A wind tunnel study of airflow patterns in a naturally ventilated building

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Choinière, Y., Blais, F. and Munroe, J. A. 1988. A wind tunnel study of airflow patterns in a naturally ventilated building. Can. Agric. Eng. 30: 293–297. A simple wind tunnel was built to develop an airflow pattern visualization technique using a geometric scale model of a building. The tunnel was used to evaluate the performance of three different air inlet configurations for summer ventilation in a naturally ventilated building. These air inlet configurations were the following sidewall panels rotated about a horizontal axis to 15°, 30° or 60° from vertical, or vertical panels (simulating the common plastic curtain system) of four different heights. As well, the effect of small windbreak panels outside the sidewall opening was investigated. Wind speeds of 0.42, 0.64 and 2.78 m/s were evaluated. Results showed similar airflow patterns with either the rotating or vertical panels. The windbreak panels created some extra turbulence, especially with the larger openings, which improved mixing. A threshold Reynolds number of 5400 was established for a scale model of a naturally ventilated barn shown in Canada Plan Service plan M-3433.

INTRODUCTION

Natural ventilation is defined as "the movement of air through specified building openings due to the natural forces produced by wind and temperature difference" (Hellickson and Walker 1983).

Simango and Schulte (1983) stated that "the knowledge of the air flow pattern within a building helps to predict the effectiveness of a livestock ventilation system, and would enable one to better understand the animal's thermal environment".

Studies reported by Ogilvie and Boyd (1985) showed that during warm weather the stack effect becomes insignificant compared to wind ventilation. In this situation, a natural ventilation system depends essentially on wind pressure as its motive force.

Pattie and Milne (1966) used a 1:10 scale model of a poultry house to visualize air-flow patterns and to measure air velocities for different air inlet configurations. They demonstrated that at Reynolds numbers of 0.20, 0.65 and 0.91 times that of the prototype, there were no significant differences in either the airflow patterns or velocity distributions. The same observation was made by Timmons (1984) who established a threshold Reynolds number for a slot ventilated airspace under isothermal conditions.

Information on airflow patterns in wind-ventilated buildings for different air inlet designs is not readily available (Bottcher et al. 1985). Thus, a study to determine such airflow patterns for a naturally ventilated swine grower-finisher barn (Canada Plan Service plan M-3433) would be quite useful.

The determination of a threshold Reynolds number based on the observation of air flow patterns would allow the use of simple models for such studies provided appropriate limitations on windspeed were respected.

OBJECTIVES

The objectives of this study were as follows:

(1) To establish a threshold Reynolds number above which airflow patterns inside the model will be similar under isothermal conditions.

(2) To visualize isothermal (warm weather) air patterns for four types of air inlet using a 1:20 scale model of a naturally ventilated gable roof hog barn.

(3) To examine the effect of solid pen fronts along the center alley on air distribution patterns.

METHODS AND PROCEDURES

Visualization technique

Mitchell and Ross (1977), and Ogilvie and Boyd (1984) used a water flume to visualize the airflow patterns in naturally ventilated barns while Aynsley et al. (1977) and Simango and Schulte (1983) used a neutral buoyancy bubble technique in a wind tunnel.

Because of their high initial costs, neither of these two techniques was used in this study. Rather, a simple wind tunnel with smoke was used to allow qualitative determination of air patterns.

A simple $600 \times 600 \times 4000$-mm-long wind tunnel was built in the facilities of the Alfred College of Agriculture and Food Technology, Alfred, Ontario. It was constructed with a 38×89-mm frame and a cardboard lining and powered by a 0.1-kW axial flow fan. Wind speed was measured using a thermistor-based sensor. Speeds at four equally spaced points (Figs. 1 and 2) in the vertical direction were used to calibrate the wind tunnel and to establish an average reference speed.

The model was a geometric 1:20 scale reduction of a naturally ventilated grower-finisher barn (CPS M-3433) with a sloped ceiling. It was constructed of plexiglass and attached to a black wooden base.

Airflow patterns were visualized using a smoke generator burning mineral oil. The hot smoke was generated 3 m upstream of the wind tunnel inlet in an attempt to achieve isothermal conditions. The airflow patterns were observed as smoke moved into or out of the model. After filling the model with smoke, the smoke generator was stopped allowing observation of the
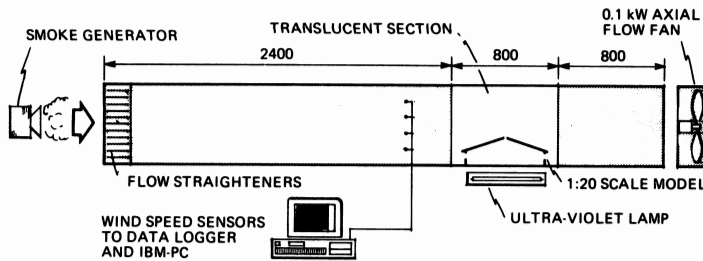
Figure 1. Wind tunnel. All dimensions are in millimetres.

model as it cleared. It was thus possible to visualize the dilution and mixing throughout the model. The tests were recorded on video tape for later analysis.

