A visualization study of flow patterns in a model of a modified-open-front (MOF) swine barn

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Iwaniw, M. A., Harrold, T. and Ogilvie, J. R. 1989. **A visualization study of flow patterns in a model of a modified-open-front (MOF) swine barn.** Can. Agric. Eng. **31**: 65–71. A water flume visualization study was conducted on a 1/10 scale model of a modified open front (MOF) swine finishing barn in order to determine the effects of inlet/outlet geometry on the interior flow patterns. The experimental configuration simulated isothermal conditions with the oncoming flow normal to the front of the building, at two values of Reynolds number (based on the size of the barn door opening), $Re = 25\ 000$ and 43 000. A hydrogen bubble technique was used, and the qualitative results were recorded on videotape. Three distinct flow patterns were observed out of a total of 24 configurations tested: (1) a totally recirculating flow, which occurred when the rear outlet door was completely closed; (2) a partially-blocked flow, which occurred when the rotating main door was parallel to the oncoming flow; and (3) a flow consisting of a primary stream through the model which induced a secondary, circulating region whose size depended on the door opening angle. The fact that these patterns can be classified implies that the flow distribution within a MOF structure may be predicted if the inlet/outlet geometry is known, and these predictions can be used in the design of effective natural ventilation systems.

INTRODUCTION

Ventilation replaces the warm, humid air inside a livestock building with fresh, cooler air from the outside. The resulting temperature control and decrease in relative humidity and gaseous contaminant concentration provide a favorable environment within the building for optimum livestock production and a comfortable working environment for humans. For effective ventilation, the outside air must mix completely with the inside air to "dilute" its contaminants. The fresh air distribution, and thus the extent of mixing, depends in part on the configuration of the air inlets and outlets.

Natural ventilation relies on pressure differences created by the wind and by buoyancy forces (the stack effect) to induce flow through a structure. Natural ventilation systems are attractive because of their low energy costs, but building flow patterns are unpredictable, resulting in incomplete fresh air mixing and poor ventilation efficiency.

Ventilation flow patterns can be obtained qualitatively by visualization. Randall (1975) conducted a series of experiments in a full-scale section of a gable-roofed, mechanically-ventilated livestock building. The tracks of neutrally-buoyant liquid-film bubbles were photographed using various time exposures; the resulting patterns indicated that air inlet design was the dominant factor in determining the airflow within the building. Koenig et al. (1978) and Choiniere et al. (1986) used chemical smoke in wind tunnel visualization tests of gable-roofed, naturally-ventilated buildings. Both reported small differences in flow patterns with different ventilation panel openings. Boyd (1985) studied both flow patterns and mixing in a prototype modified open-front (MOF) swine building located in Winterbourne, Ontario. Flow patterns were determined from a 1/25 scale model mounted on the sidewall of a water flume. Powdered aluminum on the water surface was illuminated, and the flow recorded on videotape. The flow patterns indicated that the degree of mixing appeared to be enhanced at smaller door opening angles. Ogilvie and Boyd (1985) confirmed this result quantitatively with tracer gas experiments in a wind tunnel. The rate of decay of tracer gas within the model increased as the door opening angle decreased.

Timmons (1980) stated that dynamic similarity between model and prototype is achieved with equal values of Reynolds number when only viscous and inertial forces are significant, and concluded (Timmons 1980, 1984) that models can be used to predict the fluid flow patterns in prototype structures. Many researchers have used the Reynolds number criterion for a variety of purposes: Simango and Schulte (1983) obtained flow patterns in 1/12 scale models of MOF swine buildings, and observed that the air moved in circular patterns; Bottcher et al. (1986) obtained pressure coefficients for a 1/25 scale model of a poultry barn in a wind tunnel. Pattie and Milne (1966) investigated air movements in a 1/10 scale model and prototype poultry house using chemical smoke to determine flow direction. They found that the model tests were a reliable means of investigating ventilation airflow patterns and that these patterns were independent of Reynolds number within the range investigated. (The definition of Re depended on the inlet configuration, and the range is not given.) Timmons (1979) examined the simplified configuration of a two-dimensional jet of air issuing into a rectangular enclosure using neutrally-buoyant helium filled bubbles. He found that the flow patterns became independent of Reynolds number (based on the inlet height and jet velocity) above a threshold value of $Re = 5500$.

An effective natural ventilation system can be designed if the flow patterns within the structure can be predicted. A three-phase research program has been initiated at the School of Engineering, University of Guelph, to attempt to predict these patterns. Phase 1 involves a flow visualization study to determine the flow patterns; Phase 2 deals with quantitative velocity measurements using models in a wind tunnel; and Phase 3 is the development of a computer simulation to predict the velocities and patterns determined in Phases 1 and 2. This paper reports the results of Phase 1, whose objectives were:

1. To develop a reliable, consistent technique of flow visualization within the School of Engineering at the University of Guelph;

2. To examine the effect of inlet geometry on the extent of mixing for MOF livestock buildings; and

3. To determine whether the flow patterns of this particular natural ventilation system can be predicted from the inlet/outlet geometry.

Objectives 2 and 3 were limited to summer conditions of isothermal ventilation due to wind pressure only.

