A wind tunnel study of wind direction effects on airflow patterns in naturally ventilated swine buildings

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Choinière, Y. and Munroe, J.A. 1994. **A wind tunnel study of wind direction effects on airflow patterns in naturally ventilated swine buildings**. Can. Agric. Eng. **36**:093-101. 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 one side versus two sides of the barn; 4) solid versus 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 degrees 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 zones of slow smoke dispersion inside the model.

Des essais de visualisation de la circulation de l'air à l'intérieur d'un modèle réduit en trois dimensions d'une étable ventilée naturellement ont été effectués dans une soufflerie à couche atmosphérique. Les paramètres étudiés furent: 1) l'angle d'ouverture des portes rotatives dans les murs; 2) allée centrale versus allées latérales; 3) ouvertures dans un versus les deux murs latéraux; 4) l'ajout d'un mur central de division avec ou sans ouvertures; 5) différentes largeurs de l'ouverture au faîte du toit; 6) l'addition d'ouvertures aux extrémités du modèle. Chaque modification au modèle réduit de base fut testée pour les directions du vent provenant en angle de 0, 30, 60, et 90 degrés. La circulation de l'air fut observée grâce à un système d'injection de fumée et enregistrée sur bande vidéo. C'était avec les vents perpendiculaires aux différents modèles réduits que la circulation de l'air fût généralement la plus uniforme. Pour les vents parallèles à la longueur du bâtiment, l'ajout de fenêtres aux extrémités a réduit considérablement les zones de dispersion lente de la fumée à l'intérieur des modèles réduits.

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, dust, and gaseous contaminants generated within the building. Control of air movement inside the barn is also required to produce specific comfort zones for livestock. Observation of the air movement inside a barn can help to determine the performance of the ventilation system used.

Information on three-dimensional air flow patterns in wind ventilated buildings is not readily available. It was therefore decided to extend the two-dimensional work reported by Choinière et al. (1988b) to three dimensions to consider wind direction effects on airflow patterns in a naturally ventilated barn. To do this, a 1:20 scale model of a naturally ventilated swine finishing barn with a sloped ceiling and similar to that shown in Plan M-3433 of the Canada Plan Service (1990) was constructed and tested in a wind tunnel. Since airflow patterns during the summer were of most interest, tests were conducted under isothermal conditions.

LITERATURE REVIEW

Ogilvie and Boyd (1985) studied the effectiveness of natural ventilation with 1:10 and 1:25 scale models of modified open-front barns. 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.

Mitchell and Ross (1977), Ström (1987), and Choinière et al. (1988b) studied isothermal airflow patterns for two-dimensional models of naturally ventilated barns with gable roofs. The latter studied the effects of sidewall opening configuration and interior pen partitions on air flow patterns inside a typical gable roofed naturally ventilated swine building. Using a 1:20 scale model in a wind tunnel under isothermal conditions, they determined that there was no significant difference in two-dimensional airflow patterns for Reynold's Numbers above 5400. The only three-dimensional study for a similar type of building was by Kelly et al. (1986), who used a water table technique to simulate airflows in calf houses.

OBJECTIVES

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

1. observe three-dimensional airflow patterns inside the model for different wind angles;
2. determine the effect on airflow patterns by sidewall door opening angle, ridge opening width, endwall

windows, the addition of a cross-wall at midlength, and sidewall doors open on the leeward side only.

METHODS AND PROCEDURES

The model used was a 1:20 geometric reduction of a naturally ventilated grower-finisher barn with a sloped ceiling similar to that shown in Plan M-3433 (Canada Plan Service 1990) (Fig. 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 was constructed using a wood frame and plywood sheeting (Fig. 2). The tunnel was composed of four sections. The first contained airflow straighteners and wooden blocks to create interference in order to simulate a natural wind profile representative of open country. The second section contained the model itself and included glass windows for visual observations. A light source was located in the third section and the fan housing was located in the fourth.

