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A MODEL STUDY OF WIND DIRECTION EFFECTS ON AIRFLOW PATTERNS IN NATURALLY VENTILATED SWINE BUILDINGS UNDER ISOTHERMAL CONDITIONS

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ABSTRACT

Smoke was used in a wind tunnel to visualize three dimensional airflow patterns inside a scale model of a naturally ventilated barn with gable roof and sloped ceilings. The design parameters studied were: 1) opening angle of rotating doors in the sidewalls; 2) centre versus side alley layout; 3) doors open on only one vs. two sides of the barn; 4) solid vs. partially open dividing wall at the building midlength; 5) ridge opening width; and 6) addition of openings in the barn endwalls. Each building configuration was tested with the building oriented at 0°, 30°, 60° and 90° to the wind direction. Airflow patterns were observed and recorded on video tape. The optimum ventilation patterns were obtained for winds perpendicular to the building length. For parallel winds, the addition of windows in the end wall reduced the size of stagnant air zones inside the barn.

INTRODUCTION

Agricultural buildings are used to provide a controlled environment for livestock. The ventilation system should provide an acceptable temperature level, supply enough fresh air to satisfy the needs of the animals, and remove moisture, odours and gaseous contaminants generated within the building. Control of air movement inside the barn is also required to produce specific comfort zones which improves pen cleanliness. The study of air movement inside a barn can help to determine the performance of the ventilation system used.

A 1:20 scale model of a naturally ventilated swine finishing barn (similar to that shown in Canada Plan Service (CPS) plan M-3433) with a sloped ceiling was built and tested in a wind tunnel in order to observe airflow patterns under isothermal conditions.

LITERATURE REVIEW

Reynold's Analogy

Pattie and Milne (1966) and Timmons (1984) stated that air flow patterns will behave in a similar fashion above a certain threshold Reynold's number. The Reynold's analogy provides for dynamic similarity when using a scale model.

Ogilvie and Boyd (1985) used the building length as a reference dimension for their 1:10 and 1:25 scale models. They concluded that it is suitable to use scale models to simulate ventilation parameters in naturally ventilated barns under isothermal conditions, i.e. when the difference in temperature between the inside and the outside of the model is negligible.

Choinière et al. (1988b) suggested a threshold Reynold's number of 5400 using sidewall height as a reference dimension for a 1:20 scale model.

Mitchell and Ross (1977) and Ström (1987) studied isothermal airflow patterns for two-dimensional models of naturally ventilated barns with gable roofs. Choinière et al. (1988b) similarly studied the effect of sidewall openings and solid pen fronts (centre alley). Kelly et al. (1986) studied three-dimensional models of calf houses using a water table technique. It was decided to extend the two-dimensional work reported by

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Choinère et al. (1988b) to three dimensions in order to consider wind direction effects on airflow patterns in a naturally ventilated swine barn.

OBJECTIVES

A 1:20 scale model of a naturally ventilated swine barn was tested in a wind tunnel in order to:

1. observe three dimensional airflow patterns inside the model for different wind angles of incidence;

2. determine the effect of different structural modifications such as the addition of a cross-wall at midlength, and endwall windows; and

3. determine building orientation recommendations in relation to the prevailing wind direction.

METHODS AND PROCEDURES

The model was a 1:20 geometric reduction of a naturally ventilated grower-finisher barn with a sloped ceiling similar to that shown in CPS plan M-3433 (Figure 1). It was constructed of 5-mm thick plexiglass and attached to a black wooden base on a turntable. Adjustable rotating doors were installed in the sidewall openings of the model.

Wind Tunnel

An open-circuit wind tunnel with a working section of 2.4 m X 1.83 m was built using a wood frame and plywood sheeting (Figure 2). The tunnel was composed of 4 sections. The first contained airflow straighteners and blocks to create the required airflow conditions in the working section. The working section was next and included glass windows and contained the model itself. A light source was located in the third section while the fan housing was located in the fourth.

The tubeaxial fan was powered by a 5.6 kW motor equipped with an ammeter for monitoring the power input. Fluctuation in the power supply resulted in minor variation of the fan speed.

Wind Tunnel Calibration

Davenport (1960) used the power law (Eq.1) to describe a wind profile over an open country field:

$$\frac{Vz}{Vzg} = \left(\frac{Z}{Zg}\right)^E \quad \ldots\ldots\ldots\ldots (1)$$

where V_z is the mean wind speed at any given height Z, and V_{zg} is the maximum free wind velocity which occurs at height Z_g, typically 300 to 600 m. The constant E is called the topographical roughness coefficient. In this study, E = 0.17 was selected to match the conditions tested by Ogilvie and Boyd (1985) for an open field situation.

To reproduce a wind profile similar to that over an open field, a rough topographical zone was created by placing various wooden or concrete blocks and pieces of cloth on the floor of the tunnel upstream of the model. Windbreak fences were also installed near the air flow straighteners to reduce the air velocity below the reference height (0.5 m). Air flow straighteners were added at the tunnel entrance to eliminate any rotational flow. Air velocity measurements were made using a hot wire anemometer.

For a 1:20 scale model, the standard reference elevation of 10 m above the surface used by climatological stations is equivalent to 0.5 m above the floor of the wind tunnel. The air velocity at this location was used as the reference velocity in order to compute the Reynold's number.

Observation Techniques

A smoke generator (MDG Model 2000) was used to observe the air flow patterns. With this generator, dense, white, odourless, non-toxic smoke, propelled by CO_2 under pressure, was introduced into the model interior through five perforated copper pipes. Lighting and video equipment were then used to record the smoke patterns.

Reynold's Analogy

Preliminary tests were performed using wind speeds from 0.9 to 2.0 m/s in the wind tunnel. The airflow patterns in the model were not affected by this variation of velocity indicating that the fully turbulent state was achieved (Iwaniw et al., 1986).

All subsequent tests were performed using a reference wind speed of 1.13 m/s. The computed Reynold's number for this wind speed was 9800 using the wall height as the reference dimension. This result was above the threshold Reynold's number of 5400 used by Choinière et al. (1988b) for the previous two dimensional studies.

Description of Variables

Table I indicates the tests performed in relation to six structural variables: 1) opening angle of rotating sidewall doors; 2) centre versus side alley layout; 3) sidewall doors open on one versus two sides of the barn; 4) solid versus partially open wall at the building mid-length; 5) ridge opening width; and 6) the use of openings in the barn endwalls. Each of these variables was studied for four wind angles of incidence relative to building length: 0°, 30°, 60° and 90°. A wind parallel to the building length would thus be referred to as wind at 0°.

Centre versus side alley layouts were compared, as both are used in Ontario. The alley partitions (pen fronts) were solid. The addition of a wall across the building at midlength was tested to simulate a building with two rooms. Openings in the endwall were tested as a means of eliminating stagnant air zones noted near the windward end of the building particularly when wind was parallel to the building length. In order to verify some possible winter management practices (Choinière et al. 1988a), doors open on just the leeward or on both sides of the barn were tested.

Observations included noting general air flow patterns in the model, the air inlet and outlet zones, and the stagnation and mixing zones.

Airflow rates were not measured quantitatively. Video recordings were made using one camera for the top view and another for the side view. The rate of decay of the smoke in the model after the smoke generator was stopped was noted and assumed to be a qualitative measure of the ventilation rate.