EXPERIMENTAL PROCEDURE

The prototype structure for this study is the same as that used by Boyd (1985). A 1/10 scale model was constructed of 6-mm clear acrylic. Interior details such as the penning arrangement and floor type were omitted and exterior features, i.e., the various inlets and outlets, were simplified so that the inlet/outlet geometry was the only varying parameter in determining the flow. The main doors and the inlet and outlet baffles were adjustable by rotation, while the smaller inlets below the main doors were fixed (Fig. 1).

The experiments were conducted in the water flume at the School of Engineering, University of Guelph. The hydrogen bubble technique (Merzkirch 1974) was adopted for several reasons. First, the bubbles are not injected into the flow and so have no initial velocity or turbulent structure which might distort the ventilation flow pattern. Secondly, they can be generated steadily within the model itself, so that there is no constraint on their flow direction as is the case with a surface tracer. Finally, their small size (of the order of the diameter of the generating cathode, typically 0.04–0.1 mm in diameter) and low rise rate (1–2 mm/s) result in a long observation time (Wilkinson and Willoughby 1981).

The experimental apparatus and procedure were developed by Harrold (1985, unpublished report, School of Engineering, University of Guelph). The model was rotated 90° about its long axis, so that the model floor rested on the side wall of the flume. The front of the model was normal to the oncoming flow. In this position, a plane parallel to the water surface represents a two-dimensional "slice" of the flow (Fig. 2).

The hydrogen bubbles were generated by eight 0.12-mm-diameter stainless steel wires, 150 mm apart, running horizontally (with respect to the water flume) from the model floor to its roof. The wires were connected in parallel to the negative terminal of a DC power supply which delivered 5A at 35V. The positive terminal was connected to the metal frame of the water flume. The bubbles were created by electrolysis at the wire (cathode) and were swept away by the passing flow. Light from a high-intensity source was directed toward the flume wall, where it passed through a 2-mm slit located 70 mm below the water surface. This illuminated a plane parallel to the flow surface. A video camera was positioned above the water flume to record the streaklines formed as the hydrogen bubbles were swept away from uninsulated 25-mm segments of the wire. The flow was steady-state for each 5-min test period.

The buoyant velocity of the hydrogen bubbles was negligible compared to the velocity of the flow. However, it did cause the bubbles generated on one wire to rise out of the illuminated plane in approximately 1s. In the same time interval, the flow had reached the next downstream wire, where another set of streaklines was generated. When recorded on videotape, these successive streaklines combine to give a complete flow pattern within the model.

The 940-mm-wide water flume was operated at a constant flow rate of 36 L/s (600 gpm). Tests were conducted at water heights of 337 and 204 mm to obtain mean velocities of 0.11 and 0.19 m/s and Reynolds numbers (based on the size of the door opening) of 25 000 and 43 000, respectively. These velocities are equivalent to actual windspeeds of 0.14 and 0.25 m/s in the prototype.

The inlet and outlet settings for the various tests are shown in Table I. The outlet baffle had three settings: completely open (normal to the wall); 45°; and completely closed. The inlet baffle was either fully open (normal to the front wall) or closed. The rotating door had four positions, measured from the vertical: 30, 45, 60 and 90° (parallel to the oncoming flow). A total of 24 configurations at each Reynolds number was studied. Each test produced approximately 5 min of videotape, which was examined to determine the major features of the flow, i.e., stagnant areas, vortices, etc. These observations of the mean flow patterns were then transferred onto diagrams.

DISCUSSION OF RESULTS

A water flume simulation with a fixed model orientation limits the experimental results presented here to the case of isothermal ventilation due to a wind which is normal to the front of the building. This situation is most likely to occur in the summer, when the outside temperature differs from the inside temperature by only a few degrees. As well, the simulated wind speeds

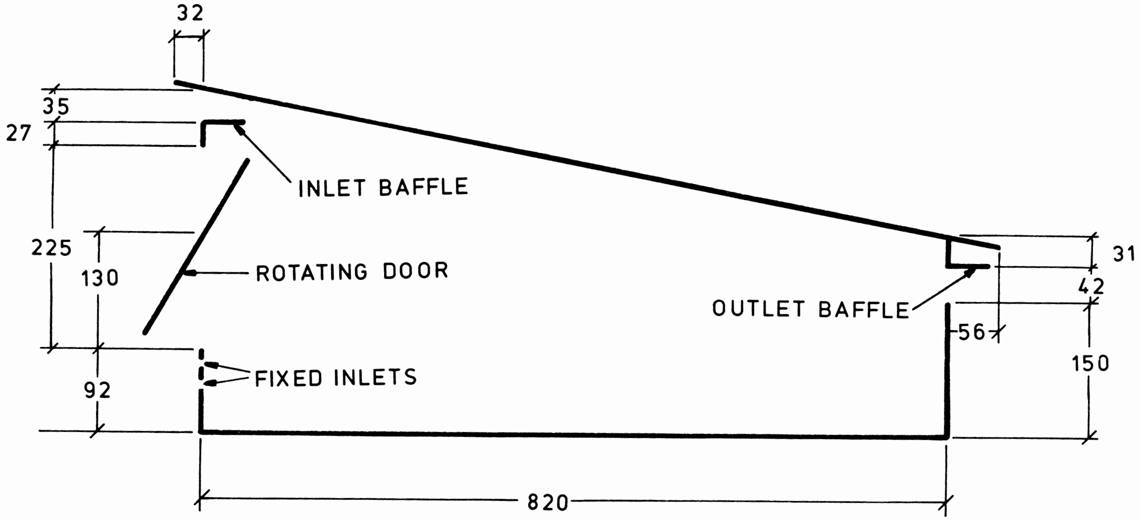

Figure 1. Simplified 1/10-scale model of a modified open front (MOF) swine barn.

