilated hog finishing barn with a conventional ridge opening and large sidewall doors, MacDonald et al. (1985) measured interior CO_2 concentrations of 400 to 800 ppm during warm weather and about 3000 ppm during cold weather. The increase in the CO_2 concentration was attributed to a reduction of the ventilation rate.

Hitchin and Wilson (1967) reported that gas mixing inside a ventilated airspace is mainly due to air currents and that "mixing is never perfect ... measurements made at one point in a room may not be reliable." This fact has also been reported by others such as Barber and Ogilvie (1984) and Boyd (1985).

Studies of airflow patterns for naturally ventilated buildings conducted by Choinière et al. (1988a, 1988b) indicated that zones of under and/or over ventilation existed both across and along the buildings. These observations enforced the statement of Hitchin and Wilson (1967) that air should be "sampled at several points, mixed and the combined concentration" then used to determine the ventilation rate.

According to the data of Feddes (1989), the computation of ventilation rates should reflect the time period of the day. CO_2 production increased during feeding time, and was higher during the day as compared to the night. These changes in the production rate of CO_2 could influence the calculated ventilation rates.

CO_2 Production by Finishing Hogs

Feddes et al. (1983) studied the effects of temperature and feeding method on the CO_2 production by finishing hogs. In particular they found that the CO_2 production rates for feeding on the floor versus in a feeder were 1.47 and 1.59 L/(h.kg metabolic weight) respectively.

OBJECTIVES

A naturally ventilated building for finishing hogs, with large sidewall openings and a continuous ridge opening, was investigated for three different ridge opening widths: 0 mm (closed), 25 and 125 mm. The objectives were:

1- to compare the building thermal performance in relation to the ridge opening width;

2- to compare the ventilation rates achieved for different ridge opening widths based on measurements of CO_2 concentration;

3- to study the effects of exterior temperature, wind direction and speed on ventilation rate.

METHODS AND PROCEDURES

Barn Description

Tests were performed in a warm naturally ventilated hog barn owned by Albert de Wit, RR 4, Spencerville, Ontario. The barn was 10.8 x 23.0 x 4.35 m high at the ridge, and was oriented north-south. Scissor trusses provided a sloping ceiling. Adjacent buildings were mainly to the north of this barn, and thus caused a minimum of interference to the prevailing southwesterly winds. Each side of the barn had nine rotating ventilation doors, 2100 mm x 900 mm high. The opening of these doors was controlled by a modulated automatic control system based on thermostats (Choinière et al., 1987).

Fig. 1 shows the horizontally projected opening area (8.32 m^2 total on each sidewall) when the rotating doors were fully open. This represented 15% of the sidewall area. Controversy still exists as to whether the opening area should be described as this projected area, or the area perpendicular to the incoming airstream. Using the latter, the total opening area would represent 25% of the sidewall area. For the present study, the method of describing opening area has no influence on the calculation of the ventilation rate. However, it would influence the design recommendations.

The barn had a ridge opening length of 19.2 m. During this study, the ridge opening width was set at either 0, 25 or 125 mm using a manual cable and winch system.

Instrumentation and Test Procedure

The airflow patterns were observed using Drager air current tubes (smoke).

As shown in Figs. 2 and 3, 20 thermocouples were used to determine the temperature distribution over a cross-section at the centre of the barn while 22 other thermocouples located 0.9 m above the floor (Choinière et al. 1987) indicated temperature distribution along the length of the barn. Exterior temperature, and wind speed and direction were monitored near the barn using a standard 10 m high weather station. All the sensors were read every 10 s and their readings then averaged for each 5 minute period. These data were then used to compute the long term average temperatures and standard deviations for each thermocouple location.

The CO_2 concentration inside the barn was monitored based on an average of 21 points made up of 7 locations in each of 3 similar cross sections (Figs. 2 and 3). Plastic tubing (5 mm) and a centrifugal fan extracting a total of about 5 L/s was used to draw air simultaneously from the 21 locations into a mixing box. The CO_2 concentration in this box was measured every 10 s and the readings averaged over a 5 minute period. The exterior CO_2 concentration was measured once during the day 2 to 3 times per week. It was always between 325 and 350 ppm.

During the test period, the target temperature at pig level was 18.5°C corresponding to optimum conditions for finishing hogs weighing 50 to 90 kg. When the inside temperature was above 18.5°C, the automatic control system maintained the rotating doors fully open.

Tests were carried out between June 6 and August 10, 1988. The ridge opening width (0, 25 or 125 mm) was changed every three days. However, because of problems such as equipment or instrumentation failure, the equivalent of approximately 850 h of data were obtained during this time.

Temperatures at pig level and over the central cross section were plotted for each three day test. This allowed observation of the thermal behaviour of the barn over a range of weather conditions, and comparison of the thermal performances using the three different ridge opening widths.

The ventilation rates were calculated using the proposed equilibrium method described by Feddes et al. (1983) and Feddes and DeShazer (1988). A CO_2 production rate of 1.59 or 1.47 L/(h.kg metabolic weight) was selected according to the feeding technique (feeders or floor feeding) (Feddes et al. 1983).

In order to depict open country conditions, only the data concurrent with wind from the south to west sides of the barn were considered for the calculation of ventilation rates. As shown on Fig. 3, the wind direction was divided into five direction segments of 22.5° each. For each ridge opening width, the wind speed and direction frequency distributions were determined and plotted.

Pig Cleanliness, Behaviour, Weight and Feeding

Overall pen cleanliness and pig behaviour were noted twice per week. Notes included the number of pigs per pen (typically 15 hogs per pen, or 0.72 m^2/hog), pig average weight and pen cleanliness rated as follows: very dirty, dirty, dirty-clean, clean-dirty, clean or very clean. A very dirty pen would have a layer of manure over the floor and the hogs would be dirty. At the opposite end of the scale, a very clean pen would show no manure in the sleeping and eating areas and there would be no trace of manure on the hogs. A total of 300 finishing hogs ranging from 55 to 90 kg were housed in this barn during the study. Records of the feeding methods were kept. The hogs were fed twice a day at 8:00 to 9:00 h and 18:00 to 19:00 h.