RESULTS AND DISCUSSION

Figures 3 through 10 show the general airflow patterns in plan view at ceiling level and at pen level, and in elevation view for the open ridge and for one or more cross-sections along the length of the building. On each drawing, the broad arrows show the general air movement while the narrow arrows indicate the streamlines. Dotted areas indicate zones of low circulation or stagnation.

Doors Open on Both Sides

Figure 3 shows results for a model of a typical barn with a 150 mm wide ridge (full scale) and doors open on both sides.

For wind perpendicular to the building length air entered by the windward doors and followed the ceiling towards the leeward doors. However, recirculation occurred near floor level where air moved from the leeward side to the windward side. The ridge acted as an exhaust over its entire length. After stopping the smoke generator, smoke decay appeared uniform throughout the model except in the regions close to the centre alley partitions. Similar observations were noted by Choinière et al. (1988b).

For wind at 60°, some horizontal rotational movement occurred at both ends of the building but streamlines near the center of the building did not appear to be affected by this rotational movement. A stagnant zone was observed at the windward end of the model.

As shown by Aynsley et al. (1977), Hellickson et al. (1983) and Vickery et al. (1983), wind angle of incidence affects the external pressure distribution around a naturally ventilated building and determines whether an opening is an air inlet or outlet.

The negative pressure zone on the leeward side of the model next to the windward end was a major outlet zone. Air exhaust through the ridge was not as uniform as with wind at 90°.

The horizontal rotational movement observed for wind at 60° was amplified when wind was at 30°. Some air entered by the leeward doors near the leeward end and the stagnant zone near floor level at the windward end was larger.

For wind parallel to the barn, air entered both sides of the building towards the leeward end, moved lengthwise and exhausted towards the windward end. The ridge acted as an inlet near the leeward end and as an exhaust near the windward end.

The rate of smoke decay generally was lower for wind angles of 0° and 30° as compared to 60° and 90°, indicating that the efficiency of ventilation was lower for wind parallel to the building length. Vickery et al. (1983) reported similar results and showed that the airflow coefficient dropped severely for a naturally ventilated building when wind angles of incidence were below 30°.

Effect of Angle of Rotation of the Sidewall Doors

Previously, Choinière et al. (1988b), using a two-dimensional model, demonstrated that for winds perpendicular to the model sidewall door opening angles of rotation of 15°, 30° and 60° from vertical produced very similar primary airflow patterns inside.

In the present study, for all the conditions tested, there was no observable difference in the airflow patterns as a result of changing the door angle of rotation.

Effect of Central Versus Side Alley

Figure 4 illustrates airflow patterns observed for a side alley layout. The primary flow path was similar to results presented by Choinière et al. (1988b) using a model with no alley partitions, however here, some stagnant zones were observed in the alley areas. Otherwise airflow patterns were similar for either the centre or side alley layouts.

Effect of a Wall at Midlength of the Barn

The addition of a solid wall across the building at midlength simulated a building with two rooms (Figure 5). The general air patterns in each of the two rooms were similar to that observed in tests without the central wall (one room) for any given wind direction, however, the stagnation zones were generally larger in the leeward room as compared to the windward room. As well, the rate of smoke decay was considerably greater in the windward room indicating higher ventilation efficiency.

Effect of a Central Wall with Two Open Windows

As shown on Figure 6, the addition of two openings (windows) in the central wall did not change the general air flow patterns shown in Figure 5. However some air did move from the leeward room to the windward room for wind angles of 30° and 0°, which helped to reduce the stagnant zone in the leeward room.

Effect of Ridge Opening Width

Three ridge openings representing 0, 300, and 600 mm full scale were tested and compared with the standard ridge opening width of 150 mm.

Generally, the primary airflow patterns previously noted in Figure 3 were not influenced by ridge opening width. However, at floor level, the wider ridge opening reduced the stagnant zone at the windward end of the building.

Based on visual observations, the rate of smoke decay increased with the wider ridge openings, thus indicating an increase in the ventilation rate.

Effect of Ridge Open the Entire Length of the Building

A typical CPS design such as M-3433 shows the ridge closed at both ends of the building for a length of 2.4 m. Figure 8 shows that the airflow through the ridge was enhanced by leaving the ridge open to both extremities of the building. Observations indicated that in every case tested, having an open ridge for the entire length of the building decreased the size of the stagnant zone in the windward end of the building. As well, at the leeward end, the ridge acted as an exhaust more consistently as compared to the shorter ridge opening in which case air tended to pulse back and forth (Figure 3) i.e. entering and leaving the building. It should be kept in mind that this was under isothermal conditions representing summertime with doors open on both sides of the building. In summer time then, opening the ridge for its total length might help reduce the stagnant zone at the windward end, especially for wind parallel to the building length.

Addition of Windows in the Endwall

The addition of endwall windows did not change the airflow patterns for wind perpendicular to the building. However, as shown in Figure 9 and comparing with Figure 3, the airflow patterns at both ends of the building were affected for the three other wind directions tested and especially for 30° and 0°. With wind at 30°, the first two windward sidewall doors acted as air outlets. As well, the leeward endwall windows acted as outlets. For winds at 60° and 30°, a small amount of short circuiting was observed at the leeward end where air entered by the windward sidewall doors to exhaust directly by the endwall windows.

The addition of windows in the endwall generally increased the exhaust through the ridge especially for wind at 30° and 0°. A reduction or disappearance of the stagnant zones and a higher rate of smoke decay were observed as compared to without endwall windows.

In practice, the addition of endwall windows could help eliminate stagnant zones in the windward end of the building during warm weather.

Effect of Doors Open Only on the Leeward Side of the Barn

With this configuration, ventilation is accomplished only by the leeward doors and the ridge. The windward doors were closed and sealed to prevent infiltration.

Figure 10 shows that for wind at 90°, air entered near the mid-length of the barn and exhausted at both ends. The ridge acted as an exhaust over its entire length. Wind directions other than 90° caused a horizontal rotational air movement from the leeward end to the windward end. The windward end of the ridge acted as an exhaust while the leeward end was not consistent and at times acted as either an inlet or exhaust.

Effect of Ridge Opening Width with Only Leeward Doors Open

The same airflow patterns were observed for both ridge opening widths, however, observations indicated that the rate of smoke decay was higher with the wider ridge opening.

CONCLUSIONS

A scale model of a naturally ventilated swine finishing building was used to study the effect of structural modifications and wind angle of incidence on interior airflow patterns. The results showed that:

1. Wind perpendicular to the building (90°) provided the most uniform airflow patterns along and across the building.

2. Wind at 0°, 30° and 60° created horizontal rotational air movements within the building.

3. Airflow patterns observed at the floor level were recirculation patterns only.

4. The vertical airflow pattern over a barn cross-section varied along the length of the building for winds other than at 90°.

5. With no endwall windows, stagnant zones were always observed at the windward end for winds at 0°, 30° and 60°.

6. The opening angle of the sidewall rotating doors did not greatly influence the airflow patterns.

7. Centre versus side alley layouts, with solid pen fronts, had limited influence on the air flow patterns.

8. The addition of a wall across the midlength of the model created similar airflow patterns in the two rooms. Observations showed that the rate of smoke decay was greater in the windward room as compared to the leeward.