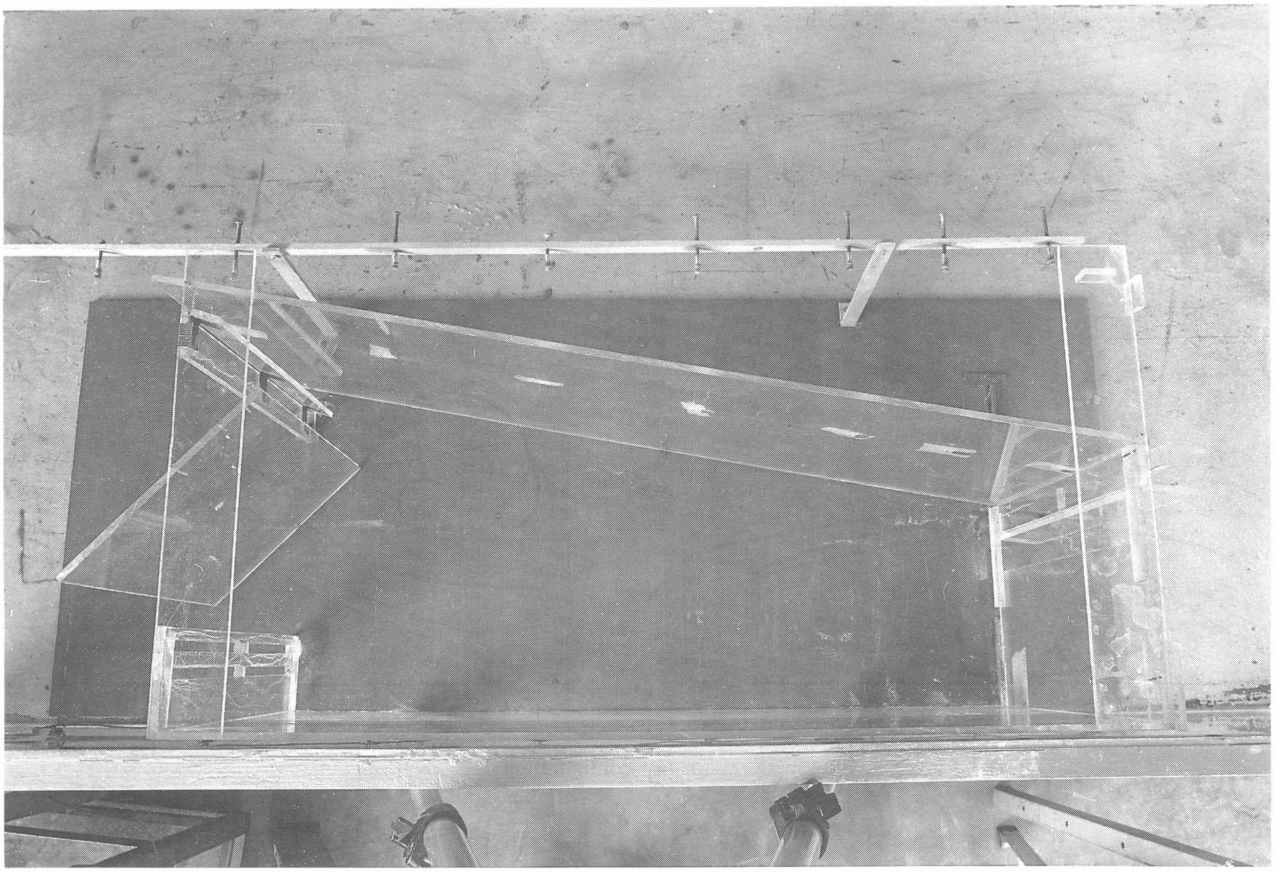

Figure 2. Scale model mounted on the sidewall of the water flume.

Table I. Test configurations

Test	Outlet baffle	Inlet baffle	Rotating door angle
1-1a	Fully open	Closed	30°
1-1b	Fully open	Closed	45°
1-1c	Fully open	Closed	60°
1-1d	Fully open	Closed	90°
1-2a	Fully open	Open	30°
1-2b	Fully open	Open	45°
1-2c	Fully open	Open	60°
1-2d	Fully open	Open	90°
2-1a	45°	Closed	30°
2-1b	45°	Closed	45°
2-1c	45°	Closed	60°
2-1d	45°	Closed	90°
2-2a	45°	Open	30°
2-2b	45°	Open	45°
2-2c	45°	Open	60°
2-2d	45°	Open	90°
3-1a	Fully closed	Closed	30°
3-1b	Fully closed	Closed	45°
3-1c	Fully closed	Closed	60°
3-1d	Fully closed	Closed	90°
3-2a	Fully closed	Open	30°
3-2b	Fully closed	Open	45°
3-2c	Fully closed	Open	60°
3-2d	Fully closed	Open	90°

are low when compared to actual wind velocities. However, Pattie and Milne (1966) and Timmons (1979) have shown that, if the flow within the building has reached a fully-turbulent state, the observed flow patterns are independent of Reynolds number or wind speed.