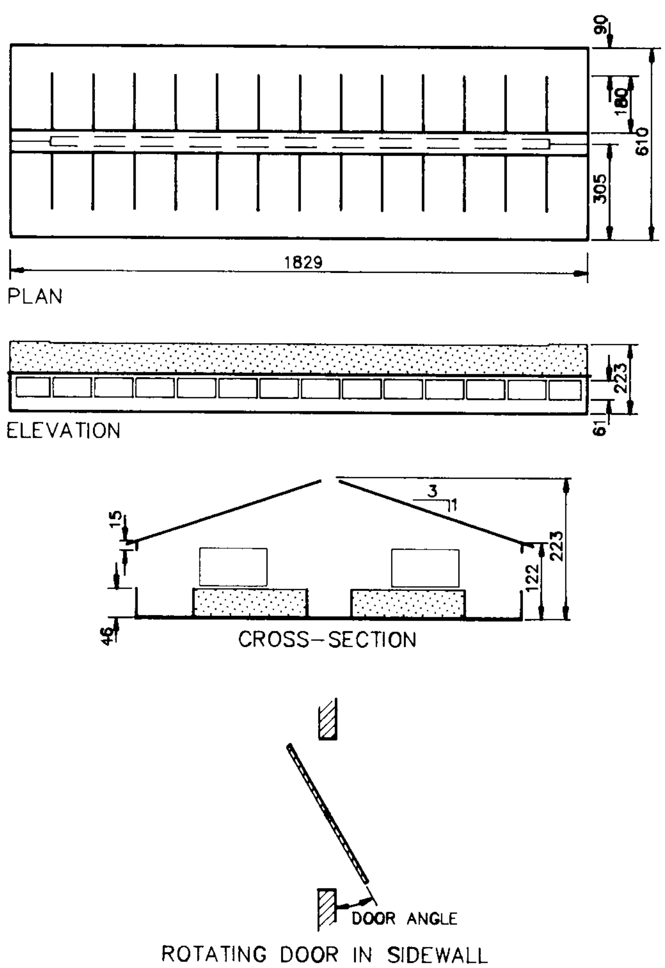

Fig. 1. 1:20 scale model of a naturally ventilated swine finishing barn (all dimensions are in mm).

Wind tunnel calibration

To simulate wind effects on buildings, it is necessary to reproduce the natural wind conditions inside the wind tunnel. Davenport (1982) and Plate (1982) described the necessary criteria to calibrate a wind tunnel. A power law (Eq. 1) is commonly used to describe a wind profile over open country (Davenport 1960, 1982; Aynsley et al. 1977).

$$\frac{V_z}{V_{zg}} = \left(\frac{Z}{Z_g}\right)^E \qquad (1)$$

where:

V_z = mean wind speed at a given height Z,
V_{zg} = maximum free wind speed which occurs at height Z_g (typically 300 to 600 m), and
E = topographical roughness coefficient.

In this study, values of E between 0.17 and 0.19 were selected to match the conditions for an open field situation. This range of E was recommended and used by Aynsley et al. (1977) and Plate (1982).

According to Aynsley et al. (1977) and Davenport (1982), the turbulence intensity, I, is defined as:

$$I = \frac{\sigma_{Vz}}{V_z} \qquad (2)$$

where σ_{Vz} = standard deviation of the wind speed at a height Z. In this study, the turbulence intensity was calculated for wind parallel to the wind tunnel length. Values of the turbulence intensity were within a range of 16 to 20% in the region of 50 to 500 mm above the floor of the wind tunnel. This range was found acceptable by Davenport et al. (1977), Handa (1979), and Plate (1982).

Wind speed measurements were made using hot wire anemometry and differential pressure systems. 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 wind speed at this location was used as the reference velocity when computing Reynold's number.

Reynold's analogy

Pattie and Milne (1966), Timmons (1984), and Bottcher et al. (1986) stated that for a given building, airflow 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 under isothermal conditions.