9. The addition of two windows in this central wall reduced the stagnant zones observed in the leeward room.

10. The ridge opening width had a limited influence on the primary airflow patterns. Observations indicated that the rate of smoke decay increased with the use of wider ridge openings.

11. Opening the ridge the total length of the building as opposed to having it closed for a short distance at each end reduced the size of the stagnant zone at the windward end.

12. The addition of two endwall windows reduced or eliminated the stagnant zones in the windward end especially for wind at 0° and 30°.

13. A building could be ventilated using only leeward doors and a continuous ridge opening. A higher rate of airflow would be expected using wider ridge openings.

PRACTICAL APPLICATIONS

Choinière et al. (1987b and 1988a) demonstrated that the wind angle of incidence to the building had a significant effect on the thermal performance of a naturally ventilated swine building during moderate and cold weather. They recommended that the optimum building orientation should be perpendicular to the prevailing winds. Based on the present study, varying the wind angle of incidence from 60° to 90° did not create major changes in the air flow patterns.

The orientation of a building should be a compromise between wind angles of incidence over the entire year. Figure 11 shows the percentage of time wind comes from a particular direction during the full year and for the summer period only (June, July and August) for Eastern Ontario (Kemptville). During a given year, the wind direction is expected to be between SW and NW 53% of the time and between SE and NE 23% of the time. Thus, the wind angle of incidence for a North-South oriented building would be greater than 45° for 75% of the time. Considering the summer period only, this would be 72% of the time.

Thus for Eastern Ontario, a North-South building orientation would be preferred.

Two Adjacent Naturally Ventilated Rooms in the Same Building

It is recommended that the livestock room requiring the higher ventilation rate be located at the predominantly windward end of the building. Based on Figure 11 for Eastern Ontario for a North-South building, this would be the south end.

Ridge Opening Width

Controversy exists between promoters of wide ridge openings (Meyer and Goetsch, 1984), users of buildings without ridge openings (Anon, 1984, Barrie and Smith, 1986) and users of buildings with limited ridge openings (Bruce 1979, Choinière et al. 1988c).

Based on the scale model results, the widest ridge opening (representing 600 mm in a full-scale barn) provided the greatest ventilation rate, however this is for isothermal conditions and in practice would not necessarily lead to significantly lower temperatures in a barn. Observations, with wind direction parallel to the building length, showed that the addition of two windows in the endwall of the building, used with a typical ridge opening width (150 mm full scale), reduced the stagnant zones as much as did increasing the ridge opening width to 600 mm (full scale).

For warm weather, no data are presently available on the thermal performance of naturally ventilated swine buildings using various ridge opening widths.

Recommendations

1. For Eastern Ontario, naturally ventilated buildings should have a North-South orientation.

2. With two or more adjacent naturally ventilated rooms, the one requiring the larger ventilation rate should be located at the predominantly windward end of the building.

3. The addition of two windows in the endwall is recommended, especially for hot weather conditions.

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TABLE I. COMBINATION OF PARAMETERS TESTED IN THE WIND TUNNEL

Test Categories	Parameters				
	Wind angle relative to building length (°)	Sidewall door opening angle relative to vertical (°)	Ridge opening (full scale) (mm)	Alley location	Endwall windows
DOORS OPEN BOTH SIDES	90	15	150	C*	WC**
	90	30	150	C	WC
	90	60	150	C	WC
	60	60	150	C	WC
	60	30	150	C	WC
	60	15	150	C	WC
	30	15	150	C	WC
	30	30	150	C	WC
	30	60	150	C	WC
	0	60	150	C	WC
	0	30	150	C	WC
	0	15	150	C	WC
	0	30	150	S*	WC
	30	30	150	S	WC
	60	30	150	S	WC
	90	30	150	S	WC
SOLID CENTRE WALL	0	30	150	C	WC
	30	30	150	C	WC
	60	30	150	C	WC
	90	30	150	C	WC
CENTRE WALL WITH OPENINGS	90	30	150	C	WC
	60	30	150	C	WC
	30	30	150	C	WC
	0	30	150	C	WC

TABLE I. COMBINATION OF PARAMETERS (CONT'D)

	Wind angle relative to building length (°)	Sidewall door opening angle relative to vertical (°)	Ridge opening (full scale) (mm)	Alley location	Endwall windows
RIDGE OPENING EFFECT	0	30	0	C	WC
	30	30	0	C	WC
	60	30	0	C	WC
	90	30	0	C	WC
	90	30	300	C	WC
	60	30	300	C	WC
	30	30	300	C	WC
	0	30	300	C	WC
	0	30	600	C	WC
	30	30	600	C	WC
	60	30	600	C	WC
	90	30	600	C	WC
RIDGE OPEN FOR ENTIRE LENGTH OF THE BUILDING	0	3	150	C	WC
	30	30	150	C	WC
	60	30	150	C	WC
	90	30	150	C	WC
END WALL WINDOWS	90	30	150	C	WO
	60	30	150	C	WO
	30	30	150	C	WO
	0	30	150	C	WO
LEEWARD DOORS OPEN 30°, WINDWARD DOORS CLOSED	90	0/30	150	C	WC
	60	0/30	150	C	WC
	30	0/30	150	C	WC
	0	0/30	150	C	WC
	90	0/30	300	C	WC
	60	0/30	300	C	WC
	30	0/30	300	C	WC
	0	0/30	300	C	WC