RESULTS AND DISCUSSION

Temperature Distributions

From July 6 to 9, 1988, the interior temperature did not drop below 18.5°C. The automatically controlled rotating sidewall doors always remained at their fully open position. Fig. 4 shows the temperatures measured in the four corners of the building during this typical 3 d period. Comparison of Figs. 4 and 5 show that interior and exterior temperature peaks occurred at the same time.

As observed by Boyd (1985), the building responded quickly to exterior changes in temperature.

During the day, there was no difference between the exterior and interior temperatures, i.e. natural ventilation was occurring under isothermal conditions. Temperature differences of 3 to 7°C occurred however during the night. Fig. 4 also indicates some interior temperature gradients along the building. During the night events, as indicated in Fig.6, the wind was mainly from the south southwest. This created air circulation patterns from the north to the south end of the barn as described previously by Choinière et al. (1987 and 1988b). The lower temperatures were recorded at the north end (the main air inlet zone) and the warmer temperatures at the south end (the main air exhaust zone).

Even though there was an interior temperature gradient along the building, temperature at any given location was stable (< 1.5°C of standard deviation) during the night period. It should be noted that these temperatures were above the target temperature of 18.5°C.

Temperature Versus Wind Direction and Speed

During the time observed in Fig. 6, the wind direction shifted from west to south between day and night. These typical wind direction changes were also previously observed by Choinière (1989). South winds are considered to be the poorest with respect to efficiency of ventilation for this building since they are parallel to the building length.

The peaks of wind speed (Fig. 7) coincided with the peaks of exterior temperature (Fig. 5) during the day period. This phenomenon had a positive impact on natural ventilation since it provided higher ventilation rate potential during periods of higher exterior temperatures.

Effect of Ridge Opening Width

Based on the thermal performance of the building, there was no noticeable difference among the three ridge opening widths during the day period.

During the night, when low wind speeds and adverse wind directions occurred, slightly higher interior temperature gradients were observed with the totally closed ridge. There was no apparent difference in building thermal performance using ridge opening widths of 25 or 125 mm for the weather conditions encountered.

Pigs Behaviour and Cleanliness

During the 8 weeks of the study, the hogs were "dirty-clean" on average. Pens with self-feeders were generally dirtier than those floor fed. This could be due to the more continuous pig activity in the pens with feeders. At the end of July and the beginning of August, many pens become "dirty" and "very dirty" since some hogs were lying on the slotted area and some were defecating in the sleeping area. The exterior temperatures peaks and fluctuations were similar during the month of June and the beginning of July. Humidity levels were higher during the latter part of the test period (mid-July, August). These higher humidity levels may have had an effect on pig cleanliness.

No noticeable difference was noted in average hog cleanliness for any of the three ridge opening widths.

Operator Comments

The operator disliked operating with the ridge closed. His preference was for the ridge opening of 25 mm mainly because it reduced rain infiltration as compared to the ridge opening of 125 mm. As well, he enjoyed the extra sunlight entering the building with the ridge opening of 25 mm as compared to the closed ridge. Despite our records taken on animal cleanliness, the operator felt that he noticed an improvement in hog cleanliness with an open ridge versus a closed ridge.

CO_2 Concentrations

Fig. 8 shows CO_2 concentrations for the closed ridge tests based on the average of measurements from the 21 sampling locations.

The lowest CO_2 concentrations were monitored during the day period and were coincident with peaks of exterior and interior temperatures (Figs. 4 and 5). According to the model of Feddes and DeShazer (1988), lower CO_2 concentrations coincide with higher ventilation rates. Based on the equilibrium method, CO_2 concentrations of 400 ppm would indicate ventilation rates of 4 to 5 air changes per minute.

Generally, the lowest CO_2 concentrations were recorded when the wind speed was above 2 to 3 m/s and when the wind direction was perpendicular to the building length. As shown by Aynsley et al. (1977) and Vickery et al. (1983), a model for wind induced natural ventilation should include the combined effect of wind speed and direction.

Calculated Ventilation Rates.

Because of the cycle of the plants from daytime photosynthesis to nighttime respiration, Desjardins (1989) indicated that under low wind speed conditions the concentration of carbon dioxide in and over corn fields could increase from 350 ppm during the day to 400 to 600 ppm during the night. This increase occurs rather abruptly at sunset. Since the test facility was adjacent to a corn field only CO_2 data collected between 6:00 h and 20:00 h were used in computing ventilation rates. In addition, data representing concentrations less than 400 ppm were deleted when calculating ventilation rates as this concentration was considered too close to that assumed for outside, and could lead to erroneous interpretation. Simultaneous measurements of exterior and interior CO_2 concentrations were not made as only one CO_2 analyzer was available.

Spot checks indicated that when, on occasion, there were temperature gradients in the barn, indicating less than perfect mixing, there was also some variation in CO_2 concentrations. The latter tended to vary directly with local temperature; i.e. higher CO_2 concentrations coincided with higher local temperatures indicating a lower local ventilation rate. Data were therefore omitted when temperature gradients were noted in the barn.

In order to make comparisons based on ventilation rate, the wind speed and direction frequency distributions for the different ridge opening width tests should be considered. For the ridge opening widths of 0, 25, and 125 mm, a total of 927, 642, and 217 data points were selected respectively. Figs. 9 and 10 show meteorological data of wind direction and wind speed frequency distributions during the tests of the different ridge opening widths. These distributions appear to be similar to the frequency distributions of wind speed and direction for Eastern Ontario as observed by Choinière (1989) . Thus it would appear that sufficient data points were obtained to reflect typical conditions.

Fig. 11 presents the preliminary results of calculated ventilation rates. It appears that a ridge opening has a positive effect on the ventilation rate as compared to a totally closed ridge but a larger ridge opening width of 125 mm does not present any particular advantage over a minimum ridge opening width of 25 mm. This might not apply if the sidewall openings were considerably smaller than those in the barn tested here.