From their studies of natural ventilation for residential buildings, Cermak et al. (1984) reported that for low-rise buildings with sharp edges (eaves, wall corners, etc.) tested under isothermal conditions, the pressure distribution would be independent of Reynold's number above a value of 2×10^4. In their study, the reference length used was the width of the building. This was consistent with the work of Choinière et al. (1988b) who recommended that a Reynold's number above 5400 should be used to maintain stable airflow patterns, using sidewall height as a reference length. According to Aynsley et al. (1977), Timmons (1984), Cermak et al.

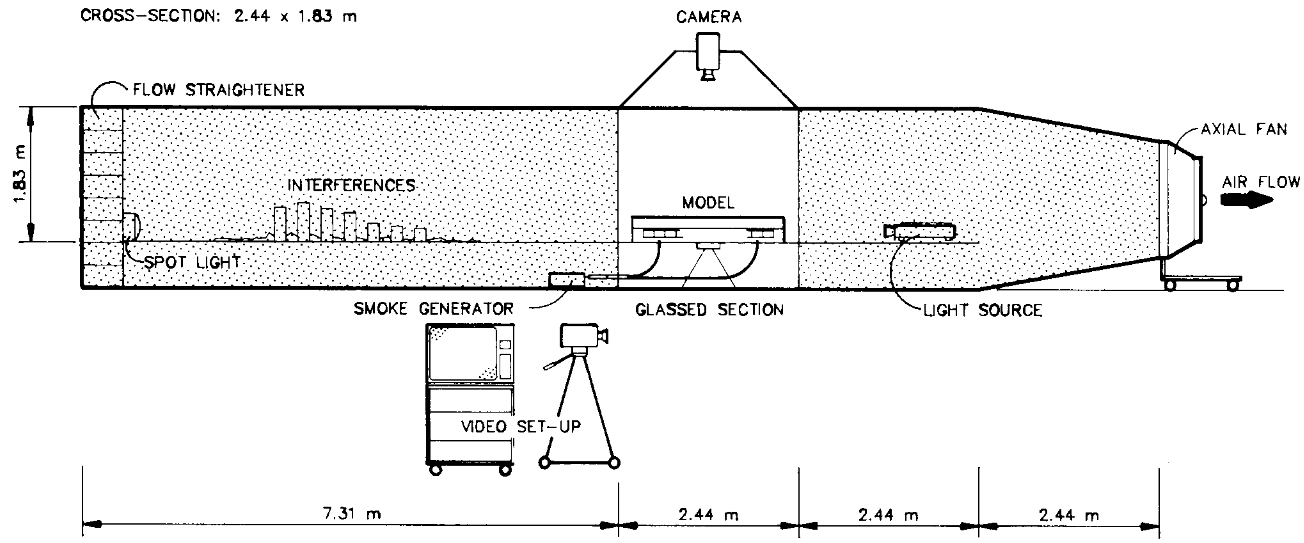

Fig. 2. Schematic diagram of wind tunnel.

(1984), and Iwaniw et al. (1986), changes in building geometry would alter the threshold Reynold's Number.

Preliminary tests were performed using wind speeds from 0.9 to 2.0 m/s in the wind tunnel. The airflow patterns within the model were not affected by this variation of wind speed indicating that the fully turbulent state was achieved. All subsequent tests were performed using a reference wind speed of 1.1 m/s. The computed Reynold's number for this wind speed was 7442 using the sidewall height as the reference dimension, or 44,700 using the building width as the reference dimension.

Observation techniques

A smoke generator (Smoker Model 2000, MDG Industries, Montreal, QC) was used to determine the airflow patterns. With this generator, dense, white, odourless, non-toxic, neutrally buoyant smoke, propelled by CO_2 under pressure, was introduced into the model through five 6-mm diameter perforated copper pipes. Lighting and video equipment were then used to monitor and record the airflow patterns. Video recordings were made using one camera for the top view and another for the side view.