The experimental results for Re = 25 000 are presented in Figs. 3–8. Similar mean flow patterns were obtained at Re = 43 000, indicating that this flow was independent of Re. Thus, the patterns presented here can be used to describe actual flows at wind speeds of 0.14 m/s and higher. Each diagram is identified according to the test label given in Table I, and a flow pattern classification, I, II, or III, is indicated in the lower right-hand corner.

Three distinct flow patterns are evident. Pattern III occurs when the door opening angle is set at 90°, for all settings of inlet baffle and outlet. Pattern II occurs when the outlet is completely closed, for all settings of inlet baffle and door opening angle (except 90°). Pattern I occurs in all remaining configurations.

Pattern I (all configurations in Figs. 3 through 6, except those labelled ''d'') is characterized by a primary flow through the model from inlet to outlet. The inlet baffle (when open), the fixed inlets, and both the upper and lower door openings act as inlets. The flow through the inlet baffle and upper door opening is directed along the roof to the outlet. The flow through the lower door opening (which separates from the door at angles of 30 and 45°) and the flow through the fixed inlets is entrained by the upper flow midway along the length of the barn. This

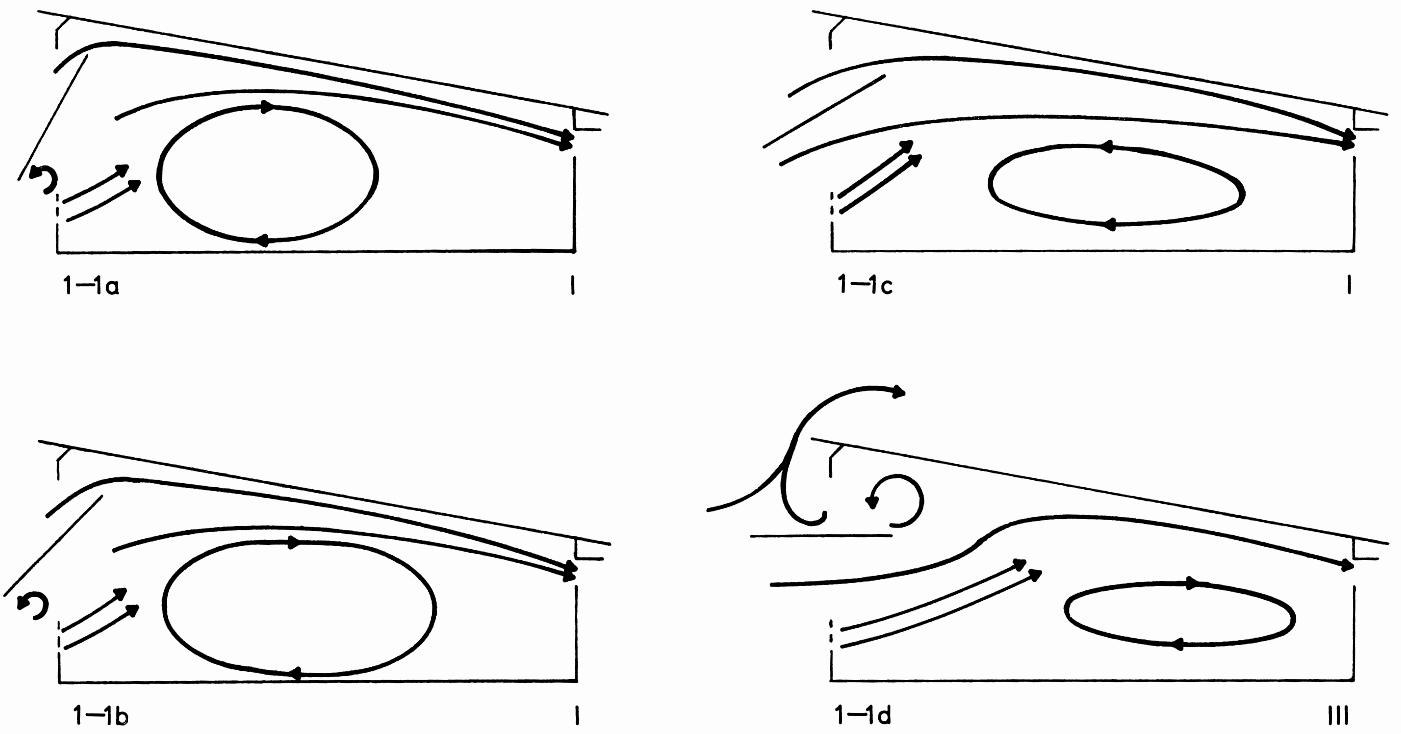

Figure 3. Flow patterns for test configuration 1-1. *Re* = 25 000.