Some calculated ventilation rates of 2000 to 4000 L/s are noted. This would be equivalent to 7 to 14 L/s per hog. These values would be in the order of 1/4 the recommended ventilation rates for finishing hogs as given by Turnbull et al. (1988) for warm weather temperature control.

As reported by Choinière (1989), the adverse effects of these low ventilation rates would depend on the frequency, and number of consecutive hours during which they occurred. The relation between the meteorological data (wind speed and direction) and the ventilation rates should be investigated for local conditions in order to verify the feasibility of using natural ventilation for that region.

Design of Naturally Ventilated Buildings

Since the interior and exterior temperatures are approximately the same during the hot period of the day, the required opening area (sidewall or ridge), for design purposes, should be based on wind forces only. The chimney effect is minor at this time. It appears that even with no ridge opening, the large sidewall openings can restrict interior temperature increases during the night during periods of low wind speed and adverse wind direction. The use of chimneys as proposed by Choiniere et al. (1988c), in lieu of a continuous open ridge, for winter ventilation would appear to be quite adequate for summer ventilation as well in this naturally ventilated finishing barn. Chimneys 600 x 600 mm every 8 m would be equivalent in area to a ridge opening width of 45 mm.

Conclusions

A naturally ventilated swine finishing barn with large sidewall openings and a continuous ridge opening was investigated using three different ridge opening widths (0, 25 and 125 mm). From this study, it can be concluded that:

1) isothermal conditions (similar interior and exterior temperatures) were maintained during the day for the three ridge opening widths tested. Slightly higher interior temperature gradients were observed with the closed ridge during the night period as compared to either of the open ridges.

2) to provide sufficient ventilation during the peaks of exterior temperature during the day period, the size of the sidewall and ridge opening areas of naturally ventilated buildings can be based on wind forces only. The chimney effect is minor at this time.

3) for design purposes, a minimum ridge opening width of 25 mm, as compared to a totally closed ridge, appeared to have a positive effect on the ventilation rate.

4) there appeared to be no advantage of using the large ridge opening width of 125 mm over the minimum ridge opening width of 25 mm based on thermal performance and measured ventilation rates. It must be remembered however that this building had what is considered sufficient sidewall openings areas provided (15% of the sidewall or more).

Further Studies

In order to properly design natural ventilation for swine finishing buildings, more research is needed to obtain:

1) a prediction model for carbon dioxide production by finishing hogs based on animal activity (feeding, sleeping, etc.)

2) a prediction model for designing naturally ventilated buildings based on ventilation rate as determined from effective area of sidewall and/or ridge openings, local wind speed and direction.

3) the relationship between meteorological data including wind speed and direction, and the ventilation rates of naturally ventilated buildings. This would permit determining the number of consecutive hours when low ventilation rates could be expected.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge K. Boyd P.Eng, Education and Research Fund, Ontario Ministry of Agriculture and Food, Agri-Centre, Guelph, Ontario; C. Weil, P.Eng., Regional Manager, Agricultural Engineering Services and M. Paulhus, P.Ag., Principal, Alfred College of Agriculture and Food Technology, Alfred, Ontario, for their support and funding.

Special thanks are addressed to Albert de Wit and family, R.R. 4, Spencerville, Ontario for their extensive and helpful contribution during this study.

Thanks are also extended to Andrew Olson, Engineering technologist, Rick Pella, draftsman, Harold Jackson, P.Eng., and Dr. L.P. Lefkovitch, statistician, Engineering and Statistical Research Centre, Agriculture Canada, for their assistance.

The financial support provided by Ontario Hydro, Technical Services and Development for Agriculture is greatly appreciated.

REFERENCES

Aynsley, R.M., Melbourne, W.H. and Vickery, B.J. 1977. Architectural aerodynamics. Applied Science Publishers Ltd., London, Ont. 250 pp.

Barber, E.M. and Ogilvie, J.R. 1984. Incomplete mixing in ventilation airspaces. Part II. Scale model study.Can. Agric. Eng. 26(2):189-196

Barrie, I.A., Smith, A.T. and Yeo, M.L. 1985. Hot-weather performance of ACNV. Farm Building Progress. April. pp. 23-27.

Boyd, K.G. 1985. Experimental analysis of ventilation due to wind in models of a modified open front swine finishing barn. MSc. Thesis, University of Guelph, Guelph, Ont.

Choinière, Y., Ménard, O., Blais, F. and Munroe, J.A. 1987. Thermostat location for a naturally ventilated swine Barn. Paper No. 87-4554, Am. Soc. of Agric. Eng., St.Joseph, MI

Choinière, Y., Blais, F. and Munroe, J.A. 1988a. A wind tunnel study of airflow patterns in a naturally ventilated building. Can. Agric. Eng., 30(2):293-297.

Choinière, Y., Munroe, J.A., Dubois, H., Desmarais, G., Larose,D., and Blais, F. 1988b. A model study of wind direction effects on airflow patterns in naturally ventilated swine buildings under isothermal conditions. Paper No. 88-113, Can. Soc. of Agric. Eng., 151 Slater St., Ottawa, Ont. K1P5H4.

Choinière, Y., Munroe, J.A., Desmarais, G., Renson, Y. and Ménard, O. 1988c. Minimum ridge opening widths of an automatically controlled naturally ventilated swine barn for a moderate to cold climate. Paper No. 88-115, Can. Soc. of Agric. Eng., 151 Slater St., Ottawa, Ont. K1P5H4.

Choinière, Y. 1989. Natural ventilation of low rise buildings by the wind; development of a model to predict average ventilation rates and the frequencies of consecutive hours below minimum limits of ventilation rate with summer meteorological data. Presented to Dr. H. Tanaka, Ottawa University. Alfred College of Agricultural and Food Technology. April. 48 pp.

Desjardins, R. 1989. Private communications on the concentration of carbon dioxide during the summer time. Land Resources Research Centre, Agriculture Canada, Ottawa, Ont. K1A0C6.