Reynolds analogy

According to Pattie and Milne (1966) and Timmons (1984), airflow patterns will remain constant above a certain threshold Reynolds number. Reynolds analogy provides the dynamic similarity for a geometric scale model. The Reynolds number is the ratio of the inertia to viscous forces in a fluid stream. It can be stated as:

$$R_e = \frac{VL}{\nu} \qquad (1)$$

where:

V = reference velocity (m/s);
L = reference dimension (m);
ν = kinematic viscosity (m²/s).

Simango and Schulte (1983) used the building length as a reference dimension in their wind tunnel study on a 1:12 scale model modified-open-front (MOF) naturally ventilated barn. They used four test wind speeds: 0.67, 2.24, 4.47 and 6.70 m/s.

Ogilvie and Boyd (1985) also used the building length as a reference dimension for their 1:10 and 1:25 scale models, and wind speeds equal to 2.5, 5.0, 7.5 and 10.0 m/s. They concluded that it was suitable to use scale models to simulate ventilation parameters in naturally ventilated barns under isothermal conditions. Bottcher et al. (1985) used the total building height as the reference dimension. For a 1:25 scale model of a poultry house, their calculated upstream Reynolds number was 20 000.

For this study, the height of the wall was chosen as the reference dimension as it allowed changes in inlet configuration
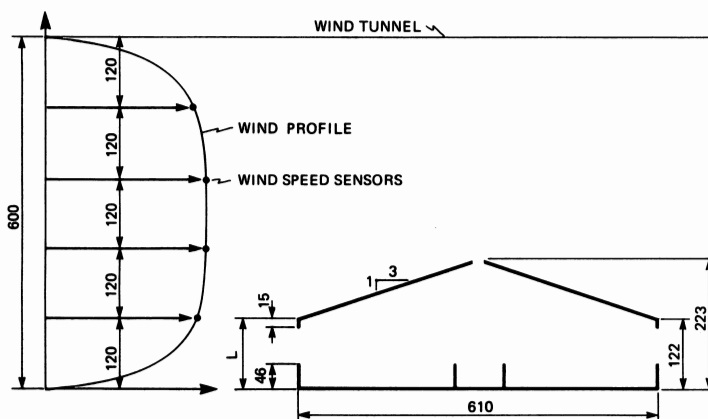
Table I. Reynolds number based on side wall height $L = 122$ mm

Average velocity (m/s)	Reynolds number†
0.42	3500
0.64	5400
2.78	23500

†$\nu = 1.452 \times 10^{-5}$ m²/s; $T = 15°C$.

without changing the Reynolds number. Three test wind speeds of 0.42, 0.64 and 2.78 m/s were used. Each of these was calculated based on the average of the four wind speed measurements (Fig. 2) of the wind tunnel velocity profile.

Table I gives the calculated Reynolds numbers obtained for this experiment based on wall height.

Inlets

Bird (1984) reported that most gable-roofed livestock buildings used either commercial above-center pivot rotating doors or site-built top-hinged doors while Kains (1984) showed a vertically adjustable plastic curtain for MOF swine buildings. Jedele (1979) reported the use of insulated solid vertical panels for gable roof buildings. Finally, Turnbull (1984) described gable roof barns in Australia using vertical plastic curtains with the addition of a weighted curtain hanging from the eave to act as a draft control.

For this study, above-center pivot rotating doors and vertical panels were selected for modelling because of their popularity. Doors were opened by rotating 15°, 30° or 60° from vertical (Fig. 3). Alternatively, vertical panels in the model could be adjusted to provide a slot opening of 2.5, 7.5, 19, or 30.5 mm (Fig. 4).

Simulations of a windbreak suspended from the eave were also performed. All linear measurements were scaled by a factor of 20 for the model. The various configurations tested are given in Table II. Only equal openings on both sides of the building model were tested.

Center alley pen fronts

A test was performed to visualize the effect of the center alley pen fronts on the ventilation patterns. Both solid and open pen fronts were simulated.