C: Centre alley, S: side alley

** WC: Windows closed, WO: windows open

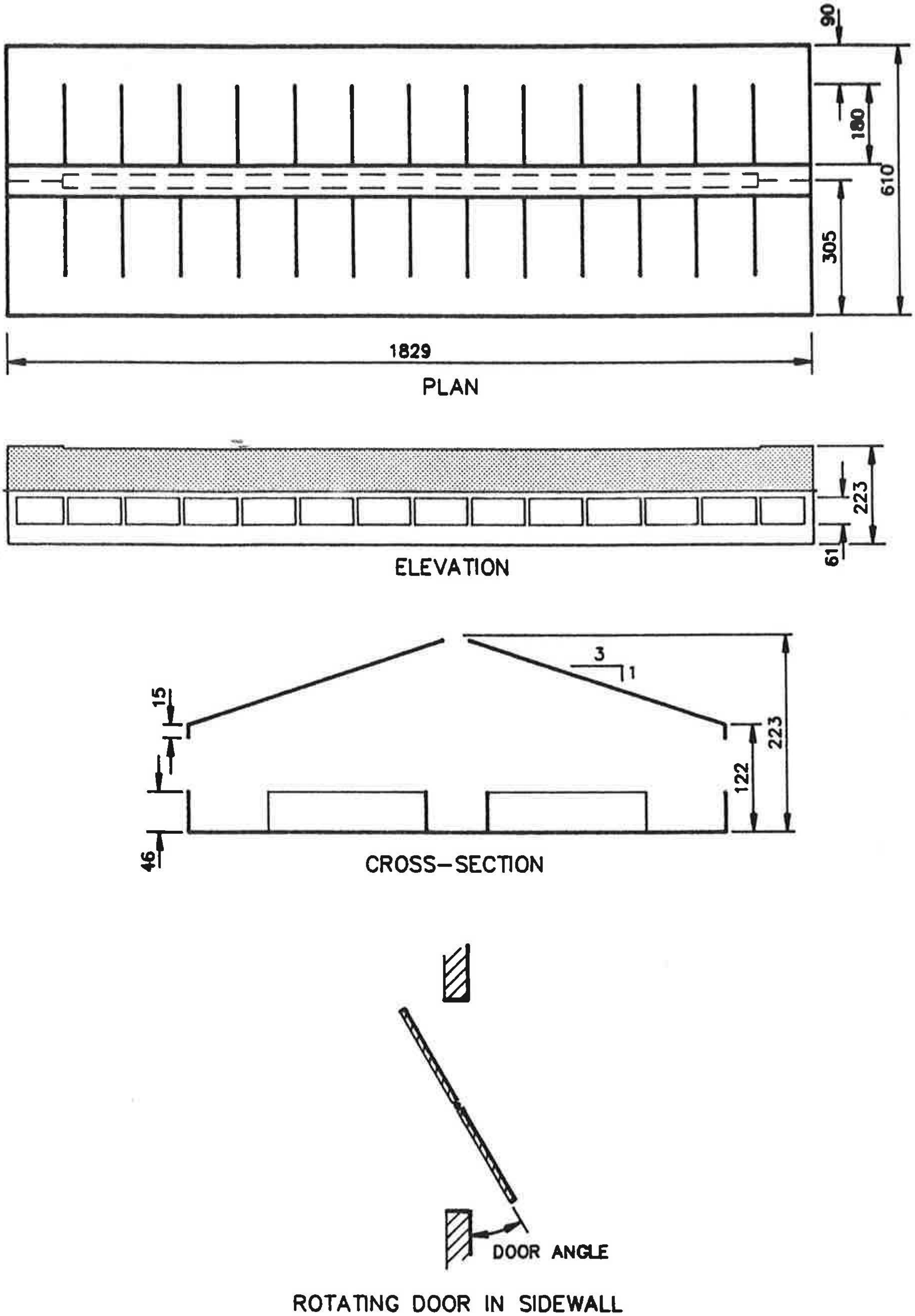
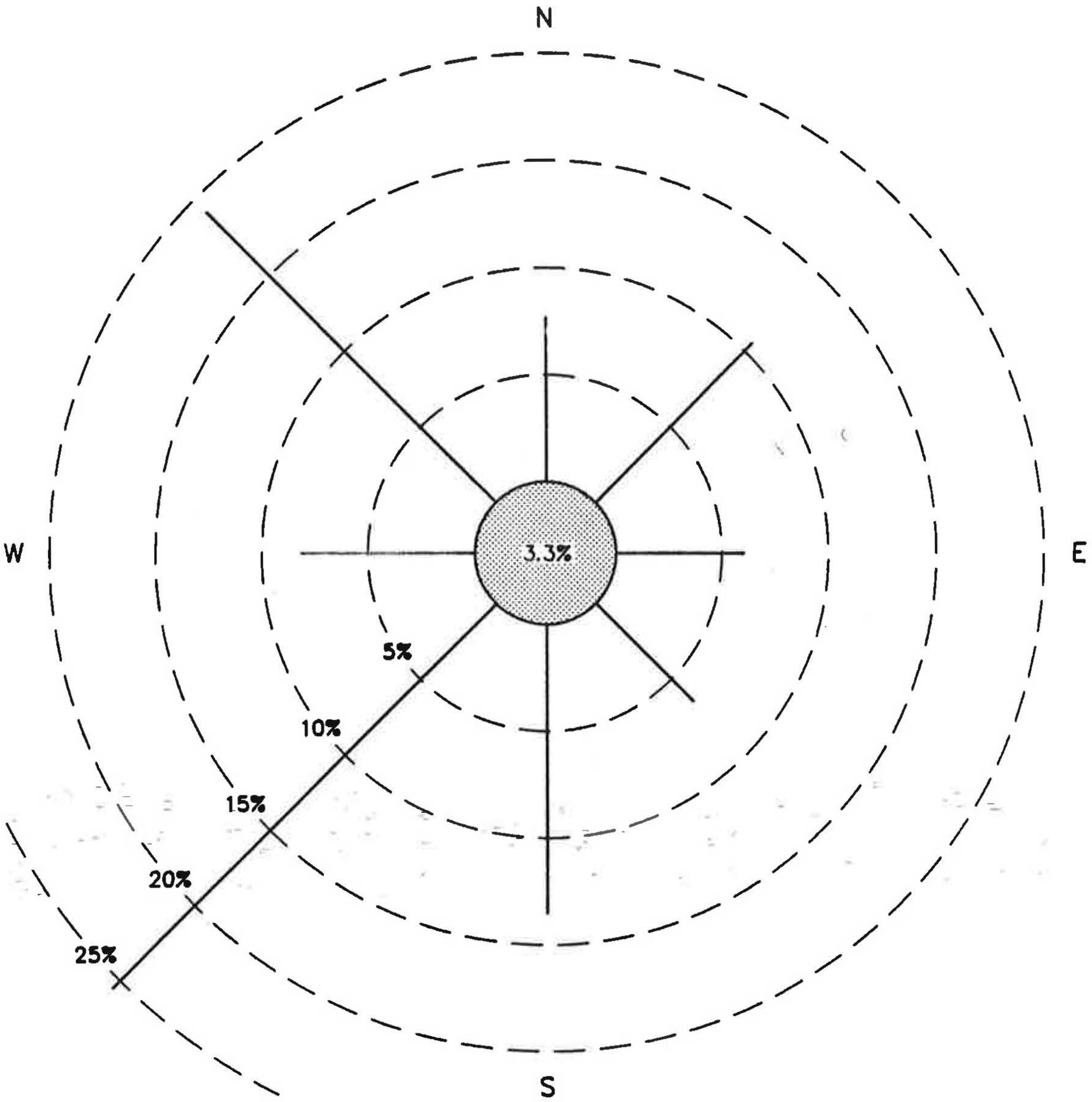


Fig. 1. 1:20 scale model of a naturally ventilated swine finishing barn (all dimensions are in mm).



MEAN WIND PERCENTAGE FREQUENCY

	N	NE	E	SE	S	SW	W	NW	CALM
YEAR	7.7	10.6	5.8	6.4	13.6	25.4	8.1	19.1	3.3
SUMMER (JUNE–JULY–AUGUST)	6.8	6	3.5	7.9	17.1	32.3	6.2	16.5	3.7

Fig. 11. Wind rosette - mean wind percentage frequencies on yearly basis (1970-80), for Eastern Ontario (Kemptville).