Feddes, J.J.R. 1989. Private communications on the production rates of carbon dioxide by finishing hogs. University of Alberta, Edmonton, Alta. T6G2G6.

Feddes, J.J.R., Leonard, J.J., McQuitty, J.B. 1983. The influence of selected management practices on heat, moisture and air quality in swine housing. Can. Agric. Eng. 25(2):175-179.

Feddes, J.J.R. and DeShazer, J.A. 1988. Feed consumption as a parameter for establishing minimum ventilation rates. Trans. Am. Soc. of Agric. Eng. 31(2):571-575.

Hitchin, E.R. and Wilson, C.B. 1967. A review of experimental techniques for the investigation of natural ventilation in buildings. Building Science. 2:59-82.

Kammel, D.W., Cramer, C.O., Converse, J.C. and Barrington, G.P. 1982. Thermal environment of insulated naturally ventilated dairy barns. Second International Livestock Environment Symposium. Publication 3-82, Am. Soc. of Agric. Eng., St-Joseph MI. pp. 62-71.

MacDonald, R.O., Houghton, G. and Kains, F.A. 1985. Comparison of a naturally ventilated to mechanically ventilated hog finishing barn. Paper No. 85-402, Can. Soc. of Agric. Eng., 151 Slater St., Ottawa, Ont. K1P5H4.

Meyer, D.J. and Goetsch, W.D. 1984. A new ridge design for naturally ventilated swine buildings. Paper No. 84-4075, Am. Soc. of Agric. Eng., St-Joseph, MI.

Moulsley, L.J. and Fryer, J.T. 1985. Air leakage of broiler houses. Farm Building and Engineering, 2(2):17-19.

Owen, J. 1982. A design basis for pig buildings. Second International Livestock Environment Symposium. Publication No. 3-82. Am. Soc. of Agric. Eng. St-Joseph, MI.

Turnbull, J.E., Huffman, H.E. and Bird, N.A. 1988. Choix des ventilateurs pour les bâtiments abritant le bétail. Service des Plans Canadiens. Plan No. M-9705. 10 pp.

Vickery, B.J., Baddour, R.E. and Karakatsanis, C.A. 1983. A study of the external wind pressure distributions and induced internal ventilation flow in low-rise industrial and domestic structures. Report No. BLWT- 552 - 1983, Boundary Layer Wind Tunnel Laboratory, University of Western Ontario., London, Ont.

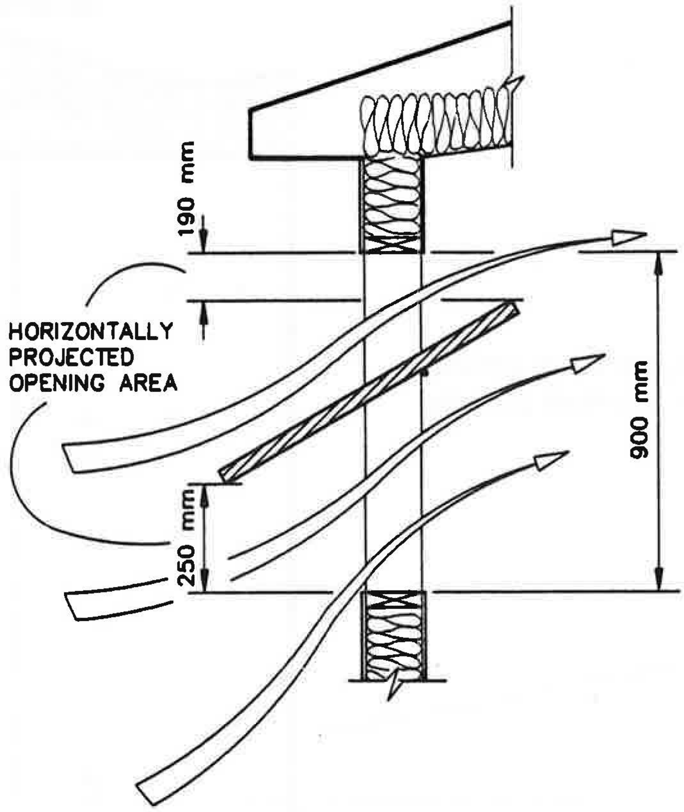

Fig. 1 Rotating sidewall door for a naturally ventilated building.