Figure 2. 1:20 scale model of hog barn, Canada Plan Service plan M-3433. All dimensions are in millimetres.
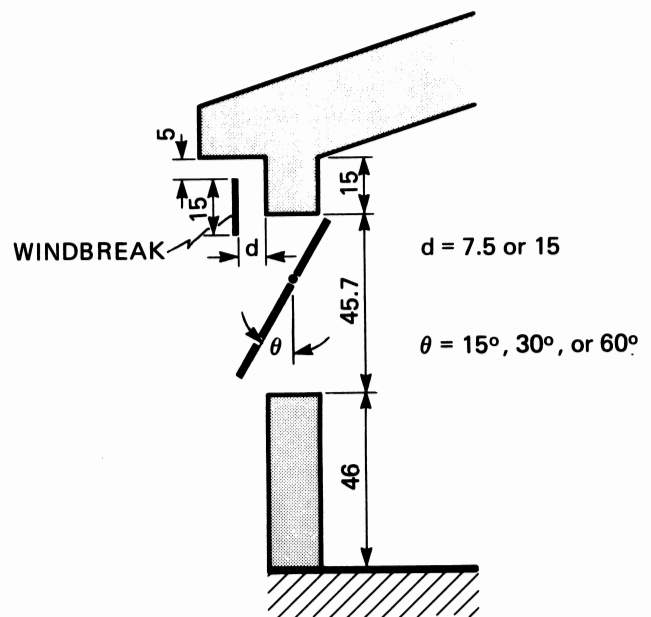

Figure 3. Angles of rotating door and positions of windbreak tested (1:20 scale model). All dimensions are in millimetres.
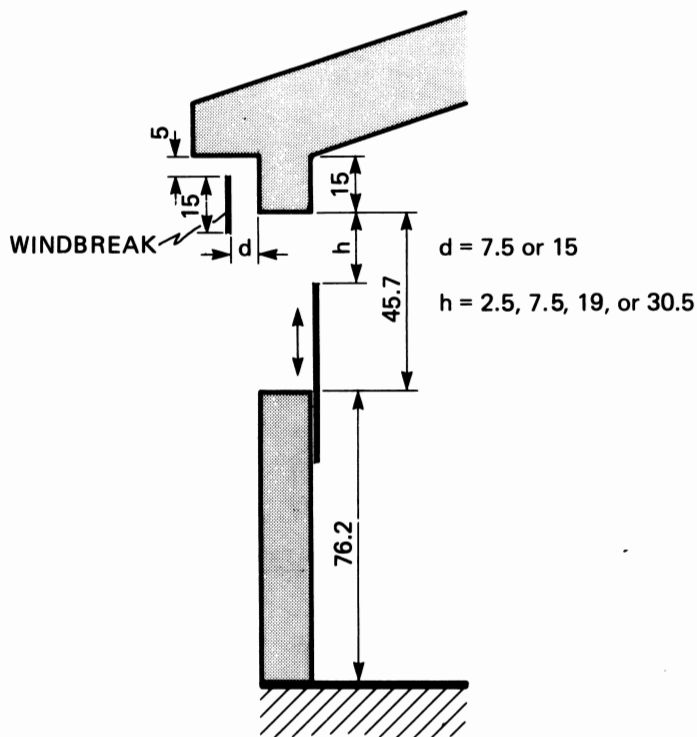
Figure 4. Positions of vertical panel and locations of windbreak tested (1:20 scale model). All dimensions are in millimetres.

d = 7.5 or 15

h = 2.5, 7.5, 19, or 30.5

RESULTS AND DISCUSSION

Reynolds analogy

With the 1:20 model tested, the airflow patterns were different between the low velocity of 0.42 m/s (R_e = 3500) and the two higher velocities of 0.64 and 2.78 m/s (R_e = 5400 and 23 500, respectively). The differences in pattern between velocities of 0.64 and 2.78 m/s were small. Since the Reynolds number was evaluated using the wall height as a reference dimension, a minimum Reynolds number of 5400 should be respected to obtain some stability for the air flow patterns.

According to Aynsley (1977) and Timmons (1984), changes in building geometry would require further model testing and an evaluation of another threshold Reynolds number. The effect of a horizontal ceiling for example could be studied in this fashion.