Observations were made of general airflow patterns within the model and air inlet and outlet zones were noted. Airflow rates were not measured quantitatively. 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. Particular zones where smoke was slow to disperse were also noted.

Description of variables

Table I indicates the tests performed in relation to combinations of the following six construction 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 midlength; 5) ridge opening width; and 6) 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 degrees. 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. As shown in Fig. 1, pen partitions were solid except near the back of the pen, which would typically coincide with a slatted floor. Pen fronts were also 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 zones where smoke appeared slow to disperse. Such zones were noted near the windward end of the building, particularly when wind was parallel to the building length. To verify some possible winter management practices (Choinière et al. 1988a), situations with doors open on just the leeward or on both sides of the barn were tested.

RESULTS AND DISCUSSION

Figures 3 through 10 show the general airflow patterns in plan view near ceiling level and near floor level. Elevation views for the open ridge and for one or more cross-sections along the length of the building are also shown. On each drawing, the arrows show the general direction of air movement. Dotted areas indicate approximate zones where the smoke tended to take more time to disperse. According to Barber and Ogilvie (1984), these zones of slow smoke dispersion could be attributed to the transport of smoke from one region to another or lower local air exchange rates. In many cases, it was difficult to evaluate the relative contribution of each of these phenomena.

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 (Fig. 3a), 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

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 boths 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
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	30	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°, 60 windward doors closed	90	0/30	150	C	WC
	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 alleys
WC: Windows closed, WO: windows open

appeared uniform throughout the model except in the regions close to the centre alley partitions where the smoke took a long time to disperse. Similar observations were noted by Choinière et al. (1988b) and Choinière (1991).

For wind at 60° (Fig. 3b), some horizontal rotational movement occurred at both ends of the building but streamlines near the centre of the building did not appear to be affected by this rotational movement. A zone of slow smoke dispersion was observed at the windward end of the model. Air exhaust through the ridge was not as uniform as with wind at 90°.

As shown by Aynsley et al. (1977), Hellickson et al. (1983), and Vickery and Karakatsanis (1987), 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. As well, Choinière et al. (1990, 1992) and Choinière (1991) demonstrated that the sidewall and ridge openings have a strong influence in determining inlet and outlet zones.

The horizontal rotational movement observed for wind at 60° was amplified when wind was at 30° (Fig. 3c). For 30°, some air entered by the leeward doors near the leeward end. As well, the zone of slow smoke dispersion near floor level at the windward end was larger than for wind at 60°.

For wind parallel to the barn (Fig. 3d), air entered both sides of the building towards the leeward end, moved lengthwise, and exhausted towards the windward end. The air both entered and exhausted at the leeward end of the ridge, while the windward end acted as an exhaust only.

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 and Karakatsanis (1987) reported similar results and showed that the airflow coefficient for a naturally ventilated building was considerably reduced for wind angles of incidence less than 30°.

Effect of angle of rotation of the sidewall doors

Using a two-dimensional model, Choinière et al. (1988b) previously demonstrated that for winds perpendicular to the model, sidewall door opening angles of rotation of 15°, 30°, and 60° from vertical produced very similar interior primary airflow patterns. For all the conditions tested in the present study, there was no observable difference in the airflow patterns as a result of changing the door angle of rotation even though this increased the effective area of the sidewall openings. However, the rate of