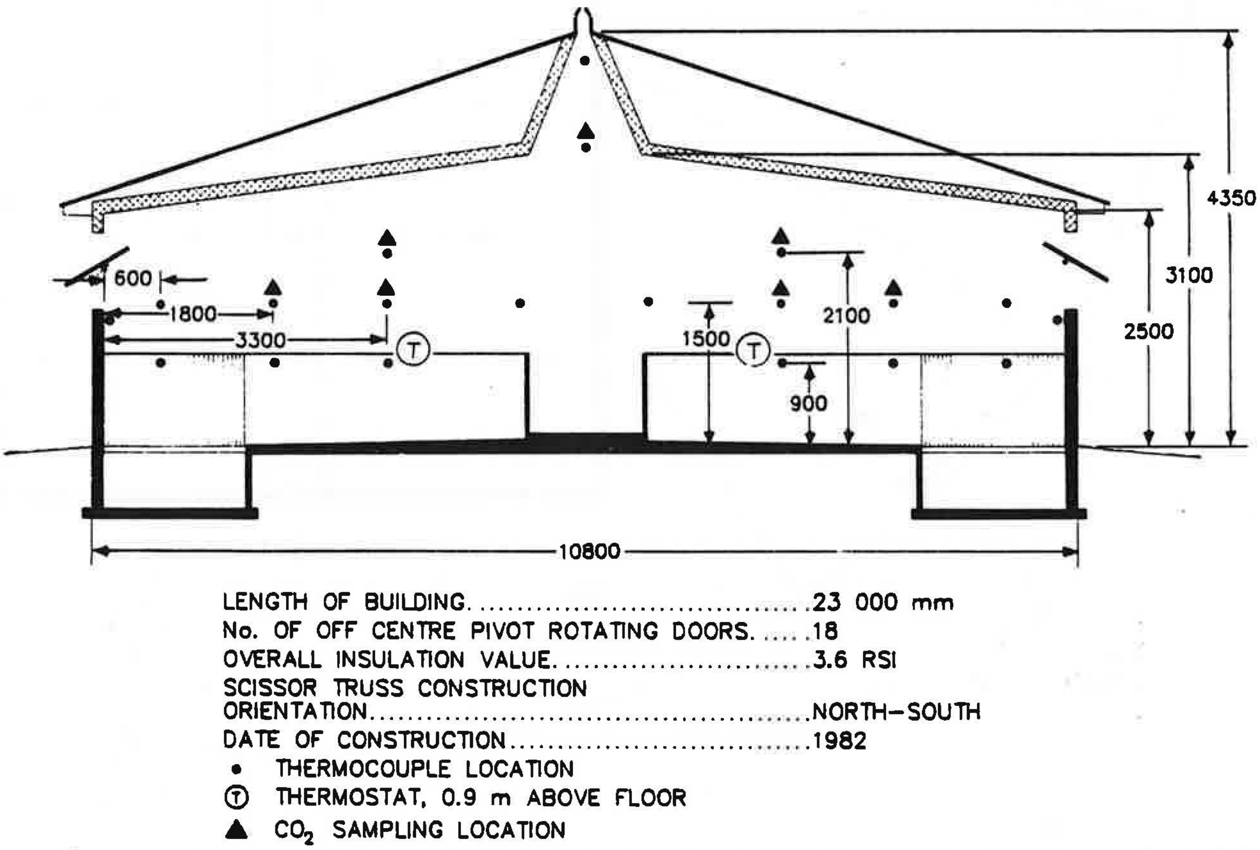

Fig. 2 Central cross section of barn showing locations of thermocouples and CO_2 samplings.

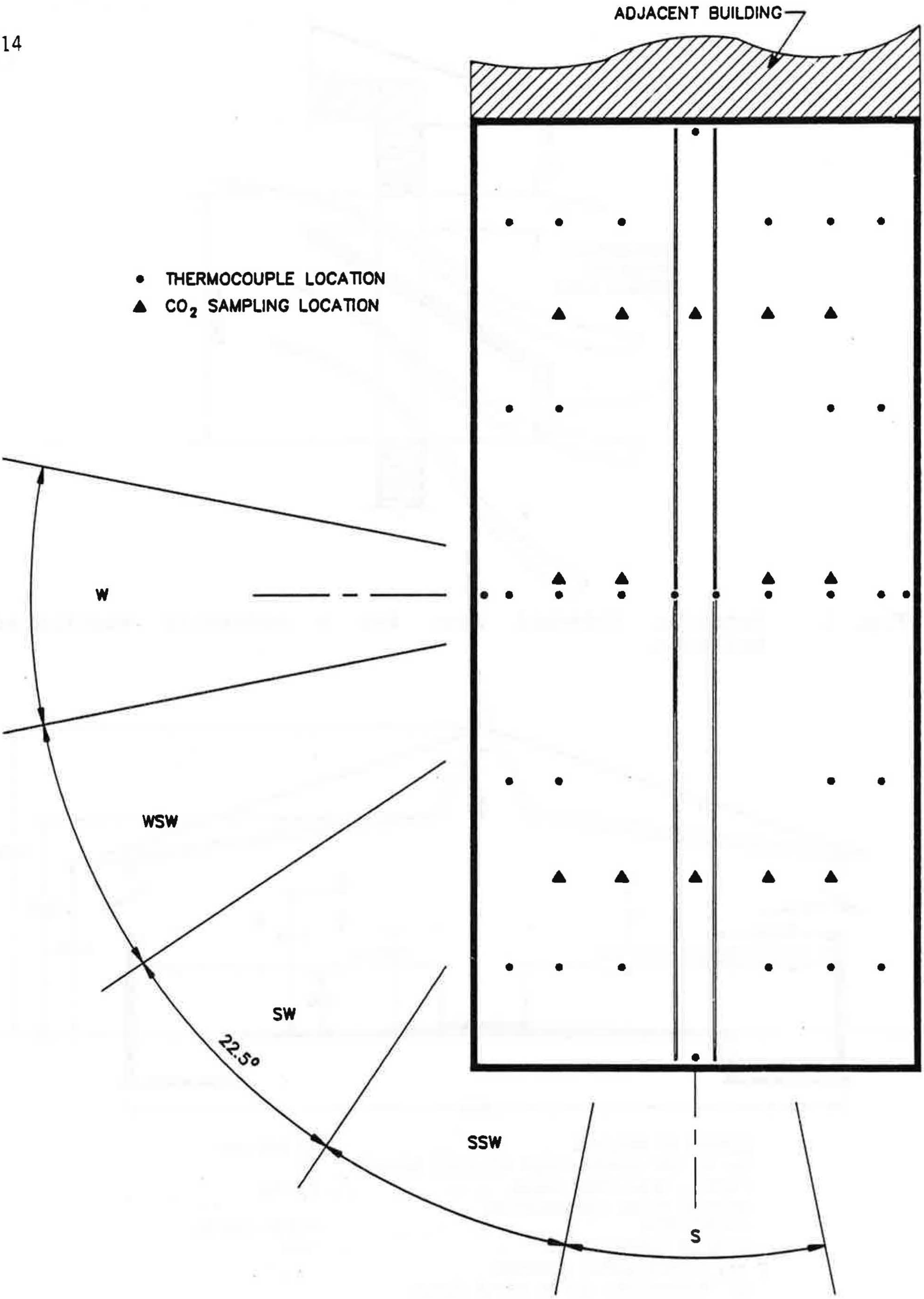

Fig. 3 Plan view of barn showing wind directions and locations of thermocouples and CO_2 samplings.