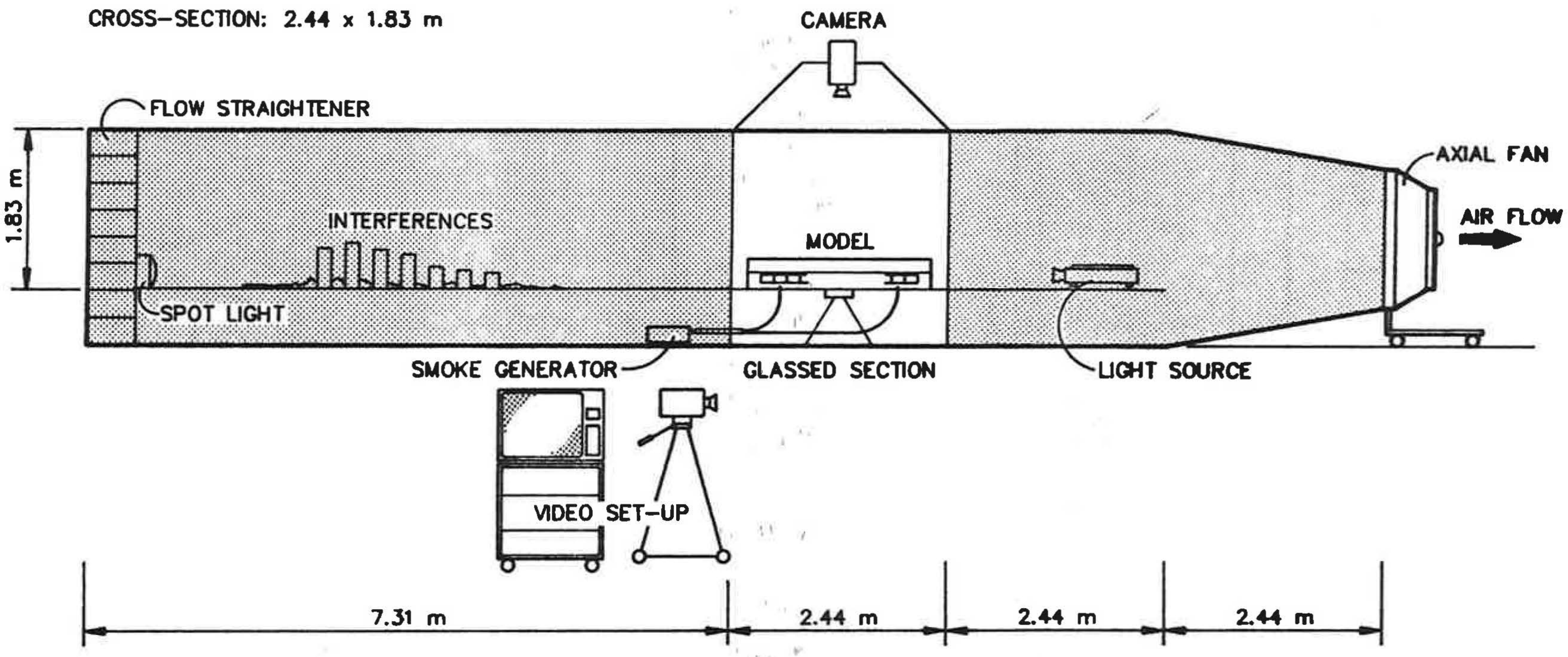


Fig. 2. Schematic diagram of wind tunnel

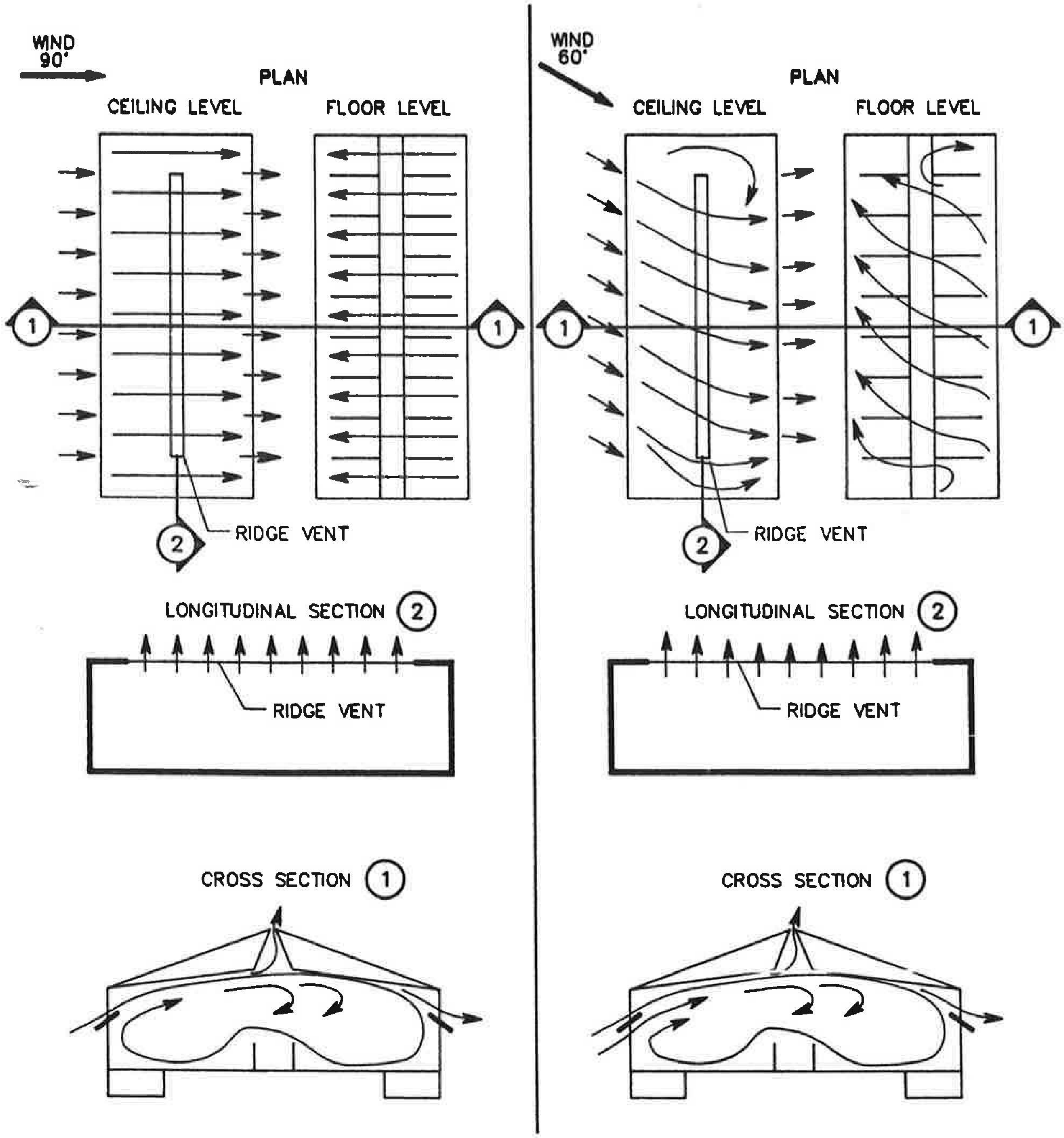


Fig. 3a. Airflow patterns with standard ridge opening (150 mm full scale), doors open (30°) both sides, wind at 90° and 60°.