Table II. Air inlet configurations

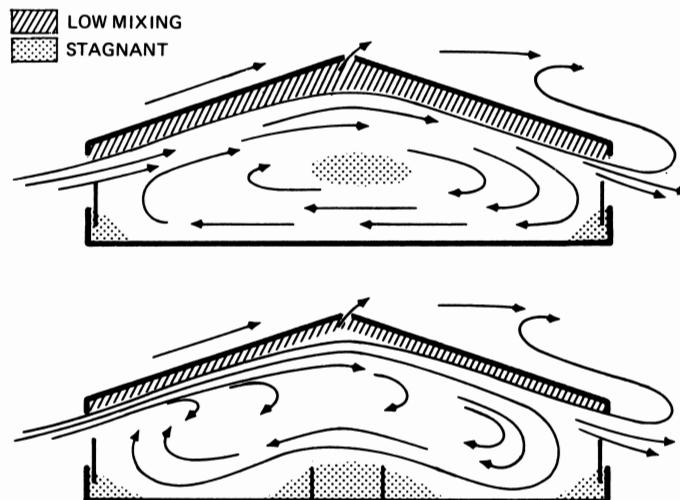| Rotating door inlet		Vertical panel inlet	
Rotation from vertical (degrees)	Location of windbreak from inlet (mm)	Opening width (mm)	Location of windbreak from inlet (mm)
15	None 7.5 15	2.5	None 7.5 15
30	None 7.5 15	7.5	None 7.5 15
60	None 7.5 15	19	None 7.5 15
		30.5	None 7.5 15

Figure 5. Effect of center alley solid pen fronts; inlet opening 19 mm; wind speed 2.78 m/s (1:20 scale model).

Effect of center alley solid partitions

The center alley solid partitions have a strong effect on the airflow patterns. As shown in Fig. 5, the solid partitions induce regions of circulating flow to the left and right of the center alley. These two regions appeared to reduce the size of the unmixed region close to the ceiling and of course the size of the stagnant zone in the center area. Since the partitions interfere with airflow the overall air speed inside the model was reduced.

Rotating doors

Figure 6 shows the airflow patterns for a wind speed of 0.42 m/s (R_e = 3500). The inside air movement is very slow. Only minor differences were observed in air patterns for the three angles of opening except that the 15° opening was more restrictive. The addition of the windbreaks induced more turbulence near the inlet.

Figure 7 shows the airflow patterns obtained for wind speeds of 0.64 (R_e = 5400) and 2.78 m/s (R_e = 23 500). The patterns for both of these speeds were similar. Both showed incoming air moving further across the barn before rotating than with the lower speed of 0.42 m/s (R_e = 3500).

The higher wind speeds induced many secondary rotational patterns within the model. They also caused more circulation close to the ceiling. Two main regions of circulation were located to the left and right of the center alley. A large portion of the main stream moved to the opposite wall and turned back towards the inlet side. No stagnant region was observed except in the alley between the two solid partitions. A part of the main stream also exited directly by the leeward wall openings.

There was no difference in the air pattern for doors rotated to 15° or 30°; however, for 60°, there appeared to be more air
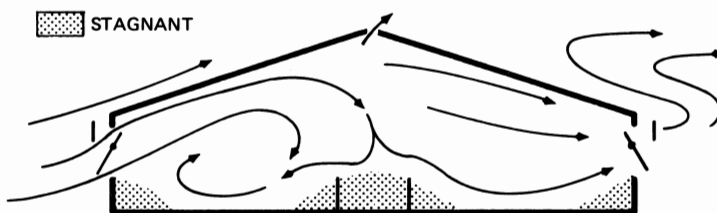

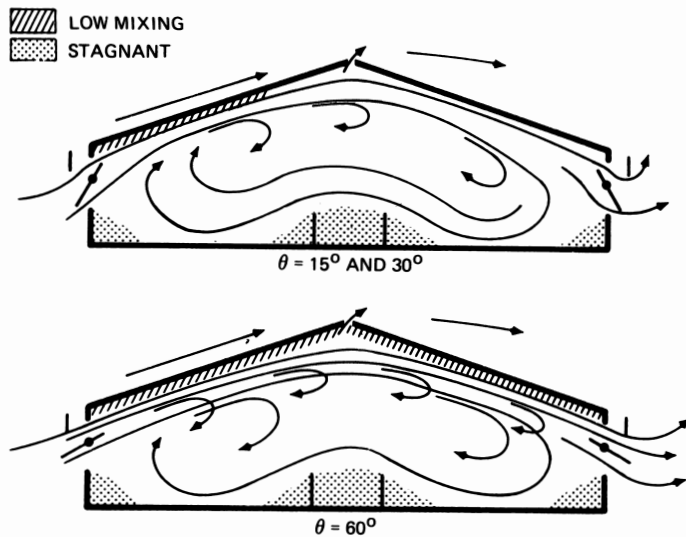Figure 6. Airflow patterns with rotating doors and windbreaks; 15°, 30° and 60°; wind speed 0.42 m/s.

Figure 7. Airflow patterns with rotating doors and windbreaks; 15°, 30° and 60°; wind speed 0.64 and 2.78 m/s.