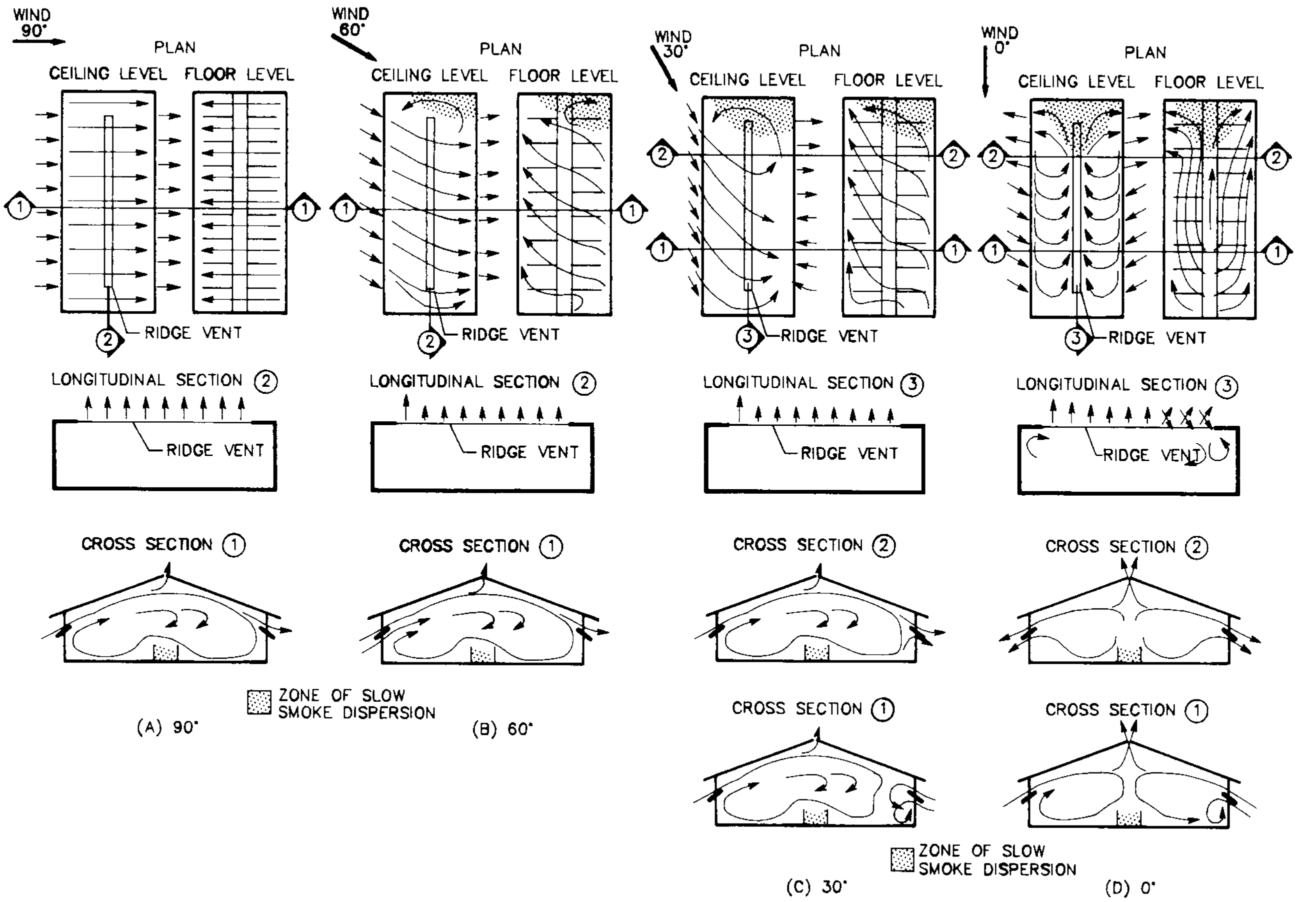

Fig. 3. Airflow patterns with standard ridge opening (150 mm full scale), doors open (30°) both sides, (a) wind at 90°, (b) wind at 60°; (c) wind at 30°; (d) wind at 0°.