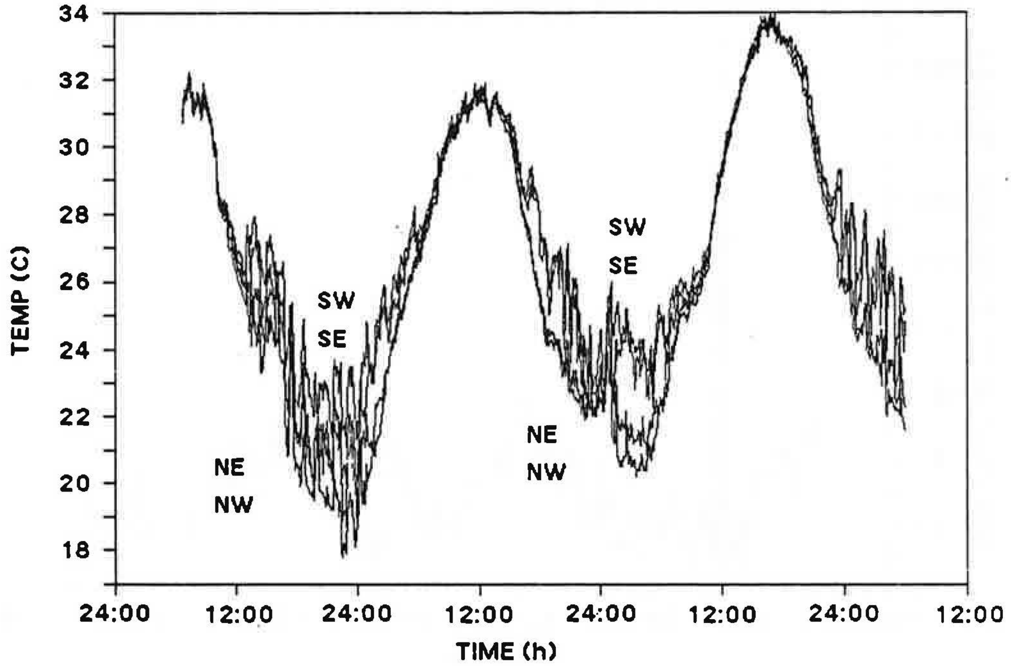

Fig. 4 Plot of temperatures measured in four corners of the barn with ridge closed during typical 3 d period (July 6-9, 1988).

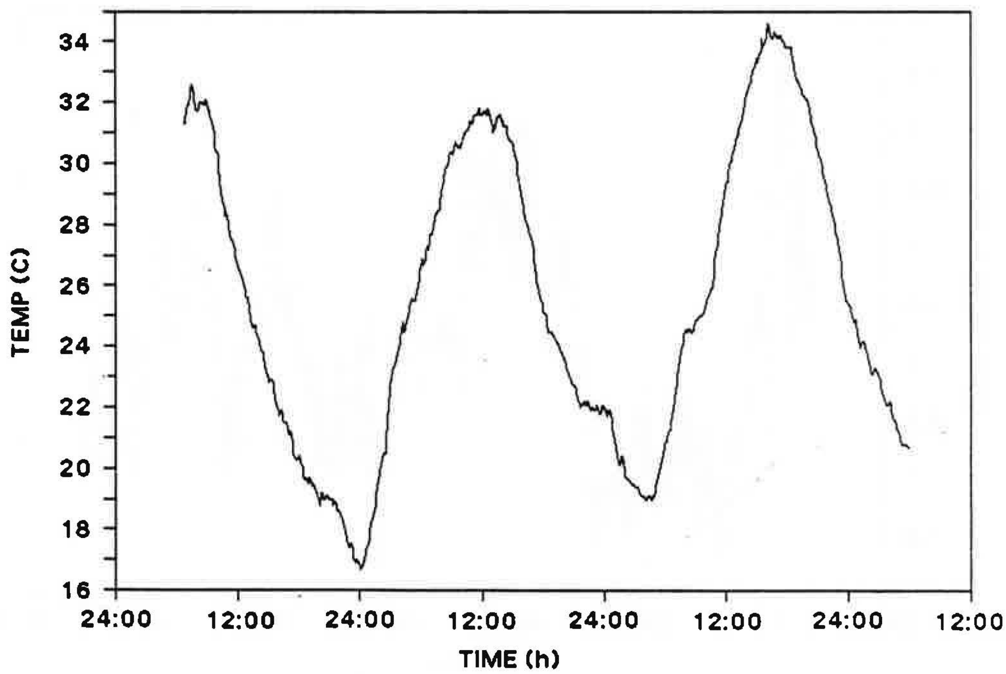

Fig. 5 Exterior temperature (July 6-9,1988).