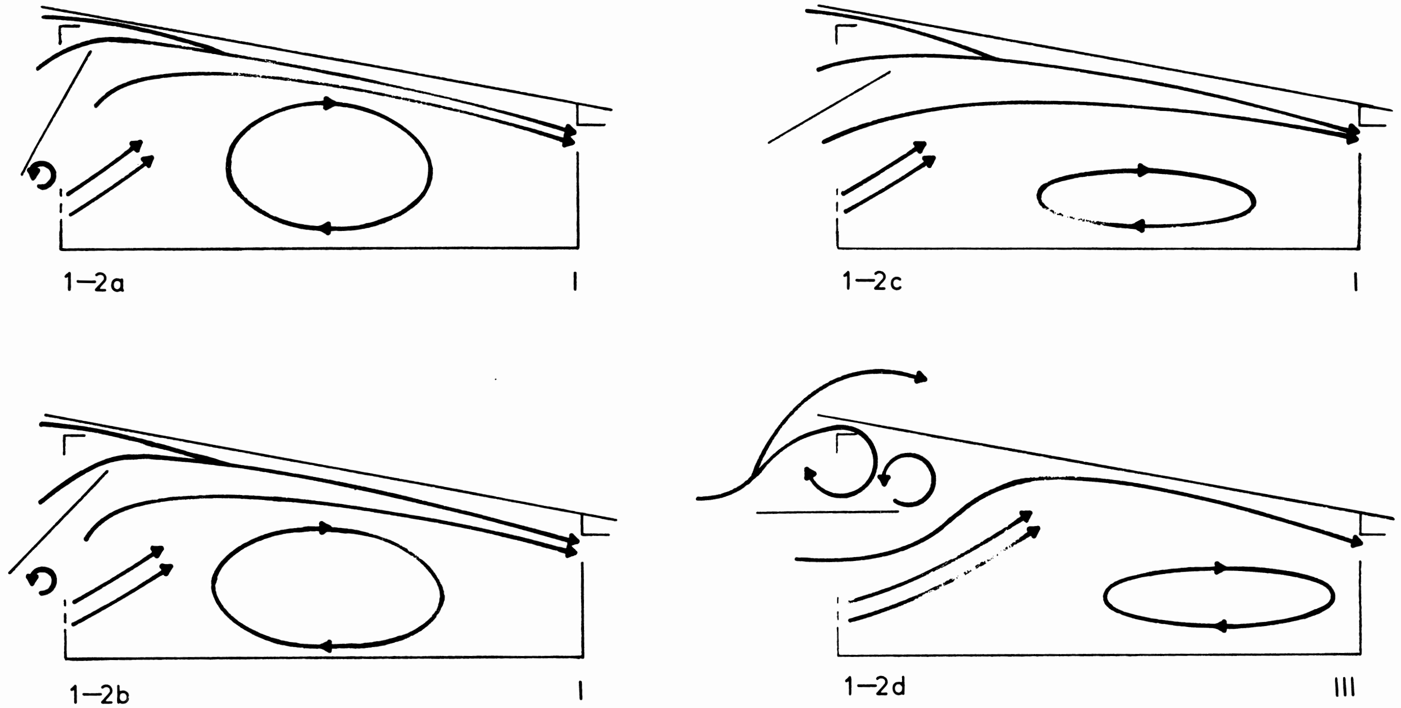

Figure 4. Flow patterns for test configuration 1-2. *Re* = 25 000.

primary flow induces a secondary flow, a large vortex, which occupies most of the central area of the model. There is a small stagnant zone in the rear lower corner. As the door opening angle is increased, the primary flow occupies more of the model: the central vortex becomes smaller, and the fluid in the stagnant zone is entrained by the primary flow. Mixing between the incoming flow and the interior fluid occurs in the central circulating vortex: a portion of the mixed flow is removed at the outlet; the remainder continues to circulate.

Pattern II (all configurations in Figs. 7 and 8, except those labelled "d") is characterized by a large, slow-moving vortex which occupies most of the flow area. The flow enters the model through the inlet baffle and upper door opening, follows the roof line towards the back wall, then moves down to the floor and returns to the front wall. The lower door opening and the fixed inlets act alternately as outlets and inlets. When the flow enters through these lower openings, it is entrained into the main circulatory motion. At the smaller door opening angles, the