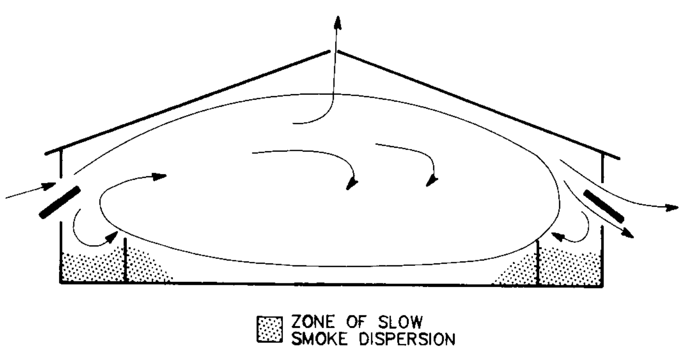

Fig. 4. Airflow patterns with side alley layout, solid pen fronts, wind angle of incidence 90°.

smoke decay was greater with door angles of 60° as compared to 15°.

Effect of centre 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. Some zones of slow smoke dispersion 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 (Fig. 5). The general airflow patterns in each of the two rooms were similar to those observed in tests without the central wall (one room) for any given wind direction. For wind directions of 0°, 30°, and 60°, the zones of slow smoke dispersion 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 rates.

Effect of a central wall with two open windows

As shown in Fig. 6, the addition of two openings (windows) in the central wall did not change the general airflow patterns from those shown in Fig. 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 zones of slow smoke dispersion 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 commonly used ridge opening width of 150 mm. Generally, the primary airflow patterns previously noted in Fig. 3 were not influenced by ridge opening width. However, the wider ridge

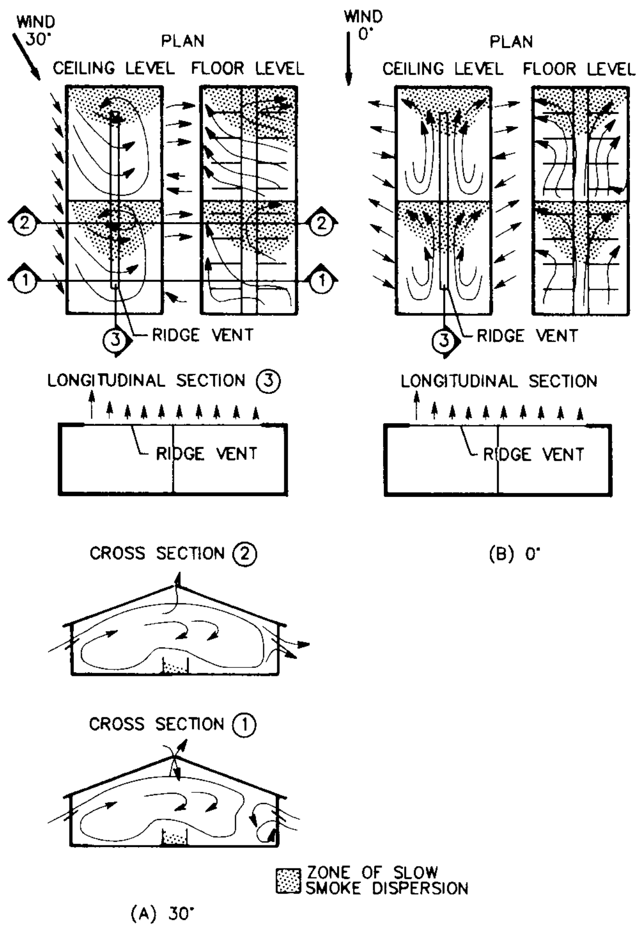

Fig. 5. Effect of solid wall at midlength; (a) wind at 30°, (b) wind at 0°.

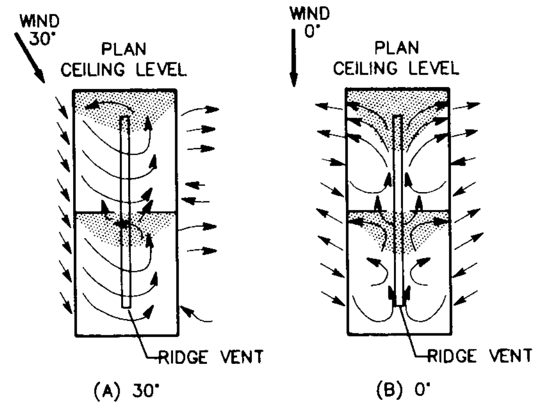

Fig. 6. Effect of openings in cross-wall at building midlength; (a) wind at 30°; (b) wind at 0°.