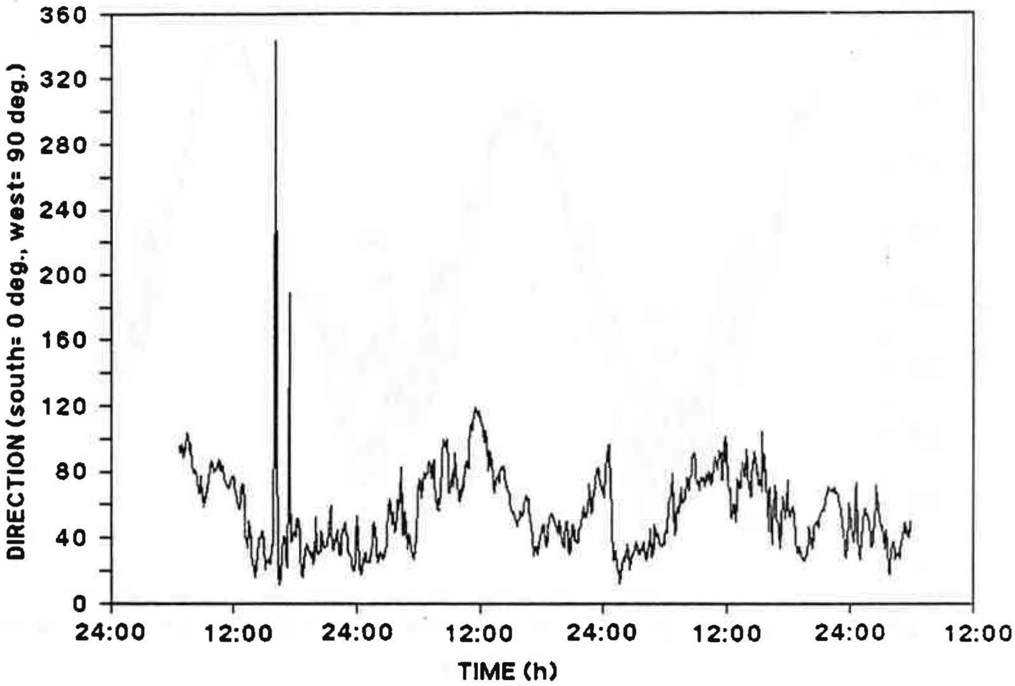

Fig. 6 Wind direction (July 6-9, 1988).

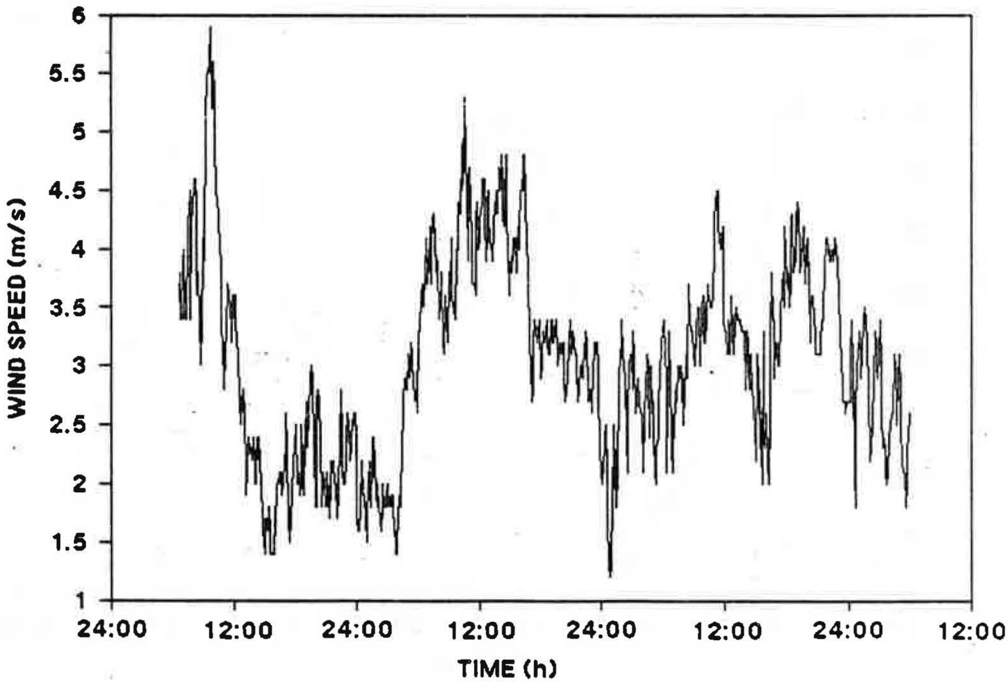

Fig. 7 Wind speed at 10 m height (July 6-9, 1988).

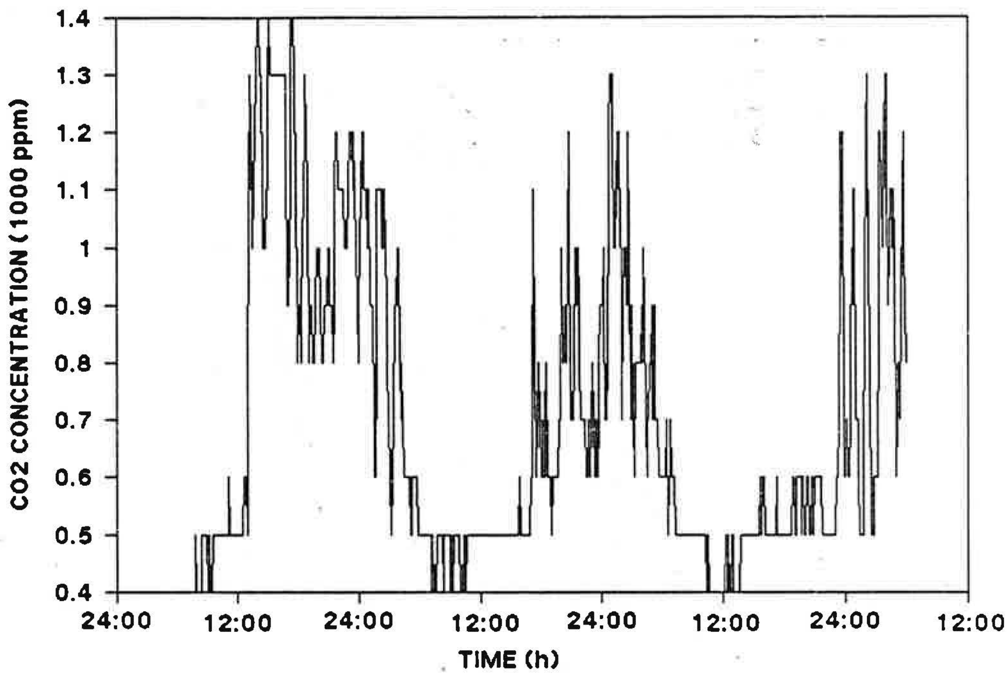

Fig. 8 CO_2 concentration with the ridge closed (July 6-9, 1988).