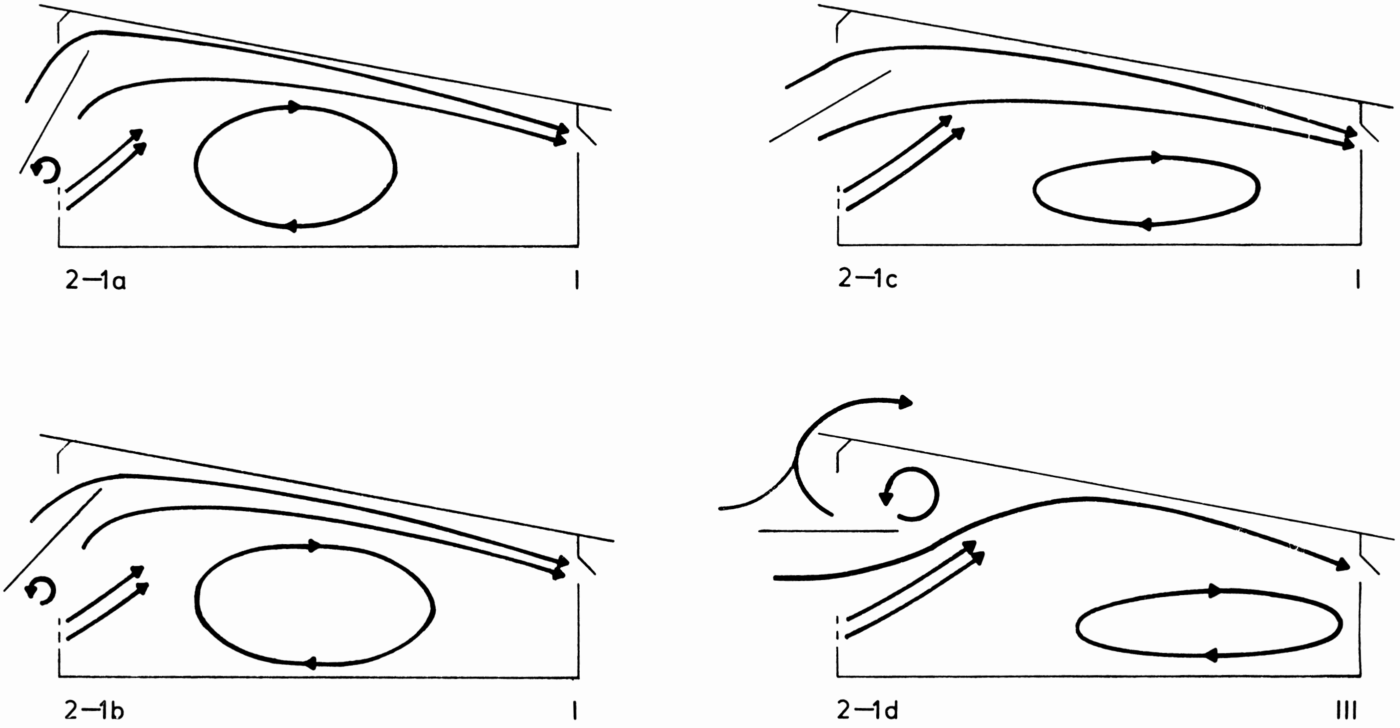

Figure 5. Flow patterns for test configuration 2-1. *Re* = 25 000.

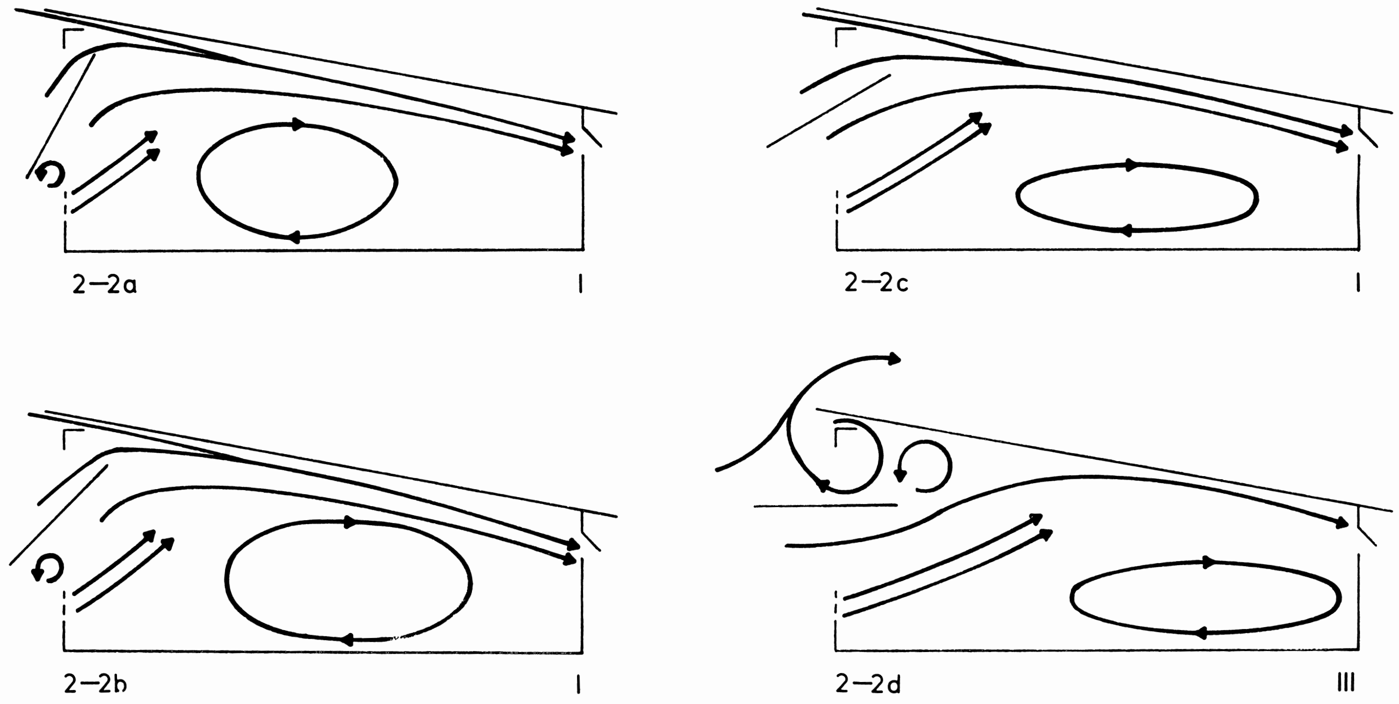

Figure 6. Flow patterns for test configuration 2-2. *Re* = 25 000.

motion does not extend to the back wall, and there is a stagnant zone in that region. As the door opening angle is increased, the flow does move to the back wall, and the fluid in the stagnant zone is entrained. There is very little flow into the model; the flow simply circulates around the perimeter, and mixing appears to be minimal.