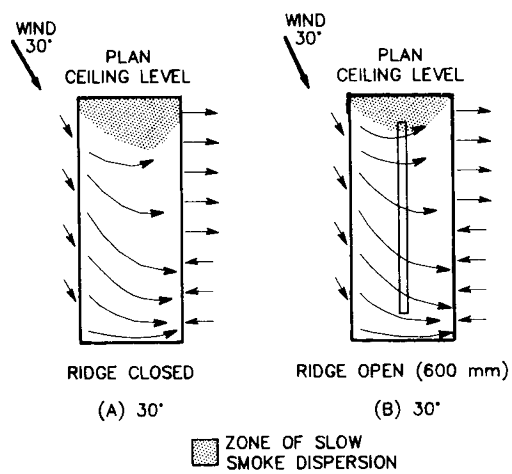

Fig. 7. Effect of ridge opening width.

opening reduced the zone of slow smoke dispersion at floor level at the windward end of the building (Fig. 7). Based on visual observations, the rate of smoke decay increased with the wider ridge openings, thus indicating an increase in the ventilation rate. Choinière (1991) and Choinière et al. (1992), using a pressure difference method, reported similar increases of ventilation rate.

Effect of ridge opening for the entire length of the building

A typical design such as Plan M-3433 (Canada Plan Service 1990) 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 the entire length of the building. Observations indicated that for wind directions of 0°, 30°, and 60°, having an open ridge for the entire length of the building decreased the size of the zone of slow smoke dispersion in the windward end of 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 practice, during summertime, opening the ridge for its entire length might help to enhance air quality near 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 Fig. 9 and comparing with Fig. 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 appeared to slightly increase the exhaust through the ridge especially for wind at 0°. A reduction or disappearance of the zones of slow smoke dispersion and a higher rate of overall smoke decay were observed as compared to without endwall windows. In practice, the addition of endwall windows could help reduce potential air quality problems at the windward end of the building during warm weather.

Effect of sidewall 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

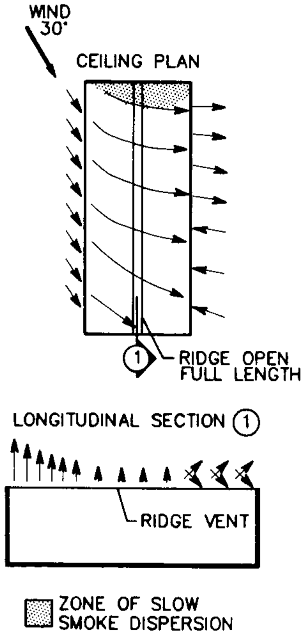

Fig. 8. Effect of ridge opening length.