Figure 8. Airflow patterns with vertical panels and windbreaks; wind speed 0.64 and 2.78 m/s.

moving directly from inlet to outlet along the ceiling. This was defined as a "short-circuit" by Barber and Ogilvie (1982). Ogilvie and Boyd (1985) also noted a drop in the mixing factor when the angle of rotating doors in the MOF model was increased.

The addition of the windbreak improved mixing in this region. With doors at 60°, and with the addition of the windbreak, this unmixed zone had essentially disappeared.

Vertical panels

For the lowest velocity (0.42 m/s) ($R_e = 3500$), there was essentially no difference between the airflow patterns for the rotating doors or the vertical panels. For very small slot openings (2.5 mm) patterns were difficult to observe due to the small quantity of smoke entering the model.

There was very little difference between airflow patterns for the higher velocities of 0.64 ($R_e = 5400$) and 2.78 m/s ($R_e = 23\,500$) (Fig. 8); however, both patterns were different from that for the low velocity of 0.42 m/s. The 2.5-mm and 7.6-mm-wide inlets produced excellent mixing. The main air stream followed the ceiling inducing patterns of secondary rotation. A portion of the main stream exited the leeward opening while a portion rotated back towards the inlet. There was no observable effect of the windbreaks on the airflow patterns, for the inlet openings of 2.5 and 7.6 mm.

The larger openings (19 and 30.5 mm) produced larger air streams, larger zones of circulation, and a thin unmixed region close to the ceiling. The addition of windbreaks improved mixing, and the unmixed zone close to the ceiling on the leeward side disappeared. The closest position of the windbreak ($d = 7.5$ mm) appeared to improve air mixing.

Air inlet configurations effect

Randall (1975) presented general rules that could be used to predict qualitatively the form of pattern to be expected for mechanical ventilation. These rules also apply to natural ventilation since the moving fluid is the same. He stated that primary paths from the inlet to the outlet create secondary rotations and that the design of the air inlet is the dominant factor controlling the airflow pattern. In this study the airflow patterns were similar using rotating doors or vertical panels; however,
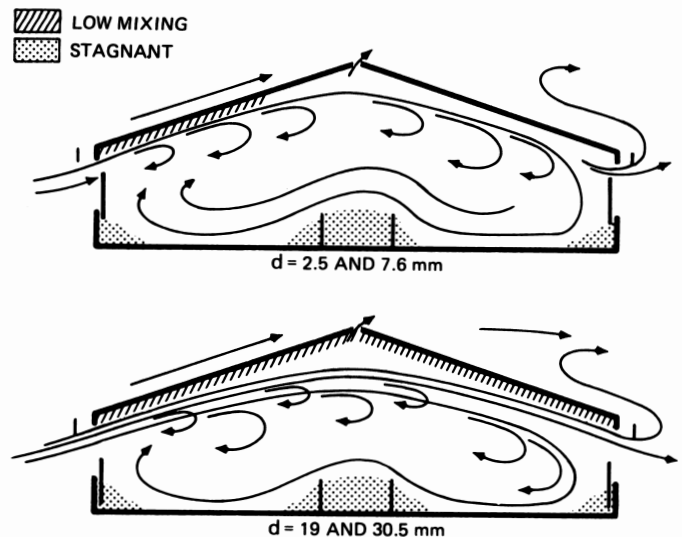
the rotating doors appeared to direct the incoming air more towards the ceiling resulting in less mixing as compared to results with the vertical panel.

In this study, clear zones were observed near the ceiling for the test with rotating doors set at 30°, and more so for 60°. Clear zones were also noted for the tests with vertical panels for openings of 19 and 30.5 mm. These clear zones indicate local areas of minimum mixing.

Windbreak effect

As noted by Turnbull (1984), the utilization of windbreaks outside the air inlets could be effective in improving air mixing when using the rotating doors or the vertical panels, particularly when the openings are large. The windbreak placed at 75 mm (model) from the opening had more of an effect than at 15 mm for both types of inlets.

CONCLUSIONS

Based on this model study, the following conclusions can be made:

(1) The threshold Reynolds number for the 1:20 model tested appeared to be between 3500 and 5400.

(2) The solid pen fronts created two zones of circulation, left and right of the center alley. This improved air mixing in the room.

(3) Similar airflow patterns were observed using either rotating doors or vertical panels for inlets.

(4) Unmixed or low mixing zones were observed near the ceiling when the rotating doors are set at 30° or 60° or when the vertical panels were opened at 19 or 30.5 mm.

(5) The addition of a simple windbreak improved mixing with both the rotating doors and vertical panels, especially for the larger openings.

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