Pattern III (all configurations labelled "d" in Figs. 3–8), with the main door at 90°, is characterized by a vortex at the trailing edge of the door. The flow enters the model through the lower door opening, moves toward the roof, and appears to divide. One part of the flow follows the roof to the outlet: the other moves back upstream to form a vortex above the trailing edge of the door. Both the upper door opening and the inlet baffle appear to behave as outlets. This unexpected flow pattern led to a further series of experiments in which the front portion of the model was examined more closely. These further observations have been incorporated into Figs. 3 through 8, in all test configurations labelled "d". They show that the inlet baffle

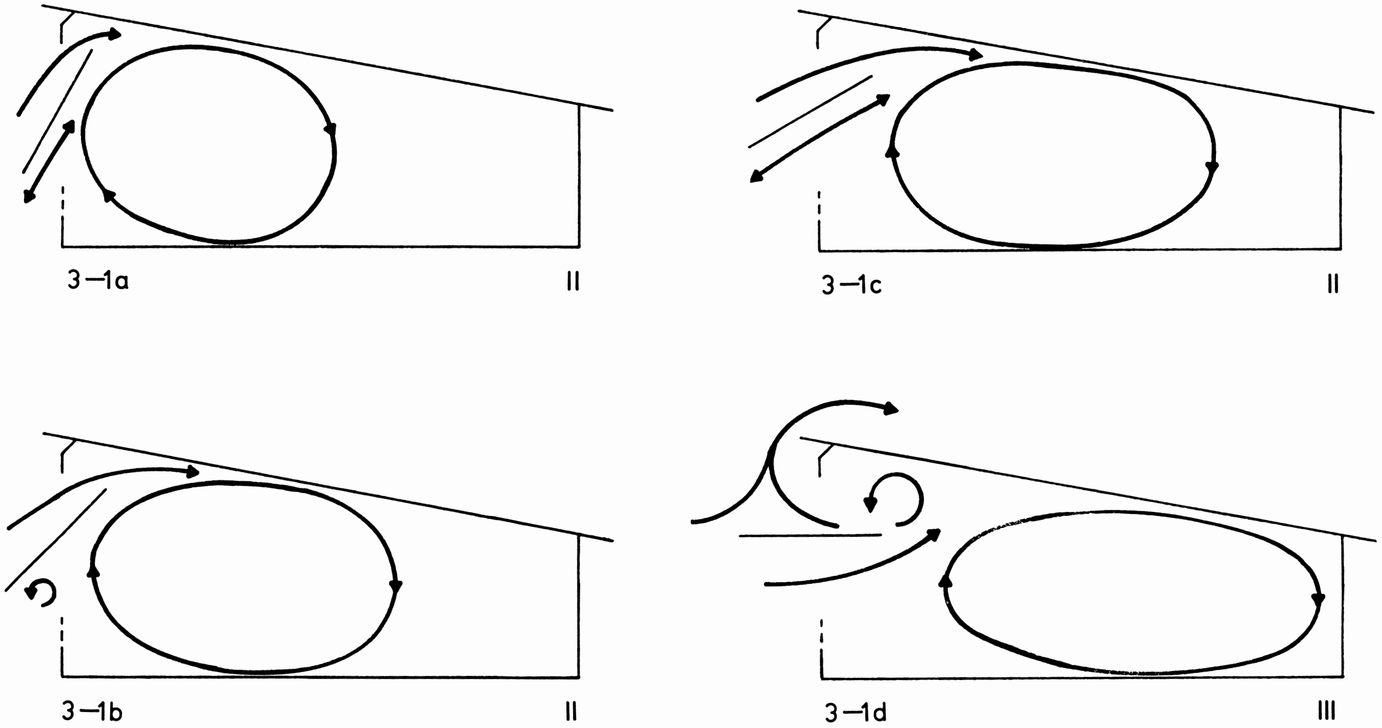

Figure 7. Flow patterns for test configuration 3-1. *Re* = 25 000.