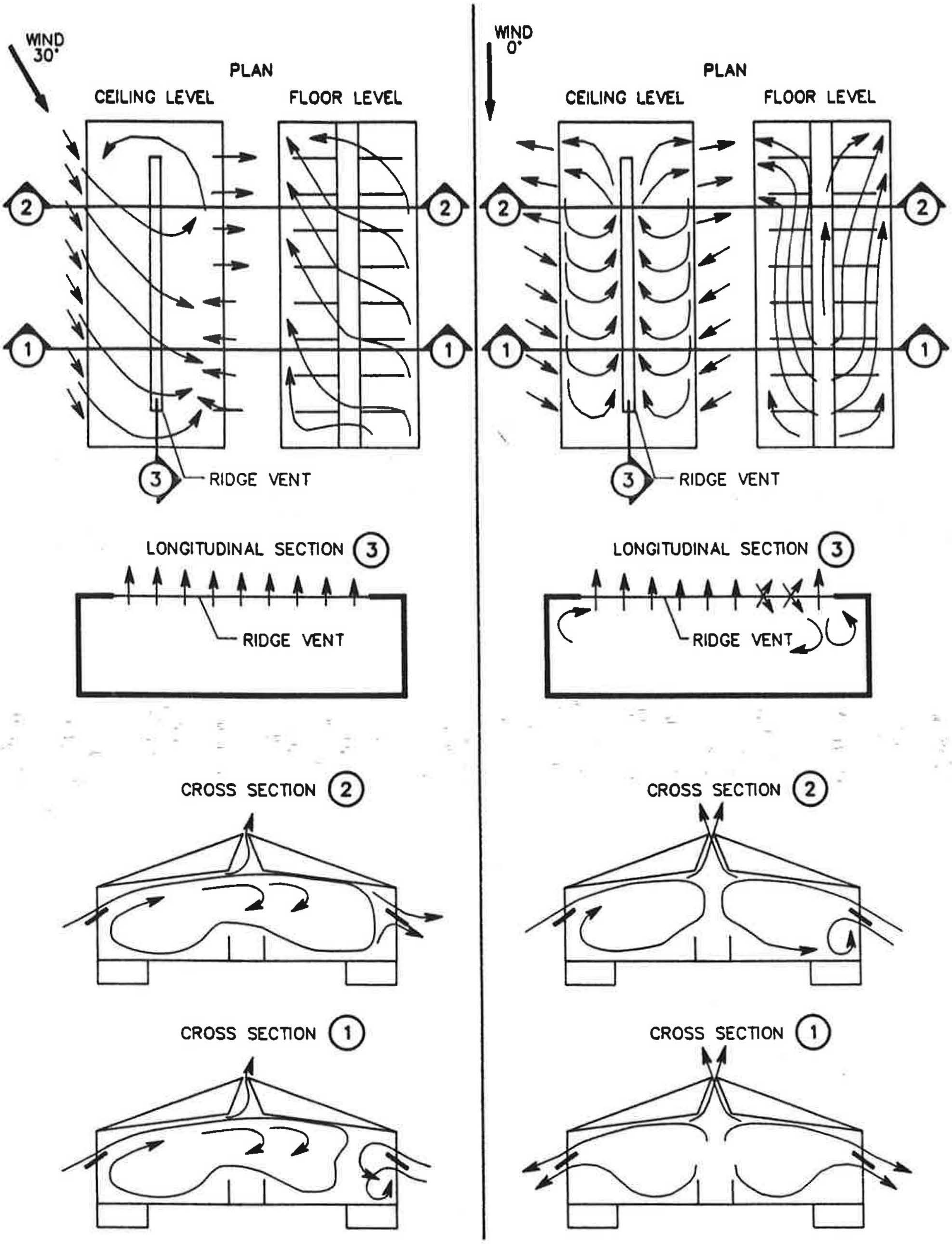


Fig. 3b. Airflow patterns with standard ridge opening (150 mm full scale), doors open (30°) both sides, wind at 30° and 0°.

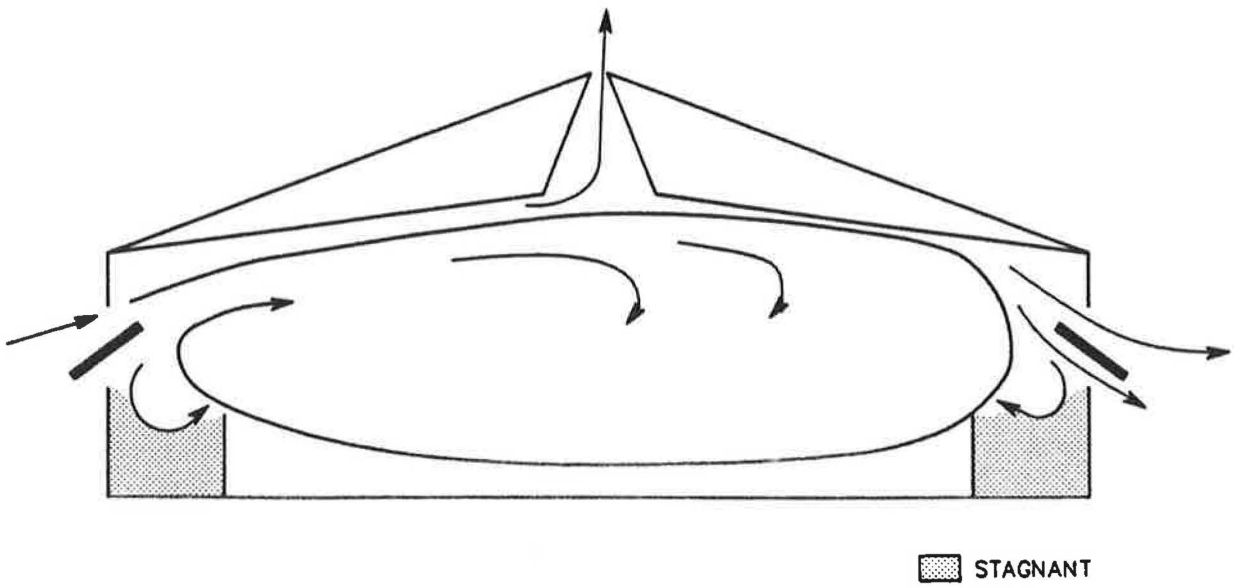


Fig. 4. Airflow patterns with side alley layout, solid pen fronts, wind angle of incidence 90°.