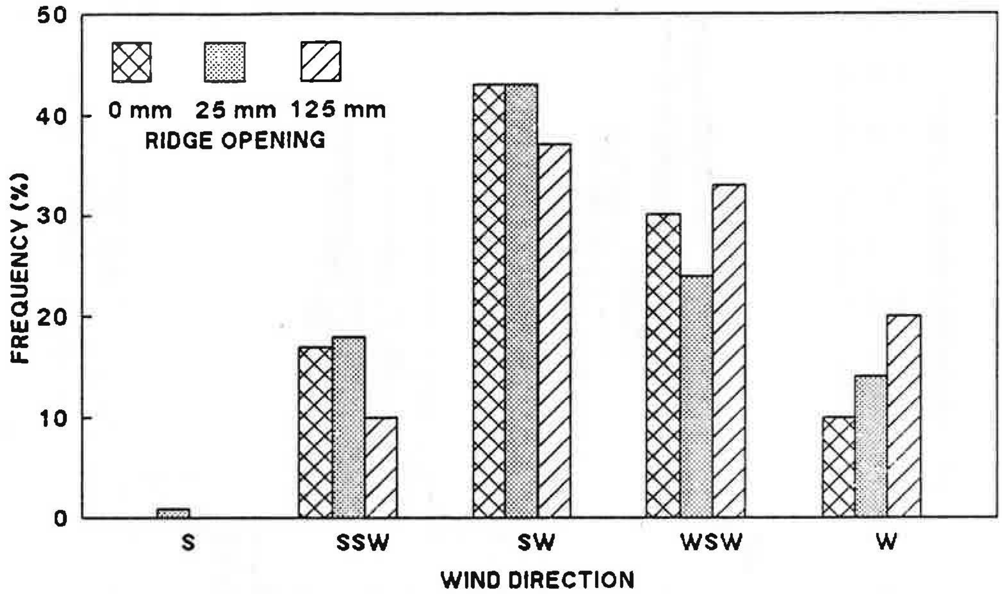

Fig. 9 Wind direction frequency distribution for ridge opening widths of 0, 25, and 125 mm.

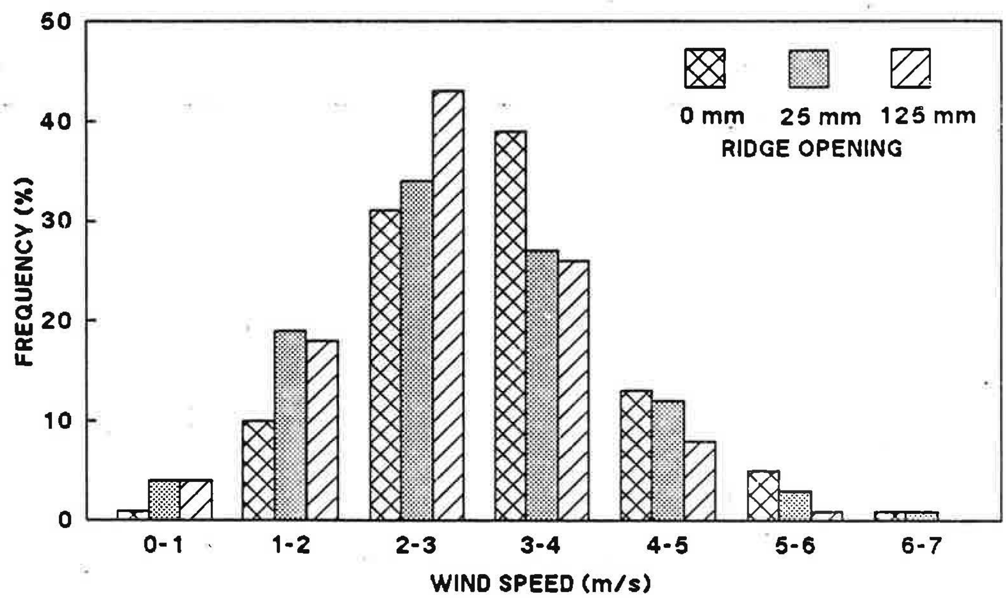

Fig. 10 Wind speed frequency distribution for ridge opening widths of 0, 25 , and 125 mm.

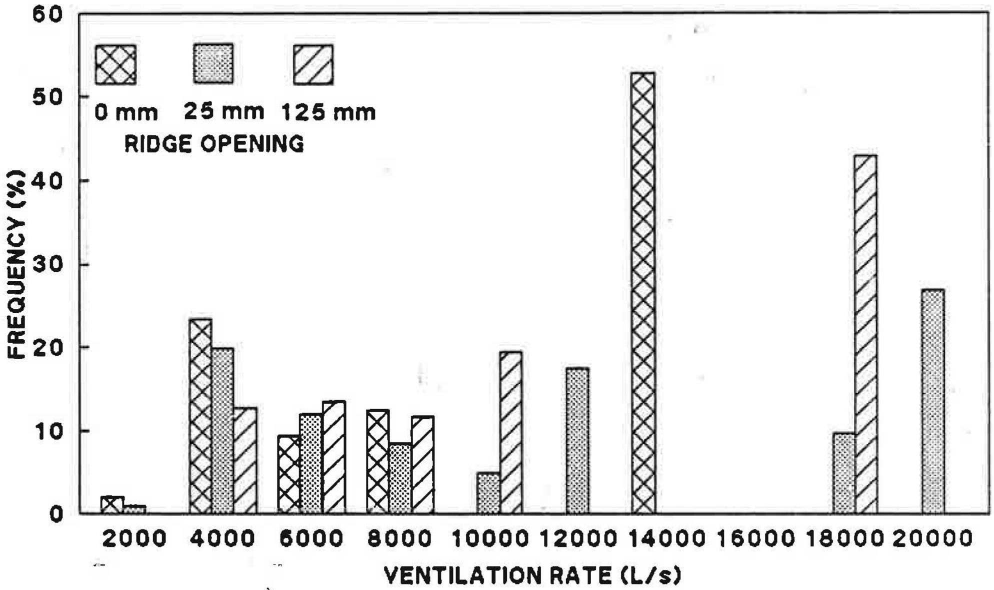

Fig. 11 **Calculated ventilation rate frequency distributions for ridge opening widths of 0, 25, and 125 mm.**