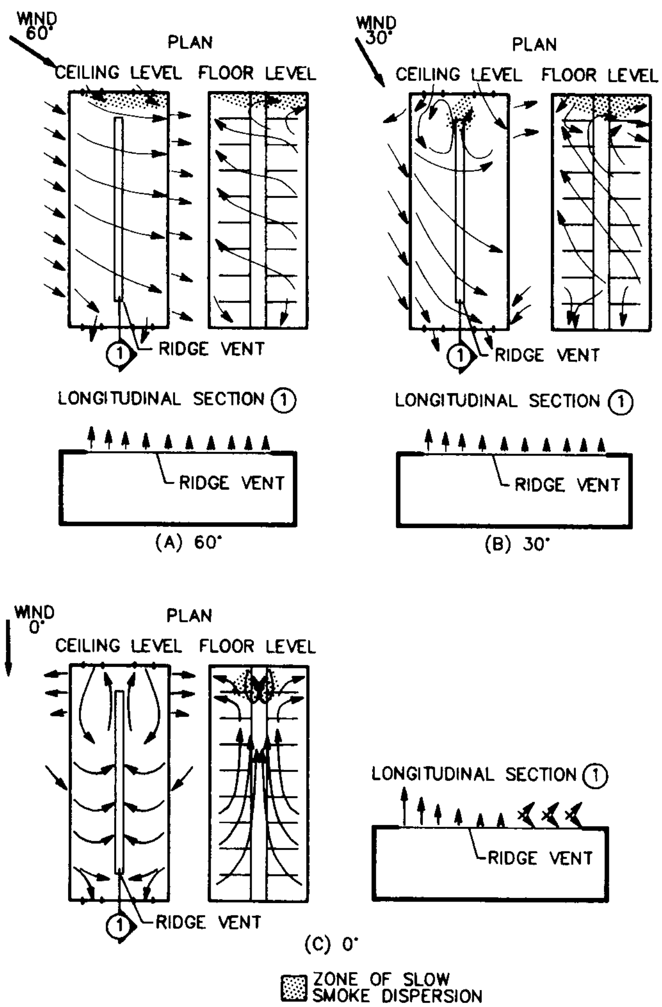

Fig. 9. Effect of openings in endwalls; (a) wind at 60°; (b) wind at 30°; and (c) wind at 0°.

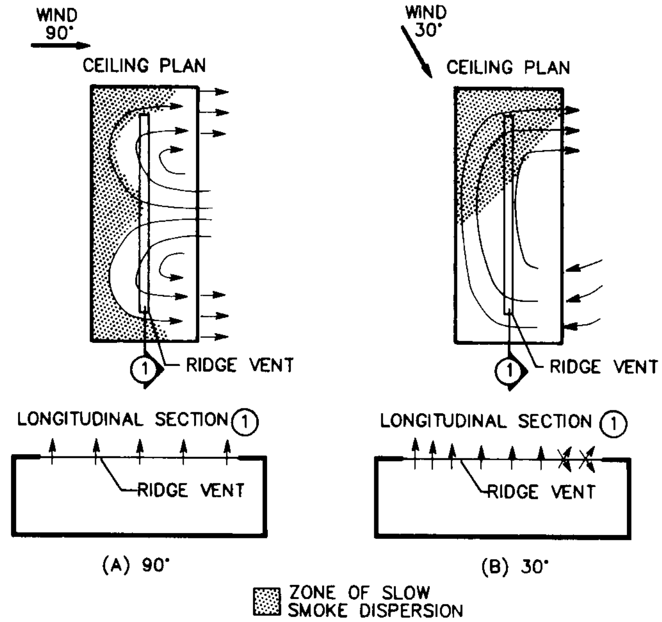

Fig. 10. Effect of doors open only on leeward side; (a) wind at 90°; (b) wind at 30°.

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. The same airflow patterns were observed for both ridge opening widths (150 and 300 mm full scale). 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 under isothermal conditions. 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. The airflow pattern over a barn cross-section varied along the length of the building for winds other than at 90°.
4. With no endwall windows, zones of slow smoke dispersion were always observed at the windward end for winds at 0°, 30°, and 60°.
5. Changing opening angle of the sidewall rotating doors did not greatly influence the airflow patterns, in spite of changes in effective sidewall opening areas.

6. Centre versus side alley layouts, with solid pen fronts, had limited influence on the air flow patterns.
7. 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.
8. The addition of two windows in this central wall reduced the zones of slow smoke dispersion observed in the leeward room.
9. 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.
10. Opening the ridge over the total length of the building as opposed to having it closed for a short distance at each end reduced the size of the zone of slow smoke dispersion at the windward end.
11. The addition of two endwall windows reduced or eliminated the zones of slow smoke dispersion in the windward end especially for wind at 0^o and 30^o.
12. It is possible (but not recommended) to ventilate a building using only leeward sidewall doors and a continuous ridge opening.

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