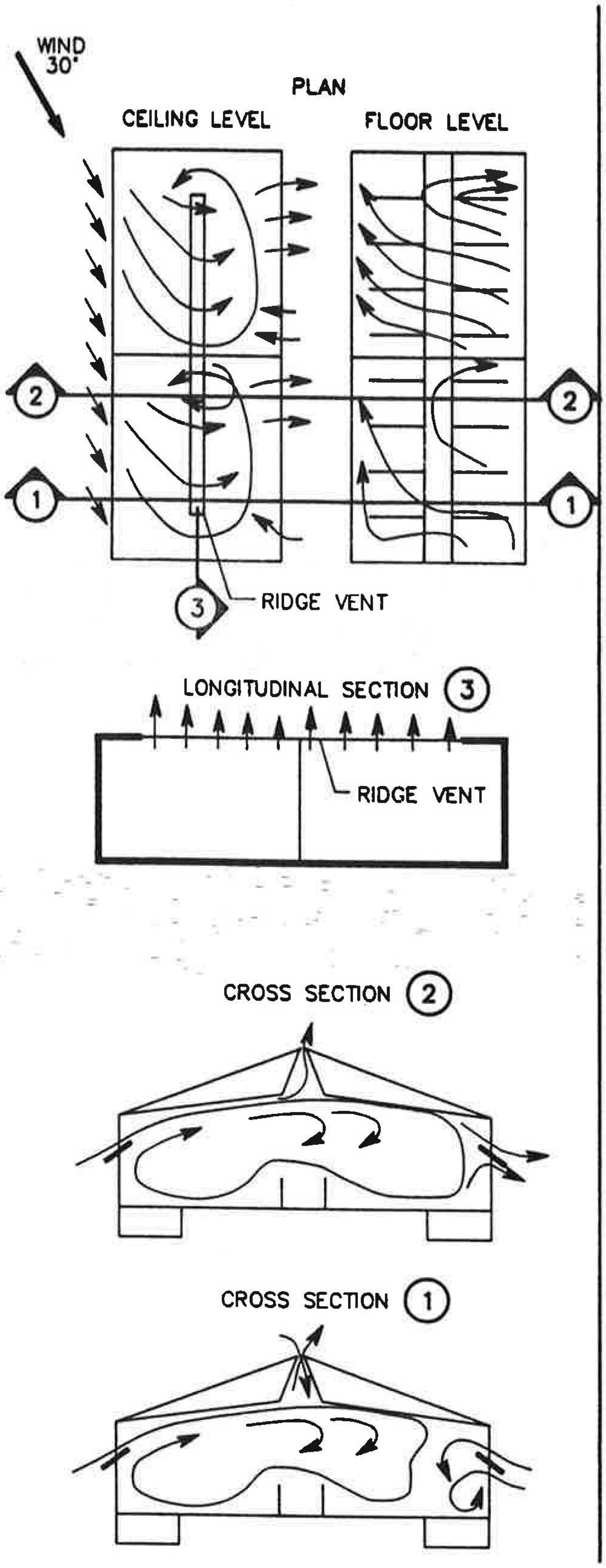


Fig. 5. Effect of solid wall at midlength, wind at 30° and 0°.

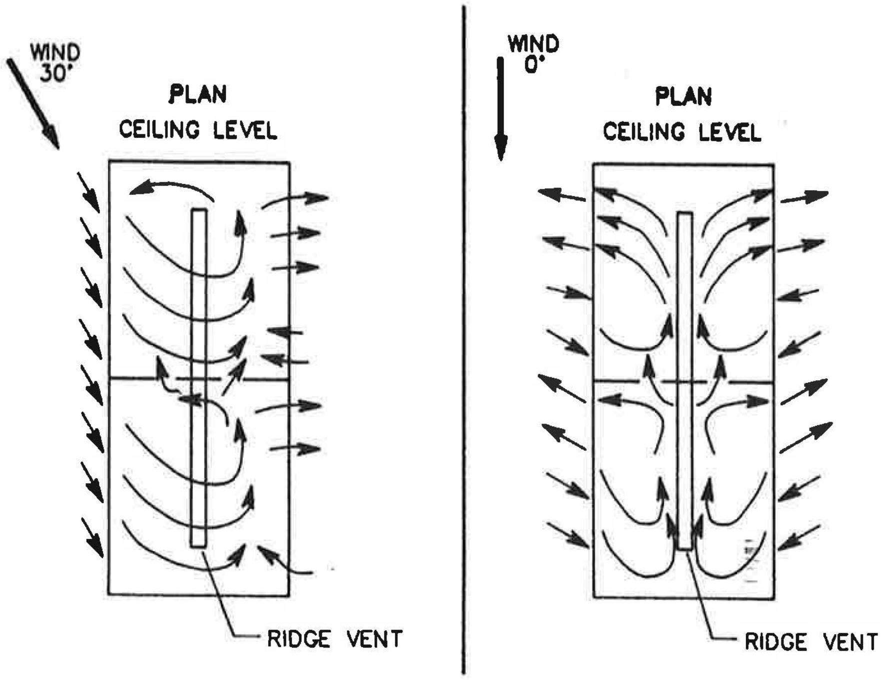


Fig. 6. Effect of openings in cross-wall at building midlength.

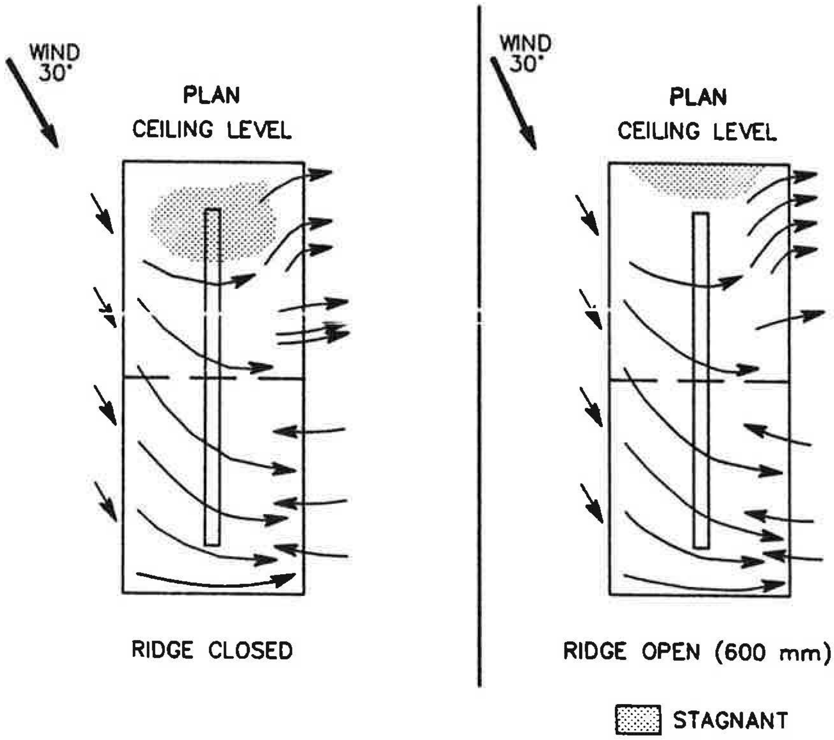


Fig. 7. Effect of ridge opening width.

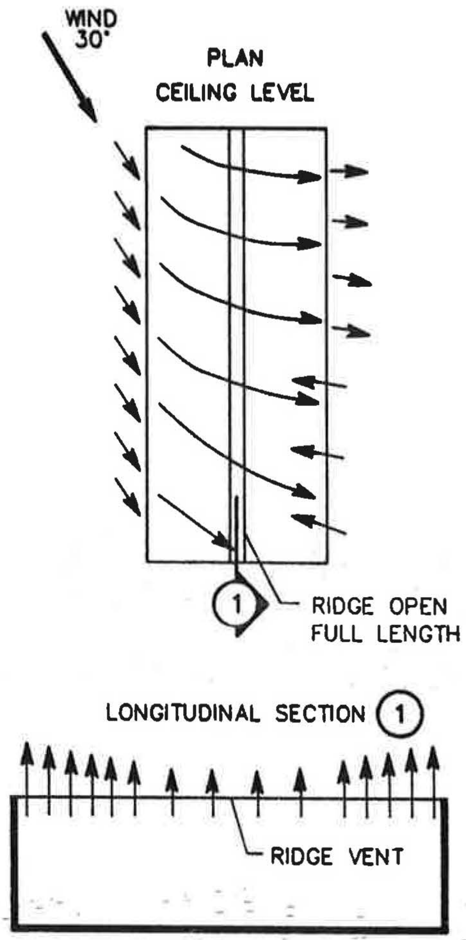


Fig. 8.   Effect of ridge opening length.