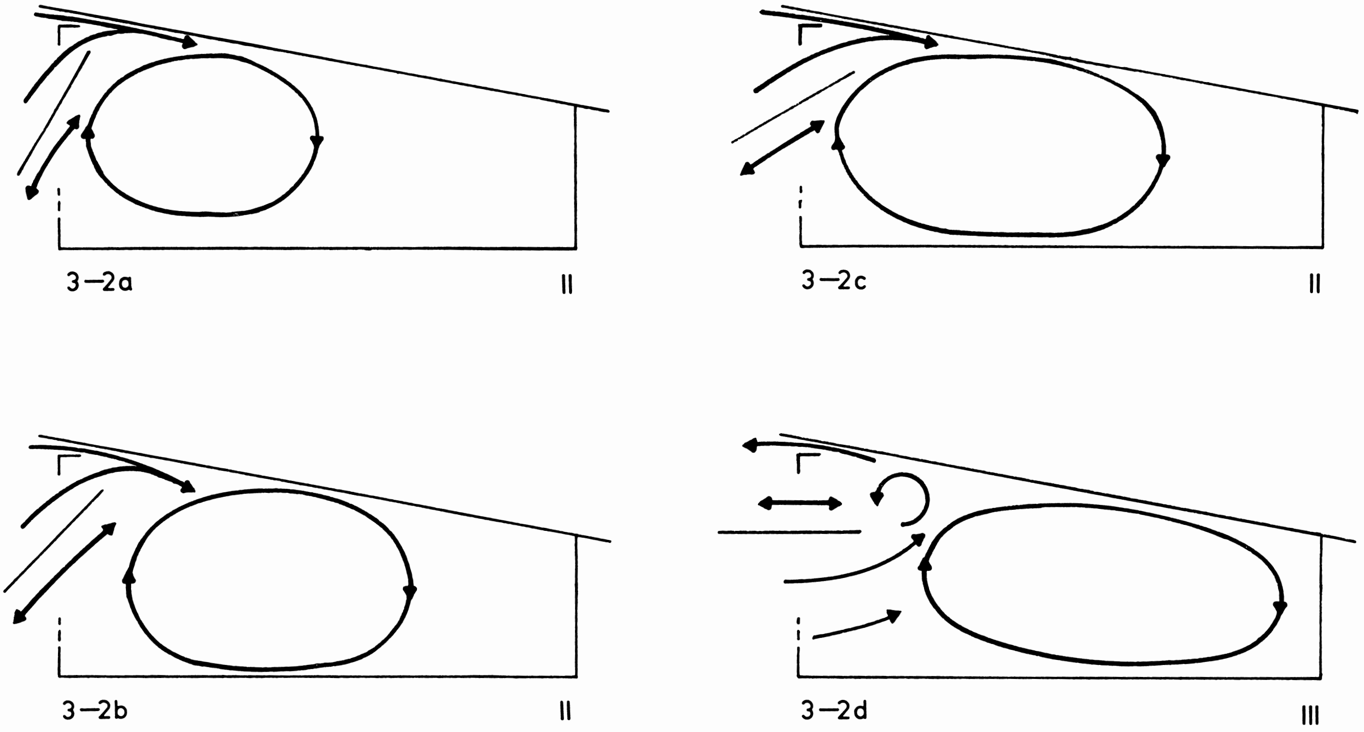

Figure 8. Flow patterns for test configuration 3-2. *Re* = 25 000.

is indeed an inlet, except in Test 3-2d when the outlet is completely closed. The vortex flow divides as it impinges on the door; part of it becomes a counter-rotating vortex above the leading edge of the door. This vortex acts as a blockage to the oncoming flow, which is diverted over the roof of the model rather then entering it through the upper door opening. The incoming flow from the lower door opening mixes well with the incoming flow, but, because of the restriction, may provide insufficient exchange for good ventilation.

Pattern III could have been the result of flow blockage in the water flume, since the model occupied approximately one-third of the cross-section. To test this possibility, smoke tests were conducted at the prototype during weather conditions closely approximating those of the water flume tests (isothermal flow normal to the front of the barn). The vortex at the trailing edge of the upper surface of the door was observed, indicating that it was not a blockage effect particular to the experiment, but an actual flow phenomenon.

For each test configuration, the flow patterns were the same for both Reynolds numbers (25 000 and 43 000). This implies that the flow within the model has reached a fully-turbulent state at some threshold Reynolds number which is below Re = 25 000. Timmons (1979) determined this threshold value to be Re = 5500; however, he subsequently stated (Timmons 1984) that the value depends on the actual physical size of the model itself. This seeming violation of the laws of similarity indicates that some other parameter, such as the pressure distribution within the building, has some effect on the flow.

CONCLUSIONS

With the limitation to isothermal flow normal to the front of the building, the objectives set out in the introduction have been met.

1. The hydrogen bubble technique is a reliable, consistent method of obtaining a qualitative picture of the flow patterns within a model of a livestock structure. (Objective 1)
2. Investigation of the inlet geometry, as described in Objective 2, shows that the flow patterns within a naturally-ventilated MOF structure depend strongly on the inlet/outlet configuration.
3. Three basic flow patterns were observed over the range (24) of inlet/outlet configurations studied. Thus it appears that the flow patterns can be predicted if the inlet/outlet geometry is known. (Objective 3)

The following conclusions may also be drawn from the observations:

4. With the rear outlet closed, the flow within an MOF building is a slow circulation with minimal incoming air (Pattern II). This may not provide sufficient flow for situations which require high rates of air exchange, such as summer (isothermal) ventilation.
5. Pattern III is not the result of the experimental configuration (blockage in the water flume), but a true representation of the flow. Further experimentation is necessary to determine whether the flow into the building, which is restricted, provides sufficient ventilation.
6. The recommended summer (isothermal) ventilation configuration is one which produces Pattern II. For low ventilation requirements, a small door opening angle may provide sufficient mixing to produce the required air exchange rate.

Flow visualization techniques can only provide a qualitative representation of fluid flow. Analytic techniques are necessary to quantify whether any of the flow patterns discussed above provides sufficient air exchange and ventilation, and these measurements will be the subject of future work.

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