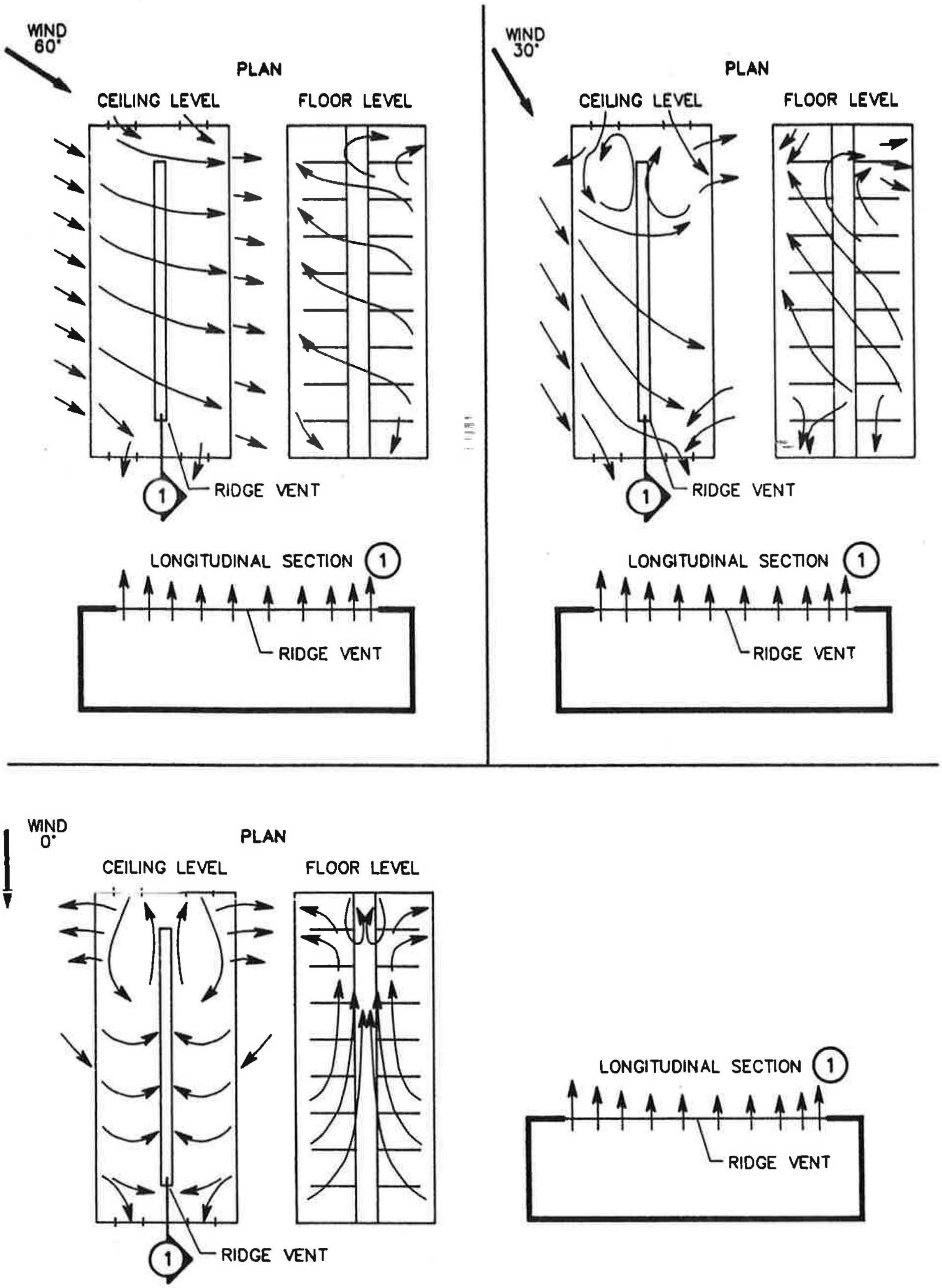


Fig. 9. Effect of openings in endwalls, wind at 60°, 30° and 0°.

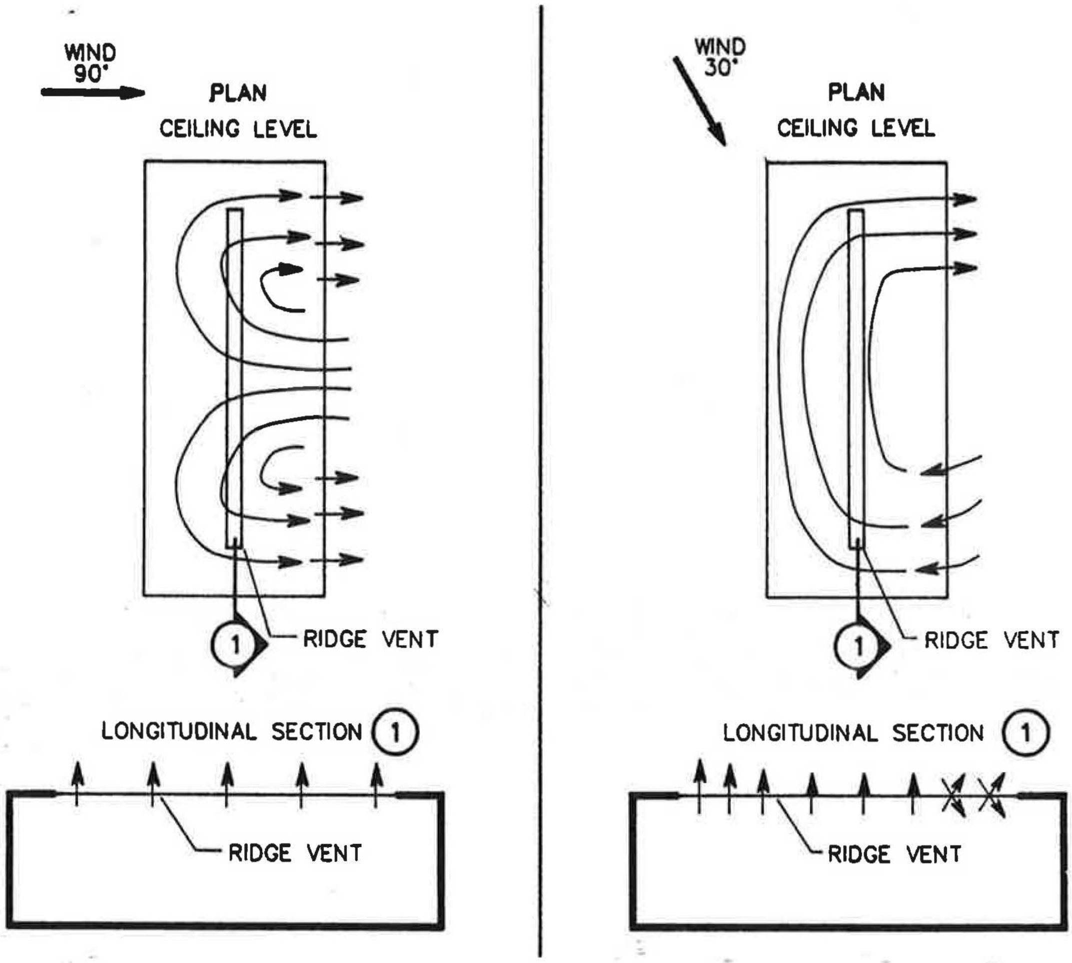


Fig. 10. Effect of doors open only on leeward side.